DEVELOPMENT OF WOOD-CRETE BUILDING MATERIAL

BY

EBOZIEGBE PATRICK AIGBOMIAN

A thesis submitted for the degree of
DOCTOR OF PHILOSOPHY

Department of Civil Engineering
School of Engineering and Design
Brunel University
September, 2013

STATEMENT OF ORIGINAL AUTHORSHIP

All work in this thesis has not been submitted for any form of degree in any higher educational institution in the past. I do believe to the best of my understanding, that this thesis contains no material which has been published or written by another person unless due and appropriate citation has been made.

KEYWORDS

A number of words used in this thesis work shows how important these words are in relation to the subject matter discussed in this thesis. These include: Wood-crete, Tradical Lime, Sawdust, Compressive Strength, Thermal Conductivity, Water absorption, Sustainable, Affordable, Housing, Development, Materials and Waste.

ABSTRACT

Main concerns in the building industry includes the development of alternative building materials that reduces the amount of energy spent during manufacturing process and easier to work with.

Wood-crete is a composite material developed in this study, made up of wood waste (sawdust), paper, tradical lime and water. Wood-crete is developed to provide an alternative material in construction solving problems associated with the delivery of low-cost housing across all income earners, reducing the amount of energy spent during manufacturing process of construction materials and the ease with which these construction materials are developed and solve issues related to waste management. This thesis presents the processing technologies, factors which affect the performance and properties of wood-crete. Wood-crete properties were found to be closely related to the composition of the constituent elements though compressive strength and modulus of elasticity were low when compared to other building materials like concrete and steel.

In a bid to improve the strength of the developed wood-crete, the properties were investigated based on the modification of sawdust by hot water boiling and alkaline treatments which help to modify cellulose fibre surface to reduce the hydrophilic nature of sawdust thereby improving the sawdust-matrix bonding. It was found that the surface modification, processing of cellulosic fibril and the extraction of lignin and hemi-cellulosic compounds with alkali had an effect on the compressive strength of wood-crete, with treating sawdust with 4% NaOH at 140mins of boiling time achieving the highest compressive strength and boiling sawdust from 100mins to 140mins had a gradual increase in compressive strength but reduced at higher boiling time. Furthermore, treating sawdust with NaOH more than 4% weakened the individual wood particles thus leading to poor strength of wood-crete

Additionally, the properties of wood-crete were investigated based on the type of wood sawdust – hardwood (beech and oak) and softwood (pine and cedar). Apart from individual wood density having a significant effect on the density of wood-crete, other factors such as lignin, cellulose, hemicellulose contents including fibre length of individual wood species affect the strength properties of wood-crete. The compressive strength of wood-crete was closely related to the wood species, with highest compressive strength of 3.93MPa recorded for hardwood wood-crete compared to 1.37MPa and 0.26MPa of wood-crete from softwood and mixed wood respectively

Results from thermal conductivity tests on wood-crete also show that wood-crete blocks can be produced with good insulating properties for building construction. Addition of different types of paper fibres to reduce the density of wood-crete and improve the insulating properties of composite developed also had a dominant influence on both strength and thermal conductivity, reflecting its effect on the structure of composite and contribution of self strength of paper fibres. The addition of various percentages of waste paper (de-fibred) had a significant influence on the thermal conductivity of wood-crete with 75% addition of waste paper achieving a thermal conductivity value of 0.046W/mK performed with the TCi thermal conductivity analyser. Thermal conductivity results for wood-crete made from hardwood and softwood sawdust was closely related to the chemical composition of various wood species, with softwood wood-crete having about 20% lower thermal conductivity compared to hardwood wood-crete.

The developed wood-crete was able to withstand impact load and considered, like hempcrete, most suitable for wall panelling or other non- and semi-structural applications with good thermal insulating properties. Findings of this study provides an alternative new material for the construction industry and an important background for achieving better strength of wood-crete, choosing what type of sawdust to be used for development of wood-crete and for directing a better use of this potential material with very small embodied energy and carbon negative.

DEDICATION

This work is dedicated to my parents Prof and Mrs D.O Aigbomian who worked earnestly to making sure that I come to a successful completion of my program.

I also dedicate this work to my brothers and sisters (Ofure and Airudu - now married to the Chiejina and Okpasigbe's families respectively), Mr and Mrs Austin Chiejina and family, Mr and Mrs Nosa Okpasigbe and family, Dr and Dr (Mrs) Ehiosun Aigbomian and Family, Omonzejele Aigbomian and Precious Aigbomian. You all have really been wonderful.

ACKNOWLEDGEMENTS

As the famous quotation by Lao-tzu goes “A journey of a thousand miles begins beneath one’s feet”. It has been a truly remarkably and interesting journey which so many people have been part and parcel of. It is with an unbounded joy of a successful completion that I acknowledge those who were directly involved in the progress of this work and those I was a burden to throughout the course of my studies.

I am grateful to my supervisor Prof Mizi Fan - who has been an embodiment of knowledge, for his encouragement, guidance, constructive criticism, editorial inputs (proof reading and analytical comments) and the freedom he bequeathed to develop my ideas at every stage of my project. Accept my sincere gratitude for your immeasurable support, understanding, patience and kindness which exceeded human expectations and to a great effect, helped me through some very difficult periods. To my second supervisor Prof Luis Wrobel - accept my sincere gratitude for your assistance through my academic journey. It truly has been an immense pleasure working with you.

I express my appreciation to my adorable sisters Ofure and Airudu, who all through my studies became pillars of strength, I also did realise that you were not just sisters but mothers and people like you make the world beautiful. Thank you for your loving care, the early morning calls and encouraging me to forge ahead even through bleak moments. I certainly would not forget to say thanks to my sister Precious Aigbomian, for her delicious meals (in her attempt to make me stronger and more focused) during my visit to Nigeria in 2010. To my brothers Ehiosun and Omonzejele, you are indeed great chaps and I appreciate the jokes which always made me smile and kept me going through tough times. To my nieces and nephews, Chioma, Emeka, Efosa, Chinenye, Esosa, Ehiosa and Oseremen, I say a big thank you for your understanding that uncle needed to study and now I know you would have no complaints anymore.

My profound gratitude goes to my aunties and uncles too numerous to mention who never relented in their prayers towards my success. I would especially like to honour Late Francis Iyinomen and Mrs Atakpo who showed great support at the start of my project but are not here to share this joy with me. I know you are resting in the bosom of the Lord. To my friends, special thanks to you all and may we have many years ahead to celebrate each other’s success.

I will remain grateful to Pa Isiwele, Prof Simone Osuide and Arc. Gina Omoregbe of Ambrose Alli University, Ekpoma, Edo State Nigeria, you all were responsible for framing my academic mind-set and in many ways supported me through the course of my research by providing intellectual advice and who were great inspiration for this work. It is worthy to mention here that they were amongst the first to comment on the first draft proposal of this study in 2008 and have always been there to advice, encourage and inspire me towards the completion of this work.

To my dear parents – words cannot say how grateful I am to you and how wonderful you have been in all ramifications. I owe you a lot in life in all I do. You both have been supportive and making me realise how much you wanted me to achieve this dream of mine and becoming successful in life. I hope my dream which you also share has come through. I must say thank you for giving me this rare opportunity others crave for in life.

Finally, my deepest appreciation goes to God for His unending love, blessings and faithfulness upon me, my family and friends all through these years. May His name be praised both now and forever Amen.

Table of Contents

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AIDS	Acquired Immune Deficiency Syndrome
BBC	British Broadcasting Corporation
BUMPAN	Building Materials Producers Association of Nigeria
CO_2	Carbon Dioxide
CCHPR	Cambridge Centre for Housing and Planning Research
CHP	Centre for Housing Policy
CNN	Cable News Network
CQGRD	Centre for Quality Growth and Regional Development
CSJ	Centre for Social Justice
EEA	European Economic Area
FESTAC	Festival of Arts and Culture
FGN	Federal Government of Nigeria
FHA	Federal Housing Authority
FMB	Federal Mortgage Bank
FMBN	Federal Mortgage Bank of Nigeria
FRN	Federal Republic of Nigeria
GDP	Gross Development Product
GHG	Green House Gas
HDI	Human Development Index
HDM	High Density Fibreboard
HDPD	Housing Development Plan Document
HDR	Human Development Report
HIV	Human Immune Virus
HSU	Housing Support Unit
IMF	International Monetary Fund
IWM	Integrated Waste Management
LBM	Local Building Materials
LEDB	Lagos Executive Development Board
LFN	Law of the Federation of Nigeria
MDF	Medium Density Fibreboard
MSW	Municipal Solid Waste
MSWM	Municipal Solid Waste Management
NBS	Nigerian Building Society

NDP	National Development Plan
NEAP	National Environmental Action Plan
NEPAD	New Partnership for Africa's Development
NHF	National Housing Fund
NHP	National Policy Plan
NHP	National Housing Programme
NHS	National Housing Strategy
NPR	National Rolling Plan
OSB	Oriented Strand Board
PMI	Primary Mortgage Bank
RDF	Refuse Derived Fuel
REDAN	Real Estate Developers Association of Nigeria
SWM	Solid Waste Management
UNCHS	United National Centre for Human Settlement
UNDP	United Nation's Development Plan
UNEP	United Nations Environmental Program
UNESCO	United Nations Educational Scientific and Cultural Organisation
UNWSSD	United Nations World Summit for Social Development
UN-Habitat	United Nations Habitat
WAPCO	West Africa Portland Cement PLC (Now Lafarge WAPCO)
WBWDI	World Bank's World Development Indicator
WCED	World Commission on Environment and Development
WHO	World Health Organisation

CHAPTER 1 - INTRODUCTION

1.1 Background of Study

Conventional construction methods involve wasteful resource use and create both external and internal pollutions. Natural Building, one of several alternatives to provide low-cost housing with simple manufacturing process makes use of waste materials which have low impact and the use of renewable materials [1]. Globally, the use of mass materials like cement and concrete causes significant pollution, and consumes energy and non-renewable resources which tend to be wasteful. There have also been reported health concerns related to some insulation materials and finishes which contain toxic chemicals like brominated fire retardants that also affects the eco system [1]. The development of wood-crete building material which will provide an alternative option for the building industry will help solve the problem with conventional materials.

An approach to sustainable construction is to consider alternative methods of construction which significantly reduce the cost of construction, reduce resource consumption and provide energy efficiency without causing pollution, and damaging health and the entire eco-system. Presently being considered in this thesis is to develop a material which can be used in the construction of buildings whilst reducing cost in construction process and technology which minimise manufacturing process of construction materials. Natural materials are generally lower in embodied energy and toxicity than man-made materials and they require less processing and are less damaging to the environment. Table 1.1 shows some advantages of using natural materials when compared to the use of conventional building materials.

Table 1.1 Comparison of conventional and natural materials

Conventional building	Natural building
Uses non-renewable resources and materials	Uses renewable materials which can be grown and provide cash to farmers
Uses a lot of energy in extraction – high embodied energy	Uses materials which need little energy to extract
Significant transportation costs	Should use local materials
Extraction is often damaging and causes social problems	Uses materials such as clay which is of low impact
Many metals and other polluting materials are	Materials are extracted and processed locally

extracted and refined in poor countries and shipped to rich countries	
Significant energy and chemicals are used to create energy efficient solutions	Generally little energy used
External air pollution caused by manufacturing processes	Virtually no external pollution
Internal pollution due to the use of toxic additives like solvents	Natural materials rarely cause health problems if handled properly and not treated with toxic fire retardants etc.
Waste in manufacturing and installation is a normal part of processes	Little waste if care is taken
Damage to ecosystem at end of life disposal	End of life can be recycled or returned to the earth and decompose naturally

Though the above can be said of natural materials, it is important to note that in many developing countries, the use of modern materials such as concrete, steel, aluminium is considered a symbol of wealth and power and natural materials seems less able to meet these aspirations [1]. In addition, the extraction of natural resources as building materials or as raw materials for production of building materials and building materials production itself consume energy, cause environmental degradation and contribute to global warming [2].

This problem can be solved using two different approaches as proposed by Kim and Rigdon; firstly by making maximum use of natural resources already used for conventional building material production and secondly by use of waste materials. The latter approach seems more advantageous as it will help reclaim most of our environmental problems whilst creating a new product to be used in construction. Rather than producing buildings from conventional building materials, it is important to consider the recycling of materials to utilize the minerals and energy embedded in the materials which are termed as waste.

With considerations made on the use of natural materials for buildings; it is not possible to separate them with the delivery of adequate housing and sustainable development. Housing has been defined as a building or shelters in which people live, a place to live, a dwelling etc and to Nations, a critical component in social and economic fabric which represents one of the most basic human needs [3]. Housing, as a unit of the environment has a profound influence on the health, efficiency, social behaviour, satisfaction and general welfare of the community [4]. To a certain group of people, housing means just mere shelter while to others it means more as it serves as one of the best indicators of a person’s standard of living and place in society [5]. Across the globe, various housing forms have been influenced by different values such as people's culture, beliefs, religion, climate, urbanization and most recently, professionalism [6]. However, no matter the form or value that has influenced these dwellings; they are all geared towards achieving the same purpose of serving as a resting place, sleeping and family gathering and the day to day activities of the inhabitants. It has been postulated that housing not only provides shelter for a family but serves as a centre for its total residential environment, a focus of economic activities, a symbol of achievement and social acceptance and as an element of urban and income distribution [7].

Many nations are of a heterogeneous type of society comprising of ethno-geographical regions like the north, middle belt, east, west and south exhibiting different cultures and housing forms - due to trend of civilization, cultural infiltration and technological advancement [6]. Certain types of architecture are identified with certain groups of people either as a state or nation [6]. Architecture in this dimension could be seen as the art of design of buildings and structures for convenient human habitation and utilization. It is intended that wood-crete in a broad spectrum satisfies a trinity of architectural requirements in a user that is, his physical needs (satisfactory body reaction of feeling), his emotional needs (aesthetic and psychological) and his intellectual needs (logic, orderliness and flawlessness); hence the appeal to architecture to be both art and science [8].

As a result of population growth and urbanization, housing delivery, though becoming hard to achieve is still an essential part of everyday live and wood-crete technology developed in this study would thus help reduce the manufacturing process of building construction. In developing countries for instance, poor housing delivery can be attributed to a number of factors ranging from inadequate mechanisms and systems for land allocation, funding (materials for building), mortgage institutions and infrastructure [3]. Despite the importance of housing, its delivery to low, middle and high income earners has not been made any easy. A major obstacle to this is the increase in population and rapid urbanisation coupled with discrepancy in housing needs and supply. As part of some strategies to improve housing delivery system, it is suggested that an approach towards developing a cooperative model should be made priority [9], while some authors advocates for simple land allocation system and affordable financing model [10] [11]. The development of wood-crete, creates a model that provides a building material that resists impact load, reduces manufacturing process and the ease with which material is developed

In most developing nations, the population living in urban centres has increased over the years [3]. In Nigeria, (one of the fast growing developing nations), it is suggested that over 40% of her population now live in urban centres of varying sizes [3] [12]. The incidence of this population in urban centres has created severe housing problems, resulting in overcrowding of inadequate dwellings, high rents, poor living, degradation of the environment and in a situation in which 60% of Nigerians can be said to be "houseless persons" [13] [14] [15] [16]. The National housing policy Federal Ministry of Works and Housing, Lagos in FRN 1991 report, projected the urban housing shortage to be about 5 million housing units while the rural housing shortages stood at 3.2 million (a comparison of Nigeria housing deficit is presented in appendix 1. More recent United Nations study put the overall housing deficit at 17 million units while Nigeria National Bureau of Statistics estimates are between 12 and 14 million housing units [17]. These problems have also been exacerbated by excessive inequalities in the country with Gini index of 43.7%. Another aspect of the problem which is the gap between low and high income earners puts total expenditure of the poorest 10% to about 1.9%, that of the richest 10% about 33.2% whereas in a report by United Nations Development Programme, 2008 states that about 70.8% of Nigerians earned less than $1.00 (US dollar) a day between 1990 and 2005.

As suggested by various studies, a host of issues including poverty, unemployment, landlessness, homelessness, environmental degradation and other problems continue to plague developing countries. According to World Bank's World Development Indicator, *"1.4 billion people are living in extreme poverty—more than one-quarter of the population of developing countries. But countries and regions that have reduced their poverty rates are no less successful by the new measurements. In 1990, at the beginning of the period tracked by the Millennium Development Goals, 42 percent of the people in developing countries lived on less than $1.25 a day. Over 15 years global poverty fell by an average of 1 percentage point a year"* [18]. Countries with high poverty rate face a whole lot of challenges to achieve objectives of sustainable development and housing affordability.

According to United Nations Educational**,** Scientific and Cultural Organization, Sub-Sahara Africa and South Asia are the largest regions with a concentration of people in extreme poverty in the world [19]. Poverty is a major challenge making sustainable development elusive for many African countries and most countries on the continent do not fully benefit from the opportunities of globalization. For instance, it is observed that house ownership is one of the first priorities for most households which represent the largest single investment (between 50% and 70% of household income) [15]. In addition, since most tenants belong to the low income earning group (mainly in developing countries); it has become increasingly difficult to own their own houses from their insufficient, meagre financial resources. Many as a result have reverted to self-help housing development with the use of sub-standard building materials without employing the services of building professionals. In order to achieve sustainable development in Africa, the issue of poverty must be a priority. Thus, government development initiatives must focus on alleviating poverty in order to pave way for a self-sustained society. However, except by the implement-ability of sustainable policies in a long-term, achieving sustainable development might remain elusive.

Sustainable development on its own has gained currency in the last decade, particularly in the developed world [20]. Some of the many positive impacts seen from sustainable development and construction include increasing the efficiency of resource consumption and reducing the impact of buildings on human health and the environment [21]. Other benefits from sustainability include: the extended lifespan of a project, the lifecycle cost savings, and improved indoor environment quality. In the developed world, there are initiatives to promote sustainable construction and standards have been created with which to measure sustainability. The developing nations are however striving to establish themselves with a great chance to improve sustainable construction practices in order to avoid many of the problems that have been experienced in developed countries [22]. As the discussion for sustainable development continues, there is an added pressure on resources in developing countries which means construction work should be sustainable with zero mistakes [23]. The theory of **s**ustainable development was defined in the World Commission on Environment and Development as “meeting the needs of the present without compromising the ability of future generations to meet their own needs”. Most developed countries have viewed housing projects in this light as it is a norm that when considering sustainable projects, there needs to be the incorporation of economic, social and environmental issues in the planning and design stages with the aim of providing a building that is affordable, accessible and environmentally sound [24]. However, the reverse is the case for developing countries. The notion of sustainability needs to drift away from the construction of buildings and structures. As construction occupies land and uses minerals, water, technology, chemical processes and energy in production of building materials and use, there needs to be critical examination of its impact on the environment.

A number of authors have ascertained that to save energy; protect the environment; reduce pollution and conserve resources, the process of sustainable development needs to include sustainable design; sustainable planning; sustainable financing and investment; sustainable materials; sustainable tools, technology and methods; sustainable ownership and use; sustainable professional and labour practices; sustainable institutions thereby actualizing a sustainable end product. As a result of the fast rate of urbanisation experienced in most urban areas in developing countries and the increasing pressures on what can be referred to as limited resources, there is great necessity to make sustainable interventions now while built environments are being created, rather than try and change things after they have been built.

With the present rate of underdevelopment in developing countries, there is a great opportunity for development in these countries to avoid the problems currently experienced in the developed countries [23]. An undisputable fact therefore is that sustainable construction can happen in developing countries if only all the essential elements of design both technological and contextual enablers, energy/CO_2 pollution, water, health and well-being, materials management, surface water run-off ecology, waste are developed and work together to suit their design practices and policies. Various scholars have studied the challenges of sustainability and urban development. Some studies have focused on the challenges of a sustainable environment [25], others have centred on urban governance and the challenges of urban poverty [26], gender and urbanization [27], and sustainability and urban poverty [28]. Nevertheless, it is accentuated that the delivery of sustainable housing should begin from conceptualization where housing is to be considered both as a product and a process, which takes into account the economy, social and psychological phenomenon of all parameters [29].

Achieving sustainable development has to do with having a responsive housing policy which should be in consonance with the existing national and socio-economic realities of a country. To put this in perspective, there needs to be a push for greater participation of ordinary citizens in the affairs of cities and town through a degree of power decentralized to local authorities (public participation). Existing policy or programmes should be reviewed and reinvigorated to ensure adequate sustainable infrastructural development alongside housing delivery as well as the overall urban development [30].

1.2 Statement of Problem

Issues of housing delivery in relation to cost, the manufacturing process of materials, environmental impacts from building and building materials are a major concern in the construction industry both internally, locally and globally, most especially when achieving low-cost housing and shelter-for-all. It is imperative that every rich and poor person or family should be able to afford a home, which may resist the rigors of climate and environment, and must not cause a hazard to at least the occupants. With the extraordinary rise in population, number and size of cities over the past few years, there is acute shortage of dwelling units which has resulted in overcrowding, high rents, poor urban living conditions, low infrastructure services and indeed high crime rates.

Taking a look at the developed countries using England as an example, more than two million people find their rent or mortgage a constant struggle with 1.4 million children living in bad housing [31]. In addition, 7.4 million homes in England failed to meet the Government's Decent Homes Standard which meant many households had no choice but to live in poor conditions, which had severe damage to their health and often posed dangerous hazards [32]. In 2008 / 09, 654,000 households in England were overcrowded and in 2009, the height of the economic problem across the globe, the number of repossessions rose to 48,000 from 25,900 in 2007 [31]. Overcrowding, has a detrimental effect on family relationships and health, as well as a damaging influence on children's education and emotional development.

The rapid up-swing in the prices of building materials in the last five years has further reduced the affordability on housing [15]. Construction materials and housing design play a crucial role in the bid to address housing problem. In some countries, total cost of materials on construction is about 75 per cent [33], though the cost of construction is generally about 50 to 70 percent. Some of the factors contributing include inadequate infrastructural facilities which may increase the cost of delivery of materials and the tariffs charged on the materials also shoot up the prices [33]. Further evident is that as estimates of housing projects are determined largely by the cost of building materials involved, most developers, individuals or corporate bodies have been compelled to use modern materials because of unavailability of generally acceptable local materials that can stand the test of time [33].

As the major building material used in construction is cement, in developing countries like Nigeria, does not produce enough cement domestically (appendix 2 and 3) to meet demands making it one of the world's largest importer of cement though with restriction of 70.5%

dependence on importation [15]. The minister of industry, trade and investment Dr Olusegun Aganga was quoted in ThisDay live newspaper on 29th May 2013 [34] that Nigeria now exports cements and production rate of cement is on the increase though statistical figures are yet to verify this claim. The chances of the local industry rising to the task remain very slim as only four out of the seven of the cement companies in the country are still limping along at various levels of capacity utilisation. While various factors such as artisans, craftsmen and various building materials that contribute to the overall cost of building are on the increase, it is alleged that most people are not able to afford a house/home due to the high cost of production including labour force like masons, painters, carpenters, plumbers, electricians, site labourers and materials [35]. It is therefore imperative to consider innovative ways to reduce cost in construction where possible in other for low income earners to be able to afford a house or home.

One way of combating this problem will be to look into the use of materials made out of waste and which is readily available for use. There will also be need to conserve materials, reduce their unnecessary use, make them last longer, recycle and reuse them. All of these, being considered in the development of wood-crete building material will go a long way in cost reduction of houses as materials used will be from waste thus reducing purchasing cost of materials and low level of technicality in assembling. The above shows that there is the need to focus and encourage the use of local materials that could be more effective in providing decent housing to households. There is also the need for policy and decision makers to have deeper understanding of the forces that influence and shape housing affordability of different income earners within a society. There is no doubt that large-scale development is needed to address issues such as adequate housing, rapid urbanisation and lack of infrastructure.

It is true that these problems need to be addressed in a way that is socially and ecologically responsible. One major problem facing developing countries today is macro-scale factors. These factors include: Political instability and in-transparency in governance leading to corruption in bidding, tendering and contract awards having a great negative effect on sustainable construction among other facets of socioeconomic life. During violence, people, buildings and settlements are often the first targets which have adverse on:

- Rendering people homeless and creating a growing refugee population which increases the demand for emergency shelter and settlements.

- Reducing the lifespan of buildings, either through actual destruction or lack of care and maintenance.
- Reducing incentives to invest in property development and maintenance.
- Reducing incentives for research and training, while contributing to the exodus of existing capacity.

Also central to the achievement of adequate provision and distribution of housing is the issue of managing the relationship between the price of housing and the capacity of household to pay for housing [36]. With over 1.7 million households currently on local authority housing waiting lists in England, and a huge under-supply of family-sized properties, the only solution to the current housing crisis is to build more homes [37]. In a bid to achieving housing for all, it becomes a responsibility for the government, private developers and designers to make this attainable. While the government makes regulations, policies and subsidiaries for housing, designers in the construction industry must also try to bring innovative ideas of minimising construction cost through the use of local materials as modern construction materials are on the increase. The use of waste in the manufacture of wall panels may serve as one of many solutions to not only solve the problems of waste management but also present solutions to the construction industry to attaining sustainable designs and affordable housing. A barrier to this is the reported low strength properties of some low cost composite materials like hempcrete which wood-crete being developed in this study tries to solve.

1.3 Objectives of Study

The primary objective of this research is to develop a new building material (wood-crete) using sawdust, paper and tradical lime for wall construction. Material thus developed is aimed at having optimum strength and lightweight, thus improve thermal conductivity and reduce heat absorption of wall whilst enabling people across all levels of income to be able to afford sustainable and healthy homes. Other specific objectives of this research include:

- ❖ To identify concerns with issues related to waste materials and how they can be used to achieve effective housing delivery by:
    - Reviewing the use of waste materials with major focus on the use of sawdust and paper waste.
    - Understanding the technology associated to combining sawdust and binders for building applications.

- To investigate the bonding strength between fibres and matrix for enhancement of strength properties of composite materials
- To develop and identify comprehensive products and models (material technology). Within this scope, this research focuses on the following aspects:
    - Determining the effectiveness of surface modification by alkaline treatment and water boiling treatment of sawdust
    - Understanding the developmental stages of determining the application of the developed material.
    - Examination of the developed material for insulation purposes
- To investigate the effect of different wood species on strength properties of composite.

It is expected that in this research, the current problem of housing delivery will be identified and addressed with use of waste materials namely sawdust and paper leading to a faster manufacturing process of composite, ease of manufacturing, achieving good strength properties and thermal conductivity properties. The combination of these two materials would lead to the development of a composite material “wood-crete” which would enable this researcher to make useful recommendations regarding the use of a new building material in the construction industry, environmental potentials of the new building material and the utilization of waste materials as value added products.

1.4 Research Methodology

The research design directs the research strategy by defining an action plan and propounding how answers to research objectives would be achieved. An initial literature review was done to determine relevant information associated with the concept of achieving housing delivery. Focus on literature is based on housing and the possibility of using waste to develop composite material for low-cost housing.

As the research mainly focuses on the use of waste materials, part of literature review is on waste materials in relation to the construction industry. Within this section, wood and paper wastes (main materials for this research) are reviewed giving a significant insight on different ways these waste products have been used and managed. The availability of wood and paper wastes are carefully investigated as they are of crucial importance to help establish the viability of these materials being used in the course of this study. The use of wool fibre and chicken feathers were at first considered during investigation.

Furthermore, a review on technology on the use of inorganic binders for building materials is carried out with the aim of ascertaining various processes of how composite materials have been developed in the past. Within this section, major factors such as hydration, compatibility and particle geometry which affects wood and inorganic binders for instance Portland cement are investigated. This provides a background for analysis of various types of sawdust treatments carried out to improve strength properties of wood composite. This study also makes extensive use of laboratory experiments designed to determine the viability of using the developed material by looking at different properties of the new building material which includes strength, thermal conductivity, and water absorption and fire resistance properties. These tests have been carefully chosen as they help indicate significant properties of materials to be used in building construction. These test where chosen based on the following reason:

- ❖ Compression test: For the developed materials to be used as a structural material or load bearing material, it is important to conduct a compression test to determine the behaviour of the material under crushing load.
- ❖ Fire test: Fire test to know the behaviour of the material under a specific condition. The test gives an understanding of how the developed product will perform in actual fire situations. Equipment used to conduct this test includes a cone calorimeter used to determine the heat release and combustion of the developed material.
- ❖ Water absorption test: As most construction materials are subjected to weather condition, it was important to determine the behaviour of the developed material under water absorption to ascertain the percentage increase in weight of the material after exposure to water under specified conditions and deterioration due to water attack.
- ❖ Thermal conductivity test: Thermal conductivity test was done to measure how easily heat can pass through the developed materials. It would help the research to determine if the developed materials can be used as insulation in building construction.

Results of tests were analysed and compared to British Standards and other existing materials mainly hempcrete.

During initial experimental design, sawdust was mixed with feathers and 20% of DSM bio-resin for the manufacture of wood panels. Limitation did exist due to higher percentage of resin needed to bond materials together and in addition, treatment of feathers with chemicals before use which is suggested due to feather contamination thereby leading to increase in cost. Flexibility study also involved the use of wool fibre, sawdust and inorganic binder for better insulation properties and reduction in mass of developed product by addition of wool fibre to sawdust and binder mix with the use of normal wet casting method for fabrication.

As consideration was made to the use of alternative materials due to high cost of wool fibre, two types of waste paper, de-fibred waste paper - broken down by soaking in water to form paper sludge and then dried in oven before blending and paper strip - shredded with the use of a shredder, shredded into 2mm by 10mm are considered. Normal wet casting method used during flexibility study was used for production of wood-crete. During fabrication, two different ratios (1:1 and 1:2) of sawdust to binder where used to ascertain the correlation of binder and wood particles. Mixing of various materials was carried out by first mixing reinforcement (waste paper) with water before the addition of all other materials to enable the paper to be properly wetted. After mixing of all materials, light compaction was carried out in the forming mould due to light weight of sawdust. Samples were left to set for 24hours and then 32days to cure before testing.

Optimising the properties of the developed product involved considerations made to the various types of paper reinforcements used (de-fibred and paper strips), treatment of sawdust with use of water boiling method and NaOH. The choice of using NaOH was based on studies which show that the addition of aqueous sodium hydroxide (NaOH) to natural fibre helps form a good bond and promotes the ionization of hydroxyl group. Treatment of sawdust was done by boiling sawdust at various times and at different percentages of NaOH till a peak level was reached for attaining maximum strength. Aim of the treatment was to remove extractives from wood which inhibits compatibility and hydration of wood and inorganic binders thereby improving on properties of developed material.

1.5 Scope of Study

This research aims to develop new building materials “wood-crete” and define and consider the application of a newly developed building material to be used in the construction industry for housing delivery and strength improvement compared to other existing materials like hempcrete.

The scope of this study is limited to the use of waste materials only for development of wood-crete material for housing delivery. The main reason for limiting the scope of this study to use of waste materials include the fact that for affordable housing to be achieved, consideration made to any material used for housing delivery needs to be cost effective and readily available. In addition, limiting the scope to low income earners is due to the fact that housing problems across the globe is generally more severe and profound on low income earner than high income earner.

Major housing problem is centred on developing countries because of higher levels of population density, higher population growth rates, high levels of migration, higher costs and value of property and land, and higher levels of income and employment disparity which consequently leads to overcrowding, high rents, slums and squatter settlements. Also, issues of housing affordability are of great significance in developing countries than the developed countries.

1.6 Significance of Study

As this study is based more on experimental and theoretical approach, whilst developing a new building material, it is hoped that the study will contribute to the process of developing more sustainable and affordable material that will more readily have an impact on better housing and fast delivery of housing across various income earners. The study is geared to a better understanding of the impacts of housing expenditure on housing affordability across the socio-economic groups, with a hope that it contributes to knowing and appreciating actual housing conditions thus giving rise to improved housing delivery strategies that are effective in improving adequate housing delivery.

Given the environmental problems with regards to waste pollution, one strand of waste not fully maximised in the construction industry is the management of sawdust and paper waste which currently are being land-filled or incinerated. Although this has helped in propounding a solution to the aforementioned problem, this can only be considered temporary (a short term solution) and poses health concerns to people living within the environs. Landfills are a usual source of methane gas, the second most important greenhouse gas emission that contributes to the ozone layer depletion and climate change. Its practice thus leads to a free unchecked emission of methane into the atmosphere. Though the practice of land filling and incineration has temporarily ensured a clean society, it is the least in the waste management practice hierarchy with the least economic benefits and most environmentally negative effects.

By using waste material (sawdust and paper) in the production of the new and value added material, it proffers a more sustainable approach to waste management practice that will be of immense benefit both environmentally, economically and socially.

1.7 Thesis Outline

This thesis work comprises nine chapters. A brief review of each of the chapters is given as follows:

Chapter 1 comprises an introductory session and a background of the statement of problems. This gives a background for the development of this research in line with research motivations and objectives. It includes the necessity for this study and its importance to the construction industry. This chapter thus includes the outline (methodology) on how this thesis would be carried out.

Chapter 2 presents a literature on low income housing and its associated problem of delivery. A further look into waste and waste management with major focus on construction waste and its utilization is analysed.

Chapter 3 investigates the technology and process of existing building materials mainly focused on composite materials in combination with inorganic binders.

Chapter 4 presents the developmental stages of this research work. It helps readers to have a good understanding on what materials where first considered during the course of developing wood-crete materials and how eventually the decision to use sawdust and waste paper came about.

Chapter 5 gives a comprehensive detail of the materials used (sawdust, paper and tradical lime), presents the processing technology, the developmental stages and factors which could affect the manufacturing of wood-crete in line with how the various test procedures were performed.

Chapter 6 analyses the results and discussions of development of wood-crete building materials from sawdust and waste paper. It presents results of compressive test and thermal conductivity test of wood-crete. Results across all developmental stages are analysed and compared with existing materials (Hempcrete).

Chapter 7 presents development of wood-crete from treated sawdust. It gives an insight on the necessity of modifying sawdust before use. Further results on the effect of other factors affecting wood-crete building materials including water absorption and behaviour under fire are presented.

Chapter 8 presents the development of wood-crete building material specifically from hardwood and softwood sawdust. It was necessary to make this consideration in order to ascertain the effect of various wood species and their chemical composition effects on properties of wood-crete.

Chapter 9 summarises the research thus far and presents research conclusions and recommendations for future research.

1.8 Interim Conclusions

This chapter has thus laid a good overview of the thesis. It introduced the background of the research and an extensive view of research problems. It has also illustrated the significance of the research whilst highlighting its benefits as well. The methodological approach has also been introduced, objectives of the thesis clearly identified and an outlined format of the report. In view of all that has been discussed, this thesis can thus advance with a detailed description of the research.

CHAPTER 2 LITERATURE REVIEW: LOW-COST HOUSING AND WASTE MATERIALS

2.1 Low-Cost Housing

Achieving low-cost housing greatly depends on the use of low-cost materials. Issues of low-cost housing have become a great challenge for every economy. This is because the quest for affordable housing has grown over the last few years with increase in urban migration and little or no concerns of environmental impact which puts a high number of urban populations at risk from natural and built environmental hazard. The challenge only becomes worse for developing countries such as Nigeria where a number of her populations are homeless or not with adequate shelter. Thus, the goal to attaining low-cost housing cannot be more important in the present day economy of the nation. Notable among the early literature in the housing field are [38] [39] [40] [41] [42] [43]. Their research provided a broad overview of housing problems and prospects, within the frameworks of the National Development Plans (NDP). They formed the basis for the development of much of successive national and state housing policies. While some researchers considered haphazard housing policies and obscure implementation strategies as major obstacles impeding government objectives in the housing sector and suggested the formulation of an integrated housing policy, these recommendations were seldom empirically supported.

Agenda 21, identified some adverse problems affecting most cities and towns including inhabitants which creates a challenge for government to be able to achieve a sustainable environment. Amongst these are low employment opportunities, spreading homelessness and expansion of squatter settlements, inadequate and deteriorating building stock, services and infrastructure, increased poverty and a widening gap between the rich and poor, growing insecurity and rising crime rates and lack of financial resource. Others include problems in the education and health sectors, traffic congestion, high rate of pollution, lack of green space, unavailability of water supply and poor sanitation, improper use and land with increasing insecurity in land tenures.

Most developing counties are experiencing rural-urban migration. Consequently, the way in which housing is produced and exchanged has an impact over development goals such as equity and poverty eradication [44]. Construction techniques and location of housing can influence environmental sustainability, the mitigation of natural disasters and the design of dwellings both which reflects and protects important elements of culture and often religious beliefs [44]. In view of this, the state of Nigerian cities is characterized with poor housing delivery, slums, low productivity, poverty, inadequate infrastructures, problems with transportation and high rate of crime amongst youths [45]. However, efforts being made by the government to solve this problem have had little success so far [46] as most of the housing projects embarked upon have failed to adequately cater for both the qualitative and quantitative of housing needs of the increasing urban population.

Generally speaking, the problem of inadequate housing does not seem to rest any longer on the absence or lack of relevant policies, but on the lack of commitment on the part of government at ensuring effective and good governance which recognizes the significance of decentralization of decision making and participatory processes, premised on the principles of good urban governance which are effectiveness, equity, participation, accountability and security that were adopted in the UN-Inter-Agency meeting of 2001 [47] [30]. Housing therefore should not be looked at as a problem area requiring major social spending but as a means for promoting and mobilizing savings, expanding employment and economic activity particularly as a tool for poverty alleviation [44].

It was also noted that the most important challenge in housing development strategies is how to balance market incentives and private initiative (which are essential to efficient housing delivery), with social and environmental goals and collection action (which are central to equity and sustainability). The critical evaluation of public housing providers and products has been negligible. There have been a few efforts focused on the economic aspects relating to low-cost housing and how low-income earners have been dealing with housing problems [48] [4]. Although various governments have tried in different ways to mitigate the delivery of low cost housing, there are a number of challenges still faced by government and private sectors particularly for low income and other vulnerable groups mainly in developing countries. These constraints include but are not limited to the following issues discussed below:

2.1.1 Inadequate Supply of Affordable Land

A critical problem in the delivery of low-cost housing in developing countries is land acquisition for new construction. Though there have been different measure to put an end to these problems, most of these measures have not been implemented. Taking a look at Nigeria, one of these measures initiated is Land-Use Decree of 1978 and Land Use Act of 1980 produced to make possible for urban land to be put into building production more quickly by changing ownership from traditional owners, the extended family, and indigenous community and placing it with the state governors and the state Land Allocation Committees. This decree has not been implemented and thus it is estimated that over 25% of new construction costs is attributed to land costs. Land scarcity thus leads to escalating land prices, overcrowding of existing neighbourhoods and illegal invasion of vacant land and growth of squatter settlements. To avoid this trend, there has to be provision of adequate and affordable land for low-income housing. In order to increase the supply of urban land, it is believes that the financial and technical capabilities of the municipalities must be strengthened [49]. More emphasis are laid on the necessity to create conditions that would facilitate the growth of private land development agencies and as such, governments should formulate a regulatory framework ensuring that such private sector land developers will serve all income groups [49].

2.1.2 Lack of Effective Implementation Strategies

It has been observed that failure of policy implementation has proven to have significant impact on housing sector [50]. The solution to overcoming this is for government to promote an effective facilitative role in order to harness the full potential of all sectors in housing industry. As noticed in many developing countries, most governments have adopted enabling shelter strategies and initiated actions to support the actors in the housing delivery process. This also indicates that there is extensive room for improvement and articulation in this area to make known what is on paper as a policy document and what is really happening on the ground [49].

2.1.3 Poor Promotion of Security of Tenure

Promoting security of tenure is a prerequisite for sustainable improvement of housing and environmental conditions [51]. Addressing the issue of squatter settlements with a view to upgrading them need to be carried out to prevent/reduce evictions. Governments should focus on regularization schemes in order to provide incentives to families to invest in their homes and communities whilst promoting security of tenure to also support better functioning of rental housing markets.

2.1.4 Improving Infrastructure and Services

Many authors believe that financing and facilitating infrastructure to meet basic needs of many urban communities have been difficult for the majority of governments and local authorities. Most of the time, this is owing to the high standards that make provision of infrastructure very costly. Corruption has a role to play here in most parts. It is noticed that infrastructural services are sometimes unnecessarily subsidized and these subsidies are most wrongly directed. As a result of this trend, most households in growing urban communities are beginning to see how best they can provide these services for themselves. This approach is leading to unregulated planning and random scattering of services.

2.1.5 Promotion of Housing Finance Mechanisms

Majority of housing finance mainly in developing countries being set up provide services only to a small proportion of population. For example, the United Nations Human Settlement Programme (2008) on Housing Finance Mechanisms in India reports that smaller housing finance companies have ended up merging unto parent bank as has been the case with Vibank Housing and Andhra Bank Housing. Since most national policies have not been so successful especially to low income earners in encouraging domestic savings, getting finance through informal sources of credits like borrowing becomes the order of the day. Lacking collateral, the guarantee of regular and recorded income, the low-income groups depend completely on informal credit sources, which are expensive and mostly short-term [49].

2.1.6 Utilization of Local Building Materials and Technologies

The use of building materials usually constitutes the single largest input to housing construction in most developing country cities. It is estimated that the cost of building materials alone can take up to 70 per cent of a standard low-income formal housing unit [49]. Current trend in most developing countries depends largely on imported building materials and technologies which off course has sustainability issues associated with them in line with high cost. Building materials constitutes the single largest input in construction and in low-income shelter and the value of building materials can be as high as 80% of the total cost, because of the relatively low requirements for other inputs, such as equipment, installations and specialized skills [52]. In addition, the cost of Portland cement which is considered the most commonly used binder in most developing countries [52] is very high because of energy requirements, high transportation costs in many countries and artificial price fixing due to the influence of non-technical factors.

In light of this, there is a wide notion that the use of alternative building approach should be exploited. Hence, some researchers have advocated for the use of local building materials. It is hoped that this thesis will be of significant impact in this field as main focus is on the use of locally sourced materials for facilitation of building delivery.

2.2 Wastes

A disturbing concern for the public and private sectors is to find proper disposal of urban solid waste (USW) in large cities, since suitable dumping sites for this waste are increasingly scarce due to the spread and development of large urban centres [53]. International estimates for production of civil construction waste (CCW) vary between 130 and 3,000 kg/inhab.year [53]. Waste has been defined as any material that is considered to be of no further use to the owner and is, hence, discarded. Most of these materials termed waste can usually be reused or recycled [54]. Waste is generated universally and is a direct consequence of all human activities thus waste are classified into solid, liquid and gaseous [54]. Gaseous waste is normally vented to the atmosphere, either with or without treatment depending on composition and the specific regulations of the country involved. Liquid wastes are commonly discharged into sewers or rivers, which in many countries is subject to legislation governing treatment before discharge. However, some of the legislation are either not adhered to or not implemented in most countries and thus liquid wastes are discharged into water bodies or allowed to infiltrate into the ground. Indiscriminate disposal of liquid wastes pose a major pollution threat to both surface and groundwater.

Focus on material waste taken into account for this project is sawdust and waste paper which are considered part of municipal solid waste. According to Martin Medina, [55], municipal solid waste (MSW) refers to materials discarded in the urban areas for which municipalities are usually held responsible for collection, transport and final disposal. Examples of municipal solid waste include household refuse, institutional wastes, street sweepings, commercial wastes, as well as construction and demolition debris. In developing countries, MSW also contains varying amounts of industrial wastes from small industries, as well as dead animals, and faecal matter [56].

2.2 Construction Waste

Construction waste generally consists of unwanted material resulting from alteration of the construction of buildings or structures. They range from all kinds of materials used in construction such as stone, sand, insulation, nails, electrical wiring, and rebar, as well as waste originating from site preparation such as dredging materials, tree stumps, rubble and wood damaged or unused for various reasons during construction. These wastes are said to be as high as 2.5 – 5% by the construction industry. However, some researchers have reported recently that actual construction waste is as high as 10 to 15% of the materials that goes into a building. Most of these wastes can be recycled or reused on sites most especially as some of them produce hazardous chemicals when sent to landfill.

In the UK and US, construction and demolition waste is said to account for over 50% of waste; in a typical landfill site in UK and about one-third of the volume of materials in landfill sites in the US although the majority of building types in the United States records a waste ranges from 20 to 30 kg/m^2 [57] [58]. In Hong Kong 1994 / 1995, 65% of landfill space was covered with construction and demolition waste as reported by Stokoe, et al. [59]. The Environmental Agency in the United Kingdom estimates that the true cost of construction waste management is around ten times the actual amount paid at landfill site taken into account labour cost of handling waste, storing waste, purchase price of material thrown away and the loss of potential income from salvaged materials. As a result, there has been a push towards the reduction of construction waste in the early life of construction (during design stage).

Obadan and Uga [60] asserted that in developing countries the construction industry contributes between 3 and 6% of the Gross Development Product (GDP). In developing countries like Nigeria, records from the Federal Office of Statistics shows that the contribution of construction industry to Nigeria’s gross development product (GDP) is roughly at 2% for the past 15 years which accounts for about 69% of the Nation’s Gross Fixed Capital Formation [61]. Due to lack of statistical data in Nigeria, it is difficult to ascertain the amount of construction waste. Undermining the above fact, Olomolaiye [62] noted that, estimator’s waste allowances were consistently lower than actual figures. It was discovered that four of the most significant impact on construction waste generation on site was the lack of attention paid to dimensional coordination of products, design changes while construction is in progress, designer’s inexperience in method, sequence of construction and the lack of knowledge about standard sizes available on the market [63]. Amongst these, design changes during construction recorded top followed by designer's inexperience in methods and sequence of construction.

Some of the other factors attributed to generation of waste on site include designer's unfamiliarity with alternative products, complexity of drawings, lack of information in the drawings, errors in contract documents; incomplete contract documents and selection of low-quality products. There have been calls for rethinking to minimise, reuse and recycle waste generated during construction. Contractors who play a vital role in achieving the above statement need to ensure effective control of materials from design to construction stage so as to adequately reduce processes that can lead to wastages in construction [64]. This view has also been supported by various researchers including Ekanayake and Ofori [63].

2.3 Wood Waste

Currently, the reduction in natural resources and the general disturbance of the ecological balance constitute significant environmental problems that should be taken into account by society and governments all around the world. The increase in CO_2 and CH_4 emissions, resulting from the over-consumption of fuel, from forest fires and from the decomposition of waste are to a large extent, responsible for the 'greenhouse phenomenon' which involves overheating of the planet and extreme meteorological and climatic events. Many countries from all over the world agreed to sign the Kyoto protocol to gradually reduce greenhouse gas emissions [65].

The carbon balance on earth is also considerably influenced by photosynthesis. Forests, via photosynthesis, absorb large quantities of CO_2 from the atmosphere and as a result they constitute an enormous natural carbon reservoir with an important role in regulating the 'greenhouse phenomenon'. The crucial contributions of forests to the ecological balance not only arises from the fact that they facilitate water storage but are also great recreation areas and of course provide wood which is a valuable raw material. Changes in economic and demographic growth, combined with the many advantages of wood compared with other construction materials, have resulted in an increase in demand for wood worldwide combined with an increase in the generation of wood waste [66]. Nevertheless, wood waste can potentially constitute a valuable resource for the production of various materials and products. It is known that waste wood has been recycled in to various products for many years. Generally, the main user of recovered wood is the particleboard manufacturing industry, but other uses are increasing in importance and amongst them are: pellet and wood chip incineration, animal beddings; surfacing; mulches; fermentation and composts. Figure 2.1 shows recovered wood waste from across the European countries. Amongst the benefits of wood is that it can be recycled several times before eventually being disposed of by incineration with energy recovery.

The traditional users (wood-based panel industry) of industrial wood residues and recovered wood are experiencing increasing competition for its raw material, mainly from the fast growing biomass energy generating sector. From an environmental point of view, the increased recycling of recovered wood can be seen as a positive evolution because it increases the total volume of CO_2 stored as wood-based products and enlarging the life-cycle of the fixed carbon in the new recycled products.

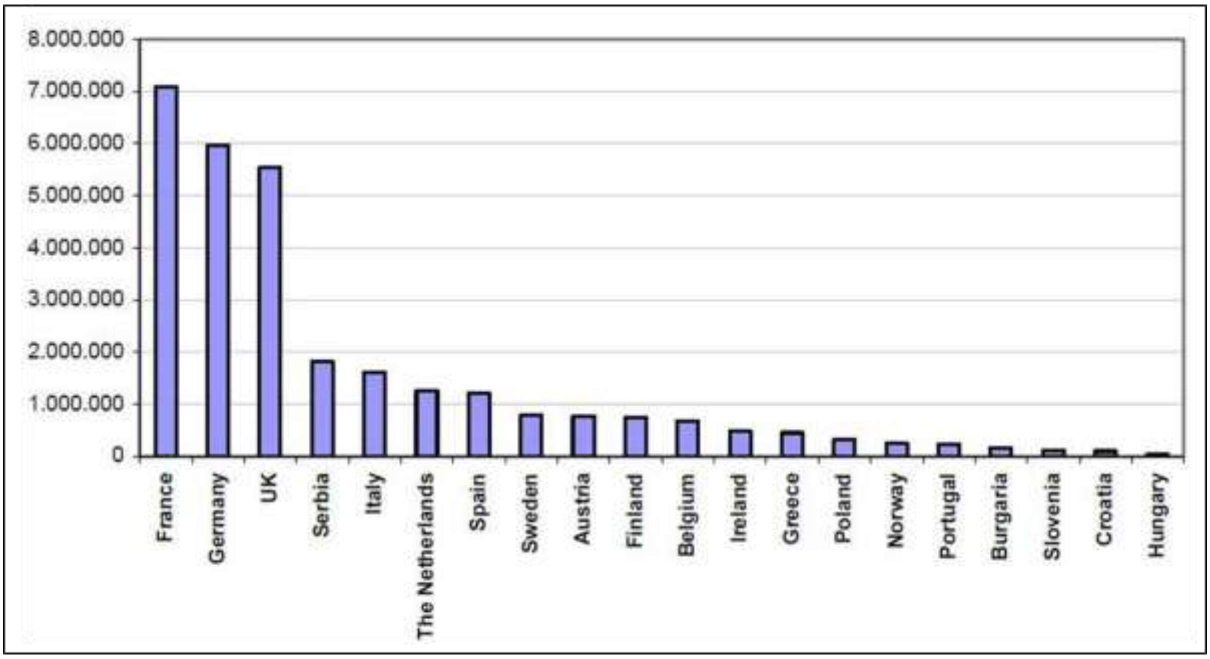


Figure 2.1 Recovered Wood in Europe

One strand of waste not fully accounted for is the management of sawdust. Sources reveal that at the moment, sawdust wastes generated are land-filled. Although this has helped in propounding a solution to the aforementioned problem, this can only be considered temporary (a short term solution) and poses health concerns to people living within the environs. Studies also show that landfills are a usual source of methane gas, the second most important greenhouse gas emission that contributes to the ozone layer depletion and climate change. Its practice thus leads to a free unchecked emission of methane into the atmosphere. This land-filling practice though has temporarily ensured a clean environment is the least in the waste management practice hierarchy with the least economic benefits and most environmentally negative effects. Although waste management agencies across the globe have taken a turn in the right direction, there is still a lot to explore on how to manage wood waste (sawdust).

In Nigerian, one of the fast developing countries in Africa with a large landed area, 39% of Nigeria's landed area is classified as forest area of which 10% is forest reserves and 16% is high forest containing timber [67]. The Federal Ministry of Statistics also records 7, 959, 047 hectares for forest reserve and an area of 812, 537 hectares for forest plantation. In 1987, the log production in Nigeria as stated in the Federal Ministry of Statistics was reported to be 6, 172 000 m^3 with an average increase of 2.6 annually. The report states that for every 1 m^3 of tree cut and removed from the forest, 0.8 m^3 goes to waste which are in the form of damaged residuals (50%), abandoned logs (3.75%), tops and branches (33.75%), stumps (10%), and butt trimmings (2.5%) which mean that 80% of the timber is wasted during logging operations [68]. As a result of this it is observed that Nigeria gave off a total of 5, 369 600 m^3 wood waste in 1987 based on the total log production of 6, 712 000 m^3 [68].

In Lagos Nigeria for instance (Nigeria's most commercial city), there are about 2150 (estimated) sawmills at the bank of Lagos lagoon. Fig 2.2 shows sawdust piles from local timber factory in Lagos, Nigeria. Each sawmills has at least one sawing machine and some have as many as three machines. An average of 8 logs is being sawn per day per mill (i.e. 103,200 logs per week of six working days). Information gathered from Lagos state authority states that the minimum girth (or diameter) of the log that can be fell and brought to Lagos for processing is 1.126m. Putting this statement into context, the minimum volume of wood will be:

(πD2/4) x 12ft x 0.3 = 0.3632m3

In one week, a minimum of 103,200 logs of wood will generate approximately 5,669.19 tons of waste [68]. This will amount to about 294,797.9 tons of waste per year. This is an enormous amount of waste for a city that can hardly cope with its domestic waste. It is, therefore, not surprising that these waste accumulate year after year with propensity to increase as the demand for wood increases. The mills presently incinerate some of these wastes as a way of management. The burning is carried out as crudely as possible, thereby introducing air pollution into the already bad situation. It is imperative to state here that the above is a calculated amount of saw-dust waste generated in Lagos as stated by [68] though in practice, the situation is worse considering the fact that some sawmills are unregistered and a majority of sawmills exceeds the minimum girth of log that can be fell and brought into Lagos for processing. It is also crucial to state that as noting has been done about these saw-dust wastes for the past years the volume of saw-dust waste at present is significantly enormous.

Figure 2.2 Sawdust piles from local timber factory in Lagos, Nigeria

2.3.1 Utilizing Wood Waste

There are a great potential that exists for developing products for housing made from wood waste and wastepaper [69]. This will definitely have a positive effect on reducing waste management problems most especially in landfill and its use in the construction industry will help reduce the total amount of building construction cost. This can be greatly achieved through the modification of existing and creation of new technologies to produce building products from recycled waste wood, wastepaper, and other materials from the MSW.

Some of the types of wood waste that might be converted into housing products includes full-sized used lumber salvaged from razed buildings, wood broken-up during building demolition, old wooden pallets, scrap wood from new construction sites, old wood utility poles and railroad ties, wastepaper in landfills, yard trimmings, and wood fibre found in the land filled sludge produced by paper mills [69]. Despite some conversion of these materials like chipping, grinding or de-fibred, its importance cannot be overlooked. As some researchers have reported, the merits of utilizing recycled wood waste cannot be over emphasised.

Wood unsuitable for construction in its native form may be broken down mechanically (into fibres or chips) or chemically (into cellulose) and used as raw material for other building materials such as High Density Fibreboard (HDF), Medium-Density Fibreboard(MDF), particleboard, Oriented Strand Board(OSB) and plywood. Amongst these also includes wood-plastic composites made by the binding of various wood waste with recycled plastics, synthetic fibres and resins and wood-inorganic composites made by bonding wood particles with inorganic matrix. The latter will thus give opportunity to depart from conventional frame and panel building systems and create the opportunities to produce a variety of moulded products that can be designed for structural efficiency as well as architectural flexibility which is acceptable to home buyers and owners, builders, producers of manufactured housing, financial institutions, and regulatory agencies. For wood waste to be utilised in the construction industry, there needs to be design and testing to meet structural performance, fire performance, environmental performance (including moisture effects and durability), insulating and acoustical properties, and toxicity hazards.

2.3.2 Waste Paper

In the last 40years, it is reported that worldwide consumption of paper has risen by 400% with 35% of harvested trees being used for paper manufacture. In the United States alone, paper waste accounts for up to 40% of its total waste which adds up to 71.6 million tons of waste per year (United States Environmental Protection Agency). Paper waste like other wastes faces the additional hazard of toxic inks, dyes and polymers that could be potentially carcinogenic when incinerated or comingled with groundwater via traditional burial methods such as modern landfills.

Waste paper may have some components that may impact the environment negatively, such as inorganic ink or some of the materials used to make up the paper. The logging of old growth forests accounts for less than 10% of wood pulp. Amongst the environmental problems associated with paper include air pollution, water pollution, wood pulping process and deforestation which is a common problem associated with developing countries as well as developed countries though most developed nations have initiated sustainable measures to tackle this problem. Waste paper finds its use in mainly packaging but there are current research looking into how to produce both structural and non-structural housing components from recycled wastepaper fibre. United Nations report states that the annual rate of deforestation in Nigeria is of serious concern. A measure to mitigate the problems as suggested in the report is by having a sound forest implementation policies and enforcement [23].

2.4 Use of Local Building Materials

Building materials often constitute the single largest input to housing construction. In the United Kingdom, there has been a rise since 2010 in the price of housing construction materials

(Figure 2.3) but a fall of 2 percent noticed in 2012 still gives an indication that more needs to be done to further reduce the price of housing construction materials [70].

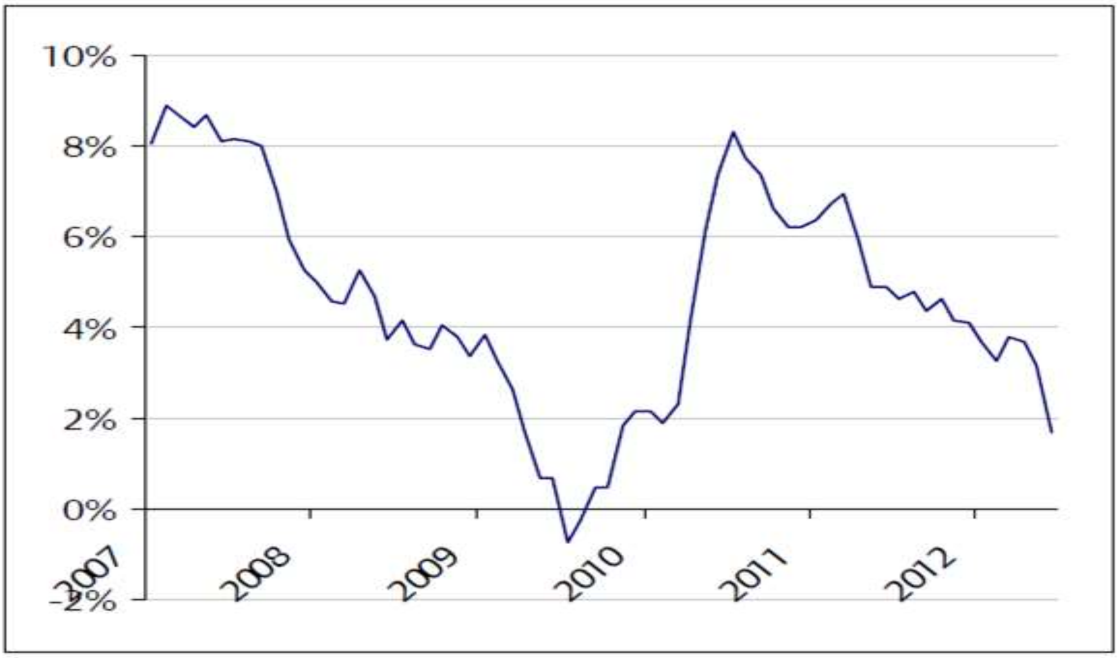


Figure 2.3 Price of housing construction materials in UK [70]

The price is on the increase most especially in developing countries as most developing countries now have restriction in place on the importation of cement which is one of the most popular building materials. In Nigeria, this problem has been more compounded with low level of production of cement domestically (appendix 3). There is also no promotion in the use of clay, timber and other building materials which has only but resulted in high increase in price of cement. It is important that materials used for construction is readily available for use. This factor has been thought through hence the choice of wood waste.

Factors that have contributed to the low use of local building materials include lack of basic infrastructures and services, housing finance mechanisms, community participation and on a wider note, having a stable political environment for implementation of policies and regulations. Building materials are one of the major factors affecting the effective delivery of housing in the construction industry. In the construction industry, building materials plays an important part because materials constitute the single largest input in construction often accounting for about half of the total cost of most or any construction products [71] [72] [73] [74] [75]. For the development of a country’s economy, the importance of the building and construction industry cannot be overlooked [76]. The construction industry can thus be summarised as a source of livelihood for a nation. [77].

There are three different groups of materials as stipulated by the United Nations [78]. Firstly, the modern or conventional building materials which are material based on modern conventional production methods like concrete, steel and glass; secondly, traditional which relates to materials that have been in local production from ancient times using small-scale rudimentary technologies, e.g. laterite, gravel, thatch, straw, stabilised mud, Azara and raphia palm; and thirdly, innovative materials which are materials developed through research efforts aimed at providing alternatives to import-based materials e.g. fibre-based concrete, ferro-cement products etc. Despite the success of innovative materials, there are calls for the return to the use of local building materials. Some of the reasons include a call for more sustainable approach in building construction and the high costs of both the modern and innovative building materials and inadequacy in supply not counting the technological knowhow and expertise associated with installation process [79] [80] [81] [82].

The use of these locally sourced materials depends highly on their availability and the technology involved in implementing their use. As reported by various researchers [83] [84] [85], if technologies, which have low import input, can be operated and maintained with available skills developed, the bottlenecks of prohibitive costs and irregular supply can be overcome over time. For this to thrive there needs to be support from the government in other to be able to convert the locally sourced materials into commercial scale use. Government activities in housing hampers the use of local resources where they continue to build and manage houses, and thereby making same mistakes by setting material standards, and building codes, which are ill suited and far too expensive for the poor majority [86]. Some of the problems usually attributed to the use of locally sourced materials consist of;

2.4.1 Quality of Output and Design Limitations

It is a general belief that construction done with local materials are usually not of good qualities. This compounded with the problem of unavailable standards for quality production of local materials makes the issue more complex [83]. The lack or unavailability of standards means that the output of the productive process will not have a basis for standardisation and acceptance. However, most projects that have incorporated the use of local materials have recorded success in recent times an example is the secondary school project in Gando Burkinafaso which won the regional holcim award Africa Middle East in 2001 designed by Diebedo Francis Kere [87].

2.4.2 Demand for Local Material and Inadequate Supply

One other reason for the unpopularity of local materials is as a result of fewer demands for these materials which lead to low viability in the market [83]. There is a general feeling that local materials when used, are of low quality which makes demand for them very low. It was reported that in 1976, the Federal Government of Nigeria established seven clay brick factories and though these plants were designed with an installed capacity of 1.5 million bricks annually, as at the year 2002, they were on the average running at 15 to 25 percent capacity due to low patronage [72] [75]. Government needs to lead by example in this field by having policies that promotes the use of local materials and incorporating the use of locally sourced products in their projects.

2.4.3 Inappropriate use of Local Building Materials and Technical Problems

Some researchers have reported the inappropriateness use of local building materials construction application and lack of skilled workmanship which results to most projects been abandoned. The full range of what constitutes local building material is unknown while the lack of basis for cost comparison between local building materials and the conventional materials has always been a problem [72]. Several scholars classify technical limitation with the use of local building materials and legal problems associated with their use as another problem needed to be addressed. Other authors have objected to the return of local building materials in modern buildings [80]. One reason given is that these materials cannot satisfy the new needs of building forms and functions and that it is not possible to provide enough materials to satisfy demand. A number of researchers are of the view that better understanding of the failings of these materials and their innate characteristics, overcoming their shortcomings and ways to use them with confidence can be gained through the application of new knowledge and techniques [88]. It is therefore important that when considering developing new local materials for construction, the technicalities are kept simple but of standard.

2.4.4 Transport and Cost Implication

Issue of transportation has always been a problem in the use of local building materials. There have been issues with the transportation of materials from sites where materials are of excess to areas where they are not. There is also the concern of the cost of maintenance after building. However, the existence of this problem should not be viewed as a reason to abandon these materials but rather a valuable challenge to accomplish. Using local available materials helps reduce cost of energy consumption when compared to using materials that are shipped across country or imported from other continents. Locally sourced materials can be readily available much more quickly than if shipped from a distance and can be harvested and processed in a customized fashion for specific needs.

Despite the shortcomings attributed to the use of locally sourced building materials, which includes uncertain durability and life span of products, low aesthetic value and poor social acceptability by the general public, there are some benefits associated with their use which include:

- Providing affordable housing
- Reducing cost of constructions
- Provision of employment opportunity
- Meeting increasing demand for housing stock
- Use of environment friendly resource
- Energy conserving alternative
- The development and propagation of indigenous technological ingenuity and skills of the local people.
- Enlarging and promoting the economic strengths of people and the country at large.
- Provides a source of study and research for both present and future generations.

The areas of potential benefit of incorporating local building materials in building construction include:

- Providing affordable housing for the citizenry though, the general bias is that it will only be suitable for low-income cadre of society.
- Reducing costs of construction since materials found locally will be used thus eliminating costs associated with manufactured products and transportation.
- The development and propagation of indigenous technology and the provision of employment. These will invariably contribute to the economic growth of the nation.

2.5 Interim Conclusions

It is true that reducing the cost of materials in building construction has a significant influence on the total cost of building. There needs to be innovative ways to adopt and vigorously pursue a housing delivery strategy that is ‘end-users driven’ [89] through the use of low-cost materials (waste products). Professor Olumide Olusanya as quoted in Nigerian Tribune [90] stated that “sustainable systems building has become imperative for mass housing production in a developing economy because carrying on with housing development using conventional building methods would only hinder housing growth mainly in developing countries. A mass housing would therefore be based on the use of local content using local components that are available and of low-cost.

In light of the above discussion on policies and regulations, different authors advocates for the governments to engage on an “Enablement Strategy” to housing which would see the government to assume the role of “supporter” in contrast to “provider” in the housing sector [91]. This implies that rather than embarking on the construction of dwelling units, the government should rather concentrate on reforming and managing the legal, regulatory and financial policy framework [92] in such a way as to create an environment for people and the private sector to provide housing. There has to be commitment and genuine participation of all groups in society to make this goal a reality. The need to forge partnership of not only shareholders but also stakeholders in environmental issues should be considered. Broad public participation in policy development, combined with greater accountability, is essential to achieving sustainable development. In order to achieve a great step forward, there will be need for integration between individuals, groups and organizations in environment and development decisions, most especially those which can affect immediate communities. One thing that is generally accepted is that there needs to be a change of focus from full direct housing construction to that of providing enabling environment for the sector (a level playing field).

Due to the problems associated with the environment, there is requirement for a bilateral and multilateral collaboration to facilitate creative innovations on how to curtail the global issues of waste. One of such methods to combat waste is turning them into value added products. This will help provide those in the wood and paper industries a means of discarding their wastes whilst enabling the creation of new commercial viable environmental friendly product for the construction industry. It will thus provide a solution for instance to the increasing amounts of wood and paper wastes.

On building materials, though there are a number of challenges associated with the use of local building materials, there is however some positives for being adopted as alternatives to conventional building materials as earlier discussed. There needs to be change in pricing and subsidy structures to give encouragement to the production of local materials and awareness on the use of LBM. Local building materials also have the potential to enhance a sustainable construction practice.

Their advantages are numerous to mention ranging from environmental principles which includes renewable, energy efficient, affordable, recyclable potentials to social involvement which includes self-construction, family and community working together. A lack of understanding and information on the advantages of alternative building materials have resulted in designs based on concrete blocks wall systems. Use of local building materials and methods has significant impact on lowering transport costs and environmental impacts, reduce waste and often have some major cost advantages.

The next chapter will provide an insight on some composite materials of similar properties with wood-crete being developed in this study.

CHAPTER 3 TECHNOLOGY FOR DEVELOPMENT OF INORGANIC BUILDING MATERIALS

3.1 Introduction

It has long been recognised that buildings and their use contribute significantly to $C0_2$ emissions, perhaps more than 50% of total emissions [93]. There has been a growing debate on finding ways of meeting housing and building needs while having a low impact on the planet. Bevan and Woolley noted that two main approaches have been observed. Firstly, there are those who focus on getting the main stream construction industry to make buildings more energy efficient, even though they rely on high embodied energy petrochemical based insulations, cement, bricks and concrete while others have tried to search for lower impact alternatives that are healthier and less polluting. There is now a range of building methods and materials derived from natural low impact sources [1] such as earth, straw, fibre reinforced polymer components, recycled materials and so on [94] [95].

Wood-inorganic composites offer the potential to be fire resistant with good thermal conductivity and are likely to be highly resistant to attack by decay fungi and insects. The use of inorganic materials to bond waste wood fibre, chips, and particles has proven to be technically feasible in commercial products such as sound insulation board, gypsum fibre-board, and low-density cement-bonded wood building blocks [69]. Furthermore, it has been acknowledged that the range of products can be greatly extended if means are developed to convert waste wood into desirable particle sizes. Examples of areas they can be used include, wall construction for residential that combines studs, sheathing, and siding into a single panel, cladding, balcony parapets, flooring, sound barriers, garden and fence walls, interior partitions, and wall linings in areas requiring higher durability. Their uses are however not limited to the aforementioned. The combination of wood fibres with inorganic binders provides a unique opportunity to utilize recycled waste and low-grade wood fibre [69]. Some major inorganic building materials currently used include hempcrete and wood composites.

3.2 Hempcrete

Hempcrete is probably most similar to the wood-crete developed in terms of processing technology; aim to achieve a low carbon footprint and reduction in construction cost thus leading to affordability in construction. Hemp, like many natural materials has been used for centuries as a reinforcing binder in “concrete,” in drainage work and for rope and cloth making. Hemp-lime construction is a composite construction material and building method that combines fast growing renewable and carbon sequestrating plant-based aggregates (hemp shive) with a lime-based binder to form a lightweight material that is suited to solid walls, roof insulation and under-floor insulation and as part of timber-framed building [93]. Hempcrete is formed by mixing together hemp shive and lime-based binder. The lime helps bind the hemp aggregates together creating a material of modest structural strength and stiffness and also acts as a protection for the shive from biological decay, mainly through its ability to wick water away from the hemp shive and its high alkalinity. Hemp lime can be used to form solid non-load bearing panels or blocks, typically as part of timber or other framed buildings. The use of Hemp shives were introduced in the early 1990s in France in a bid to make concrete lightweight [96]. However, there has been a growing research on the use of hemp lime in the UK, funded by the Department of Food and Rural Affairs (DEFRA 2009) through the National Non Food Crops Centre (NNFCC 2009). Mixture of hemp shives and cementitious binder creates a building material with different properties including mechanical, thermal and acoustic properties that differ from those of conventional concrete. With a low density, thermal conductivity, better acoustic insulation properties its ability to regulate internal relative humidity through hygroscopic material behaviour, contributing to healthier building spaces and providing effective thermal mass, such material is advantageous for use in construction [97] [98] [99]. Hemp concrete when used for wall application is not load-bearing. One significant benefit of hemp lime construction is its capacity to sequester $C0_2$ into the building fabric. It seems possible that hemp lime can make a major contribution to offering a genuinely zero-carbon solution to sustainable construction most especially when government policies are becoming increasingly concerned with reducing carbon emissions and finding more efficient ways of meeting current targets.

Chopped hemp hurd can be mixed with a range of building limes and cast as a form of “concrete” to create walls [1]. The use of hemp however has been mainly as insulation in building but where it has been used as a load bearing material is in combination with a timber stick frame using plywood shuttering. The lime in the mixture helps to preserve the timber frame and the hemp lime mixture sticks to the wood very well which helps to create a composite structure that is very strong. The composite provides a reasonably good level of thermal insulation with the added advantage of retaining warmth due to its thermal mass. This form of walling is also a breathing wall, allowing the passage of moisture vapour whilst able to absorb quite high quantities of water and then release it again without damage. Hemp wall are known for their warmth which makes it particularly good for climates where there is a high level of humidity. Hemp is relatively easy to construct though joinery skills are needed to create the timber frame when used as a load bearing wall. During construction, hemp material is strong enough for formwork to be removed almost immediately but then takes 2 weeks to dry out and 2 - 3 months to reach its full strength [1]. Hempcrete is produced by mixing hemp shive or hemp fibre and lime with water which creates a lightweight lime and hemp mixture (Fig 3.1). Hemp shives have a highly porous structure and strong capillarity effects thus, during hempcrete production, a significant excess of water is required with respect to what is needed to slake the lime. Apart from method of casting, hempcrete can be sprayed on surfaces mainly when used as a roofing material. Main reason for this is that the spraying method help reduces the density of hempcrete. In the spraying method, lime and shive is conducted by air through a hose, and water is added just before the hose outlet. The degree of compaction can easily be controlled by varying the distance of projection.

Mukherjee [100] reported that using a hemp material that includes both shive and fibres does not appear to create a mechanically stronger hempcrete compared to only using shive. The proportions of the hemp lime can be varied according to the density and characteristics required. Once the material is mixed with a small amount of water, it can then be cast into walls, roofs or floors to produce a solid insulating mass using shuttering or by spraying.

The hempcrete mass is solid enough to hold together quite quickly between 12 – 24 hours of setting period and about 35days to cure. It has been reported that a higher compressive strength of 2.4MPa is achieved at 215days compared to 1MPa at 35days [101]. Drying and curing time varies according to the mix and climatic conditions but usually about four weeks.
When hempcrete has dried out, it becomes a strong and solid composite which creates a weather proof mass providing significant amount of strength, thermal insulation, thermal storage and a substrate, which can take a variety of finishes.

Some authors have reported that compressive strength values for Hempcrete vary from 0.02 to 1.22MPa [96] [102], depending on the composition of the mixture design. It is reported that the hemp lime ratio of 3:1 is similar in strength to a 4:1 and 5:1 mix [99]. In addition, depending on the amount of hydrated lime in the binder mix, the maximum compressive strength is obtained after a period of time ranging from several months up to several decades [102]. Splitting tensile strengths, depending on the mixture, vary from 0.12 to 0.23 MPa [99].

Hempcrete when used for wall construction ensures that water does not find its way inside cavity which destroys insulation because they are monolithic with only vapour permeable plaster on both external and internal side [103]. This helps to allow the wall to take on the extra humidity in the air inside or outside the building. The water inside the walls is kept until the air humidity drops down and the released back. The monolithic nature of hempcrete contributes to its property as a good insulation material. Hempcrete wall made of 300mm has a U-value of 0.23 - 0.36 W/mK. A lower U-value can be further achieved with thicker walls. Research shows that the energy lost in the first 24 hours from a hempcrete wall-section with a U-value of 0.29W/m2.K equated to an average heat loss of only 0.11W/m2.K. As a result of this, hempcrete unlike traditional construction materials performs well in real life conditions where heating is constantly turned on and off. Walls constructed with hempcrete retain heat from our radiators and release it back when the temperature drops during winter whereas in summer, the opposite process is observed, as cooler air is preserved. It is observed that the temperature in hempcrete homes during the winter is 2°C higher than houses built with conventional material having the same U-value [104]. In addition to the good insulating properties of hempcrete, hemp walls are said to have excellent sound qualities though not as good as traditional wall materials. On fire performance of hemp walls, BRE carried out a standard fire test on a 300mm thick hemp wall. It was discovered that the wall survived a temperature of about 1000oC as one wall of a kiln with the outer surface remaining below 70°C for a period in excess of three hours until the test was halted. It is claimed that the wall passed a fire rating of 1hr BS EN 1365-1:1999.

Thermal conductivity has been reported ranging from 0.07 to 0.11 W/mK [96] [102]. The compressive strength values in combination with the low Young's modulus of the hempcrete mixtures indicates that the material in its present form cannot be used as a load bearing material. Presently, hempcrete is used in combination with other structural material to form load bearing structures (Fig 3.2). More rigidity and higher compressive strength are needed if hempcrete is to be used as a stand-alone load bearing material.

Figure 3.1 Mixing of hempcrete [100]

Figure 3.2 Hempcrete used in combination with timber frames

3.3 Straw Bale

Straw is one of an alternative material used in the construction industry which offers good thermal insulation properties and a much lower environmental impact than many current mainstream construction materials. Straw is a waste product of grain production which generates a substantial amount of carbon dioxide emission when burnt after harvest. Straw, in the form of straw bales, is an agricultural by-product and because of the limited uses found for the 12 million tonnes produced annually in the UK, it is viewed as a waste material [105].

Avoiding destructive combustion when waste straw is used helps reduce a significant amount of lumber and synthetic materials used in building products. Just like hempcrete, straw bale is suitable as infill insulation for timber frame buildings with either an external render or timber rain screen finish [106] [107]. Straw provides a vapour-permeable wall construction using a locally sourced, low-impact material, although it does need careful detailing and construction to avoid the ingress and retention of moisture.

A downside of the use of straw bale in construction is that it is labour intensive and the skills needed though a fairly simple method. Straw bales may be used in both infill (non-loadbearing) and modest loadbearing wall applications. Non-loadbearing straw bale walls are mainly used for external infill above the damp-proof course level in moderate or sheltered environments. Bales come in various sizes and can be constructed either on site or as prefabricated panels delivered to site already enclosed in a protective outer finish, such as lime render. In addition to the other general benefits of offsite construction (speed of construction, reduced waste – which is biodegradable), straw bale is particularly well suited to prefabricated construction, as the risks of water damage during construction, and of fire associated with loose-cut straw, can be minimised [106]. After construction, straw bales are of fire resistance when carefully plastered on all sides with moisture being of great disadvantage of the use of straw bale. However, with carefully designed foundation and roof, and with windows and doors fitted towards the outer face of the wall, the damage posed by moisture can be significantly reduced. During construction, straw bale building walls can be protected using rain screens, appropriate damp-proofing to reduce the degradation of the straw walls. It is also important to ensure that miscellaneous penetrations through the walls are detailed to ensure that they do not allow moisture to build up.

Straw bales can also be used for semi-loaded structural walls. During construction, bales are usually stacked on top of each other and pinned with metal rods or bamboo sticks without any mortar. While compressive strength is very low (governed by displacement rather than material failure), 450 mm-thick bale walls are capable of supporting 0.8–1.0 tonnes/m length, sufficient for domestic-scale buildings and loadings [106]. Its density in construction is normally between 100 – 120 kg/m^3. Thermal properties of straw bales were found to be dependent on the density of the bales [105]. Goodhew et al stated that a load-bearing straw bale wall requires bales to have a higher density, typically more than 110 kg/m^3 while a non-load-bearing straw bale used for infill can tolerate a lower density usually within the range of 80–100kg/m^3. Bales can be finished with stucco, lime or cement and this helps to plays a significant structural role by increasing resistance and improving stiffness, protecting the straw from decay and enhancing fire resistance. As a result of simplicity in method of construction, skills for straw bale construction can be learned easily and fast. Due to the nature of the material, straw bales provide lightweight, large building blocks which form a tough wall infill that can receive a vapour-permeable lime render finish internally and externally. Straw is popularly known as a roofing material for thatched roofs and also finds its use in vertical or lateral (racking) load-carrying capacities in walls. Straw can be sourced from wheat or barley from local farmers. Durability of straw bale depends on various factors including the binder used to form the bale, type of plastering and skills adopted during construction. Constructing with straw has great potential where wall space is not at a premium and like hempcrete and several building materials, straw bale requires appropriate detailing, planning, protection and maintenance when used for construction.

3.4 Wood-Cement Composites

The technology of mixing sawdust with cement is to produce a composite enjoying the desirable attributes of concrete with some of the inherent merits of wood. One attribute of this technology is to produce a light-weight material, with better insulating qualities than normal concrete. Cement-bonded wood composites have the potential to provide a wide range of products for building applications by using a wide range of recycled wood based materials [108]. The use of waste paper (recycled newspapers and magazines), old pallets, construction waste, and small-diameter tree stems have been used for both experimental and commercial products. A better understanding of the fabrication process resulting in material properties is thus very important. The development and use of wood-cement composites attest to their attraction as building materials. In addition to their resistance to fire, wood-cement bonded materials have a special attraction for use in warm, humid climates where termites and decay are a major concern [108].

In recent times when wood-cement has been used, it provides a durable surface as well as one that can be easily embossed and coloured for an attractive, low-maintenance finished product. The raw materials used are compatible with a range of processing methods to provide a variety of products that are easily machined with conventional woodworking tools. Preliminary research results suggest that wood-cement composites can be manufactured to exhibit a range of unique energy-dissipating properties, which are advantageous in areas subject to seismic and/or heavy wind loads [108].

Private industry has taken the lead in research to develop and use wood-cement composites in building construction. Research shows that cement-bonded wood-excelsior panels have been in use for more than 60 years with major emphasis on acoustics, fire resistance, and aesthetics, rather than strength and stiffness. Further research has focused on the development of fibre-reinforced cement cladding products which normally use about 8 to 10 percent wood by weight compared to 20 to 40 percent for wood particle composites and rely on appearance and durability rather than on strength and stiffness for their acceptance [108]. Wolfe and Gjinolli [108] reports on the two categories of wood-cement composites: wood particle-cement composites which have been in use as architectural, fire-resistant, and acoustic panels and wood fibre-reinforced cement products which were developed primarily as a substitute for asbestos-cement and are relatively new, developed and promoted mostly in the last 25 to 30 years.

3.4.1 Cement-Bonded Particleboards

Cement bonded particle boards generally have densities in the range of 300 to 1,300 kg/m3 with maximum bending strengths often limited to less than 10MPa [108]. According to Evans [109], debarked logs, usually coniferous species, are stored for at least 2 – 3 months prior to processing to reduce their moisture and sugar content. Wood particles are then prepared in the same manner as for conventional particleboard. Logs are processed to produce chips approximately 10 – 30mm in length and 0.2 – 0.3mm in thickness, which are then further reduced in size using knife ring flakers or hammer mills. The resulting flakes are screened into three classes; fines, standard and coarse flakes. Fines are used for the board surface and standard - size flakes are used for the core of boards. Coarse flakes are returned for further reduction in size. Wood flakes are mixed with Portland cement and water in the following ratio by weight — wood 20%: cement 60%: water 20%. The moisture content of the flakes is monitored continuously and the volume of water added to the mix is adjusted accordingly. Calcium chloride (2–3% w/w) may be added to the mix to accelerate the setting of the cement. After the mixing, cement-coated wood flakes are fed to a forming station where a continuous mat of uniform thickness is deposited on an endless series of caul plates running on a conveyor. The mat is cut into lengths corresponding to the size of the caul plate and a stack of mats is compressed to about a third of its original height over a period of 2 – 3min at a pressure of approximately 2.4Nmm^{-2}. While the stack of cauls is still in the press, clamping arms are attached to it so that, on release from the press, the batch of mats is still held in a compressed state. These are transferred to a heated chamber at 70 – 80°C for 6 – 8hours to facilitate cement hardening. The clamps are released at the end of this period and the cauls are removed for boards to be air-dried, trimmed and then stacked for 12 – 18days to allow the cement to cure. The boards are further dried and conditioned prior to shipment and can be sanded on one or both sides. Common board thicknesses are 12 and 18 mm, but boards as thin as 8mm and as thick as 40mm can be produced.

3.4.2 Wood-Wool Cement Board

It has been reported by some researchers that in 1920s there was a practice whereby wood chips where used in cement to make building blocks and early 1940s saw the production of cement-bonded wood composite commonly called wood-wool, which uses a wood: cement ratio in the range 0.4 to 0.6 by weight. Wood-wool is made with a ribbon like particle called excelsior coated with cement and pressed into panels that have densities in the range of 300 to 500 kg/m3 [108]. Generally, wood-wool finds its use as non-combustible and sound-absorbing ceiling and wall panels. According to Evans [109], wood-wool is manufactured from wood-fibre (7 – 8.5%), sand (60%), cement (30%), and aluminium trihydrate (3 – 4%). The wood-fibre, which is usually obtained from softwood chemical (Kraft) pulp, acts as a reinforcing agent in the boards, a role previously played by asbestos fibres in an older generation of building materials. The manufacture of wood-fibre reinforced cement composites involves washing the sand and reducing it to a fine powder using a ball mill. Bales of Kraft pulp are added to a vat containing water and agitated to re-disperse the fibres. Fibres are then refined in conical refiners to increase their ability to interact with sand and cement [109]**.** The cement, sand, fibres and additives are combined and diluted to form slurry with a solids content of 10%. The slurry is fed into a tub containing three screen cylinders which pick up the slurry mix and deposit it on a felt-like belt moving at 80m min^{-1}. The belt is then turned so that the slurry is on top and while this is occurring the fibre-cement mat is trimmed at its edges by water jets and partially dewatered using vacuum suction boxes. The mat passes under a large drum that winds layers of fibre-cement around itself. A cut-off knife or wire releases the mat from the drum and it is then deposited onto a conveyor belt. After leaving the conveyor belt the fibre-cement mat is cross-cut; mats are cured by autoclaving for 6 – 8hours at temperatures and pressures of approximately 200°C and 900KPa, respectively.

Also, as described by Evans [109], wood-wool cement boards are made from either debarked softwood or hardwood logs that have been stored for varying periods of time to reduce the starch and sugar content of the wood. After storage, logs are cross-cut into billets and these are shredded on a cutting machine to produce wood-wool. Typical wood-wool strands used in the manufacture of WWCB are approximately 3 mm wide and 0.5 mm thick with lengths up to 40 – 50 cm coinciding with the lengths of the billets processed by the shredding machines. Coarser wood-wool is often used in the manufacture of very thick boards. When hardwood species with a high extractive content are used, the wood-wool may be soaked in cold water overnight to remove any soluble low molecular-weight sugars and heartwood extractives that might interfere with cement hydration reactions.

Wood-wool may also be treated with inorganic compounds such as calcium chloride, again to reduce the inhibitory effects of soluble wood components on the setting of cement. Wood-wool is air-dried and mixed with cement using a cement-to-wood ratio of 2:1 to 1:1. The mixed material is conveyed to a mat former and a pre-determined weight of cement-coated wood strands is deposited on a forming board. The mats are then stacked and pressed in a hydraulic press at room temperature in batches of 8–12. The pressure used for pressing varies, depending on the degree of densification required in the final board, but can be as low as 80KPa for low-density insulation boards. The stack is clamped under pressure for 24h to allow for initial cement cure to occur. Boards are then de-clamped and post-cured for 2 – 3 weeks before trimming and finishing. Generally, fibres added to cement composites is aimed at increasing energy of fracture thus by bridging gaps, the fibres prevent stress concentrations at crack tips, thus retarding brittle fracture mechanisms and dissipating energy in the form of fibre pull-out or rupture.

3.4.3 Factors Affecting Wood Composites

Amongst the factors that affect wood-cement composites includes compatibility of wood with cement, hydration reactions and particle geometry. One of the main factors when examining the suitability of wood for the manufacture of wood–cement composites is the effect the wood has on the hydration (setting) of cement [109].

- **Hydration** - A key issue that has been addressed over time is the effect wood has on the hydration (setting) of cement. When wood and water are added to cement, hydration reactions occur and heat is evolved [109]. Evans [109] reported that during the initial stages of hydration, di- and tri-calcium silicates are converted to tobermorite gel ($Ca_3Si_2O_7.3H_2O$) and calcium hydroxide ($Ca(OH)_2$). The latter increases the pH of the wood–cement mixture to approximately 12.5, which facilitates dissolution of wood constituents, particularly low molecular-weight carbohydrates and heartwood extractives. When these substances interfere with cement hydration, strength properties of wood-cement composites are significantly reduced. The effect of cement hydration differs from wood species. Some reports have noted that there exists a correlation between hydration characteristics and compressive / tensile strengths of wood-cement composites [110]. There is a relation between wood-cement hydration and wood-cement compatibility. In the work of Hachmi and Moslemi [111], it was discovered that wood extractives has adverse effect on the exothermic hydration characteristics of Portland cement, which in turn affects the wood cement compatibility.

❖ **Compatibility of wood with cement** - The presence of inhibitory substances such as starch, sugars, hemicelluloses and extractives in wood are known to affect and influence cement curing / setting time. It has been reported by Singh and Garg [112] that extractives in wood prolong the setting time of cement and Xu and Stark [113] also discovered that wood extractives has a significant delay in wood-cement hydration. The presence of these compounds causes a possible interference with cement hydration and setting which results in wood–cement composites of inferior strength [114] [115]. With variation in the percentages of extractives in various types of wood (hardwood and softwood), the hydration time of different types of wood when mixed with sawdust is thought to be variable. Some studies have accelerated the setting times of wood-cement composites by the addition of chemical additives while other studies have concentrated on the extraction of soluble sugar and extractives in wood for better bonding between sawdust and cement [110] [116]. Those with significant effect is due to greater quantities of cement-inhibiting compounds that are easily leached from the wood in the alkaline environment of cement [117] and those with less effect contain soluble compounds which, although present in the wood, are in small quantities. Wood species that greatly inhibit cement hydration are classified as incompatible with cement and therefore unsuitable for the manufacture of wood–cement composites [109].

❖ **Particle geometry** - The geometry and size of particles as well as density depends on the application of wood-bonded cement composites [118] [119]. It is reported that smaller particles increase the adhesive consumption because of enlargement of the surface [110]. Frybort, et al. [110] noted that as wood particle volume increases, the regions of stress concentration around adjacent particles become more diffuse, thus resulting in an increased resistance to the stresses applied. The ratio of constituent materials has as well been reported to play a significant influence in mechanical properties of wood-cement composites. Studies have shown that MOR increases as the cement-wood ratio is lowered [120]. However, a greater cement-wood ratios result in higher MOE values since MOE is dependent on the total amount of stiffness and incompressible cement matrix [110] [120].

3.5 Interim conclusions

The technology and mechanism of inorganic building materials has been presented. A unique feature of inorganic building materials is that their manufacture is adaptable to end of cost and technology spectrum. Inorganic building materials exhibit manufacturing versatility; products can be manufactured on a small scale using simple tools and low technical skills required. With advantages in high fire resistance, wet and dry rot resistance, freeze-thaw resistance, termite and vermin resistance, excellent workability, exceptional insulation and acoustic performance (WWCB), low cost and ease of manufacture, it was thus decided to apply the mechanisms illustrated above in the development of wood-crete building material. Issues related to hydration, ratio of material mix, geometry of particles and compatibility of wood and matrix has as well been presented. These issues give a clear insight on factors that affect the development of composite materials mainly made from fibre materials. It helps the researcher to have a good understanding on what considerations to be made whilst developing wood-crete.

CHAPTER 4 – PRELIMINARY EXPERIMENT ON THE DEVELOPMENT OF WOOD-CRETE

4.1 Introduction

This chapter describes the developmental stages considered before the development of wood-crete being presented in this thesis. A description of initial materials is considered and test results are presented.

The development of wood-crete started with consideration made on making lightweight composite materials from waste products. Initial materials considered included mixing sawdust and chicken feather with bio-resin, mixing sawdust and wool fibre with inorganic binders.

Composite is the term used to describe any two or more constituent materials with significantly different physical or chemical properties, that when adhesively bonded together, produce a material with characteristics different from the individual components. The focus on composite material in this research is based on sawdust (waste material from the sawing of wood).

The first attempt considered was to make panels by mixing sawdust with feather and bio resin (DSM). The use of DSM, a bio resin was considered due to the health effects associated with formaldehyde resins.

4.2 Feathers

Feathers are one of the epidermal growths that form the distinctive outer covering on birds. They are considered the most complex integumentary structures found in vertebrates. Feathers are known to aid flight for birds but over the years, they have found their use in thermal insulation and waterproofing. The main reason for considering feather at initial stage of research was to exploit the properties which range from soft and excellent at trapping heat, and known for its lightweight for use in the construction industry. Another significant reason for choosing feather is as a result of the large amount produced as waste in the poultry industry which makes it readily available for use. Feathers consist of keratins which are slow in their decomposition which makes it difficult in waste management. Feather waste has been used in a number of industrial applications as a medium for culturing microbes [121] biodegradable polymers, [122] and production of enzymes [123].

Some benefits associated with the use of feather for this research are listed as follows:

- ❖ Use of feathers would help local suppliers save both financial and environmental costs during waste disposal.
- ❖ The use of waste feathers reduces the environmental impact caused by the production of virgin alternatives.
- ❖ Avoidance of material going to landfill

4.3 Resin

Resins are natural or synthetic organic compound consisting of a non-crystalline or viscous liquid substance. Generally, natural resins are typically fusible and flammable organic substances that are transparent or translucent with either a yellowish to brownish colour gotten from certain trees and plants. Natural resins are formed in plant secretions and are soluble in various organic liquids but not in water while synthetic resins consist of a large class of synthetic or manmade products that have some of the physical properties of both natural resins but are different chemically. Natural resins are categorized as oil soluble or spirit soluble (spirit is alcohol or related solvents), and are insoluble in water. Recently, natural resins have been almost entirely replaced by synthetic resins, which are divided into two classes, thermoplastic resins (which remain plastic after heat treatment) and thermosetting resins (which become insoluble and infusible on heating).

DSM bio-resin (Paraleg) was considered as the binder though adhesives in the form of urea, phenol and melamine formaldehyde are generally used to bind together particle mix, with the former being the most favoured resin in use. DSM is a thermoset resin (Palapreg ECO P55-01) designed for use in sheet and bulk moulding compound. The resin is composed of 55% renewable resources which makes it a composite resin with high bio-based content. DSM claims that high renewable content of Palapreg ECO P55-01 does not reduce material's product performance under industry testing.

4.4 Sawdust

Sawdust is composed of fine particles of wood and is a by-product of cutting, grinding, drilling, sanding, or pulverization of wood with a saw or other mechanical tools. One major application of sawdust in the construction industry is its use in particleboards. Particleboard (PB) is a panel product made of sawdust and wood shavings bonded together by urea formaldehyde or other synthetic resin and pressed into sheets. Used primarily as core material for doors, furniture and cabinets, particleboard is often covered on one or both sides with veneer or another surface finish. In housing construction, particleboard is used under carpet or other finished surfaces as floor underlayment and stair tread; it is also used as floor decking in mobile homes. Sawdust was chosen as the main material intended to be bonded with DSM resin for the production of inorganic panels. Sawdust of 1mm and 2mm particle size was considered for the production of panel. This was done to be able to compare the difference in percentage use of resin and strength properties of sawdust-bonded DSM panels. In addition, specification for particle sizes generally requires that particles be slender for attaining high strength.

4.5 Tradical Lime

Binders (Tradical lime HB) was sourced from Lime Technology Ltd. Generally, the first step of lime production involves finding a suitable raw material which includes discovering calcium carbonate based stones (limestone or marble). Air-lime is produced by heating high purity limestone at temperatures around 900°C. The definition of pure air lime products according to criteria (including fineness, reactivity, and available lime) and quality control in production provides confidence in their application. The air-limes, pure or formulated, fulfilling these quality levels for the building industry receives the brand label Tradical.

4.6 Sample Preparation

4.6.1 Bioresin-Sawdust Composites

The first step of making bioresin-sawdust composite is the preparation of wood particles. Sieved sawdust needed to be dried for 24hours at 100^0 C so that the overall moisture level of the particles is significantly reduced for the purpose of bonding with liquid resins (usually between 3 – 10%). Particle drying is a critical step in production of bioresin-sawdust composite and the moisture content of the particles leaving the dryer should usually be in the range of 4% to 8%. After drying, the particles were blended with an adhesive (DSM resin). Due to the use of bio-resin, different percentages of resin to weight of sawdust was tried until a 20% peak level for resin to sawdust mixture was attained which was considered workable. However, between three and ten percent by weight of resin is the standard requirement used to impact properties such as fire resistance. Blending was done in a small blender with rapid mixing and shorter blending times.

The resin-soaked wood was blended to form a consistent paste and placed in a mould already prepared for hot press. Hot-press temperature was in the range of 100 °C to 120 °C, and pressure in the range of 2 to 3MPa. The formed panel was then pressed down for easier transportation to the final curing ovens. Individual sheets are held under pressure as the air around them is superheated. This allows the resin to harden and form a very strong bond with the wood fibres (Fig 4.1).

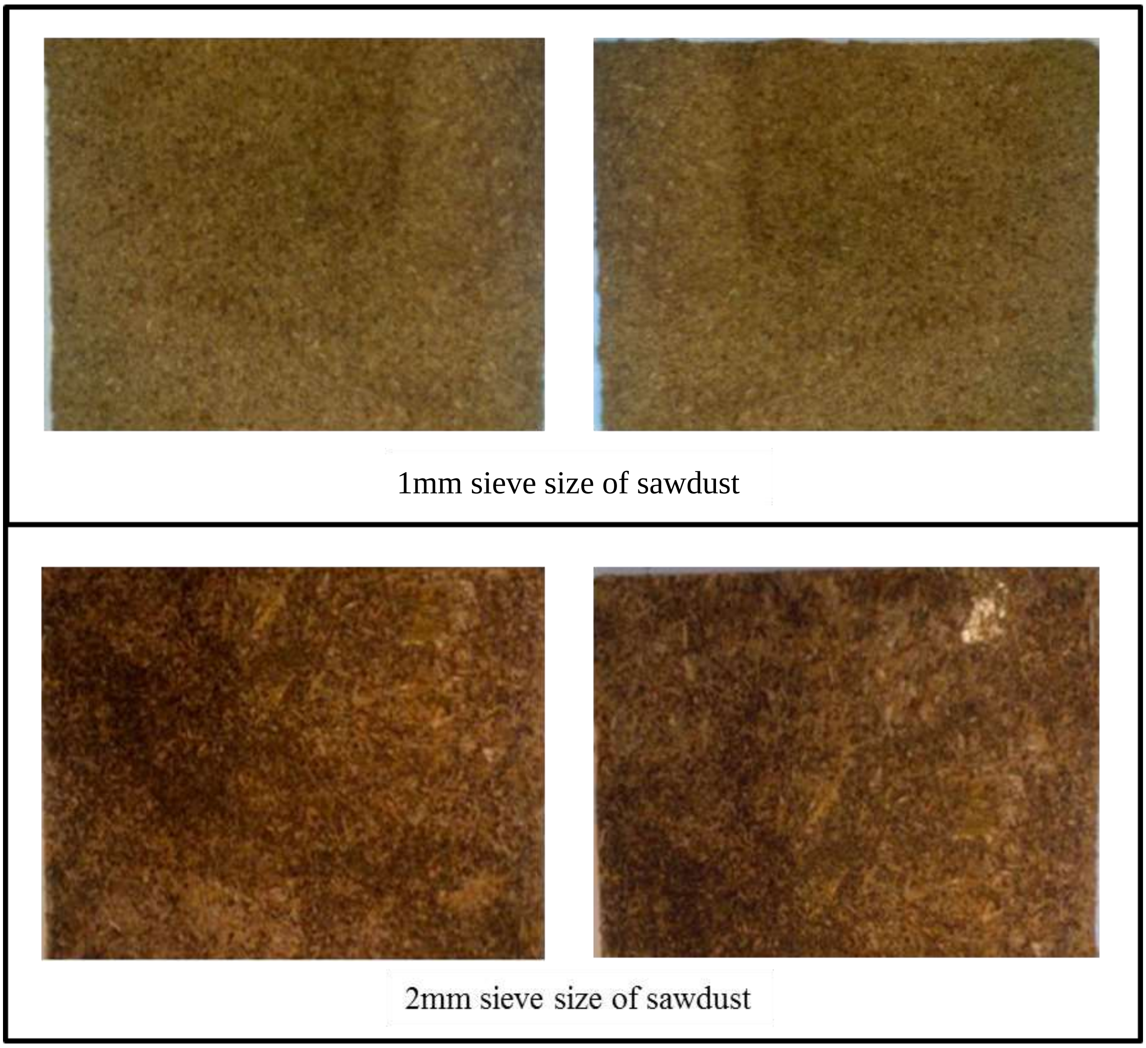


Figure 4.1 Wood panel samples made with DSM resin

4.6.2 Sawdust composites

Binders (Tradical lime HB) was sourced from Lime Technology Ltd. UK and commercial Ordinary Portland cement (OPC) was mixed with sawdust sourced from the Wood Workshop at Brunel University, London. The sawdust particles were refined to 1mm mesh size. Wool fibre also a constituent in this experiment was cut into smaller sizes of 3mm in length. The wool fibre was then mixed with sawdust and Tradical lime to improve the insulating properties and reduce the density of block samples. Before making samples to standards, it was important to make small samples to know the compatibility of sawdust, wool and binder (Fig 4.2).

Figure 4.2 Initial samples of sawdust, wool fibre and tradical lime

4.7 Initial Results

Initial composite samples made from sawdust and wool fibre showed a good bonding between sawdust and fibre, workability between materials was established and the possibility of blocks being used as an insulating material as a result of wool fibre.

4.8 Full Experiment on Sawdust-Wool Blocks

4.8.1 Experimental Design

Preceding block formation, the wood particles were dried in the oven at 100^0C for 24 hours to reduce the amount of water and then mixed with Tradical lime at the designed ratios. Wool fibre added was calculated in percentage ratio of sawdust by weight. These various ratios of sawdust to Tradical lime were designed with the intension of ascertaining the effect of lime compositions on the strength properties of sawdust. Sample blocks were made by mixing wool in water before the required amount of sawdust and lime were added in the mixer. Amount of water added was 20% of total mix weight. This was determined at the level mix was considered workable. The mix was uniformly distributed into the cylindrical and square moulds which were treated with a mould release agent. The mixtures were placed in a forming mould for 24 hours before de-moulding while maintaining a relative humidity between 46% - 49% for all samples. Preparation of specimens for testing strength properties was based on BS EN12390-2 [12]. Blocks were moulded in the dimension of 100mm x 200mm for cylindrical mould and 100mm x 100mm x 100mm for square moulds. It was important at this stage to use both cylindrical moulds and square moulds as they both offer different advantages to experimental procedure. Cylinders blocks can be cast in single-use or rigid metal moulds whereas square moulds can only be cast in rigid metal moulds. However, as a result of capping needed to distribute the applied load evenly over the ends for cylindrical moulds, square moulds was considered more useful since cubes do not need to be capped as they can be flipped on their sides for loading. This consideration is important for reduction in experimental and testing procedure. The actual volume of the blocks was taken from the measurement of samples after drying while sample mass was determined using a weighing scale. The density of the blocks was calculated from mass and volume. Three replicates were taken for each type of blocks. The de-moulded blocks were further cured for 32 days and tested for compressive strength at 20°C/65% relative humidity by applying a gradually increasing load under an universal Instron (Fig 4.3). The test pieces were placed between a supporting base and a flat steel plate. The machine applied a uniform load at a rate of 6mm/min until the maximum failure load was reached. The maximum load (in Newton) was automatically recorded and the compressive strength was calculated as maximum failure stress per unit area.

Figure 4.3 A – Wool composite block samples, B – block under compressive test

Table 4.1 Experimental mixture design

Samples	**Sawdust / Binder ratio**	**% of Wool Fibre**	**Density (Kg/m3)**	**Compressive strength (MPa)**
CYLINDRICAL MOULD SAMPLES				
A	S/TL (1:2)	5	656	2.11
B	S/TL (1:2)	10	644	2.31
C	S/TL (1:2)	20	641	2.67
D	S/TL (1:1)	5	618	1.01
E	S/TL (1:1)	10	609	1.25
SQUARE MOULD SAMPLES				
F	S/TL (1:2)	5	601	0.55
G	S/TL (1:2)	10	597	0.63
H	S/TL (1:2)	15	592	0.69
I	S/TL (1:1)	5	591	0.39
J	S/TL (1:1)	10	584	0.42
K	S/TL (1:1)	15	578	0.49

S = Sawdust, WF = Wool Fibre, TL = Tradical Lime

4.9 Results and Discussion

4.9.1 Compression Strength of Blocks

Compressive strength of blocks are summarised in Table 4.1. It is observed that compressive strength increased with reduction in density of blocks. It is suspected that the wool fibres added to mix helped reduce the density of blocks significantly. Also observed is that compressive strength was higher for samples made with S:TL of 1:2 compared to samples made with S:TL of 1:1 (Figure 4.4). Overall, there was 32% increase in compressive strength of cylindrical blocks made of S/TL 1:2 compared to S/TL 1:1 and 18% increase in compression strength of square blocks made of S/TL 1:2 compared to S/TL 1:1. In addition, the compressive strength of cylindrical block was significantly higher than those of square blocks. This defies normal expectations where compressive strength of square blocks is usually higher than those cylinder samples due to ratio of height to cross-sectional dimension [124]. One reason for the unusual result can be due to the compaction in various moulds and possible experimental errors.

During compressive test, main failure mode noticed was ductile followed by shear cracks. However, this needed more test for confirmation (Fig 4.5).

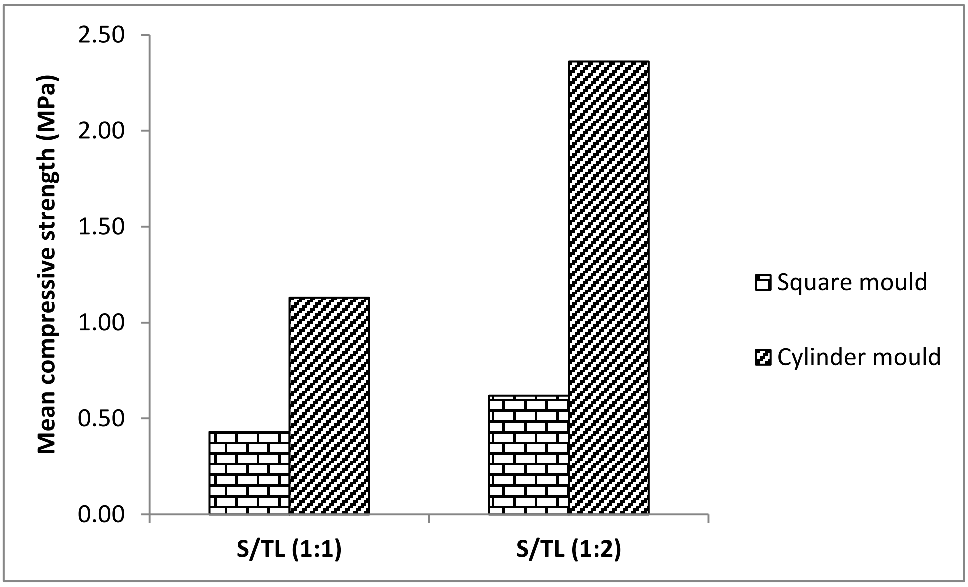


Figure 4.4 Mean compressive strength against sawdust – tradical lime ratio

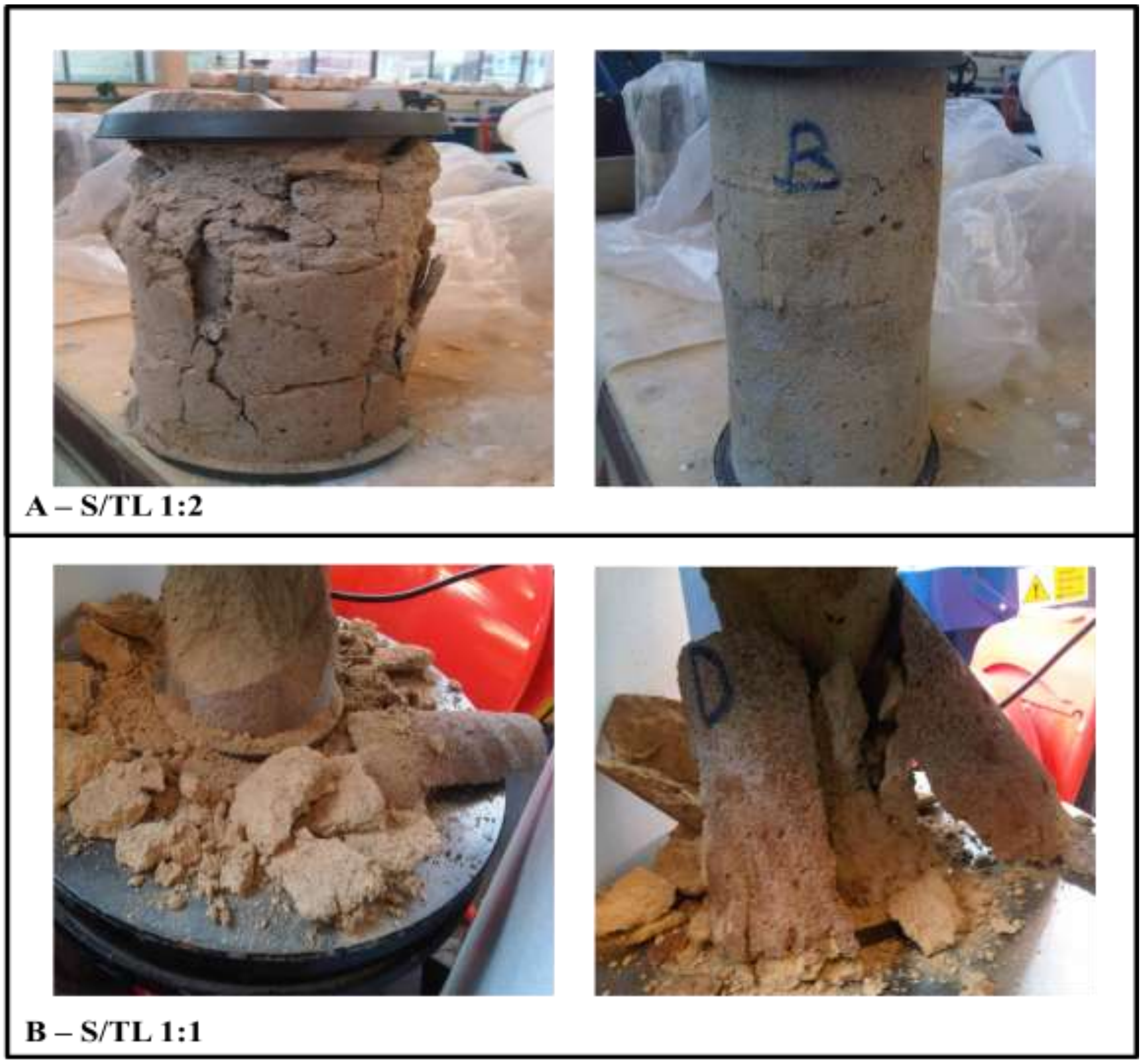


Figure 4.5 Compressive strength of samples with various percentages of sawdust / lime / water and fibre

4.9.2 Effect of Wool Fibre on Compression Strength

Results show that there was an increase in compressive strength with increase in percentage of wool fibre for cylinder and square samples of S/TL ratio 1:2 and 1:1 (Fig 4.6). However, it is envisaged that the most obvious effect of wool fibre would be on insulating properties of blocks samples [125]. There was an increase in compression strength of blocks with an increase in the proportion of wool fibre, for both square samples and cylindrical samples. For square blocks, compressive strength increased from 0.55 to 0.69 (about 11.3%) when percentage of wool fibre was increased from 5 to 15% for S:TL (1:2) and from 0.39 to 0.49MPa (about 11.4% increase) for S:TL (1:1).

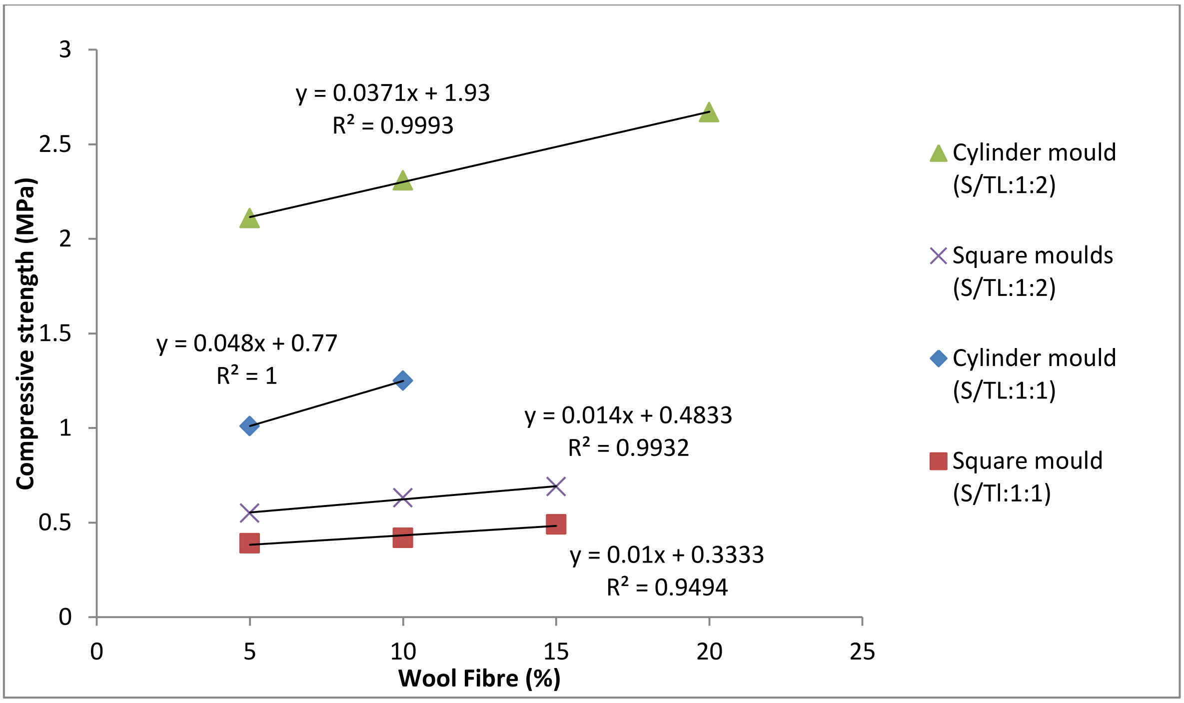


Figure 4.6 Compressive against percentage of wool fibre

4.9.3 Correlation of Density and Compressive Strength

The densities for blocks for S:TL (1:2) and S:TL (1:1) series are plotted against compressive strength in Figures 4.7. It is observed that compressive strength increases linearly with the decrease of density (Fig 4.8). Compressive strength increased from 0.55 to 0.69 MPa when the density decreased from 601 to 592 kg/m3 for S:TL (1:2) and from 0.39 to 0.49 MPa when density decreased from 578 to 591 kg/m3 for S:TL (1:1). Low density resulting in an increase in compressive strength has been observed in some composite materials like foam concrete. The reason for this can be drawn to air bubbles in the mix which provides stability for the composite material and once the material hydrates, load transfer takes place via the matrix around the bubbles [126]. Overall, an increase in density of 1.1% resulted in an increase in compressive strength of 7.8%.

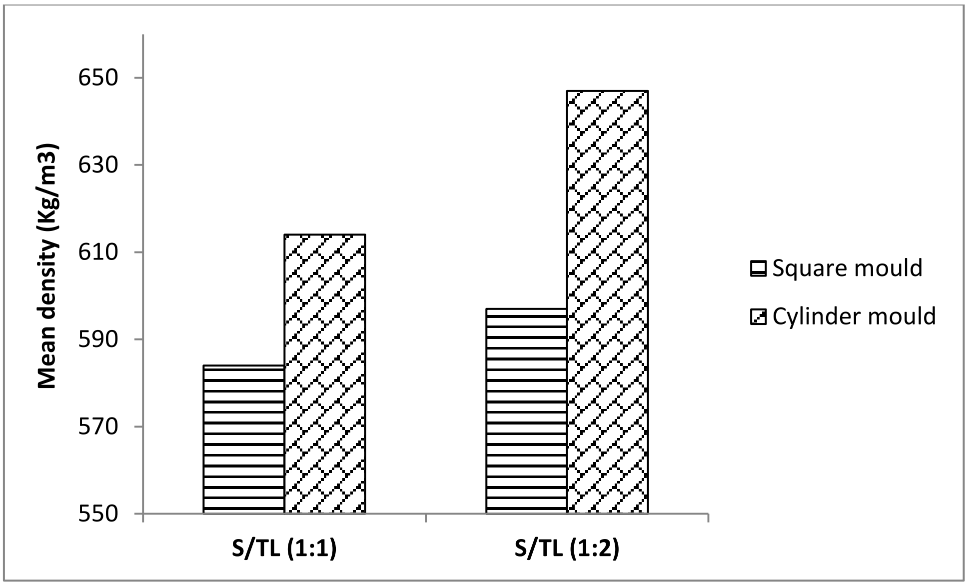


Figure 4.7 Mean density against sawdust – tradical lime ratio

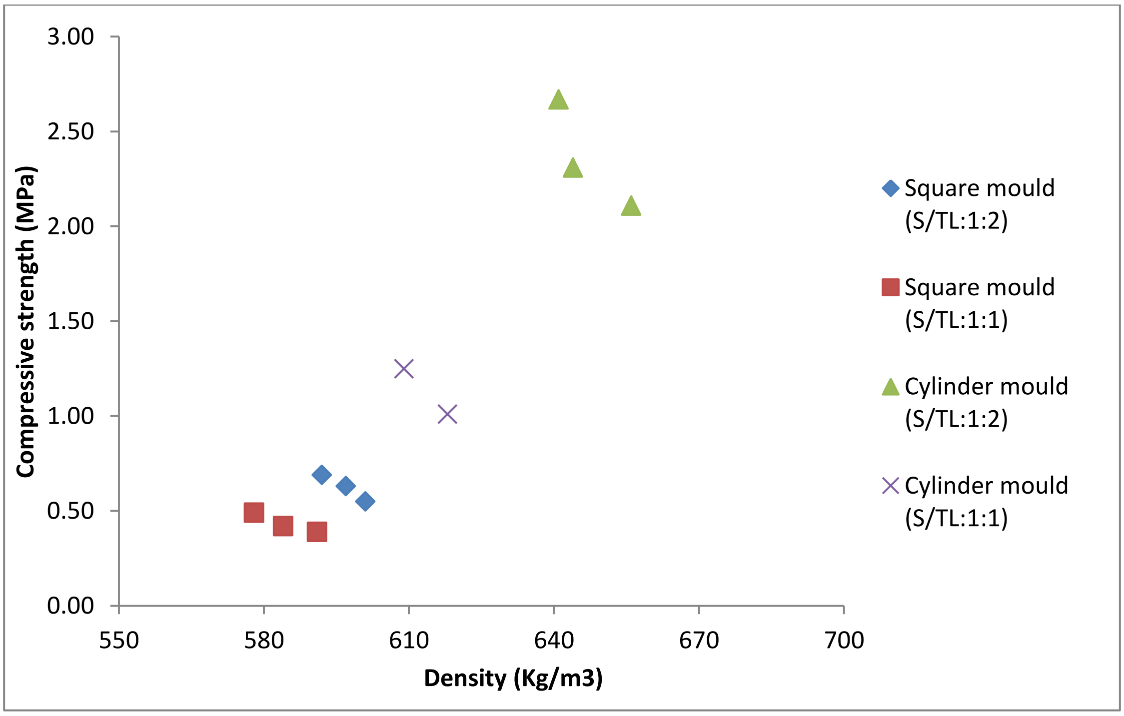


Figure 4.8 Compressive strength against density

4.10 Interim Conclusions

1. Square samples made with S:TL of ratio 1:2 achieved a compressive strength of about 7.8% higher than samples made with S:TL ratio of 1:1.
2. Results showed that increasing the percentage of wool fibres helped reduce density of blocks.

3. There was a corresponding increase in compressive strength with increase in percentage of wool fibre.
4. Comparing samples of same mix, (A, B, C, D with F, G, I, J), it is observed that cylindrical samples has about 54% increase in compressive strength.

4.11 Outcomes and Recommendations from Preliminary Study

1. **Using organic and inorganic binder**: The organic resin (e.g DSM resin) was first tried. It can be seen that there is an improvement of the sawdust blocks. However (tradical lime) was more efficient compared to organic binder (Bioresin sawdust composite). The major setback why this process was not exploited any further was the amount of percentage of resin needed to bond sawdust and feathers together. This was considered to be very expensive. The 20% weight ratio to sawdust of resin used for bonding was considered too high as normally, about 3 – 10% is required for bonding. This however gave room for the consideration of organic binders including cement and lime.
2. **Using reinforcements**: The trial firstly used feathers. Feather waste contains parasites which meant they needed to be cleaned with chemicals and uncontaminated making their use, expensive. It has been reported that feather surface is the home for some ectoparasites, notably feather lice (Phthiraptera) and feather mites. Wool on the other hand showed reduction in mass of composites; achieve a better environmental balance, reduction in costs and manufacture of composites.

It can be concluded that there is significant benefits of adding reinforcements (wool fibre). This was then further discussed within the group and it was decided to try waste paper because waste paper was cheap and it is readily available for commercial use. From results of compressive strength above, sawdust - lime constituents needs to be properly and carefully investigated. This is because a sawdust mixture needs a lot of water in order for it to be thoroughly wetted before compaction in the mould. Lime also has the ability of water retention which makes sawdust – lime mix a bit difficult and requiring more water when compared to sawdust – cement mix.

3. From the results of the tests carried out, the following recommendations were suggested:

- ❖ There exist the possibility for the partial replacement of cement work with sawdust and lime in the production of lightweight panels though this needs to be further investigated thoroughly.
- ❖ Minimum ratio mix between sawdust and lime has been found to be 1:2 for compaction to take place. Any ratio less than this would be unsuitable for bonding.
- ❖ Organic materials are subject to deterioration over time hence sawdust and lime application should be carefully enhanced and coated.

  Based on the above,
- ❖ It is recommended that studies on how to improve the performance of sawdust / lime be looked into.
- ❖ Insulation properties of sample materials
- ❖ Consideration made to availability of material.
- ❖ Consider using similar material but with reduction in cost as wool fibre used is also expensive.
- ❖ Use of waste material but able to attain similar properties to those of wool fibres.

4. Potential for applications

- ❖ Load / non load bearing walls
- ❖ Noise barriers
- ❖ Wall panel
- ❖ Insulation material

CHAPTER 5 – METHODOLOGY (MATERIAL AND METHODS)

5.1 Introduction

This chapter gives details of the materials and methods used in the fabrication of wood-crete. Testing procedure used to study the structural behaviour of wood-crete composites and procedure used for the structural compressive testing of wood-crete along with the instrumentation and test setup are discussed as well. The details of all the constituents of wood-crete, including sawdust, waste paper and tradical lime are well outlined. Also discussed in this chapter is the process of making of wood-crete.

5.2 Materials

5.2.1 Sawdust

Sawdust or wood floor is a by-product of cutting, milling, sanding, or otherwise pulverizing wood with a saw or other tools mainly in a sawmill. Sawdust has been used as one of the main component of particleboard though coarse sawdust particles are sometimes used for wood pulp. Sawdust has a variety of other practical uses, including serving as mulch or as a fuel.

Sawdust can be defined as loose particles or wood chippings obtained as by-products from sawing of timber into standard useable sizes. Timber is one of the oldest structural materials used by man.

Olutoge [127] in his investigations into the physical properties of rice husk ash, sawdust and palm kernel shell found their bulk densities to be 530kg/m^3, 614kg/m^3 and 740kg/m^3 respectively. He concluded that these materials had properties which resembled those of lightweight concrete materials. Sawdust as it originates is normally green (not dry) and fairly uniform in size and shape. Sawdust is also commonly referred to as “wood flour,” which indicates the particles can pass through a 20-mesh gauge screen. Unfortunately, green sawdust has relatively limited uses. Green sawdust can be used for domestic heating in special sawdust furnaces, although this is not very common, as well as for smoking meats. Research shows that after being dried, sawdust can also be utilized via the gasification, combustion, and pyrolysis processes to generate electricity, heat and oil. In addition, sawdust has many desirable qualities, making it a popular material for fibre composite manufacturing. Most companies dump sawdust waste in landfill or give it away as animal bedding. Some are lucky enough to be able to sell their waste. Another way sawdust waste has been utilised is its conversion into briquettes. Not only does this process reduce the volume of the chips and shavings by up to 10 times, but it also helps increase the specific weight (gravity) of wood. The briquettes burns well, are easy to stock and can be sold to other businesses that need cheap energy. There are more ways to use wood waste efficiently. In most cases, there is enough waste and scrap to not only produce power for the entire plant, but to also heat facilities that can be used to air condition plants.

Sawdust used for experiment was sourced from the wood workshop at Brunel University, London. The sawdust is milled from different types of wood (Fig 5.1A) for other construction purposes in the wood workshop and collected in transparent bags (Fig 5.1B) by which they are taken to the laboratory for experiment.

Figure 5.1 A – Brunel University wood workshop, B – collection of sawdust in transparent bags.

5.2.2 Waste Paper

Paper making generally produces a large amount of solid waste with its fibres only limited to a number of recycled times before they become too short or weak to make high quality paper. Of the 4.6m tonnes of paper that is thrown away by households in the UK each year, only about one-third is recycled (Fig.5.2) [128]. The rest is sent to landfill sites where it is left to rot and produces the powerful greenhouse gas methane. Some of the wastes are land spread on cropland as a disposal technique, raising concerns about trace contaminants building up in soil or running off into lakes and streams. Recycling has proven to be a significant way of making good use of waste paper. Findings show that recycling one tonne of paper saves a similar amount of electricity to that consumed by a three-bedroom house in a year [129]. This equates to a saving of 1.3t of CO_2. In addition, not sending paper to biodegrade which consumes a large percentage of most local landfill space every year helps to significantly reduce methane emissions. Some companies burn their sludge in incinerators, contributing to our serious air pollution problems [129]. To reduce disposal and pollution problems emanating from waste paper, it is most essential to develop profitable building materials from them. A number of studies have been carried out on the utilization of waste paper in concrete [129] [130] which show that there is potential in the use of waste paper in the construction industry.

Waste paper has been used in asphalt road surfaces which makes use of old newspaper fibres to act as a thickener, which holds the liquid bitumen in place around aggregate of asphalt. Without it, the bitumen would drain away, allowing the aggregate to be more easily dislodged by traffic. In concrete repairs, recycled newspaper fibres are used as carriers for electrolyte solution, which enables concrete steel reinforced structures to be re-alkalised or desalinated, both responsible for the corrosion of steel reinforcement and in building constructions, homes are being built using recycled fibres as wall and loft/roof insulation, providing levels of insulation far and above that of traditional houses which makes it possible for houses to require no heating due to high standard of insulation [130]. This solution not only saves money for the home-owner or tenant, but vastly reduces the production of CO_2 gas normally generated by the heating boiler.

Figure 5.2 Waste paper site [128]

5.2.3 Tradical Lime

Lime is manufactured in various kinds of kilns by one of the following reactions:

$CaCO_3$ + heat $\longrightarrow$ CO_2 + CaO (high calcium lime)

$CaCO_3.MgCO_3$ + heat $\longrightarrow$ 2CO + CaO.MgO (dolomitic lime)

In some lime plants, the resulting lime is reacted (slaked) with water to form hydrated lime. The basic processes in production of lime are: (1) quarrying raw limestone; (2) preparing limestone for the kilns by crushing and sizing; (3) calcining limestone; (4) processing the lime further by hydrating; and (5) miscellaneous transfer, storage, and handling operations.
Air-lime is produced by heating high purity limestone at temperatures around 900°C. The definition of pure air lime products according to criteria (including fineness, reactivity, and available lime) and quality control in production provides confidence in their application. The air-limes, pure or formulated, fulfilling these quality levels for the building industry receives the brand label Tradical.
The choice to use lime over cement in this research was based on literature on how best lime performs over cement. The use of lime also allows damp to be absorbed to a limited degree and then evaporate harmlessly away [131]. Environmentally, use of lime mortars has been found to significantly reduce carbon footprint and are termed carbon neutral. Lime mortars like cement, gives off carbon dioxide during manufacture but unlike cement, re-absorbs carbon dioxide when it sets. Amongst some other benefits associated with the use of lime includes:

- During manufacture lime produces 20% less carbon dioxide than cement production.
- Lime is essential in the building of any natural house (any house built using straw bales, timber, earth etc).
- Lime is biodegradable.
- Lime is burnt at a lower temperature than cement in the production process (900°C as opposed to 1300°C), therefore making lime production not only more environmentally friendly but also more economical as well.
- Lime is recyclable.
- Lime allows the building to "breathe". Water can escape by evaporation, unlike cement where the only way the water can escape is by being absorbed into the bricks and therefore, risking damp and erosion of the building substrate.

However, during early stages of making wood-crete blocks, it was important to investigate the difference in properties of blocks made with tradical lime and blocks made with cement in order to ascertain which binder bonded well with sawdust and achieved a higher compressive strength.

Tradical lime HB used as binder in this study was sourced from Lime Technology Ltd. UK. It is claimed that tradical lime (a natural hydrated air lime) is a natural high performing construction material attaining elastic, durable, workable, vapour permeability and healthy material when used.

5.3 Methods

The performance of most materials like concrete is determined by its microstructure [132]. Microstructures are determined by its composition, its curing conditions, and also by the mixing method and mixer conditions used to process the concrete. The mixing procedure includes the type of mixer, the order of introduction of the materials into the mixer, and the energy of mixing (duration and power). To produce a good wood-crete block, it is therefore important to control how wood-crete is processed during manufacture.

To determine the mixing method best suited for a specific application, Ferraris [132] stated that the factors to be considered include the process of material production, location of the construction site (distance from the batching plant), the amount of material needed, the construction schedule (volume of material needed per hour) and the cost. To achieve the desired wood-crete, process of fabrication and production play an important role on the performance. The preciseness of each detailed process and reinforcement (waste paper) affect the test results such as the compressive strength, density and thermal conductivity. Normal wet casting method was used in the fabrication and production of wood-crete following the steps below:

- **Collection and separation of sawdust particles**: This step involved the collection of sawdust from sawmill (in this case from Brunel University workshop). Sawdust comes in various sizes thus the use of a sieve shaker was used to breakdown sawdust particles into various sizes from 0-1mm, 1-2mm and 2-3mm. This process helps to separate larger particles from smaller particles and other impurities in sawdust.
- **Drying of sawdust**: After separation of particle size, sawdust is dried in the oven for 24hours at 100°C to reduce moisture content in sawdust before use. This enables the determination and control of addition of water during production of wood-crete.

- **Breakdown of waste paper**: Waste paper in this study was used as reinforcement for wood-crete. Two different types of waste paper used were de-fibred waste paper and paper strip. De-fibred waste paper was broken down by first soaking paper in water to turn into paper marsh, drying for 24hours at 80°C and then blending into smaller particles of 1211.79μm in length and 25.97μm in breadth. Paper strip used was shredded to 279.4mm in length and 10.0mm in breath.
- **Assembly of mould**: Moulds used measured 100mm x 100mm x 100mm according to British standards [133]. It is important before casting to check the level and flatness of the mould base and the squareness of the mould forms.
- **Mould cleaning and preparation**: mould is cleaned and free from debris. Mould release agent (cream mould oil) applied evenly over the mould surface. Due to high moisture content in wood-crete during manufacturing, it is also important to make sure that joint and edges of mould are properly secured to avoid water runoff.
- **Wood-creting**: During the production of wood-crete, a required amount of waste paper is mixed before the addition of sawdust and binder (tradical lime). This process helps make sure that the waste paper (reinforcement) is properly wetted before addition of other materials. It is also essential to conduct a slump test to assess the workability of the wood-crete mix before placing in the mould. This helps to determine the amount of water content necessary for the production of wood-crete. Proper vibration (in this case tamping) is carried out to remove voids in wood-crete. Same number of tamping and consistency is carried out for all moulds as this has a great influence on the density of wood-crete. After spreading of wood-crete in mould and tamping, another main factor to be considered is levelling of wood-crete surface. This helps to flatten the surface of wood-crete thereby avoiding point load during compressive test. Point load is load applied at one point of a material during test and it may be caused due to uneven surface during production of materials.
- **Setting and demoulding**: Wood-crete is allowed to set for 24hours before demoulding. Setting is the result of the hydration of binder, producing microscopic mineral products that link adjacent tradical lime grains to each other. As hydration progresses, materials are bound more tightly together, so that it becomes more difficult for an outside force to deform wood-crete.
- **Curing**: Wood-crete is cured in open air for 32days. This was determined by taking the weight of samples until a constant value was attained for a period of 3 days.

Consistency in weight gives an indication of no further loss of moisture from wood-crete blocks.

5.3.1 Production of wood-crete with waste paper

One of the wood-crete products developed in this study involved the mixing of tradical lime with sawdust and waste paper (de-fibred). The process involved measuring the required amount of sawdust needed and tradical lime and ordinary Portland cement at the designed ratios. Firstly, sawdust needed was separated into different particle size with the use of an electric sieve shaker machine (Fig 5.3). The sieve shaker was arranged in different mesh sizes ranging from 0-1mm, 1-2mm and finally 2-3mm (Fig 5.3). The various sawdust sizes were collected from the sieve shaker and dried in the oven at 100^{0}C for 24hours before use to enable proper control of water content during experimental work.

Figure 5.3 Separation of sawdust particles

Waste paper used for this project was in the form of discarded newspapers and office waste paper. Some of the experimental work used shredded paper measuring 10mm in width by

294.4mm in length (Fig 5.4 A). Other experimental work made use of modified newspaper shown in Fig 5.4 B and Fig 5.5.

Figure 5.4 A - shredded paper, B – chopped newspaper

The newspaper was first chopped into smaller piece and then soaked in water for 2 hours. It was allowed to turn into a sludge which was then dried in oven for 48 hours at 80^0C. Following the drying process, the dried sludge was separated into smaller pieces and blended with a blender in order to break down the fibres into smaller particles (Fig 5.5) now known in thesis as de-fibred waste paper.

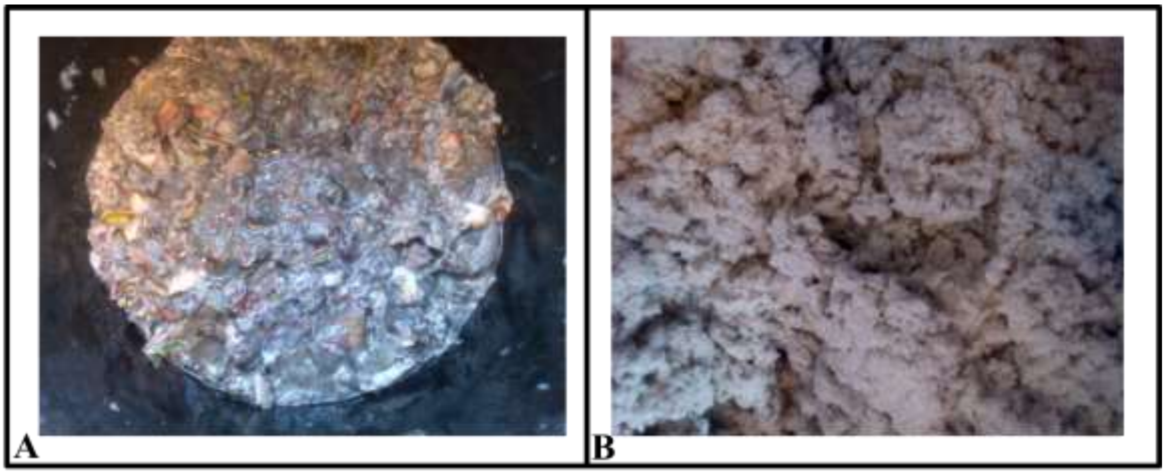


Figure 5.5 A – Waste paper sludge, B – blended waste paper (de-fibred waste paper)

The average microscopic measurement taken for 150 fibres was 1211.79µm in length and 25.97µm in breadth (Fig 6.6).

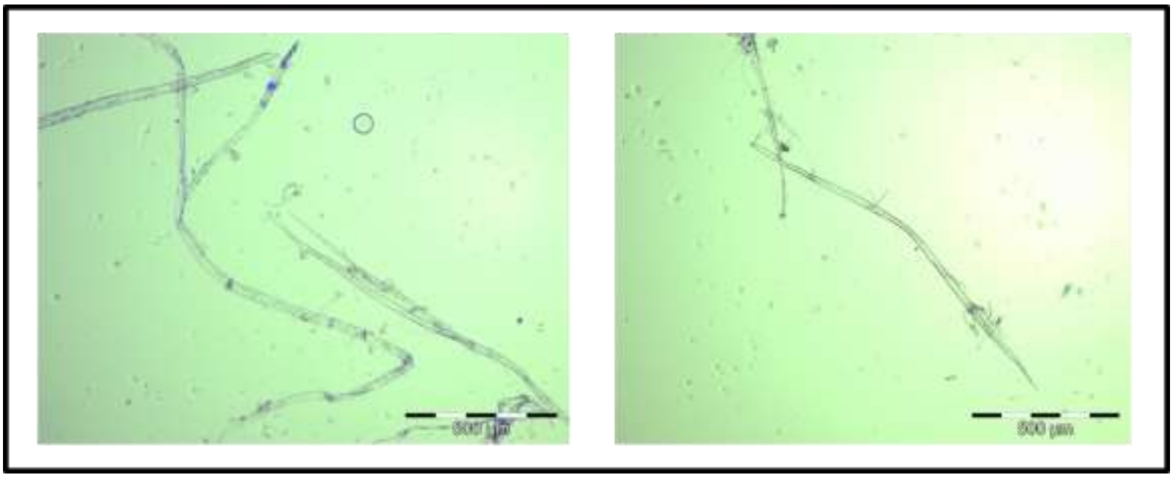


Figure 5.6 Microscopic image of de-fibred waste paper

De-fibred paper was then mixed with sawdust and tradical lime to improve the insulating properties and reduce the density of block. The paper added was calculated in percentage ratio of sawdust by weight. These various ratios of sawdust to Tradical lime / cement were designed with the intension of ascertaining the effect of lime and cement compositions on the strength of wood-crete. The ratios of sawdust to tradical lime / cement used were based on economic considerations and permissible impact on the strength ascertained using the dropping method, as explained by Zziwa, et al. [134], where preliminary trial specimens of varying compositions of sawdust and cement were made, dried and dropped from waist height (approximately 1m) to assess their structural integrity.

Wood-crete blocks were made by first mixing waste paper in water before the required amount of sawdust and tradical lime / cement was added in the mixer. This method is advised so that the waste paper can be thoroughly wetted. The amount of water added for every sample was 750ml per every 400g of sample. This was determined during trial making of samples. Mix made with 750ml of water less than 400g of total mix weight was termed unworkable while trial samples made with 750ml of water higher than 400g of total mix weight was termed to be slurry. This was important in other to be able to control the amount of water for every mix which has a direct effect on the density of sample (Table 5.1).

Table 5.1 Trial making of samples - Determination of mix ratio for wood-crete from waste paper

Water (ml)	Total mix weight (g)	Workable mix	Unworkable mix
500	400	No	Yes
600	400	No	Yes
700	400	No	Yes
800	400	Yes (Slurry)	No (slurry)
750	400	Yes	No

During mixing, it was important for individual wood particles and paper fibres to be fully encased by the binder to attain acceptable properties. Consistent and uniform mixing was carried out to allow for clumps to be broken down and binding powder (tradical lime) to be dispersed evenly throughout the sawdust and waste paper with the use of machine (Fig 5.7). Continuous mixing was done for a further few minutes after the addition of all materials in the mix. The setting of inorganic binders is the result of a series of chemical reactions causing a succession of crystallization stages [135]. The mix was uniformly distributed into the square moulds which were treated with a mould release agent. Preparation of specimens for testing strength properties was based on BS EN12390-2 (making and curing specimens for strength tests). Wood-crete blocks were moulded in the dimension of 100mm x 100mm x 100mm (Fig 5.7). It was noticed that due to the light weight of sawdust, there was almost no compaction under self-weight hence the tendency to create larger voids in moulds which could lead to low density and lower strength. Of significant note is that the degree of compaction has a great impact on the density of wood-crete. In a bid to ensure equal compaction and uniform distribution of materials in the mould, a minimum of 8 tamps was performed on each mould with minor force before levelling. The importance and advantage of tamping helps remove voids and fill gaps whilst creating a consistent end product. The mixtures were placed in a forming mould for 24 hours before de-moulding while maintaining a relative humidity between 46% - 49% for all samples. The samples were left at open air cure in the lab to attain the required amount of strength before being subjected to various kinds of tests.

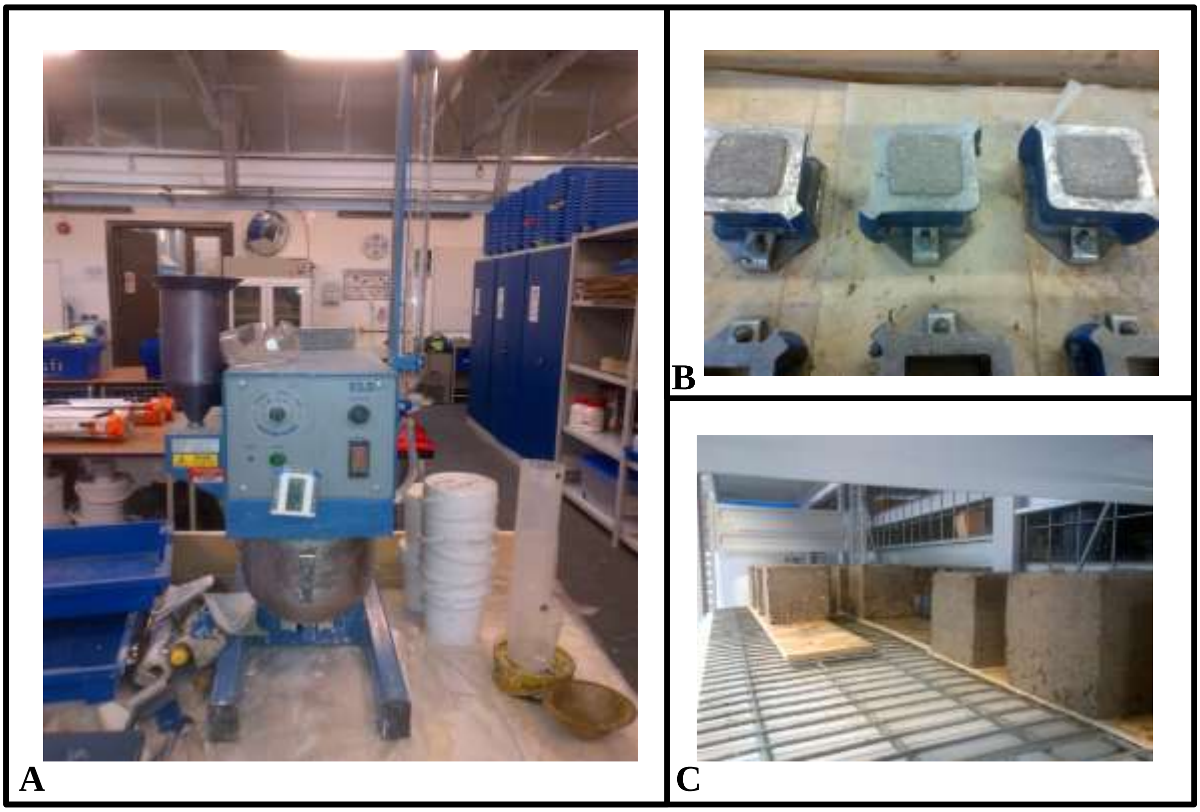


Figure 5.7 Moulding of wood-crete blocks (A – mixing machine, B – casting of wood-crete in square moulds, C – open air curing of wood-crete)

Mixing water with tradical lime and waste paper creates a wood-crete product that sets in a few hours and hardens over a period of weeks. This process varies however depending on the curing environment. It was discovered that wood-crete sets (becomes rigid) in 24hours and hardens in 32days to develop its compressive strength. The number of days was determined at the point where the density of wood-crete remained constant (i.e. no more loss of water). Normally, in principle as with concrete, strength continues to rise slowly as long as water is available for continued hydration but wood-crete should be allowed to dry out before use as water in wood-crete reduces the strength properties due to presence of waste paper. Setting and hardening of wood-crete is caused by the formation of water containing compounds, forming as a result of reaction between tradical lime and water. Stiffening, setting and hardening are caused by the formation of a microstructure of hydration products of varying rigidity which fills the water-filled interstitial spaces between the solid particles of binder.

5.3.2 Production of wood-crete with treated sawdust

Sawdust particles and waste paper where refined as discussed in the previous section. Preceding block formation, the wood particles were dried in the oven at 100^0C for 24 hours to stabilise the amount of water in sawdust particles before boiling. Sawdust was treated with NaOH at different percentages and boiling times (Fig 5.8).

Figure 5.8 Boiling sawdust

In chapter 8 of this thesis, first group of experimental design was treated with NaOH at different percentages namely 0,1,2,3,4,5,6 and boiling times namely 100,120,140,160 without the addition of waste paper and second group was treated with NaOH at different percentages namely 0, 2, 4, 6, 8 and boiling times namely 40, 60, 80, 100, 120, 140 with the addition of waste paper (de-fibred and paper strip at 50% and 75% of sawdust weight used). More details of experimental work are given in tables 8.1 and 8.2 of chapter 8. The treated sawdust solution was washed with distilled water to remove the adsorbed alkali and soluble like sugar which tends to inhibit hydration as noticed in wood-cement composites and then dried in an oven at 80°C for 24hours before being sealed in an airtight container to be used for experiment (Fig 5.9).

Figure 5.9 A - Washing of sawdust after boiling, B – storing sawdust after treatment

Two types of waste paper were used for purpose of comparison. First type of waste paper (newspaper) was de-fibred firstly by soaking in water, dried and then blended. The average microscopic measurement taken for 50 fibres was 1211.79μm in length and 25.97μm in breadth as shown in fig 5.6. Second type of waste paper (paper strip) used measured 279.4mm in length and 10mm in breath. The de-fibred and paper strips waste paper was then mixed with sawdust and Tradical lime to improve the insulating properties and reduce the density of block samples but most importantly contributing to self-strength of wood-crete. The amount of water used for all samples was calculated as shown in Table 5.1 and described in previous section.

The de-fibred and paper strips added was calculated in percentage ratio of sawdust by weight. Wood-crete blocks were made by mixing waste paper in water before the required amount of sawdust and lime were added in the mixer as described in previous section. This method is advised so that the waste paper can first be thoroughly wetted. The mix was uniformly distributed into the square moulds which were treated with a mould release agent. Preparation of specimens for testing strength properties was based on BS EN12390-2 [133]. Three replicates of samples were made for each fabrication of wood-crete. The mixtures were placed in a forming mould for 24 hours before de-moulding while maintaining a relative humidity between 46% - 49% for all samples. The de-moulded wood-crete blocks were further cured for 32 days and tested for compressive strength at 20°C/65% relative humidity by applying a gradually increasing load under an universal Instron. The actual volume of the blocks was taken from the measurement of samples after drying. Samples were sandpapered for evenness and flatness in all sides while sample mass was determined using a weighing scale. The density of the blocks was calculated from mass and volume.

5.3.3 Production of wood-crete with different wood species

The production procedure was similar to the previous sections except waste paper was not used. The process still involved measuring the required amount of materials needed (sawdust and tradical lime) and mixing with water. Amount of water used (450ml for 360g of total mix weight) was determined by making trial samples as shown in Table 5.2. The importance of individual wood particles to be fully encased by the binder (tradical lime) was also emphasised in this section. Consistent and uniformity in mixing was carried out to allow for clumps to be broken down. Samples were made based on preparation of specimens for testing strength properties (BS EN12390-2).

Table 5.2 Trial making of samples - Determination of mix ratio for wood-crete made from hardwood and softwood

Water (ml)	Total mix weight (g)	Workable mix	Unworkable mix
300	360	No	Yes
400	360	No	Yes
500	360	Yes (slurry)	No (slurry)
480	360	Yes (Slurry)	No (slurry)
450	360	Yes	No

5.4 Testing

Prior to testing, actual volume of the blocks was taken from the measurement of samples after drying. Samples were sandpapered for evenness and flatness in all sides while the mass of samples was determined using a weighing scale. The density of the blocks was calculated from mass and volume. Three replicates were taken for each type of wood-crete blocks. The test environment was kept at 20°C/65% relative humidity. Various tests were carried out including compressive test, thermal conductivity test, fire test and water absorption test. These tests are described below.

5.4.1 Compressive Test

Compressive test was carried out according to BS EN 12390-1: Testing hardened concrete – Part 1: Shape, dimensions and other requirements for specimens and moulds. The test involved applying a gradually increasing load under a universal Instron. The test pieces were placed between a supporting base and a flat steel plate. The machine applied a uniform load at a rate of 6mm/min until the maximum failure load was reached (Fig 5.10). The maximum load (in Newton) was automatically recorded and the compressive strength was calculated as maximum failure stress per unit area.

Figure 5.10 A - Instron compressive test machine, B – wood-crete under compressive test

5.4.2 Thermal Conductivity Test

The thermal conductivity of wood-crete in chapter 6 was determined by using thermal conductivity analyser which uses a novel analysis NDT technique. One major reason for choosing this method of thermal conductivity test is that the test is a non-destructive test which is a major advantage this test method has over other methods of thermal conductivity test which includes traditional guarded hot plate, transient plane source and laser flash diffusivity. Furthermore, some other advantages of using the thermal conductivity analyser are that additional sample preparation is not required and results are displayed within seconds of testing. The test procedure involves placing samples on a sensor which produces an amount of heat on application of current (Fig 5.11). The heat provided results in a rise in temperature at the interface between the sensor and the sample, typically less than 2ºC. This temperature rise at the interface induces a change in the voltage drop of the sensor element. Both thermal conductivity and effusivity are measured directly and rapidly, providing a detailed overview of the thermal characteristics of the sample material. The results are then displayed on the system's computer.

Thermal conductivity was also investigated for various wood-species (chapter 8) to explore the difference in thermal conductivity of wood-crete made from both hardwood and softwood with the use of Isomet Thermal Conductivity analyser. Sensor is placed on a sample which produces an amount of heat on application of current (Fig 5.12). Its working principles are based on the same as the seteram thermal conductivity analyser as discussed above.

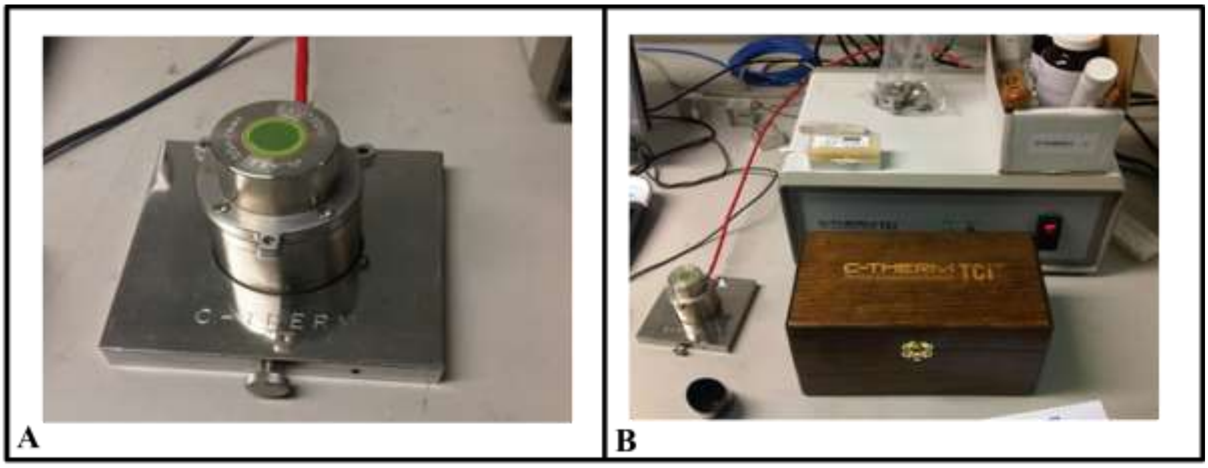


Figure 5.11 A - TCi thermal conductivity censor, B – TCi thermal conductivity analyser

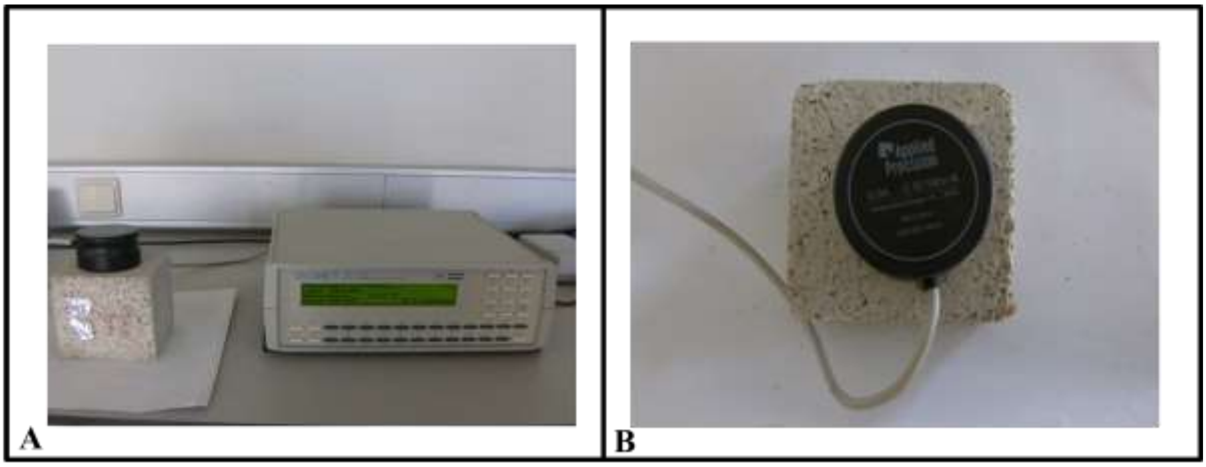


Figure 5.12 A - Isomet thermal conductivity analyser, B – wood-crete under test

5.4.3 Fire Test (Cone Calorimeter Test)

Fire test was carried out with the use of the reduced cone calorimeter test which involves exposing the surface of the test specimen to a constant level of heat irradiance, within the range 0-100 kW/m^2, from a conical heater. These conditions were based on test specimen positioning which is horizontal, a $50kW/m^2$ of heat flux exposure, test duration of 15mins use of specimen holder and frame during test and recording of observations related to specimen behaviour and times of interesting and significant events. Different samples were tested to give an indication of various behaviour of the wood-crete made (discussed in chapter 7) placing a total of 5 thermocouples (TC) used to measure the temperature of samples at specific intervals (Fig 5.13). Fire test was conducted according to BS 476-15: 1993 standards.

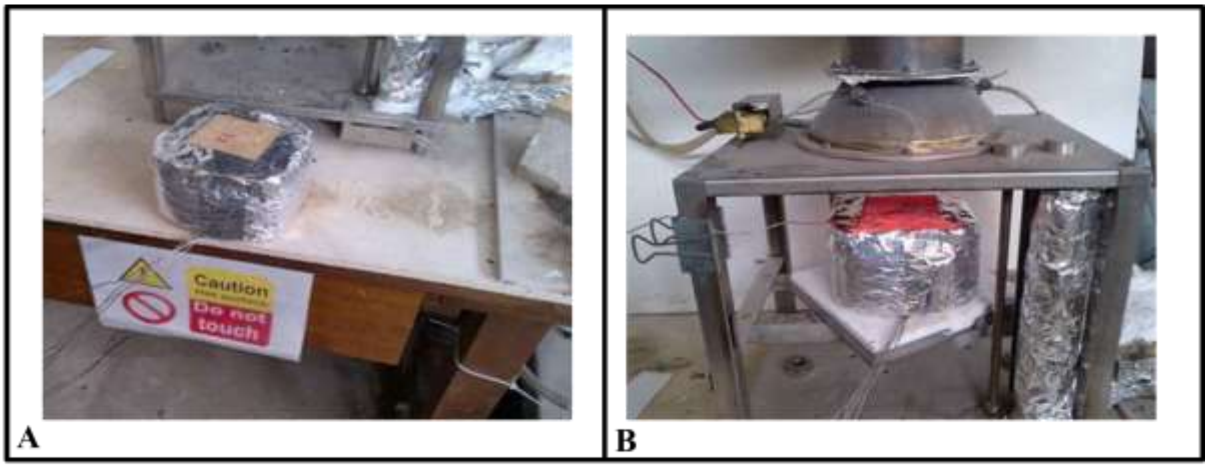


Figure 5.13 A – Preparation of wood-crete sample for fire test, B – wood-crete under fire test

One of the main advantages of conducting cone calorimetry testing is that smaller sample sizes are required, resulting in a number of benefits including:

- ❖ Lower test cost in comparison to full scale investigative European testing
- ❖ Cheaper than testing larger samples, particularly when the material is expensive
- ❖ Easier transportation and lower shipping costs
- ❖ Multiple samples can be tested and used for material comparison
- ❖ Allowing testing where an investigation is being carried out and larger samples are not available.
- ❖ Assisting with before and after testing comparison (for investigations into fire performance after exposure to weathering, UV light or frost etc.).

5.4.4 Water Absorption

Experimental set up was carried out according to long term water absorption by total immersion as described in BS EN 1208:1997 standard (Fig 5.14). It involves measuring the change in mass of test specimen, totally immersed in water over a period of 28 days. Excess water adhering to surface, not absorbed by the test sample is removed by drainage or taken into account by deduction of the initial water uptake. For this test set up, excess water on the surface not absorbed by test sample was removed by deduction method. The method involved weighing the test sample to the nearest 0,1g to determine its initial mass, m_0. The test sample is then placed in the water tank in such a position that it is totally immersed in water with the top face of the test specimen (50 ± 2) mm below the water level. Sample is removed after 10s, holding it horizontally and placed within 5s, in a plastic tray of known mass. Test sample and tray are weighed together to determine the mass of the test specimen, m_1, including the initial water uptake. Test sample is then placed in the water tank and a sufficient load is applied to keep the sample totally immersed in water, with the top face of the test sample (50 ± 2) mm below the water level (Fig 5.15).

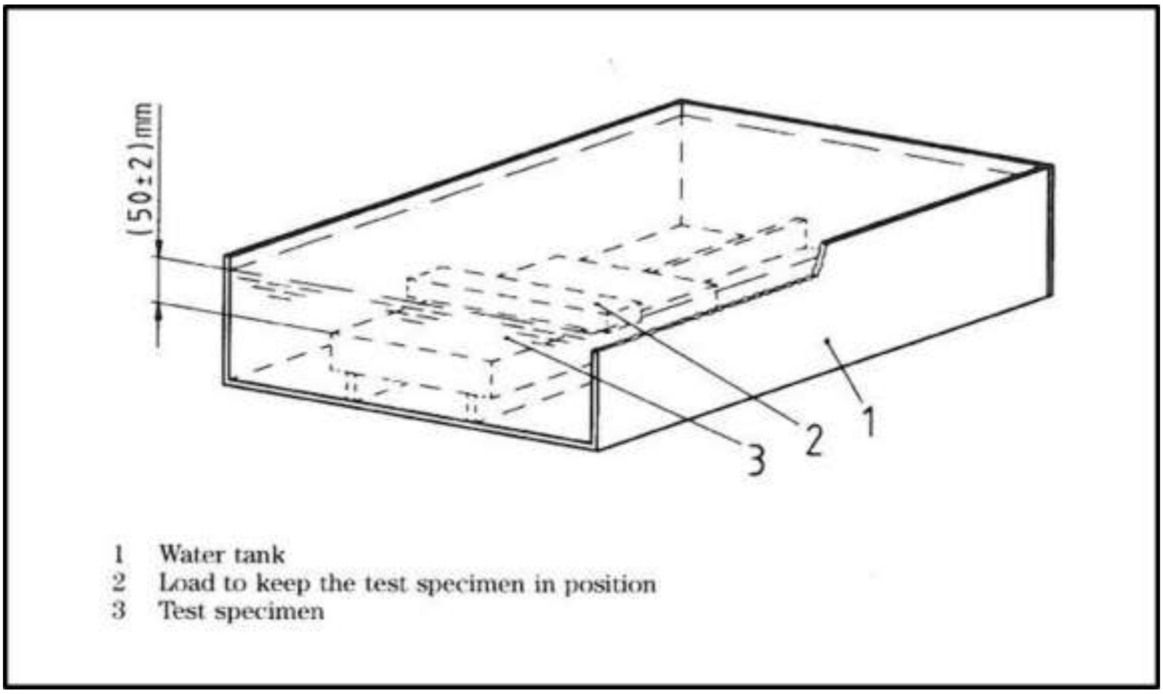


Figure 5.14 Experimental set up for determination of water absorption by total immersion (BS EN 12087:1997)

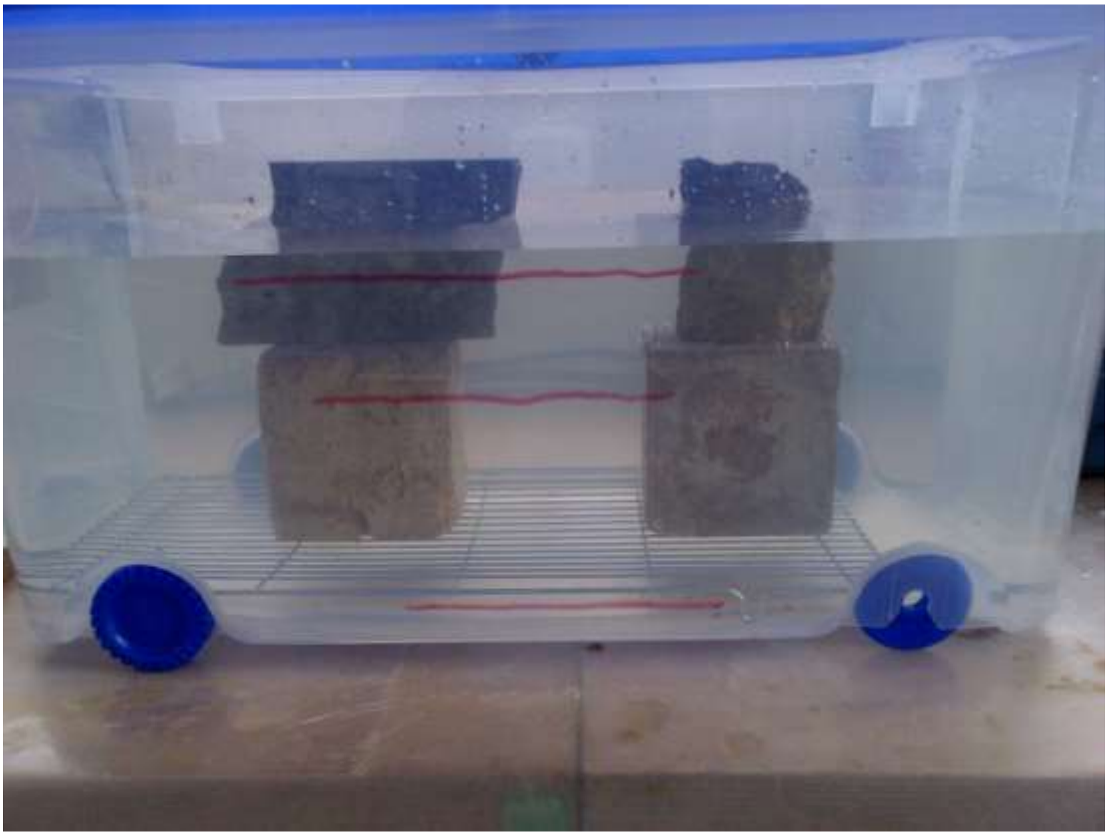


Figure 5.15 Wood-crete samples under water absorption

During the test period, water level is maintained at a constant level. After 28 days, test sample is removed from water tank holding it horizontally and placed within 5s in the plastic tray of previously determined mass to determine its mass, m_{28}. Initial water uptake is calculated by the given equation below and should be less than or equal to 0.5kg/m^2.

$$W_i = \frac{m_1 - m_0}{A_t} \qquad (1)$$

Where:

m_0 is the initial mass of the test sample in kg

m_1 is the mass of the test specimen including the initial water uptake in kg

A_t is the total surface area of the test specimen exposed to water in m^2.

The long term water absorption by total immersion is thus calculated as:

$$W_{1t} = \frac{m_n - m_1}{V} \times \frac{100}{\rho_w} \qquad (2)$$

Where:

m_0 is the initial mass of the test sample in kg

m_1 is the mass of the test sample including in kg

m_n is the mass of the test specimen after total immersion for n number of days in kg
V is the initial volume of the test sample, m^3
ρ_w is the density of water, assumed to be 1 000 kg/m^3.
W_{lt} shall be rounded to the nearest 0.1 volume percent.
After the 28day period of water absorption test, the samples were subjected to compressive test as described under compressive testing and results were compared to similar compressive test results of same samples not subjected to water absorption test.

5.5 Interim Conclusions

A background on materials and general methods (process and manufacturing technologies) employed in the investigation on the use of waste materials (e.g. wood wastes and waste paper) in the production of a novel building material (wood-crete), which is comparable to Hempcrete has been described. Main raw materials discussed included:

- Sawdust
- Waste paper
- Tradical lime

Main methodologies developed to be used in this research included:

- Production of wood-crete with waste paper
- Production of wood-crete with treated sawdust
- Production of wood-crete with different wood species

The next chapters (6 – 8) study the utilization of various wood wastes and waste paper by creating new innovative composite material (wood-crete).

CHAPTER 6 – WOOD-CRETE MADE WITH SAWDUST AND WASTE PAPER

6.1 Introduction

Wood-crete is a new material made from sawdust or other wood wastes, and Tradical Lime with consideration for cheaper and locally available materials to meet desired needs, enhance self-efficiency, and lead to an overall reduction in construction cost for sustainable development. Wood-crete has been developing in this research, intending to achieve similar properties but more cost effective as those of Hempcrete. Wood waste, a major constituent of wood-crete, may be sawdust from the sawing of wood or any other wood wastes. Since wood is used in large quantities in many different sectors and is a part of our everyday lives, the volumes of sawdust and other recovered wood available are also large. Sawdust could be loose particles or wood chippings obtained as by-products from sawing of timber into standard useable sizes.

The size of sawdust particles depends on the kind of wood from which the sawdust is obtained and also on the size of the teeth of the saw [97]. Between 10% and 13% of total content of log is reduced to sawdust in milling operations, depending largely on the average width of the blade, thickness of the timber sawed and technology of the sawing process [136]. Other wood wastes may include 1) solid or chipped wood in its natural stage without chemical contamination, 2) glued, coated lacquered wood without halogenic materials as timber preservative, 3) wood with halogenic materials (i.e. PVC) but no timber preservatives and 4) wood with timber preservatives [96]. According to COST Action E31 [137], the annual quantities of recovered wood in Europe reach about 30 million tonnes.

Particles of wood when held together with an inorganic matrix, like Tradical lime and Portland cement, form a composite that can be used for different applications in the construction industry. There are a number of merits offered by wood and inorganic binders over some conventional building materials presently used today. These composites combine the properties of both the wood fibre and matrix which makes them more valuable to the building industry.

A number of proposed advantages of developed wood-crete over other conventional wood composite materials include better insulation properties, resistance to water absorption, fire performance, and strength properties.

Wood-crete is produced with a binder known as tradical lime which is known for its elasticity, durability (long lasting quality mortars), workability, vapour permeability, healthy material (natural and solvent-free) when compared to the use of cement.

This chapter was to develop wood-crete using mixed sawdust and addition of waste paper. It presents the factors which affect the performance of wood-crete and its properties in relation to sawdust and waste paper. By using waste paper, wood-crete is not only reducing the amount of aggregate and binder but also making environmentally friendly building materials. This chapter is aimed at evaluating the fundamental mechanical properties such as compressive strength and thermal conductivity of wood-crete containing waste paper. It also analyzes the relation of wood-crete to evaluate the ductile behaviour of wood-crete.

6.2 Experimental Design

Waste paper was added in different percentages to weight of sawdust as shown in Table 6.1 and three replicates were made for each sample test making a total of 85 wood-crete blocks. In addition, it evaluates the effect of sawdust related to shrinkage because waste paper has high water absorption so high shrinkage of wood-crete was expected after curing. Different particle sizes where used to investigate the effect of particle size on wood-crete strength and also sawdust to binder ratio was varied.

Table 6.1 Experimental design

Samples	Sawdust / Binder ratio	% of Waste Paper
X1	S/TL (1:2)	75
X2	S/TL (1:2)	50
X3	S/TL (1:2)	30
X4	S/TL (1:2)	25
X5	S/TL (1:2)	15
X6	S/TL (1:2)	10
X7	S/TL (1:2)	5
X	S/TL (1:2)	0

Y1	S/TL (1:1)	75
Y2	S/TL (1:1)	50
Y3	S/TL (1:1)	30
Y4	S/TL (1:1)	25
Y5	S/TL (1:1)	15
Y6	S/TL (1:1)	10
Y7	S/TL (1:1)	5
Y	S/TL (1:1)	0
Z	S/C (1:1)	0
Z1	S/C (1:2)	0
W1	S/TL/C (2:1:1)	20
W2	S/TL/C (2:1:1)	15
W3	S/TL/C (2:1:1)	10
XX1	S/TL (1:1) – 2mm sieve	25
XX2	S/TL (1:1) – 2mm sieve	10
XX	S/TL (1:1) – 2mm sieve	0
XXX1	S/TL (1:1) – 3mm sieve	25
XXX2	S/TL (1:1) – 3mm sieve	10
XXX	S/TL (1:1) – 3mm sieve	0

S = Sawdust, WP = Waste Paper, TL = Tradical Lime, C = Cement

6.3 Results and Discussion

6.3.1 Density of Wood-Crete

It is observed that the density of wood-crete blocks was closely related to the composition of sawdust, waste paper and Tradical lime (Table 6.2). Overall the density of wood-crete decreases with the increase of the waste paper added. For X-series of wood-crete, an increase in waste paper from 5 to 75% weight of sawdust resulted in a consistent reduction in the density of wood-crete from 724 to 473 kg/m^3, about 1/3 reduction in density. This trend is also observed in the Y series of wood-crete composites made, with a reduction from 640 to 408 kg/m^3 when waste paper was increased from 0 to 75% weight of sawdust (Fig 6.1). The reason for the lower density of pure sawdust and tradical lime composites compared with those of composites with 5, 10 and 15% waste paper in the X-series experiment is still unknown. The only suspicion is the experimental deviation for some of the specimen made in this group as the cov is also abnormally high (Table 6.2).

Table 6.2 Mean density and compressive strength of wood-crete

Samples	Waste paper (%)	Density (kg/m^3)	Compressive strength (N/mm^2)*	Overall Mean
S:TL=1:2				8.14
X1	75	473	0.80 (2.0)	
X2	50	526	0.61 (15.1)	
X3	30	604	0.48 (6.4)	
X4	25	673	0.43 (7.2)	
X5	15	702	0.41 (5.5)	
X6	10	713	0.35 (5.7)	
X7	5	724	0.31 (3.8)	
X	0	616	0.26 (19.4)	
S:TL=1:1				
Y1	75	408	0.53 (4.6)	6.39
Y2	50	411	0.49 (2.9)	
Y3	30	490	0.44 (9.1)	
Y4	25	485	0.41 (10.3)	
Y5	15	505	0.36 (8.0)	
Y6	10	530	0.31 (11.6)	
Y7	5	549	0.22 (4.6)	
Y	0	640	0.21 (0.0)	18.33
S:C=1:1				7.5
Z	0	424	0.06 (37.3)	
S:C=1:2				4.2
Z1	0	543	0.10 (10.0)	
S:TL:C=2:1:1				
W1	20	397	0.27 (15.7)	
W2	15	404	0.22 (19.3)	
W3	10	416	0.18 (20.0)	
S:TL=1:1 (2mmSieve size)				15.4
XX1	25	409	0.29 (14.6)	
XX2	10	376	0.19 (22.3)	

XX	0	427	0.15 (9.3)	
S:TL=1:1 (3mm Sieve size)				12.57
XXX1	25	364	0.20 (18.0)	
XXX2	10	356	0.12 (8.3)	
XXX	0	383	0.09 (11.4)	
Hempcrete		445	0.4	
Concrete		20000	12 – 18	

* Values in ( ) are cov in %.

A comparison of the density of X series and Y series shows that the density of wood-crete blocks made with 1:2 mix ratio of sawdust to tradical lime had a higher density of 11.2% higher than that made with 1:1 mix ratio of sawdust to tradical lime (Fig 6.2). Theoretically, as the density of sawdust is lower than that of tradical lime (about 210kg/m^3 to 1201kg/m^3), it is expected that the densities of X series would be greater than those of Y series by more than 1.5 times. However, wood-crete blocks made with 1:1 ratio of sawdust to tradical lime showed a density difference of less than 1.1 times compared to similar ratio in the X series. It can thus be inferred that the sawdust may have more significant influence on the density of wood-crete than tradical lime.

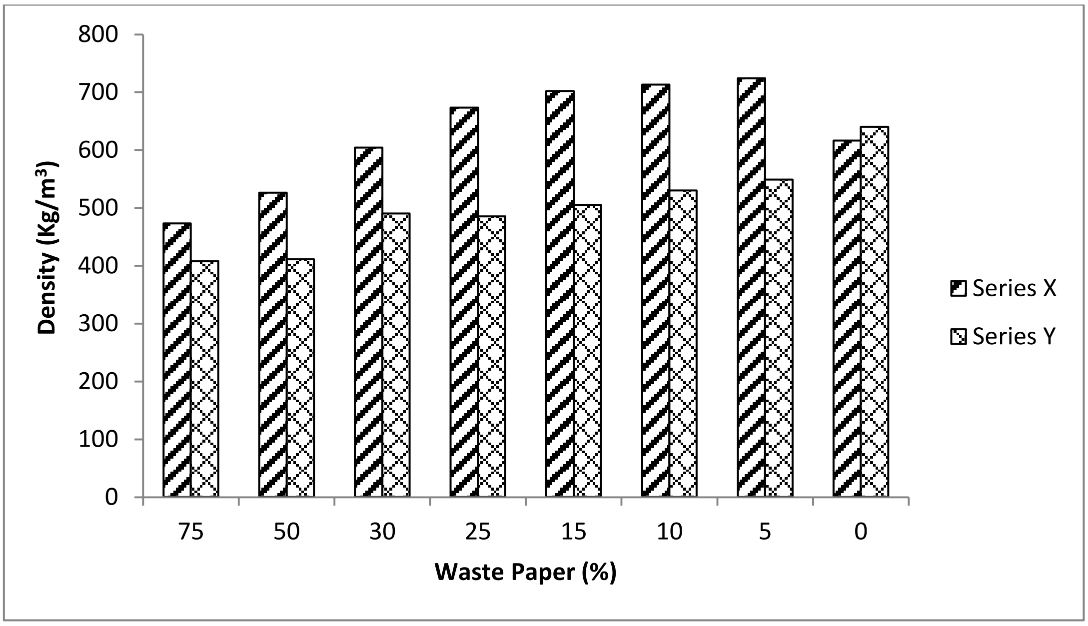


Figure 6.1 Effect of waste paper on density for X and Y Series

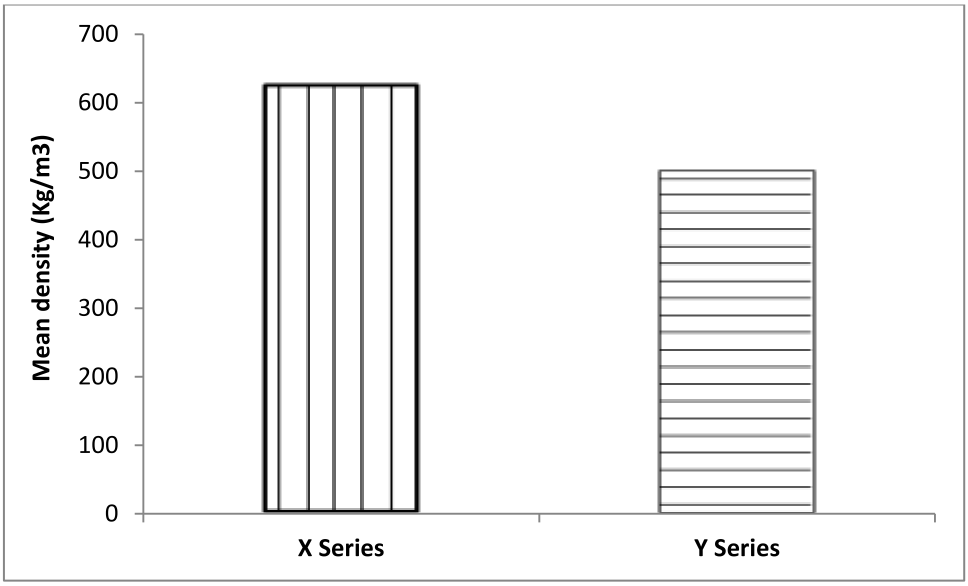


Figure 6.2 Mean density for X and Y Series

6.3.2 Correlation of Density and Size of Sawdust

Wood-crete made with 2mm sieve and 25% of waste paper, has higher density than that made with 3mm sieve at 25% waste paper, with the former being about 15% higher than the latter. A similar trend is found for the composites with 10% waste paper (Table 6.2). The density of wood-crete made with 2mm and 3mm sieve of sawdust was very low compared to the densities of all other samples made with 1mm sieve (Table 6.2). Comparing the density of samples Y, XX and XXX, it is found that density of 1mm particle size increased with 19.96% compared to 2mm particle size and 2mm particle size increased with 5.43% compared with 3mm particle size (Fig 6.3). The smaller the size of particles of sawdust, the higher the density is achieved. The geometry of sawdust particles may be related to the structure of the final composites; large particles may limit the compaction of formatting composites, resulting in a reduction in density. Lower density of sawdust itself in comparison with Tradical lime can also contribute to a lower density of the final composites.

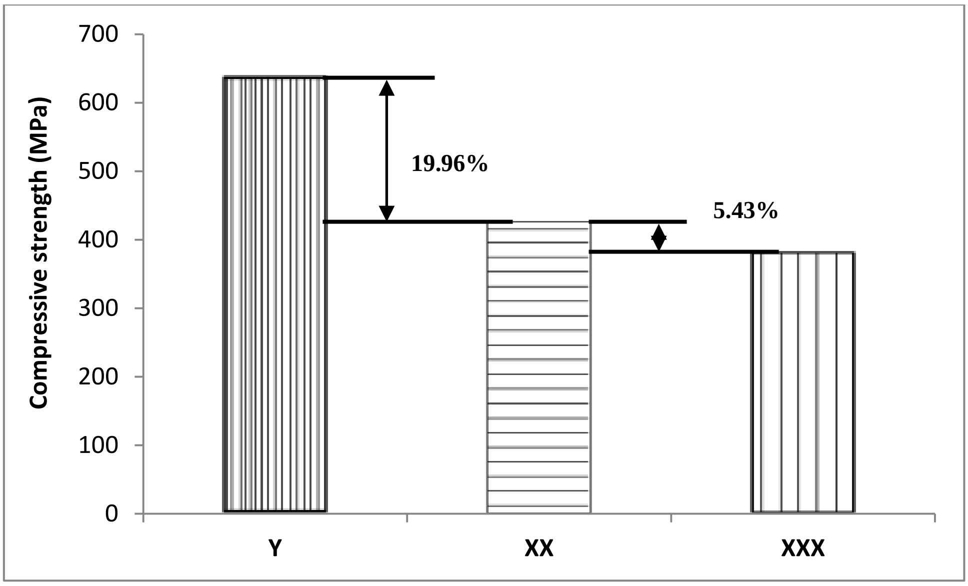


Figure 6.3 Effect of particle size on density

6.3.3 Correlation of Density and Shrinkage

The replacement ratio of waste paper of wood-crete is correlated to their density. The density of the wood-crete decreases as higher waste paper was included (Fig 6.1). Due to the low density of the waste paper (250 – 1500kg/m^3), the overall density of wood-crete is reduced. Table 6.2 indicates the trend of decreasing density of wood-crete according to increase of paper replacement ratio.

There was about 5% shrinkage of X2 wood-crete compared to X1. This continuous reduction in shrinkage was noticed across series X and series Y with increasing amount of waste paper. This means that paper replacement ratio of wood-crete affected increase of shrinkage.

6.3.4 Compression Strength of Wood-Crete

Compressive strength of wood-crete blocks are summarised in Table 6.2. It is very interesting that there was an increase in compression strength of blocks with the decrease of density of wood-crete. This may be due to the presence of waste paper in mix which acts as fibrous substance to network the materials and improve the bonding between sawdust and Tradical lime and among them whilst reducing density of blocks. This was also noticed with wood-crete made with cement binder.

Another important property of wood-crete noticed during testing was the large deformation that can undergo after reaching the ultimate load. An example of the failure is given in Figure 6.4. Main failure mode of wood-crete blocks was ductile followed by shear cracks in the core of blocks. Also noticed during compressive test is that wood-crete did not fail catastrophically a failure normally associated with concrete under compressive load. Of importance to wood-crete property is the stiffness of wood-crete blocks. When the load is removed after testing, wood-crete rebounds slightly in an attempt to return to its prior shape.

This reveals that wood-crete has a quasi-ductile behaviour unlike the sudden brittle failure associated with concrete.

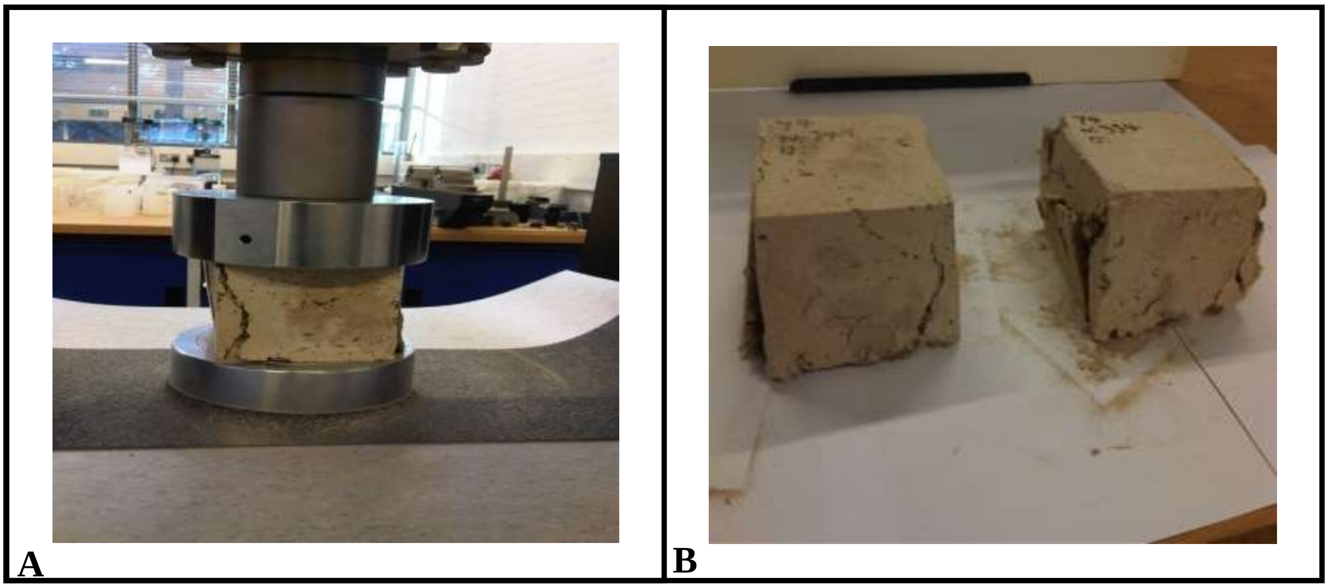


Figure 6.4 A - Behaviour of wood-crete under compressive loading, B - failure of wood-crete after compressive test

Considering that wood-crete, as other existing hempcretes, is intended to be used in combination with structural elements, such observed ductile behaviour may be attractive as it enhances the accommodation and adjustment between structural and non-structural elements which helps improve the absorption of small displacements and dumping, which always occur in houses and buildings.

The strength properties of wood-crete were not as good as those of normal concrete, but comparable to those of hemp lime composites, e.g. hempcrete. The compression strength values required for materials to be used as pavements ranges between 20 and 25 MPa while that for beams is between 20 and 35 MPa and up to 65 MPa for the reinforced concrete depending on the expected loads [134]. The compressive strength values of wood-crete composites made with waste paper were incomparable with those of concrete bricks which mean that they are not fit for a direct or stand-alone application as structural elements. The strength values, ranging from 0.26 to 0.80 MPa for wood-crete made, were rather comparable to compressive strength of hempcrete which is 0.4 MPa.

The compressive strength achieved and various densities depended upon the ratio of sawdust to lime and cement used in addition to the percentage of waste paper. The wood-crete blocks with sawdust lime ratio of 1:2 showed higher compressive strength compared to those made with a ratio of 1:1. Also observed here is that higher proportion of tradical lime in the composite helps achieve stronger blocks. The composites did fail prematurely which again suggests that the sawdust:lime:cement matrix exhibited plasticity properties to some extent. This suggestion is, however, supported by previous work [134]. There is a strong probability that the mechanical properties and dimensional stability of composites can be improved with increasing amounts of the additives as reported previously for other lime based composites [138] and also with the treatment of sodium hydroxide at different temperatures.

6.3.5 Effect of Waste Paper on Compression Strength

There was an increase in compression strength of wood-crete blocks with an increase in the proportion of waste paper, whether for the 1:1 mix or 1:2 mix of wood-crete (Table 6.2). The compressive strength increased from 0.26 to 0.80MPa when the waste paper was increased from 0 to 75% sawdust for the ratio of 1:2 of sawdust to Tradical lime (X-series) and from 0.21 to 0.53MPa when the waste paper was increased from 0 to 75% for the ratio of 1:1 of sawdust to Tradical lime (Y-series) wood-crete blocks (Table 6.2). Overall, the compressive strength consistently increases with the increase of the waste paper (Fig 6.5), reaching 54% increase in compressive strength for 75% addition of waste paper. The test results also indicated that an inclusion of waste paper below 5% did not improve the compressive strength. These results are of importance for a mixture design: an inclusion of a small percentage of waste paper may not increase compressive strength of wood-crete due probably to the lower compressive strength of waste paper itself compared to the sawdust and Tradical lime. At this point, the waste paper simply acts as filler for the wood-crete. However, a further increase of waste paper, such as from 5 - 75% in this study, could improve the structure of the wood-crete: a more consolidated bonding structure of the wood-crete may be established and hence give rise to a consistent increase in compressive strength of the wood-crete. The waste paper at this time acts as network links within the composites, improving bonding between waste paper with sawdust, between waste paper and Tradical lime and among them, and enhancing the stress transfer from one material to another within the composites.

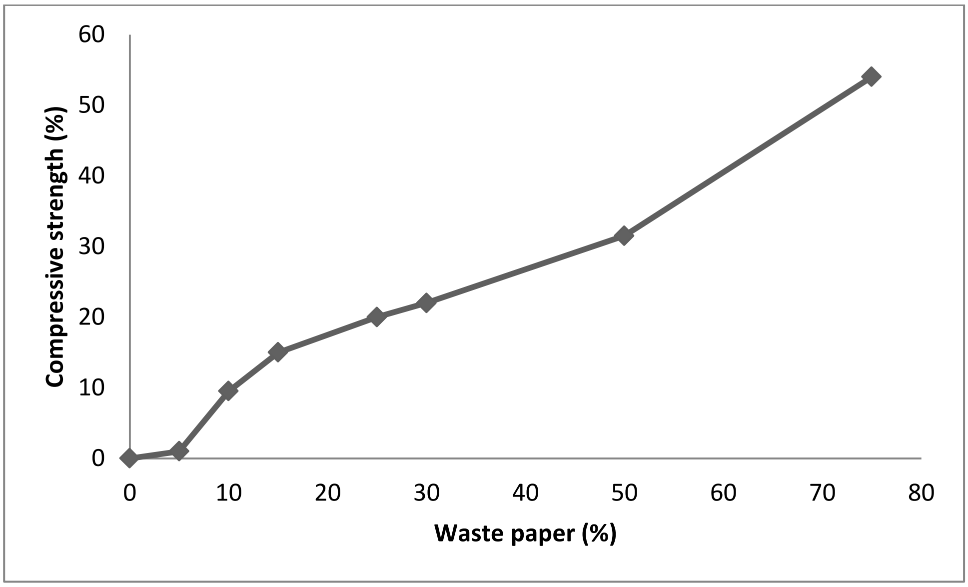


Figure 6.5 Increase in compressive strength with waste paper

6.3.6 Effect of Sawdust and Tradical Lime on Compression Strength

Figure 6.6 shows the difference of compressive strength of wood-crete made with different ratio of sawdust to Tradical lime: 1:2 for X series and 1:1 for Y series. It is apparent that lower sawdust content gives rise to a higher compressive strength of wood-crete. The strength of wood-crete with a ratio of 1:2 (sawdust: tradical lime) is about 11.22% higher than that with 1:1 ratio comparing. It is also noticed here that wood-crete achieved a compressive strength of 0.41MPa at addition of waste paper of 15% in X series while the same strength was noticed in Y series at an addition of waste paper at 25%. This was also noticed when wood-crete achieved a compressive strength of 0.31MPa with addition of 5% waste paper for X series and same compressive strength was noticed in Y series when waste paper was 10%. This gives an indication that the ratio of sawdust to tradical lime played an important role in compressive strength of wood-crete. The effect of tradical lime on compression strength of wood-crete has also been reflected in Figure 6.6. Wood-crete made with higher sawdust means lower concentration of binder ratio achieving lower compressive strength. Without waste paper, an increase in tradical lime from 50% to 70% results in an increase in the compressive strength of 25%. With 10% waste paper, an increase of Tradical lime from 45% to 65% results in an increase of 14% compressive strength, and with 50% waste paper, an increase of Tradical lime from 40% -57% results in 25% increase of compressive strength of wood-crete.

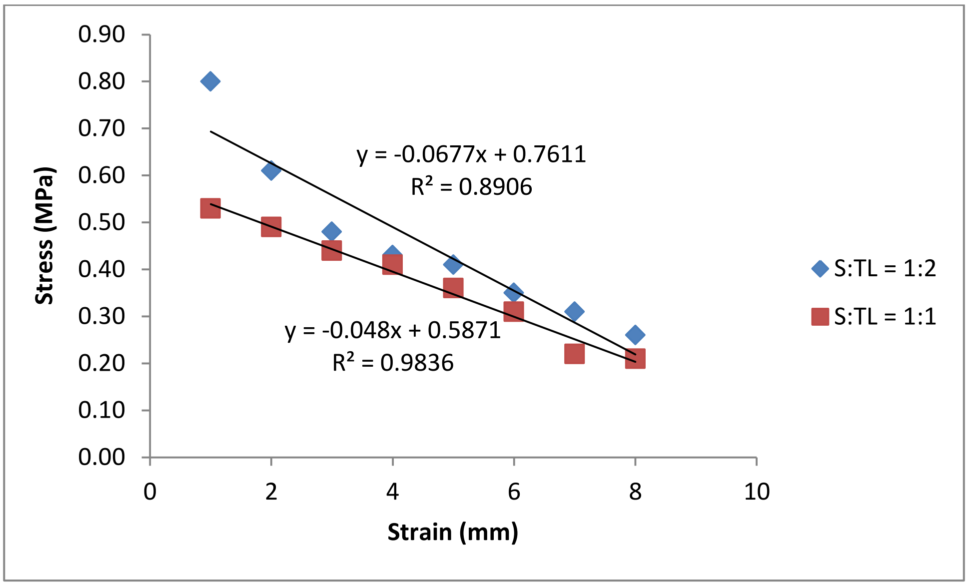


Figure 6.6 Compressive strength with different ratios of sawdust and waste paper

Figure 6.7 shows the percentage of total sawdust and Tradical lime in relation to the compressive strengths for X and Y series. It is apparent that the strength linearly decreases with the increase of total sawdust and tradical lime. The bonding between sawdust and binder and between sawdust particles may be more comprehensive and stronger for wood-crete with ratio of 1:2 than those of 1:1. The interface between particles may be more compact. This is also reflected with a higher density of X series wood-crete. Wood-crete blocks made with ratio 1:1 were fragile due to their low density which indicates poor bonding between the binder and sawdust.

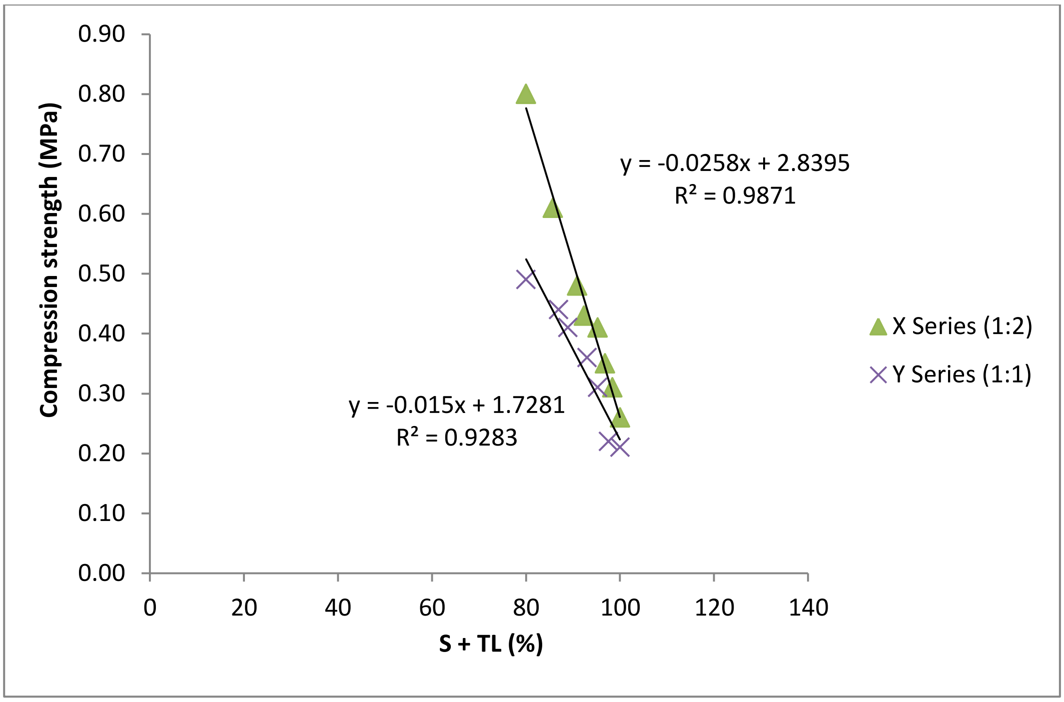


Figure 6.7 Effect of total sawdust and tradical lime on compressive strength

6.3.7 Combined Effect of Sawdust and Waste Paper on Compressive Strength

It is evident that the combined effect of sawdust and waste paper had a significant effect on the compressive strength of wood-crete. With the total sawdust and waste paper increased from 33.3% to 46.7%, the compressive strength increased about 3.5 times, see Figure 6.8 (X-series) and for Y series from 50% to 57.9%. The combined effect reflects the compaction of sawdust and waste paper: relatively small particles and paper fibres at this point may have filled many gaps between and within each other, thus enhancing stress transfer between both materials.

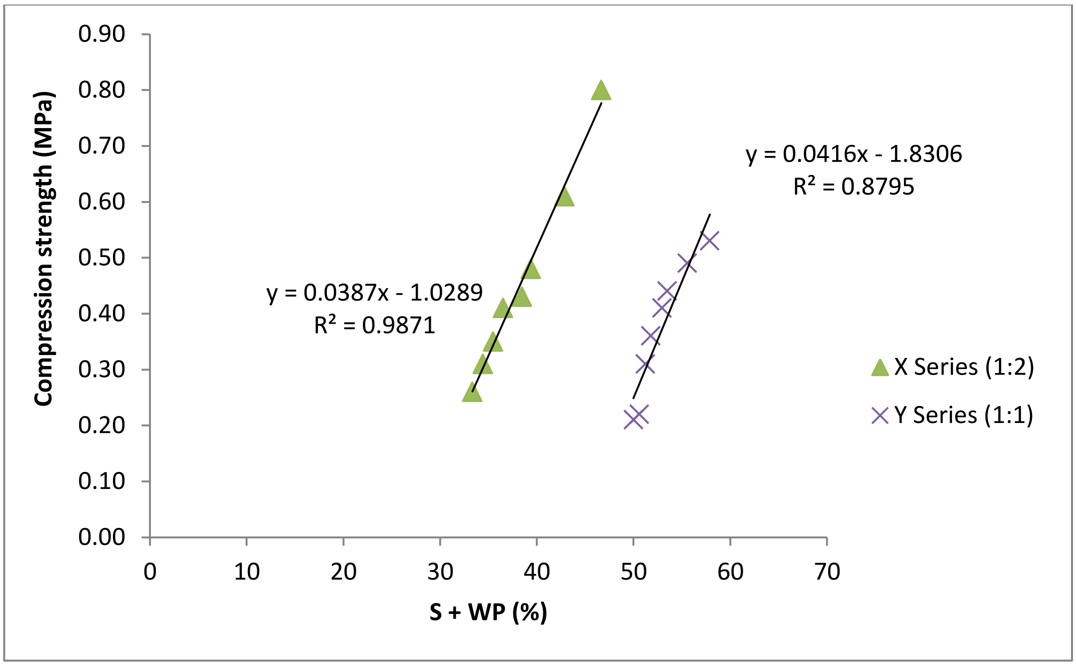


Figure 6.8 Compressive strength against total sawdust and waste paper

6.3.8 Correlation of Density and Compressive Strength

The average measured densities for the wood-crete for X and Y series are plotted against compressive strength in Figures 6.9 It is interesting that for both X and Y series wood-crete blocks, the compressive strength increases linearly with the decrease of density of wood-crete. The compressive strength increased from 0.31 to 0.80 MPa when the density decreased from 724 to 473 kg/m^3 for X series wood-crete blocks and from 0.21 to 0.53 MPa when density decreased from 640 to 408 kg/m^3 for Y-series wood-crete blocks. This result defies the normal expectation of increasing density with increasing compressive strength. The addition of waste paper may have added to the improvement of strength and a reduction in the density of wood-crete.

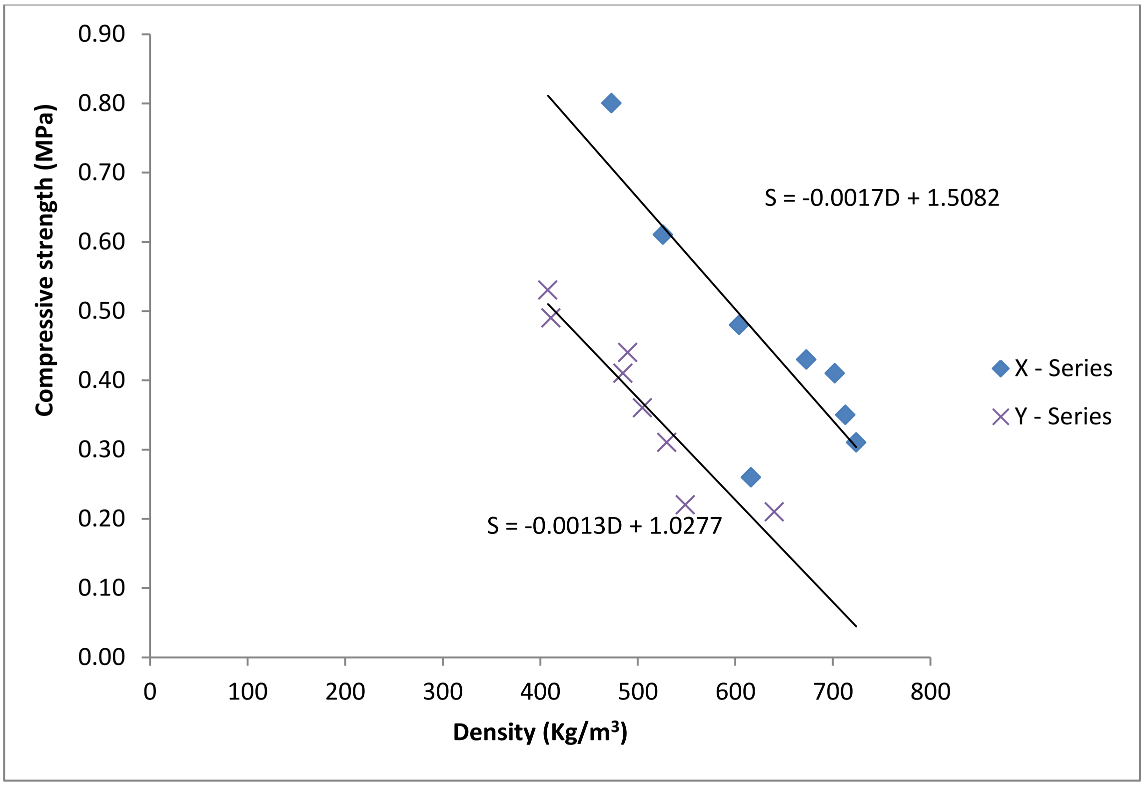


Figure 6.9 Compressive strength against density

6.3.9 Combined Effect of Cement and Tradical Lime on Wood-Crete

The test results show that wood-crete made with the combined binder of cement and tradical lime (W2 and W3) has a lower compressive strength compared to wood-crete made with only tradical lime as the binder (Table 6.2). Comparing samples W3 and Y3 made with same ratio of sawdust and percentage of waste paper, W3 has the compressive strength of 0.18MPa in comparison of 0.31MPa for Y3. The rationale behind this may be the different hydration processes of two different binders. Different hydration schedules between binders may result in 1) inconsistent structure of the cured products because of local curing process of one binder, 2) incompact structure because if one binder hydrates first, the hydrated product may be damaged during the curing process of the second binder, 3) insufficient bonding due to the lack of binder. This means the same amount of binder has been divided into two processes. When the first hydration takes place, the limited binder may not be distributed and cover the whole surface area of sawdust and paper. However, when the second hydration takes place, the hydrated products and sawdust and waste paper all work as aggregates. It is thus suggested that single binder should be used whilst making wood-crete and if the binders are to be combined, the hydration process of individual binders should be worked out for careful analyses before mixing.

6.3.10 Comparison of effect of Tradical Lime and Cement on Wood-Crete

It was important to compare the strength of wood-crete made with Portland cement to that made with tradical lime. Test results show that wood-crete made with tradical lime achieved a higher compressive strength than those made with cement. This result was same with the different ratios of 1:2 and 1:1. It is clear that this result has not been affected by the density of Portland cement being higher than that of tradical lime which is 1506kg/m^3 to 1201kg/m^3 respectively. There was significant difference in compressive strength of 44% of wood-crete made with tradical lime and cement (Fig 6.10). As discovered here with higher compressive strength achieved with tradical lime binder compared with cement and comparing the advantages tradical lime has over Portland cement as already stated in literature review, it was important to continue wood-crete manufacture with tradical lime.

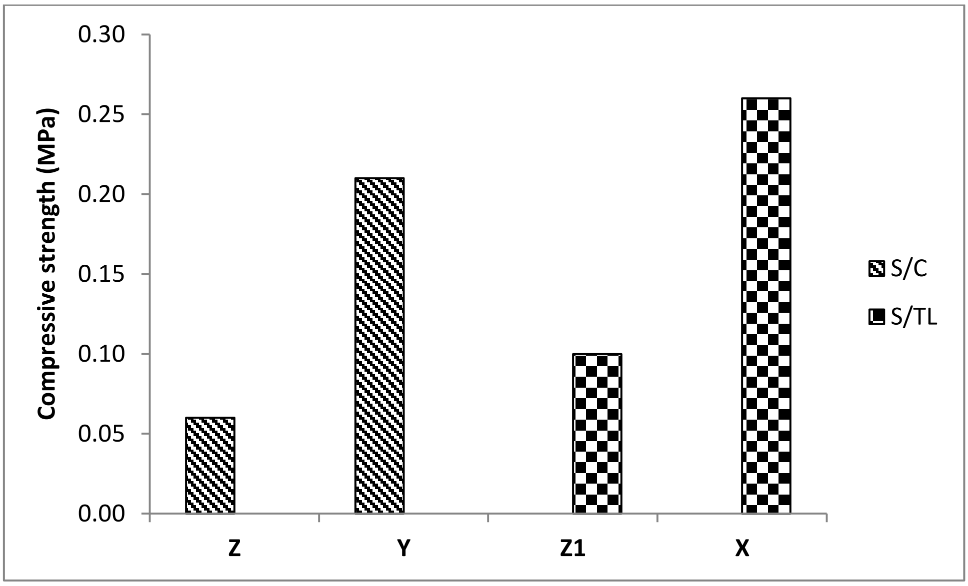


Figure 6.10 Effect of different binders on compressive strength of wood-crete

6.3.11 Effect of Size of Sawdust on Compressive Strength of Wood-Crete

Particle size of sawdust plays an important role in the mechanical properties of wood-crete. It is observed that wood-crete made with 1mm particle size (Y5) has a compressive strength of 16.7% higher than that made with 2mm particle size (XX) and 40% higher than that made with 3mm particle size (XXX). Likewise, compressive strength of wood-crete with 2mm sieve size of sawdust is higher than that with 3mm sieve size of sawdust: at both 10 and 25%

waste paper, the former is about 50% higher than the latter (Table 6.2). Although the strength is relatively low, the result proves that with smaller particles of sawdust at a higher percentage of waste paper, better strength is obtainable. This result is also a confirmation of a study on compatibility of no-fine concrete [139], where it was discovered that smaller particle size exhibits higher compressive strength. Fig 6.11 compares average compressive strength of samples Y2/Y3 with XX1/XX2 and XXX1/XXX2. The size of sawdust may have influenced the penetration of the tradical lime into the particles, that is, the larger particle may prevent a thorough penetration of tradical lime, resulting in inconsistent structure of wood-crete and hence reduction in the compressive strength.

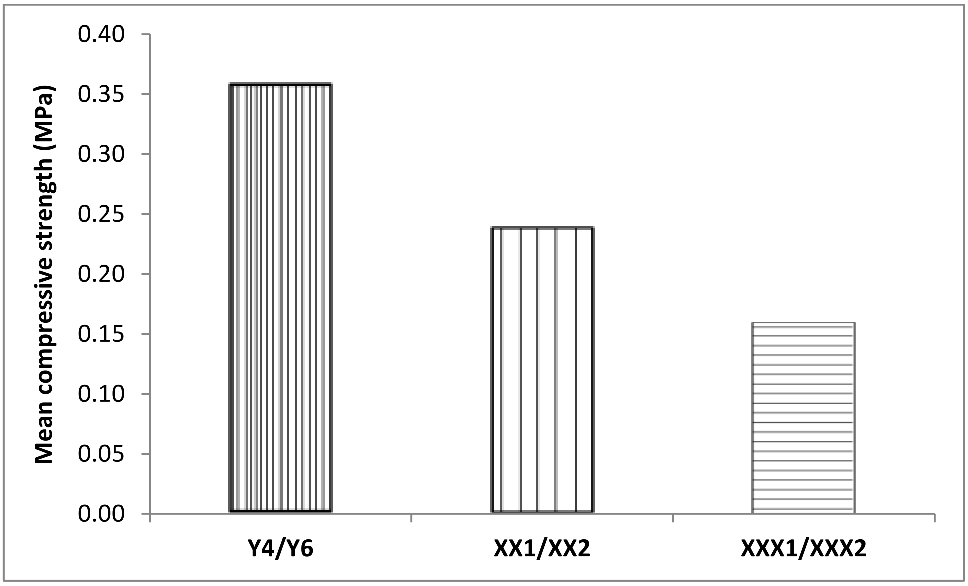


Figure 6.11 Mean compressive strength against particle size of same mix ratio

6.4 Thermal Conductivity

The test results showed that wood-crete blocks have a good thermal insulation property. Thermal conductivity of the wood-crete blocks tested (X1, X2, X3 and – X5) has a thermal conductivity ranging from 0.041 – 0.069 (Table 6.3). Thermal conductivity values achieved indicate that the wood-crete blocks can be used as in-fill wall panels since their strength is suitable for such applications with good thermal properties.

Table 6.3 Mean thermal conductivity of wood-crete: X-Series

%	Mean density (kg/m^3)	Mean compressive strength (MPa)	Thermal conductivity (W/mK)
75	473	0.80	0.046
50	526	0.61	0.069
30	604	0.48	0.063
15	702	0.41	0.052

6.4.1 Correlation of Compressive Strength with Thermal Conductivity

It is evident that an increase of compressive strength from 0.41 to 0.61 MPa, thermal conductivity increases from 0.052 to 0.069 W/mK. Further increase of the strength to 0.80 MPa, the thermal conductivity decreased from 0.069 to 0.046 W/mK. The increase in the strength of wood-crete means an improvement of both network and bonding systems of the materials which reflects in an improvement of heat conduction, i.e an improvement of thermal conductivity. However, much lower thermal conductivity (0.046W/mK) may be due to the dominated influence of nature of pores within the materials which is discussed in more details in next section.

6.4.2 Correlation of Density with Thermal Conductivity

Overall thermal conductivity increased with a decrease in density (Table 6.3). Thermal conductivity increased from 0.046 W/mK with density of 473kg/m3 to 0.069W/mK with density of 526 kg/m^3. However, further increase of density from 604kg/m^3 to 702 kg/m^3 resulted in a decrease of thermal conductivity from 0.063 to 0.052 W/mK. Thermal conductivity may be influenced by the degree of all processes of heat transfer such as heat conduction, convection and radiation. The efficiency of heat conduction is directly related to the density of material, i.e. with the increase of density, the conduction is improved, and hence, thermal conductivity increases. The convection may also play an important role in the thermal conductivity. The convection is related to the amount and geometry of pores and network system within the materials and this may be one of the reasons for the lower thermal conductivity of the wood-crete with a density of 702kg/m^3 compared to that of 604kg/m^3 because the pores may be too small for the formation of convection. The effect of porosity on the thermal conductivity of solids has also been reported by previous worker [140]. It was stated that the reduction in thermal conductivity depends on not only the volume fraction of pores but also their aspect ratio and their spatial distribution.

Both the correlation of compressive strength and density with thermal conductivity indicates that the addition of waste paper and composition of wood-crete and hence the structure of wood-crete may have played an important role on the thermal conductivity of the wood-crete blocks made. An increase in waste paper may have helped establish networks and bonding systems between sawdust particles and binder, resulting in an increase of compressive strength. A high percentage of waste paper in general resulted in reduction in density, therefore, the thermal conductivity decrease.

6.4.3 Comparison of Thermal Conductivity of various Materials

Table 6.4 Thermal conductivity of different materials used in construction in comparison to wood-crete

Materials	**Thermal Conductivity (W/mK)**	**Density (kg/m^3)**
Sheep wool	0.042	15
Gypsum board	0.18	600
Hempcrete with lime	0.13 – 0.19	445
Straw bale	0.038 – 0.052	75 - 100
Composite of expanded cork	0.036 – 0.40	160
Cork	0.045	240
Rock wool	0.042 – 0.045	150 - 200
Glass fibre quilt	12	0.040
Glass fibre slab	25	0.035
Phenolic foam	30	0.040
Polyurethane board	30	0.025
Urea formaldehyde foam	10	0.040
Steel	52	7500 - 8500
Concrete	1.5	2400
Cellular concrete	0.14 – 0.23	420 - 1250
Brick	0.27 – 0.96	1300 - 1700
Wood	0.12 – 0.3	350 - 900
Wood-crete		
75% waste paper	473	0.046
50% waste paper	526	0.069

30% waste paper	604	0.063
15% waste paper	702	0.052
Cedar	548	0.089
Pine	674	0.111
Oak	832	0.137
Beech	930	0.153

Average thermal conductivity value obtained for wood-crete was 0.058W/mK. Comparing the densities and thermal conductivity values of sheep wool and wood-crete in table 6.4 for instance, it is seen that wood-crete achieves about the same thermal conductivity value with sheep wool when their densities are of high differences. The reason for this would be as a result of air gaps in wood-crete which has a direct influence on the thermal conductivity of materials [140]. By comparing this coefficient with those of other materials used for similar applications, one may conclude that wood-crete has a good thermal conductivity.

6.5 Interim Conclusions

The compressive strength of the wood-crete ranged from 0.06MPa to 0.80MPa indicating that like hempcrete, the composite can be used as in-fills for wall panels and hollow blocks. The composites had good thermal conductivity ranging from 0.046W/mK to 0.069W/mK and thus could be used for thermal insulating materials for building construction. With some artistic designs and good wall finishes (e.g. wall papers), wood-crete blocks can be used for interior for non- or semi-structural panelling application. The properties of the composites were closely related to its composition with percentage of waste paper having an increasing effect on the compressive strength of wood-crete and ratio of sawdust to tradical lime having an effect on the bonding strength of wood-crete.

There is potential in the combined use of sawdust and waste paper as reinforcement in wood-crete composites for building construction helping in reducing waste disposal costs and generating incomes from sales of sawdust by sawmills and waste paper to the building and construction industry. One problem discovered for the low compressive strength of wood-crete was as a result of poor bonding strength between sawdust and matrix (tradical lime) used which the next chapter tries to address through the treatment of sawdust to improve the strength properties of wood-crete for structural application.

CHAPTER 7 – WOOD-CRETE MADE FROM TREATED SAWDUST

7.1 Introduction

The strength of wood-crete was discovered to be directly related to the bonding strength between sawdust and tradical lime which made compressive strength of wood-crete relatively low. The chemistry between the bonding of sawdust and binders for instance Portland cement has been argued by a number of authors [141] [142] [143]. Wood contains a number of substances, including hemicelluloses, starches, sugars, phenols and hydroxylated carboxylic acids which could dissolve and affect lime crystallization. The major problems of wood composites made from sawdust, cassava starch and natural rubber latex are associated with the hydrophilic character of the cellulose structure of fibre [144]. Researchers have suggested some propounding solutions to the above problem by stating the necessities to modify cellulose fibre surface by scientific methods to reduce the hydrophilic nature of sawdust thereby improving the sawdust–matrix bonding [144] [141]. As a result of the enhancement through different surface modification of sawdust interface, there is a significant increase in the strength of composites [142] [143]. The partial removal of the components of sawdust which include cellulose, hemi-cellulose, lignin (the main components that contribute to the strength, flexural and impact properties of composites) and pectin, waxes, and water-soluble substances [144] with alkali solution and the modification of cellulose fibre was reported by Zaikov, et al. [141]. Modification of sawdust as stated by Prompunjai and Sridach [144] include de-waxing, alkali treatment, cyanoethylation and benzolation. Several studies have noted that the reason for cohesion of matrix with the treated sawdust is that as lignin is removed, the middle lamella joining the ultimate cells becomes more plastic and homogeneous due to the gradual elimination of micro-voids [144]. It has also been stated that during modification by alkaline treatment, the hydrogen bonding in the network structure is disrupted, thereby increasing surface roughness [144]. The treatment removes a certain amount of lignin wax and oils covering the external surface of the fibre cell wall and depolymerises cellulose, and exposes the short length crystallites [142] [145]. The addition of aqueous sodium hydroxide (NaOH) to natural fibre helps form a good bond and promotes the ionization of hydroxyl group [142] [145]. The bonding between sawdust and hydrophobic matrix has a direct effect on the mechanical properties of composite materials while studies have also shown that the removal of hemicelluloses produces less dense and less rigid inter-fibrillar region [144].

This chapter thus focuses on the properties of wood-crete based on the modification of sawdust by hot water boiling, alkaline treatment and the addition of different types of waste paper (de-fibred paper and paper strip). Various treatments were proposed to optimise the property of wood-crete and the performance of the developed wood-crete was assessed.

7.2 Experimental Design

Sawdust was treated at different boiling times and with the addition of sodium hydroxide (NaOH) at various percentages to be able to ascertain a peak where sawdust particles when use for the production of wood-crete attains a high strength and low strength. Different types of waste paper (de-fibred and paper strip) were used as reinforcement to as well improve on the self-strength of wood-crete properties and a comparison was made between the different percentages of waste paper used (50% and 75%) both for de-fibred and paper strip. Three replicates were made for each type of test combination making a total of 1186 wood-crete blocks tested.

7.3 Results and Discussion

7.3.1 Effect of Water Boiling Treatment on the Compressive Strength of Wood-crete

Table 7.1 shows that the compressive strength of wood-crete increased gradually as the water-boiling time increased from 80mins to 140mins and then decreased at 160mins. The average compressive strength of wood-crete without an addition of NaOH increased from 0.25 to 0.33 MPa and then decreased to 0.28MPa. These results are in agreement with the previous studies conducted by Aigbomian and Fan [146], a compressive strength of 0.26 MPa was achieved for the wood-crete made with sawdust without boiling treatment. It is apparent that boiling time less than 120mins has little effect on the compressive strength but rather tends to weaken the bonding between sawdust and binder. This may also explain why, as boiling time increased from 140mins to 160mins, the strength of wood-crete decreased from 0.33 MPa to 0.28 MPa. This means that though the treatment helps to extract soluble from sawdust to create a better bonding between sawdust and binder, prolong boiling time may weaken sawdust particles themselves, thereby creating weaker wood-crete. The boiling time for the sawdust to be used for wood-crete production should be 140mins if no NaOH is included in the boiling water.

Overall mean values of compressive strength with duration of boiling time, for all NaOH additions tested, are 0.41 MPa with duration of 100mins, 0.52 MPa at 120mins, 0.50 MPa at 140mins and 0.37 MPa at 160mins. This again indicates that the compressive strength increased at first and then decreased with the duration of boiling time. However, the boiling time of 120mins gives the highest compressive strength compared to other treating times. There was an 11.8% increase in compressive strength when sawdust is boiled at 100mins to 120mins and a 14.9% decrease in compressive strength when sawdust is boiled from 140mins to 160mins. This illustrates the effect of NaOH on the soluble content of sawdust (Table 7.1).

Table 7.1 Experimental design and mean value of wood-crete property 1mm sawdust sieve size (without waste paper)

NaOH (%)	**Boiling time (min)**							
	100		120		140		160	
	CS (MPa)	**Den (kg/m^3**	**CS (MPa)**	**Den (kg/m^3**	**CS (MPa)**	**Den (kg/m^3**	**CS (MPa)**	**Den (kg/m^3)**
0	0.25 (8.0)	640	0.27 (1.9)	627	0.33 (18.6)	610	0.28 (5.3)	629
1	0.15 (12.3)	617	0.39 (16.7)	641	0.41 (2.2)	640	0.29 (9.9)	628
2	0.15 (8.9)	639	0.16 (10.9)	632	0.63 (3.7)	640	0.59 (2.1)	635
3	0.73 (2.4)	622	0.78 (6.6)	622	0.79 (12.0)	603	0.57 (15.8)	614
4	0.67 (5.3)	609	0.75 (8.3)	615	0.87 (5.1)	619	0.39 (10.4)	611
5	0.65 (5.7)	602	0.68 (7.2)	611	0.26 (17.0)	623	0.24 (16.9)	631
6	0.30 (9.1)	610	0.58 (11.6)	605	0.24 (4.5)	610	0.24 (5.0)	614
MEAN	**0.41 (7.4)**	**620**	**0.52 (9.0)**	**622**	**0.50 (9.0)**	**621**	**0.37 (9.3)**	**623**

CS = Compressive Strength, Den = Density, NaOH = Sodium Hydroxide, Values in ( ) are cov. in %

7.3.2 Effect of NaOH Treatment on Compressive Strength of Wood-Crete

Figure 7.1 shows that overall mean compressive strength of various treating durations of wood-crete gradually increased as the percentage of NaOH increased from 0 to 3% and then decreased as the percentage of NaOH continued to increase from 4 to 6%. It is apparent that an addition of NaOH is able to extract the soluble content of sawdust effectively. Proven here is that the treating sawdust to be used for wood-crete production should be 3% with boiling time of 130mins. Although there is only 3% decrease in compressive strength when NaOH increased from 3% to 4%, there is a drop of 33% in compressive strength when sawdust is treated further from 4% to 6%. Whilst the treatment of sawdust with NaOH helps form a good bond and promote the ionization of hydroxyl group, treating sawdust with more than 4% of NaOH tends to create a weaker bond and weakens individual wood particle fibres, hence results in low compressive strength of the wood-crete made from the treated sawdust.

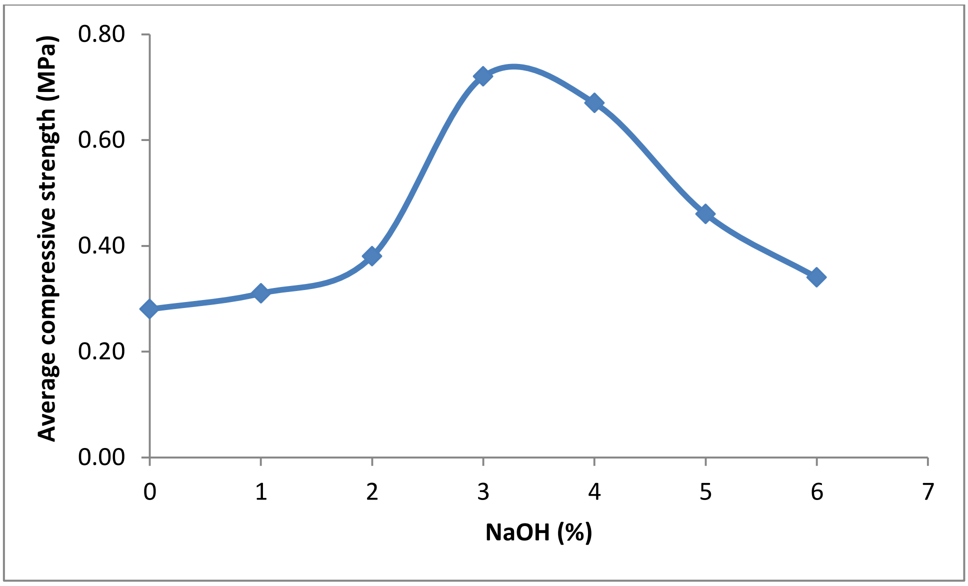


Figure 7.1 Mean compressive strength vs NaOH for all boiling times

The effect of NaOH treatment is also related to the boiling time (Table 7.1). With the 100 minutes boiling time, there is a little effect between 0 to 2 % NaOH. However, from 2 to 3 %, there is a significant increase in the compressive strength. Changing NaOH from 5 to 6% resulted in an adverse effect, with compressive strength reducing from 0.65 to 0.30MPa. A similar trend was found for boiling time of 120 minutes. When boiling time was increased to 140 minutes, even a 1% or 2% NaOH can result in a substantial increase of compressive strength, which increased about 30% or 100% respectively although over 170% increase in the compressive strength was achieved at 4% NaOH. A comparison of the last two columns of Table 7.1 (treatment times of 140 and 160mins) indicates that a long duration of boiling time may have resulted in significant effect on the strength of sawdust. The highest compressive strength was only 0.59MPa with the boiling duration of 160min in comparison to 0.87MPa with the boiling duration of 140min.

7.3.3 Combined Effect of NaOH and Boiling Time

Observed is that there was an increase in the compressive strength of blocks as the percentage of NaOH increased as well as boiling time (Table 7.2 and Fig 7.2). High compressive strength areas on Figure 7.2 are indicated with red zone and as strength decreases, colour changes from yellow, to green and blue. As reported by Vaickelionis and Vaickelioniene [147], a longer extraction time and a higher temperature (up to 100°C) afford a higher concentration of soluble materials [147]. Previous studies have shown that the major problems of wood composites are associated with the hydrophilic character of the cellulose structure of fibre and overcoming this problem means modifying the fibre surface by the physical and chemical methods to reduce the hydrophilic nature of sawdust which improves the sawdust–matrix bonding [144]. The treatment of wood fibre prevents sugar and tannins in the wood from reacting with the matrix which interferes with proper curing [147]. It can thus be inferred that the reason for the significant increase in strength of composite after treatment of sawdust is that there has been a change in the interface quality of sawdust which has consequently improved the bonding of sawdust and matrix resulting to better compressive strength.

Figure 7.2 indicates that to achieve good compressive strength, the treating regimes for sawdust should be within the range of 3 to 4% with boiling duration between 135 and 140 minutes (red zone on Figure 7.2). It is interesting to see that low percentage of NaOH at boiling time between 110 to 130 minutes gives similar result to high percentage of NaOH with longer boiling time above 155 minutes (Figure 7.2). This gives an indication that during initial boiling state of sawdust, there is no significant indication of change in sawdust matrix. However, as boiling time increases, the structural behaviour of sawdust particles begin to change and then weaken with excessive heating time. This has been further confirmed from the results from the wood-crete with an addition of waste paper (Table 7.2). Table 7.2 shows that at a low boiling time of 80 minutes, a higher percentage of NaOH is needed to achieve better compressive strength, although there is a variation when sawdust was treated from 2% of NaOH to 4% of NaOH, which may be due to the variation of raw materials or experimental variation as much higher cov values of wood-crete treated with 4% of NaOH was observed in comparison with the cov values of wood-crete treated with 2% of NaOH.

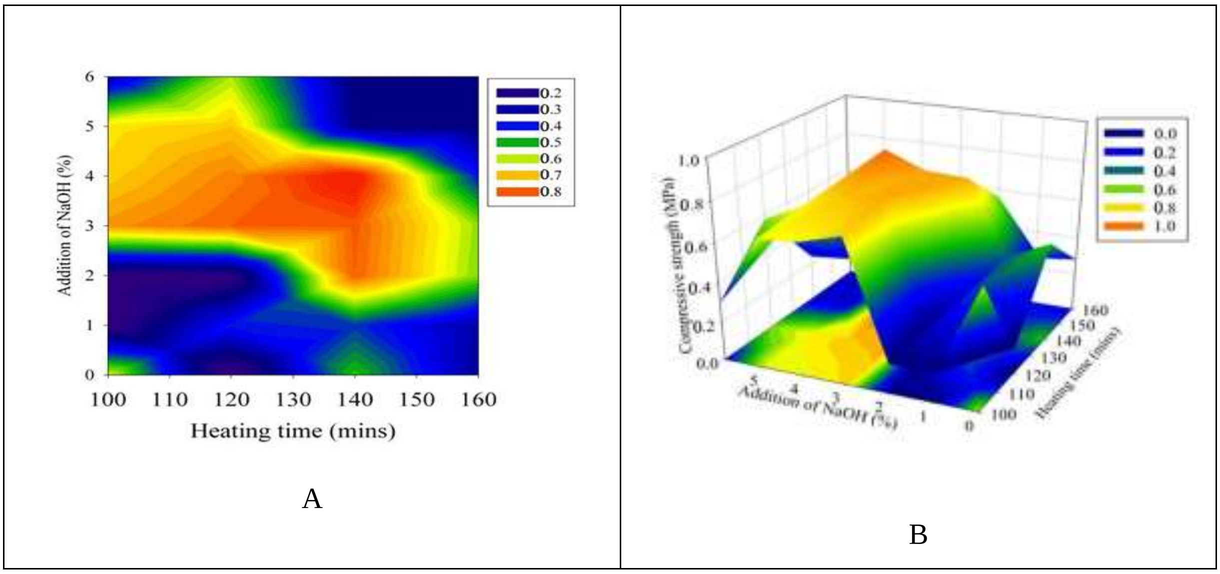


Figure: 7.2 Combined effect of NaOH and boiling time: A=2D and B=3D images

Table 7.2 Experimental design and mean value of wood-crete property at various NaOH (Boiling time 80 minutes)

NaOH (%)	50%DF		75%DF		50%PS		75%PS	
	CS (MPa)	Den (kg/m^3)	CS (MPa)	Den (kg/m^3)	CS (MPa)	Den (kg/m^3)	CS (MPa)	Den (kg/m^3)
0	0.30 (3.2)	551	0.33 (4.2)	532	0.44 (11.0)	650	0.58 (5.0)	596
2	0.62 (3.3)	539	0.72 (5.3)	520	0.81 (6.6)	642	1.03 (2.7)	591
4	0.36 (12.5)	547	0.38 (7.4)	518	0.42 (5.8)	638	0.48 (10.1)	587
6	0.73 (5.1)	536	0.80 (6.2)	513	1.06 (3.4)	641	1.01 (8.2)	583
8	0.82 (2.9)	544	0.81 (6.9)	535	0.95 (4.7)	644	1.25 (4.1)	595

CS = Compressive Strength, Den = Density, NaOH = Sodium Hydroxide, DF = de-fibred, PS = Paper Strip, Values in ( ) are cov. in %

7.3.4 Combined Effect of NaOH Treatment and Waste Paper on Compressive Strength of Wood-Crete

Table 7.2 shows the effect of treating sawdust at various percentages of NaOH on the compressive strength of wood-crete in combination with waste paper. It is observed that there was an increase in compressive strength of wood-crete with the type of paper used and in percentage of NaOH. Wood-crete made with 75% of paper strip at 4% of NaOH achieved higher compressive strength than those made with 75% of de-fibred at 4% of NaOH with about 16% increment in strength property. The same trend is noticed with wood-crete made with 50% of paper strip and 50% of de-fibred at 4% of NaOH and wood-crete made with 2% of NaOH both for 50% paper strip and 75% paper strip and 50% de-fibred and 75% de-fibred paper. Two significant evidences are confirmed here: the first is that the higher the percentage of NaOH, the better the compressive strength and the second is that the wood-crete with paper strip performs better in compressive strength than those with de-fibred paper. It is not clear why the treatment with 2% of NaOH has a better strength compared to 4% of NaOH, although there is a much higher cov for the results under 4% NaOH treatments, showing possible experimental operation variation.

7.3.5 Combined Effect of Boiling Time and Waste Paper on Compressive Strength of Wood-Crete

Figure 7.3 and 7.4 shows overall mean compressive strength across different water boiling times of both de-fibered and paper strip. The results for each individual regime of treatment are given in Table 7.4. In Table 7.3, it is observed that at a fixed percentage of NaOH with different boiling times, wood-crete made with 75% of de-fibred paper had about 3.8% increases in compressive strength compared to wood-crete made with 50% de-fibred paper. Same trend is noticed with 75% paper strip recording 11.7% increase in compressive strength than 50% paper strip. It can be seen that the average strength consistently increases with the boiling time increase, from 0.40 to 1.22MPa when the boiling time increased from 40 to 140 minutes. The correlation can be established with a good fit of linear regression (Figure 7.3).

Waste paper has also had an effect on the property of wood-crete (Figure 7.4). Overall the wood-crete with paper strips had a better compressive strength than those with de-fibred waste paper (Table 7.4 and Figure 7.4). A higher concentration of waste paper also gave rise to a better compressive strength. This is also in agreement with the results from previous study [146] which showed that 75% of de-fibred waste paper achieved a better strength than 50% of de-fibred waste paper. It is also evident that as the percentage of NaOH reduced, there was a corresponding reduction in the compressive strength of wood-crete (Table 7.4).

Figure 7.3 and 7.4 also shows that where there was an increase in percentage of waste paper and heating time, there was a corresponding increase in compressive strength of wood-crete. In general, it is observed that there is 12% increase in average compressive strength when wood-crete is made with 50% paper strip compared to 50% de-fibred paper and an 18% increase when wood-crete is made with 75% paper strip compared to that when wood-crete is made with 75% de-fibred paper. A significant observation from tables 7.4 and 7.3 shows that comparing 140mins at 4% with 140mins at 6% (when boiling time was constant and percentage of NaOH increased from 4% - 6%), it was discovered that compressive strength begins to reduce. This goes further to show that increasing the percentage of NaOH from 4% leads to a decline in strength properties of wood-crete.

Table 7.3 Experimental design and mean value of wood-crete property at various boiling time (6% NaOH)

Boiling time (mins)	50%DF		75%DF		50%PS		75%PS	
	CS (MPa)	Den (kg/m^3)	CS (MPa)	Den (kg/m^3)	CS (MPa)	Den (kg/m^3)	CS (MPa)	Den (kg/m^3)
100	0.74 (2.5)	549	0.85 (4.1)	519	1.10 (8.8)	646	1.36 (5.0)	581
120	0.92 (4.8)	544	0.96 (3.0)	525	1.05 (3.4)	643	1.23 (6.0)	585
140	0.99 (1.6)	539	1.03 (6.2)	523	1.14 (5.6)	638	1.57 (1.7)	577

CS = Compressive Strength, Den = Density, NaOH = Sodium Hydroxide, DF = de-fibred, PS = Paper Strip, Values in ( ) are cov. in %

Table 7.4 Experimental design and mean value of wood-crete property at different boiling times and NaOH

Boiling time (min)	NaOH (%)	50%DF		75%DF		50%PS		75%PS	
		CS (MPa)	Den (kg/m^3)	CS (MPa)	Den (kg/m^3)	CS (MPa)	Den (kg/m^3)	CS (MPa)	Den (kg/m^3)
40	2	0.26 (3.0)	547	0.32 (6.8)	522	0.45 (4.1)	652	0.58 (6.6)	594
40	4	0.35 (4.9)	549	0.47 (4.0)	529	0.59 (6.4)	658	0.69 (3.0)	591
60	2	0.62 (2.5)	554	0.63 (14.4)	521	0.64 (18.0)	656	0.74 (16.0)	593
60	4	0.63 (1.5)	545	0.69 (8.7)	516	0.74 (10.8)	648	0.77 (6.5)	588
100	2	0.63 (3.2)	550	0.80 (9.2)	511	0.97 (6.3)	649	1.32 (10.3)	580
100	4	0.70 (4.5)	546	0.83 (8.6)	509	0.10 (2.7)	645	1.33 (15.2)	582
120	2	0.87 (9.1)	540	0.91 (11.4)	502	0.99 (2.2)	648	1.27 (4.3)	590
120	4	0.90 (10.2)	539	0.98 (3.6)	498	1.04 (6.5)	642	1.16 (5.7)	584
140	2	0.94 (1.8)	536	1.04 (5.5)	503	1.11 (9.7)	644	1.56 (2.4)	576
140	4	1.01	535	1.06	508	1.17	630	1.62	562

		(9.0)		(7.8)		(12.3)		(10.6)	

CS = Compressive Strength, Den = Density, NaOH = Sodium Hydroxide, DF = de-fibred, PS = Paper Strip, Values in ( ) are cov. in %

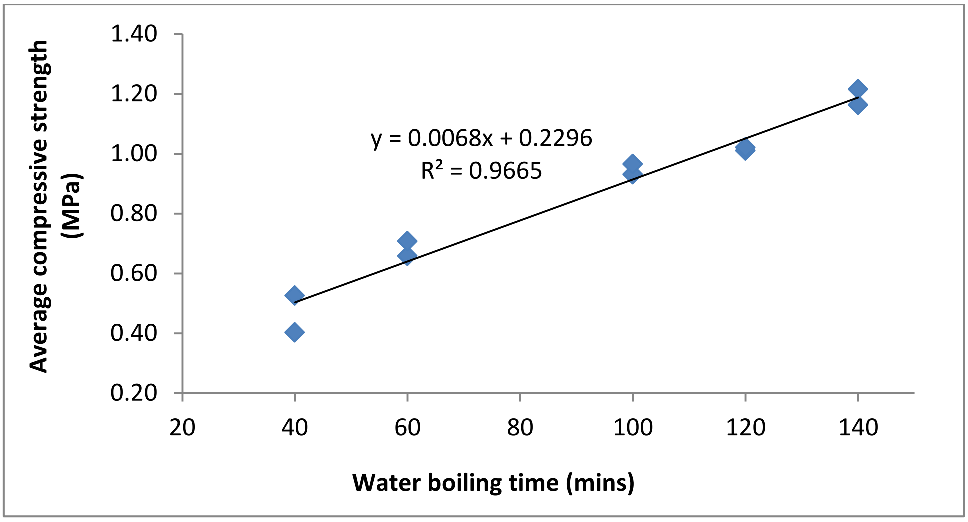


Figure 7.3 Average compressive strength vs boiling time (table 7.4)

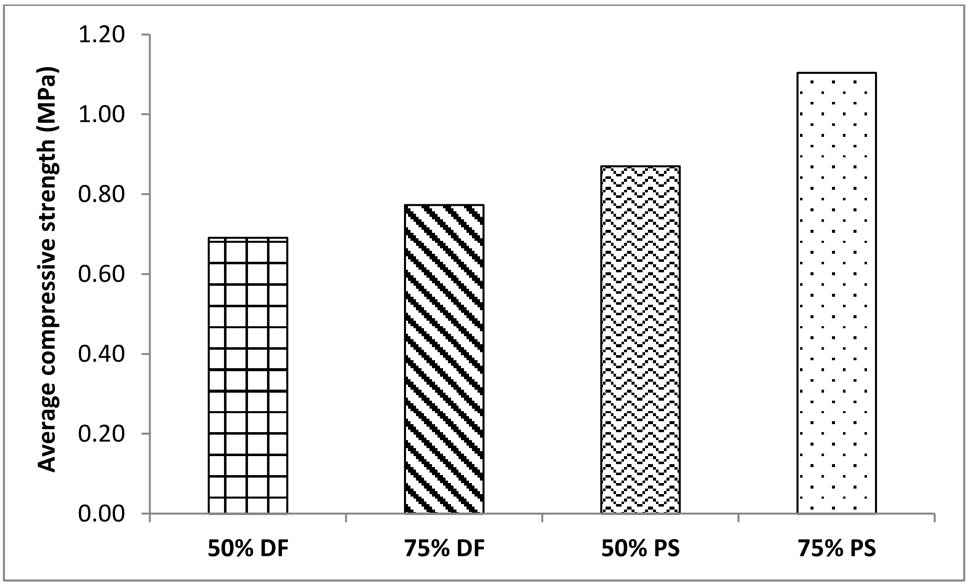


Figure 7.4 Average compressive strength vs waste paper

7.3.6 Effect of Sawdust Size on Compressive Strength of Wood-Crete

It is observed that the compressive strength of sawdust made with 1mm sieve size is higher than that made with 2mm and 3mm sieve size. Likewise, the compressive strength of sawdust made with 2mm sieve size is higher than that of 3mm sieve size (tables 7.1 and table 7.5). At 140min boiling time, wood-crete made with 1mm has 15% increase in compressive strength than wood-crete made with 2mm while a 9% increase in compressive strength is noticed from 2mm to 3mm sawdust size of wood-crete (Fig 7.5). The result further substantiates the fact that better strength is achieved with smaller particles of sawdust.

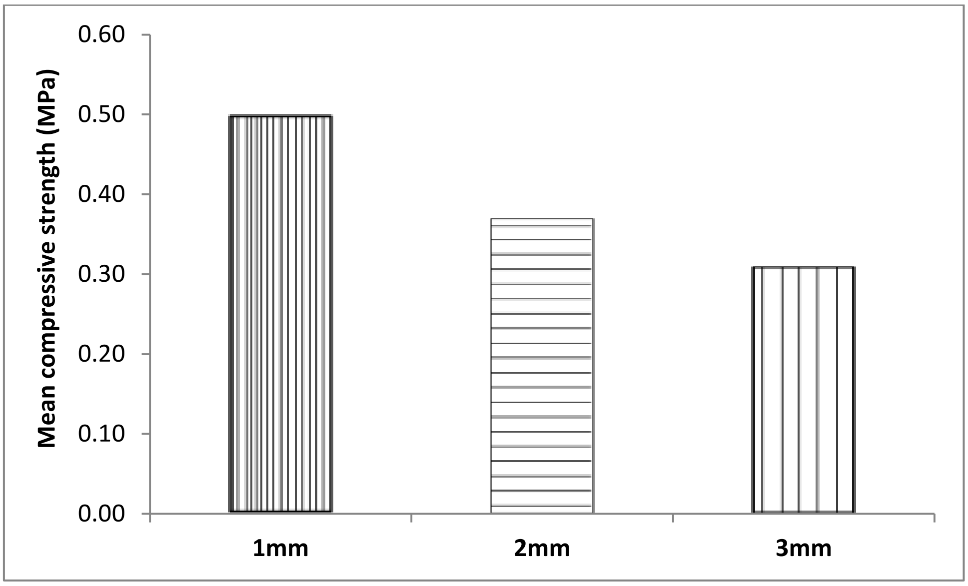


Figure: 7.5: Mean compressive strength against different particle size at 140mins boiling time

7.3.7 Correlation of Sawdust Treatment on Particle Size of Wood-Crete

Fig 7.6 shows that as boiling time increased from 140mins to 160mins, there was a considerable reduction in compressive strength of wood-crete made with different sawdust size. This shows that during boiling as particles collide with each other, heat transfer in small particle size is greater because the more the particles vibrate, translate and rotate, the greater the temperature generated amongst particles. Also, research shows that due to mass and heat transfer limitations, the larger the particle size, the lower is the yield of extracted products [148]. One can therefore conclude that during treatment, particle size 2mm and 3mm had a lesser amount of extracted soluble which reflects their low compressive strength.

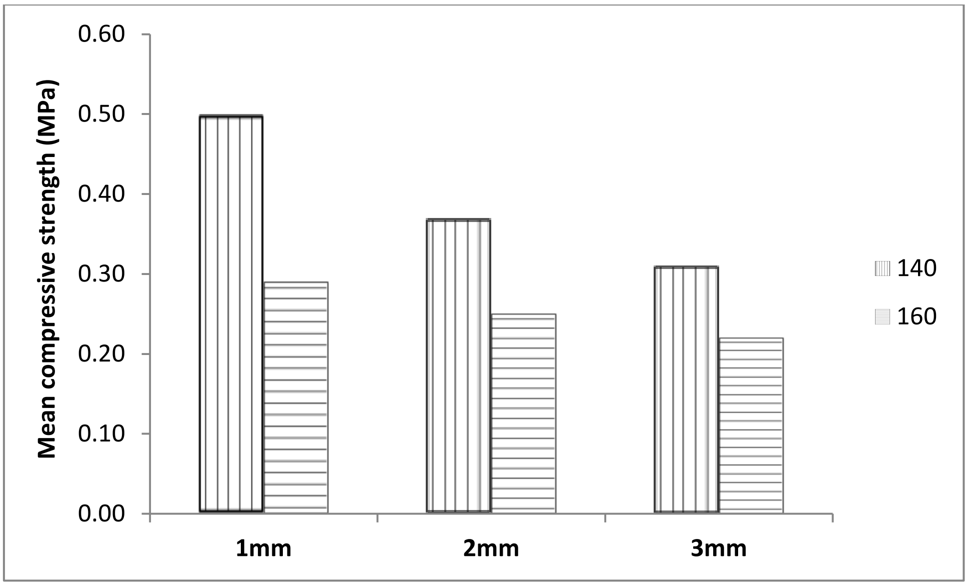


Figure: 7.6: Effect of sawdust treatment on mean compressive strength vs different particle size

Table 7.5 Experimental design and mean value of wood-crete property 2mm and 3mm sawdust sieve size (without waste paper)

NaOH (%)	Boiling time (min)							
	2mm sawdust sieve size				3mm sawdust sieve size			
	140		160		140		160	
	CS (MPa)	Den (kg/m^3)	CS (MPa)	Den (kg/m^3)	CS (MPa)	Den (kg/m^3)	CS (MPa)	Den (kg/m^3)
0	0.27 (7.1)	582	0.22 (3.9)	576	0.21 (1.8)	525	0.16 (11.3)	523
1	0.36 (5.0)	578	0.19 (6.6)	580	0.31 (5.2)	526	0.25 (1.5)	522
2	0.45 (8.0)	587	0.33 (11.2)	581	0.37 (3.6)	535	0.29 (2.0)	538
3	0.51 (2.2)	590	0.43 (6.1)	588	0.44 (2.0)	537	0.34 (6.9)	534
4	0.60 (4.3)	595	0.30 (3.3)	597	0.54 (1.1)	538	0.26 (1.4)	533
5	0.21 (5.8)	581	0.17 (2.7)	576	0.18 (4.0)	522	0.13 (12.3)	519
6	0.19 (1.4)	574	0.14 (9.7)	575	0.12 (4.7)	524	0.09 (8.1)	520
MEAN	**0.37 (4.8)**	**584**	**0.25 (7.5)**	**582**	**0.31 (3.2)**	**530**	**0.22 (6.2)**	**527**

CS = Compressive Strength, Den = Density, NaOH = Sodium Hydroxide, Values in ( ) are cov. in %

7.3.8 Comparing Wood-Crete made with Treated Sawdust and Untreated Sawdust

The effect of treating sawdust by boiling before use is shown with comparing results of untreated sawdust in previous chapter with results of treated sawdust without waste paper (Fig 7.7). It is observed that treating sawdust by boiling for 100mins had an increase in compressive strength of 22% compared to wood-crete without boiling (tables 7.1 and 6.2). Likewise, there was an increase in compressive strength of 33%, 32% and 17% when wood-crete, treated at 120mins, 140min and 160mins respectively are compared with untreated wood-crete. This result was also observed when wood-crete was treated with NaOH at different percentages compared to untreated wood-crete. Comparing wood-crete made at 0% NaOH - boiling time 100min, 1% NaOH – boiling time 100mins, 2% NaOH – boiling time 100 and 120mins, shows that treating sawdust at this stage does not improve the compressive strength of wood-crete. Thus a continuous treatment is required. However, results of treatment at 5% and 6% NaOH at boiling time 160mins both achieved a compressive strength of 0.24MPa when compared with wood-crete without treatment with a compressive strength of 0.26MPa which again proves that sawdust should not be treated at these stated levels as properties of sawdust begins to degrade.

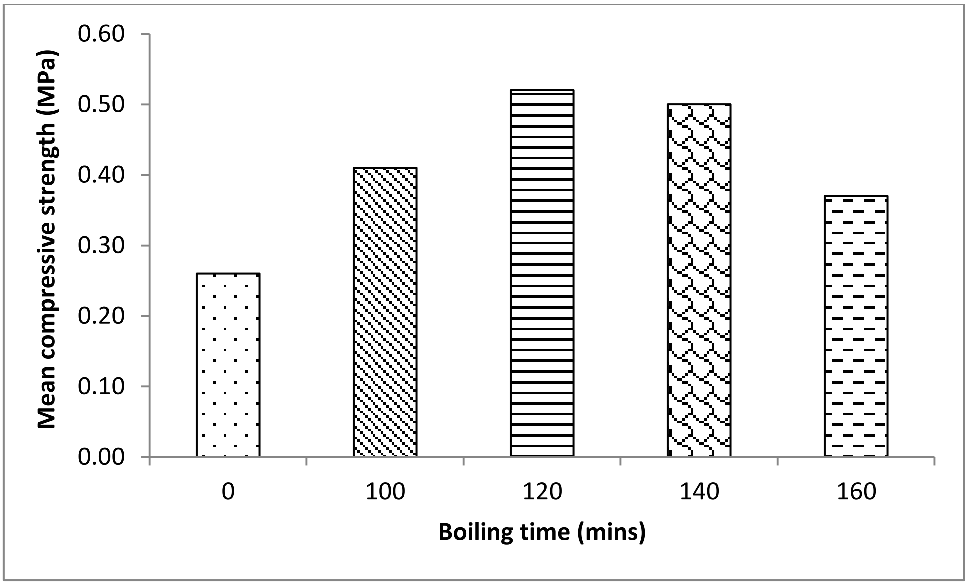


Figure: 7.7 Mean compressive strength of wood-crete made by treated and untreated sawdust

Fig 7.8 shows that even with addition of waste paper, boiling time had a significant effect on compressive strength of wood-crete. The results of sawdust treatment by boiling at 50% de-fibred waste paper shows that wood-crete begins to attain a higher strength of about 1.6% increment after 60mins of boiling sawdust compared to not boiling sawdust. However, at 75% addition of de-fibred waste paper, wood-crete begins to attain a higher strength of 1.2% increment compared to not boiling sawdust before use. As found from results (Fig 7.8), there was no increase in compressive strength at boiling time of 40mins compared to boiling time 0min. Nevertheless, it was discovered that haven attained a higher strength at boiling time of 60mins; there was a reduction in strength properties at boiling time of 80mins for both 50% and 75% de-fibred compared to boiling at 0min but strength properties increased again from 100, 120 and 140mins. The reason for a low strength attained in boiling sawdust at 80mins is unknown however what result proves is that boiling sawdust at 140mins with addition of 50% de-fibred waste paper has a 23.8% increase in compressive strength compared to boiling sawdust at 0min with addition of 50% de-fibred waste paper. A similar increase of 13.5% in compressive strength was noticed in boiling sawdust at 140mins with addition of 75% de-fibred waste paper and boiling sawdust at 0min with addition of 75% waste paper.

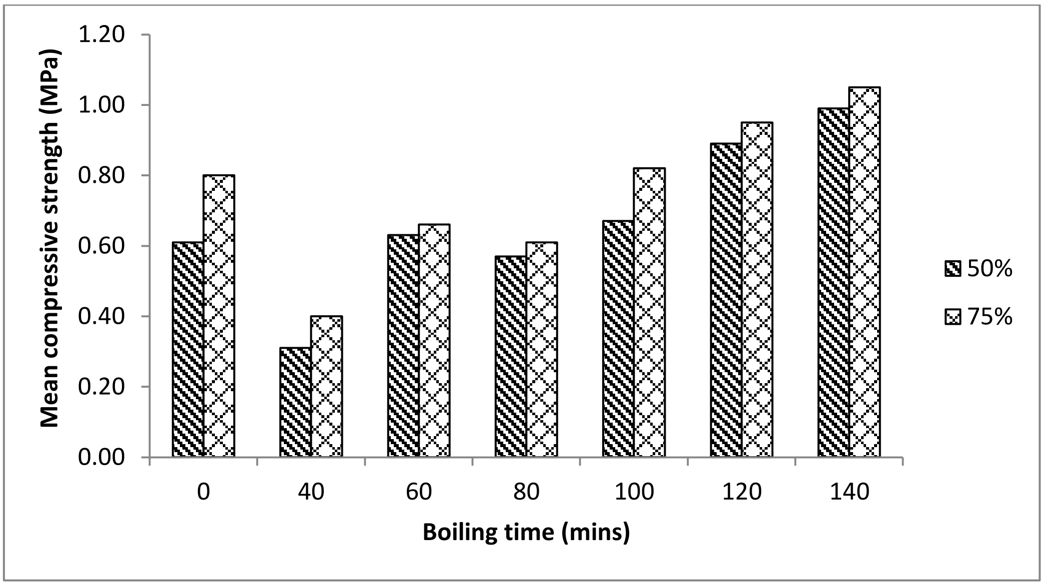


Figure 7.8 Comparing effect of boiling time on wood-crete made with treated and untreated sawdust of de-fibred waste paper

The importance of treating sawdust with NaOH is also compared here considering results in Table 7.4 and samples X1 and X2 from table 6.2. It is seen that treating sawdust at 4% of NaOH had an 8.3% and 0.6% increase in compressive strength with addition of 50% and 75%

de-fibred waste paper respectively when compared to no addition of NaOH. It is revealed here that treating sawdust from 0% to 2% NaOH with addition of 50% de-fibred waste paper consistently showed increase in compressive strength of wood-crete but was slightly different from treating sawdust from 0 to 2% NaOH with addition of 75% de-fibred waste paper (Fig 7.9). The influence of boiling time must have contributed to this variation in result which is not considered here. Most important here is that continuous treatment of sawdust up till 4% NaOH improves the compressive strength of wood-crete.

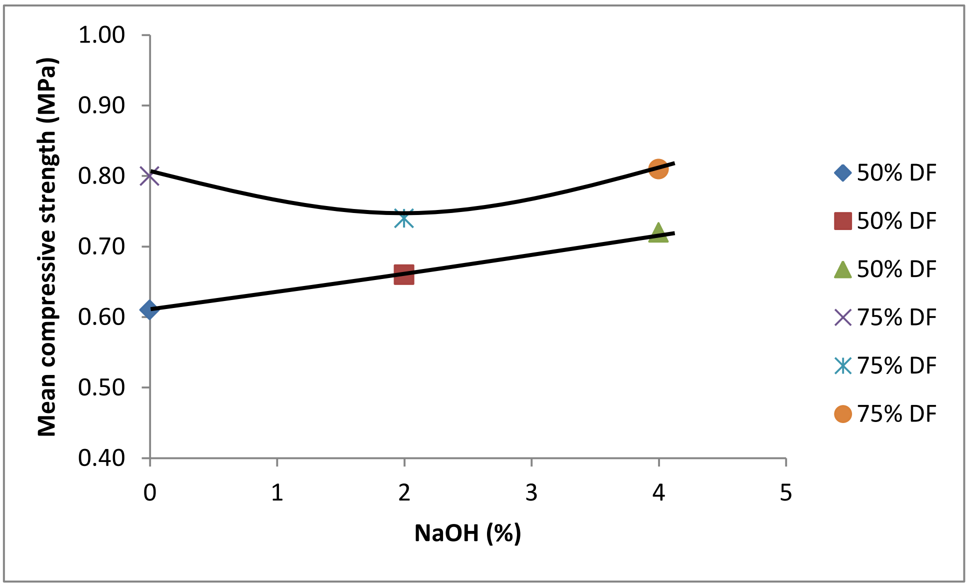


Figure 7.9 Comparing effect of NaOH on wood-crete made with treated and untreated sawdust with addition of de-fibred waste paper

7.3.9 Effect of Fibre Length on Compressive Strength of Wood-Crete

Another factor to be considered here is the effect of fibre length on the compressive strength of wood-crete. With less information on the effect of length of paper fibre on composites, a few studies showed that generally impact strength is higher with longer fibres than shorter fibres [149]. It has been suggested that the mechanical properties of composites increase with increase in fibre length [150]. Both strength and stiffness increase can be realized with increasing fibre length if (1) adhesion between wood fibres and matrix is good, (2) fibres are uniformly dispersed in the matrix and (3) fibres are adequately oriented. This study shows that overall, there is an increase in strength of wood-crete blocks made of the same conditions with paper strip compared to those made with de-fibred paper (Tables 7.2 and 7.3). Taking wood-crete with 75% addition of paper fibre as an example (Figure 7.10), the change of compressive strength can be plotted as polynomial regression with a good fit. The difference (the higher for paper strip) in compressive strength Δy is $0.0002x^2$-0.0217x+0.8881, where x is the boiling time. For example, the strength value at 140mins boiling time is about 35% higher for the wood-crete with 75% of paper strip than that of the de-fibred waste paper. Very similar trend is observed across all treatments (Tables 7.2 and 7.3).

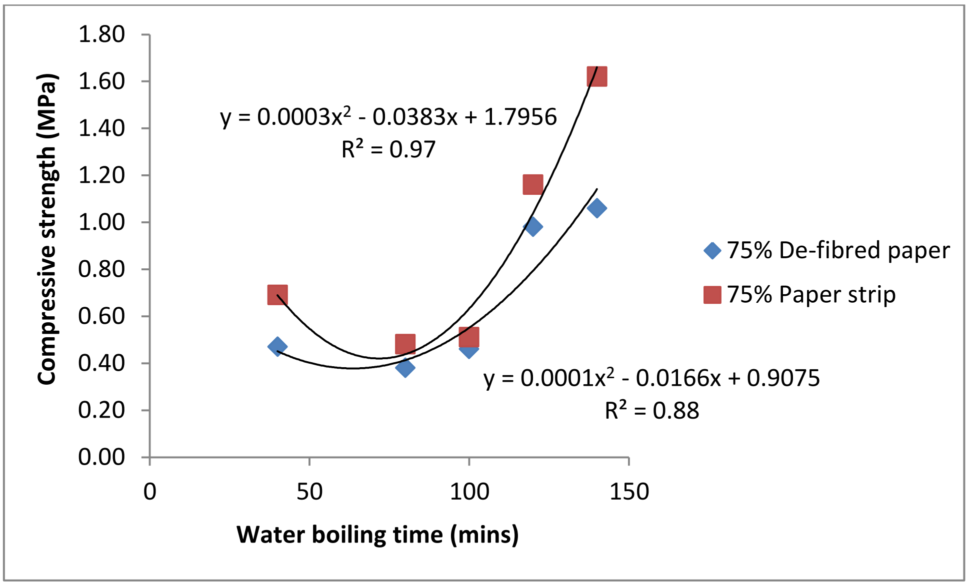


Figure 7.10 Effect of fibre length on compressive strength

7.3.10 Effect of De-Fibred and Paper Strip on Density of Wood-Crete

It was noticed that the density of blocks made with de-fibred paper was lower than those made with paper strip. Figure 7.11 shows two key points: 1) The density of wood-crete made with waste paper are almost the same for all different boiling times (Line 1) although the compressive strength is different between different boiling times; 2) The blocks made with 50% paper strip attained a higher mean density compared to those made with 50% de-fibred paper (Line 2) and the blocks made with 75% paper strip have a higher density than those with 75% de-fibred paper (Line 3). Comparing blocks made with 50% and 75% de-fibred paper, it is noticed that lower percentage of paper showed higher density. This trend is also noticed with blocks made with 50% and 75% paper strip (Table 7.2 and Figure 7.11). The reason for a higher density in blocks made with lesser percentage of paper compared to blocks made with higher percentage of paper may be due to compaction during making of wood-crete and loss of moisture.

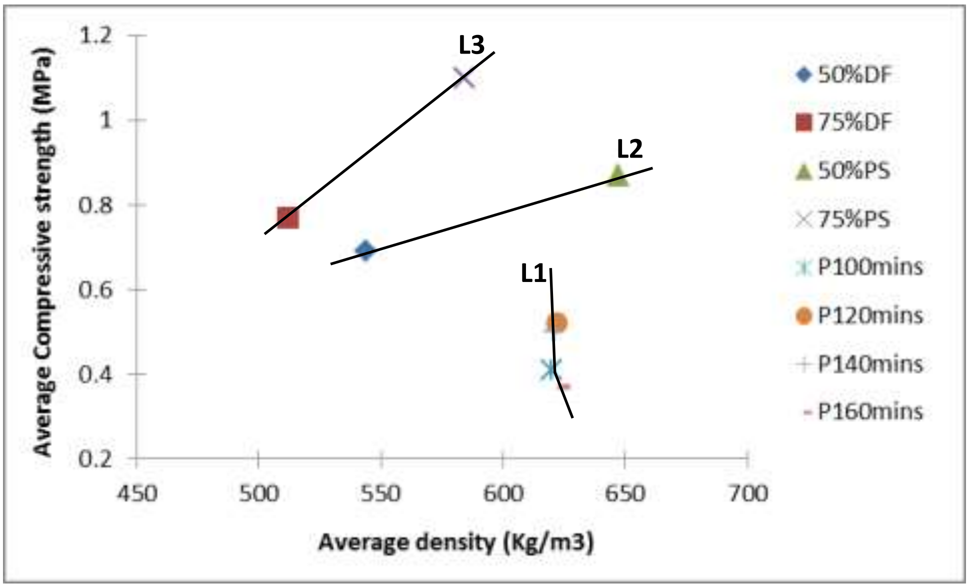


Figure 7.11 Average compressive strength vs density (table 7.4)

The mechanical properties of wood composites generally increase with increasing density. However, in previous study [146], it was discovered that as the density of wood-crete blocks decreased, there was an increase in the compression strength of blocks. This is again confirmed in this study (Figure 7.11). Considering the results of blocks made with 50% DF and those made with 75% DF, it can be seen that compressive strength increased with decrease in density. The trend also applies to those of blocks with 50% and 75% paper strips (Figure 7.11). This only suggests that the effect of fibre on mechanical properties is more significant compared to the effect of density. According to Migneault, et al. [150], the classical theory of mechanics shows that the load applied to a fibre-reinforced composite material is transferred from matrix to fibres by shear stresses along the fibre-matrix interface, thus transferring efficiency may increase with increasing fibre L/D ratio. The mechanical results observed support the argument [150] and are in conformity with the classical mechanics theory.

Also proven here is that blocks made with PS showed compressive strength significantly higher than blocks made without paper. This is a proof that the presence of fibres contributes to the strength properties of composites. The highest strength property of the treated wood-crete was 1.62MPa but not as comparable as those of normal concrete, but comparable and higher than those of hemp lime composites, e.g. hempcrete. The compression strength value of hempcrete is reported to be between 0.4 and 0.7MPa depending on mix design [96]. The compressive strength values of blocks were incomparable with those of concrete bricks which have been reported to be in the range of 20 to 35MPa and even up to 65MPa. This means that the treated blocks are not fit for a direct or stand-alone application as structural elements but like hempcrete, can be used in combination with supporting wood structures.

Test results suggest that wood-crete is a ductile material that can sustain large deformations. This kind of deformation has already been noticed and discussed in details [146].

7.3.11 Performance of Wood-Crete under Water Immersion

Water absorption behaviour has been intensively studied due to its important features as it determines end-user applications of most wood composites when they are subjected to environment where moisture conditions change rapidly. Poor resistance of wood to moisture absorption can cause dimensional instability and undesirable effects on the mechanical properties of composite materials [151] [152]. Experimental set up was in accordance with the long term water absorption by total immersion as described in EN1208:1997. After the 28 day period of water absorption, blocks were subjected to compressive strength assessment.

7.3.11.1 Water absorption

Water uptake of different blocks of wood-crete composites at different periods of immersion is shown in Table 7.6. The observation reveals the independent of the type of combinations used to make wood-crete. The water absorption increased with less amount of paper content in wood-crete. This was surprising because as expected, it was assumed that the presence of paper fibres in wood-crete would make absorption higher. The inference to this would be that the paper fibres were well coated with the matrix used and it has been reported that matrix absorbs little water [152]. This author also reported that the water absorption in composites is dependent on the presence of wood which interacts with water not only on the surface but also in bulk. The authors went further to explain that wood contains numerous hydroxyl groups (–OH), which are available for interaction with water molecules by hydrogen bonding. Three main regions where water can reside in composites may include: the lumen, the cell wall and the gaps between fibre and matrix in the case of weak interface adhesion. This thus explains the reason for high water absorption with samples made with sawdust to tradical lime ratio of 1:1 compared to those made with ratios 1:2 (Table 7.6).

Table 7.6 Effect of time of immersion on different samples of wood-crete composites

No	WP (%)	Density of samples before immersion (kg/m^3)	Water absorption (g)		
			7days	14days	28days
All samples made with de-fibred paper and sawdust : tradical lime of 1:2					
A	75	473	0.089	0.092	0.094
B	50	526	0.090	0.095	0.098
C	30	604	0.094	0.099	0.102
D	15	702	0.101	0.105	0.108
E	10	713	0.099	0.102	0.103
F	0	616	0.088	0.089	0.089
All samples made with de-fibred paper and sawdust : tradical lime of 1:1					
G	50	411	0.094	0.097	0.099
H	25	485	0.097	0.103	0.104
I	10	530	0.093	0.098	0.101
J	5	549	0.087	0.091	0.094
K	0	640	0.090	0.091	0.092

Table 7.6 also shows that across all blocks, the rate of water intake was higher in the first 7 days. The blocks without waste paper also showed a saturation point (where no more water was absorbed and the water content in the blocks remained the same) after 14days of water immersion. However, all other blocks though continued to absorb water did not show great significance in absorption rate. Overall, water absorption is low, around 0.1% even after 28days of water immersion. Test results make a confirmation that the wood-crete can be used in damp areas including bathrooms due to low water absorption rate, if it is not for load bearing purpose. However, they perform better where minimal wetting application is required.

7.3.11.2 Compressive strength of wood-crete after water absorption

The compressive test results of samples after day 28 are shown in Table 7.7. Comparing block B with G, only a 1.1% percentage difference is noticed in compressive strength likewise a 2% percentage difference when block E is compared with I (Figure 7.12 and Table 7.7). This is evident that the ratio of sawdust to tradical lime did not necessarily play a significant role in the compressive strength of wood-crete after water absorption but rather other factors like the constituent of wood-crete e.g. the addition of waste paper (Figure 7.12).

However, a significant differences in compressive strength are observed in giving an insight of how well wood-crete behaves after being subjected to adverse weather conditions, although the water uptake was very low (Table 7.6).

Table 7.7 Compressive strength at day 28

No	**WP (%)**	**Compressive strength (MPa)**	**Compressive strength (MPa)**
		28days water soaked	Dry blocks
All samples made with de-fibred paper and sawdust : tradical lime of 1:2			
A	75	0.094	0.800
B	50	0.090	0.610
C	30	0.088	0.480
D	15	0.080	0.410
E	10	0.074	0.350
F	0	0.061	0.260
No.	**WP (%)**		
All samples made with de-fibred paper and sawdust : tradical lime of 1:1			
G	50	0.092	0.490
H	25	0.083	0.410
I	10	0.071	0.310
J	5	0.063	0.220
K	0	0.068	0.210

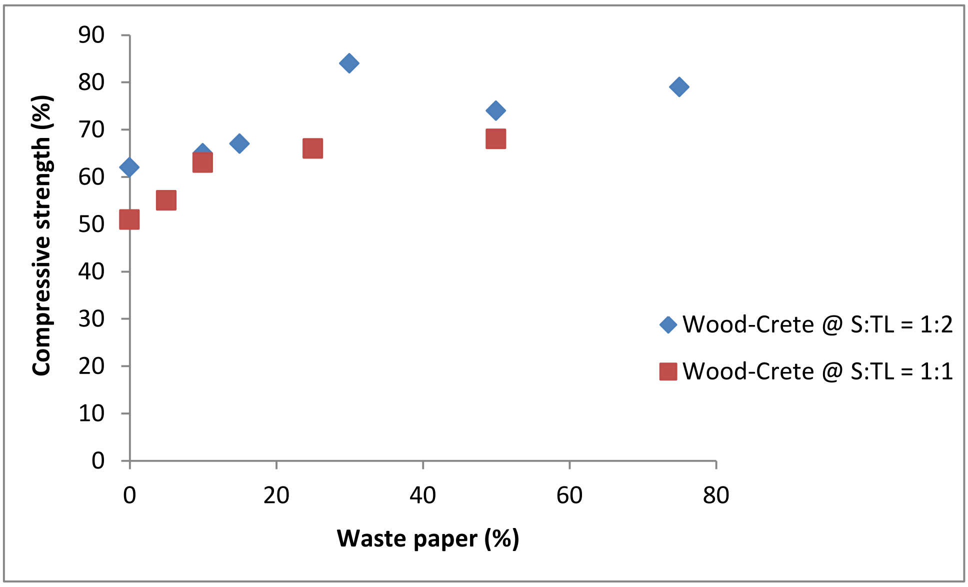


Figure 7.12 Compressive strength of wood-crete after water soaking

7.3.12 Performance of Wood-Crete under Fire

Fire testing was carried out for a number of samples to ascertain the behaviour of composite materials under small scale fire testing (Table 7.8). The cone calorimetry testing was adopted which analyses the behaviour of materials when exposed to heat and a source of ignition. Test results helped provide valuable contribution to fire behaviour of composite material when used for construction on a big scale. Fire test at this stage basically was to give an insight on behavioural pattern of material. Analysis done helps predict performance of wood-crete that can then be verified by the single item test. The tests were run according to BS476-22 1987. As standard is well known for this type of test set up, principles and drawings of apparatus are not included here.

Table 7.8 Experimental design for fire performance test

Samples	Sawdust / Binder ratio	Waste paper	Waste paper (%)
STD A1	S/TL (1:2)	Paper strip	50
STD B1	S/TL (1:1)	Paper strip	50
STD C1	S/TL (1:2)	De-fibred paper	50
STD C2	S/TL (1:2)	De-fibred paper	75

It was observed that upon testing, sample surface went in flames within 40 to 50 seconds and was out in 5 seconds. After subjecting composite blocks to 15mins of fire testing, results show that a temperature of about 700^0C was reached with thermocouple on surface of material. This result is similar across all samples tested. This gives an indication that though as expected energy was transferred within composite, however there was no rapid transfer of energy considering the temperature (Fig 7.8b and 7.8c). Like with structural insulated panels (SIP), wood-crete when used for residential buildings should be in place for at least 15mins of fire exposure. It is seen that thermocouples at 30, 50 and 70mm remained in place after about 15mins with temperature reaching 700° C which gives an indication that heat generated did not travel deep into wood-crete blocks. Figs 7.8b and 7.8c also shows that there was no effect of addition of paper type on rate of burning or ignition on composite blocks as it was observed test showed very similar results. Samples compressive test of composite blocks was to be tested after fire testing to ascertain the structural behaviour of blocks after fire but due to the continued burning of blocks, this was unobtainable. However where possible, it is recommended that wood-crete be used with a protective material facing or behind brick and concrete so as to act as a protecting shield from fire especially in areas prone to fire.

However, the best way to avoid fire is by appropriate protection of from any ignition source. Individual fire test of samples is presented in appendix 4.

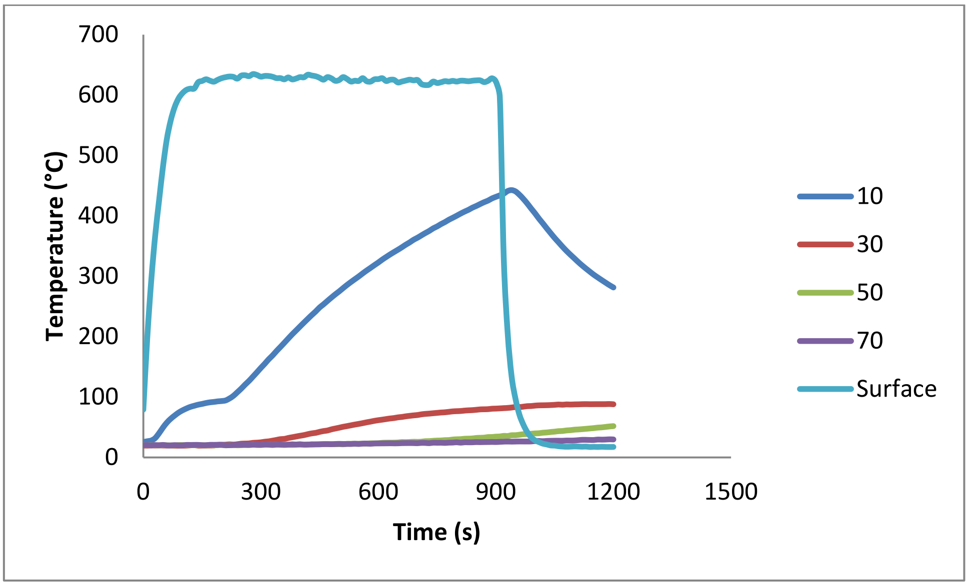


Figure: 7.13 Temperature vs Time of Samples A1

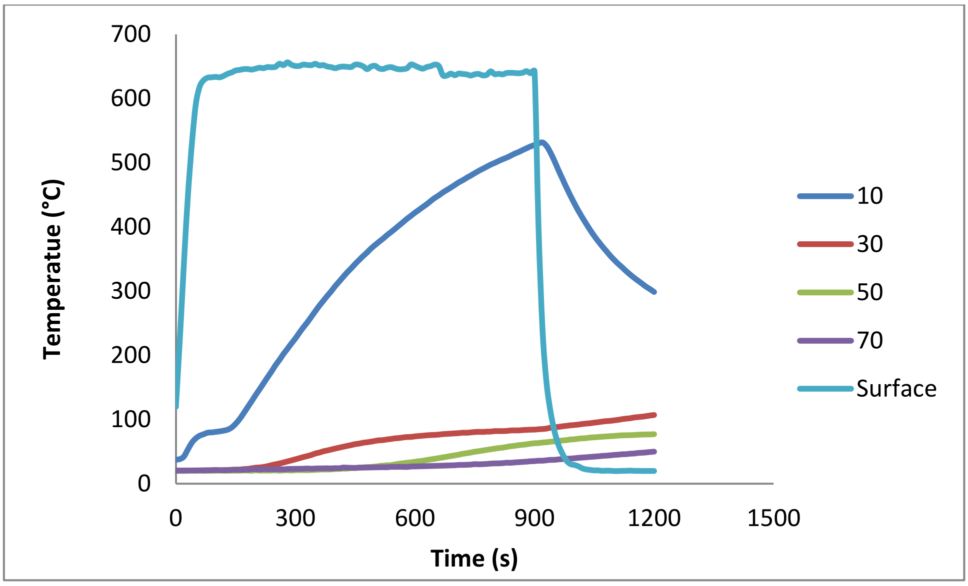


Figure: 7.14: Temperature vs Time of samples C1

7.4 Interim Conclusions

Improved wood-crete has been developed with sawdust having various treating regimes and addition of waste papers. The performance of the developed wood-crete has also been assessed under both dry condition and after subjecting to 28 day water soaking. The following conclusions can be drawn:

- ❖ Sawdust treatment resulted in a significant improvement of wood-crete, with the compressive strength being increased by about 34% for hot water boiling treatment with 4% NaOH treatment and addition of 75%PS. The magnitude of increase was related to the treatment time;
- ❖ An addition of NaOH was able to extract the soluble content of sawdust effectively, resulting in a gradual increase of compressive strength of wood-crete, but excess NaOH tended to weaken individual wood particle fibres for an adverse effect on the strength of wood-crete;
- ❖ The combined effect of boiling time of sawdust and addition of waste paper on compressive strength of wood-crete was significant. The correlation of the waste paper reinforced wood-crete with boiling time of sawdust was linear from 0.40 to 1.22MPa for the blocks developed; a higher percentage of waste paper also gave rise to a higher compressive strength;
- ❖ The geometry of waste paper had an influence on the compressive strength of wood-crete with the treated sawdust, with paper strip being more effective than de-fibred waste paper;
- ❖ The density of wood-crete made with waste paper was almost the same for all different treating times of sawdust although the compressive strength was different. However, the blocks made with paper strip attained a higher mean density compared to those made with de-fibred paper;
- ❖ 28days water soaking resulted in a little water uptake (about 0.1%) of wood-crete whether sawdust to tradical lime ratio of 1:1 or 1:2. However, the decrease in compressive strength was significant, showing that wood-crete could be used in damp areas only if it is not for load bearing purpose.
- ❖ Fire test results indicate that wood-crete can be in place for at least 15mins when exposed to fire.

CHAPTER 8 – WOOD-CRETE MADE FROM HARDWOOD AND SOFTWOOD

8.1 Introduction

This chapter investigates the effect of different wood species on the properties of wood-crete. Wood is essentially composed of cellulose, hemicelluloses, lignin, and extractives or other compounds that are found in smaller quantities e.g fats, resins, waxes, oils and starches. They are called as a group, extractives [153]. Cellulose consists of long, straight chains of glucose molecules which form the skeleton of plant wall and their fibres are long, strong and translucent. Hemicelluloses on the other hand are short, branched chains of glucose and other sugar molecules which fill space in plant wall and are more soluble in water.

Lignin in wood is referred to as the glue that holds the cellulose fibres together and makes them rigid while extractives include plant hormones, resin and fatty acids along with other substances that help the tree grow and resist disease and pests. The proportions of these various chemical constituents of wood vary, but in softwoods there are normally 40-50% of cellulose, about 25 - 35% of hemicelluloses and 17 - 24% of lignin. In hardwoods there are 40 – 50% of cellulose, 25-29% of hemicelluloses and 25 - 31% of lignin. Lignin has been reported by researchers to yield high performance concrete strength, set retarder for a cement composition and improve the compressive strength of cement pastes [154]. Furthermore, it has also been stated by Pourchez, et al. [155] that cellulose retards cement hydration process. The effect of cellulose is attributed to the increased viscosity of the water which imparts the movement of ions thus decreasing the dissolution rate of anhydrous phases and the precipitation of hydrates [155].

Softwoods are usually wood from gymnosperm trees such as conifers [156]. Just like hardwood, softwoods are not necessarily soft. Amongst some softwoods that are harder than hardwoods mainly in mechanical sense includes woods from douglas fir and yew. Though they are also less dense; less durable with high calorific values, they possess a fast growth rate and are light in colour. Softwood is the source of about 80% of the world's production of timber. Softwood fibres are of 2 – 6mm in length compared to hardwood fibres of 0.6 – 1.5mm. Pine sawdust was chosen due to its resistance to shrinkage and swelling [157]. Pine wood has a density of about 510kg/m^3. Sawdust from cedar wood was chosen due to high shock resistance [157], good dimensional stability and pleasant scent of the wood which acts as a natural insect repellent which can add natural properties to wood-crete blocks. Cedar wood has a density of 480 – 580kg/m^3.

Hardwoods are generally wood from broad-leaved trees or referred to wood from angiosperm trees [156]. Though most hardwoods are hard in nature, there is an enormous variation in actual wood hardness. Hardwoods are known for their complex structures and are characterized with the presence of vessels or pores which can vary in size, shape of perforation plates and structure of cell wall such as spiral thickenings. Hardwoods finds its use in a wide range of applications such as fuel, tools, construction, boat building, furniture making, musical instruments, flooring, cooking, barrels and charcoal manufacturing. Due to the density of hardwood, it finds its use mainly in furniture applications. Hardwoods are usually strong in compression, tension and shear (strong along and across the grains). They possess a slow growth rate and are dark in colour. Oak wood was chosen for this study due to its common use for making furniture which leads to high availability of sawdust from sawmills. As well, oak wood is known for great strength and hardness, and is very resistant to insect and fungal attack because of its high tannin content and has a density of about 750kg/m^3. Beech wood sawdust was chosen as a result of good strength properties, abrasion resistance and high in resistance to shock associated with beech wood [157] with a density of 730kg/m^3. In general, oak wood and beech wood are the most used type of wood in production of furniture in European markets [158] which makes them well known and popular in sawmills. Other parameters of wood species used in this study can be summarised in Table 8.1.

Table 8.1 Composition of different wood species

	Beech	**Oak**	**Pine**	**Cedar**
Density (kg/m^3)	730	750	510	530
Cellulose (%)	44.0	42.0	44.0	45.0
Hemicellulose (%)	24.5	29.0	28.5	13.2
Lignin (%)	22.4	25.0	28.1	29.3
Extractives (%)	2.0	4.4	3.8	10.2
Ash (%)	0.3	0.3	0.4	0.2

8.2 Experimental Design

Different types of wood species, hardwood beech and hardwood oak, softwood pine and softwood cedar were tested to determine the effect of various wood components on the strength and thermal properties of wood-crete. A total number of 54 wood-crete blocks were made.

8.3 Results and Discussion

8.3.1 Correlation of Density and Wood Species (sawdust)

An important factor for the difference in densities of wood-crete composites is due to individual wood densities of hardwood and softwood and their composition (Table 8.2). The effect of wood density on the density of wood-crete may result from two different aspects: one is the density of wood itself as a higher density means that more amount of wood and cell materials per unit volume to the wood sawdust within the wood-crete made; the other is the structure of wood. The density of wood is in general related to wood anatomy and hence the relative proportions of cell types or tissues most especially in hardwood species (vessel, fibre, axial and radial parenchyma), along with also their dimensions and distribution, which have indications of the penetration and setting of the lime matrix. The level of effect is dependent on the balance of effects between the former and the latter. In this study, the density of most hardwoods is higher than softwoods naturally and this was reflected in the density of wood-crete with the blocks made from hardwood sawdust recording an 18% increase when compared to the density of wood-crete blocks made from softwoods. Research however shows that most hardwoods have less air in them than softwoods which also affects wood density [159] [156].

Furthermore, it was also noticed during wood-crete manufacturing that the softwood sawdust was lighter in texture than those of hardwood which made compaction in the mould more difficult than when using sawdust from hardwood which was finer and dense thus making compaction more compact. Wood-crete made from the mixed wood sawdust showed 18% reduction in density compared to wood-crete made from hardwood and 0.08% increase in density compared to wood-crete made from softwood (Table 8.2). Much more reduction in density compared to hardwood blocks and only slight increase in density compared to softwood blocks infers that the composition of the mixed wood sawdust may contain more softwood than hardwood, or the composition of the mixed wood may result in ‘bridging’ due to the different stiffness between hardwood and softwood. Fig 8.1 also shows that density of wood-crete made from hardwood beech is 5.7% higher than density of wood-crete made from hardwood oak, likewise density of wood-crete from softwood pine is 10.3% higher than density of wood-crete made from softwood cedar. The highest density of wood-crete made in this study is about 70% higher than the lowest one (Table 8.2), showing a significant effect of wood species for the production of wood-crete (Table 8.1).

Table 8.2 Mean density and compressive strength of wood-crete with experimental mixture design

Samples		Particle size (mm)	Compressive strength (MPa)	Density (Kg/m^3)
Hardwood				
HW_B	Beech	1	3.93 (8.4)	934
		2	3.90 (7.0)	926
		3	3.44 (6.9)	929
HW_O	Oak	1	2.19 (3.7)	859
		2	2.07 (10.1)	821
		3	1.95 (9.2)	816
Softwood				
SW_P	Pine	1	1.37 (6.8)	696
		2	1.30 (4.5)	672
		3	1.23 (9.2)	655
SW_C	Cedar	1	0.07 (2.3)	543
		2	0.20 (8.6)	561
		3	0.18 (3.3)	539
Mixed				
MW		1	0.26 (19.4)	616
		2	0.18 (12.1)	610
		3	0.15 (8.1)	603

* Values in ( ) are cov in %. ***S = Sawdust, TL = Tradical Lime, HW_B = hardwood beech, HW_O = hardwood oak, SW_C = softwood cedar, SW_P = softwood pine, MW = mixed wood***

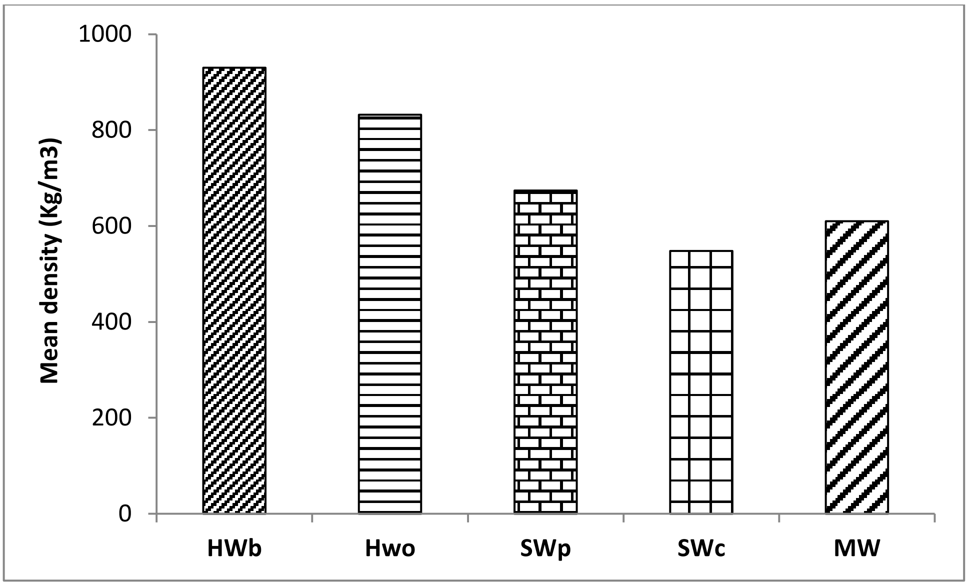


Figure 8.1 Comparison of overall density among various wood species

8.3.2 Correlation of Compressive Strength and Wood Species

Fig 8.2 shows the correlation of compressive strength and wood species. It can be seen that the compressive strength of wood-crete beech is 29.1% higher than the compressive strength of oak and compressive strength of wood-crete pine is 79.3% higher than the compressive strength of wood-crete cedar. Overall, wood-crete made from hardwood had a much higher compressive strength than wood-crete made from softwood, on average 60.2% higher for the former compared to the latter. This may be due partly to the difference in the density (17.5%) between hardwood and softwood. A higher density of wood generally gives rise to a higher compressive strength and such the wood-crete would have a higher compressive strength due to the contribution of wood itself. It has also been reported that hardwoods are usually strong in compression, tension and shear while softwoods are strong in tension but weak in shear [156]. This difference may also contribute to the higher compressive strength of hardwood wood-crete made.

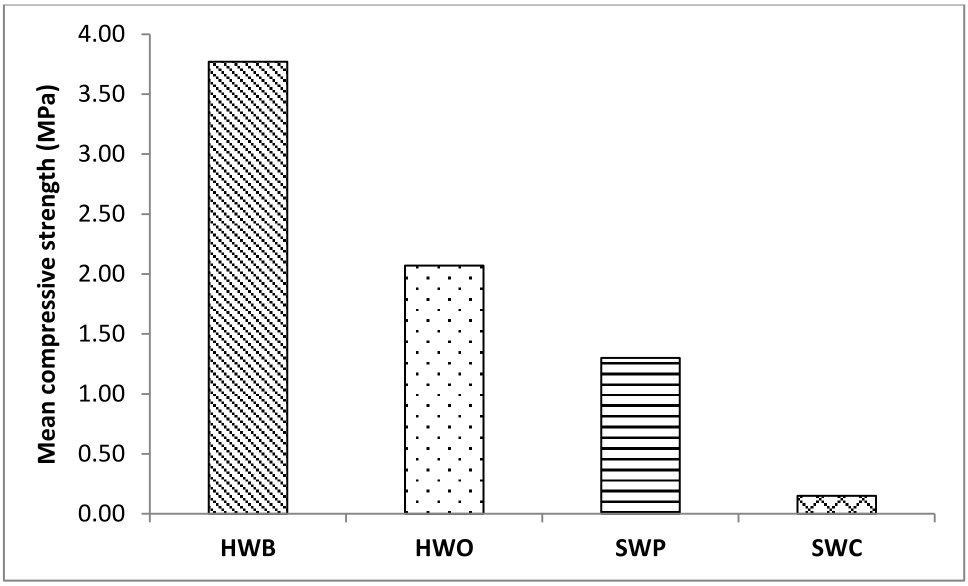


Figure 8.2 Mean compressive strength vs wood species

The property of composite is in general closely related to its density because a higher density means more compact of the composite. In order to determine the degree of compression of wood-crete made with various densities of wood species, i.e. hardwood and softwood species in this study, it was necessary to calibrate the density of blocks by taking into account the ratio of mix of wood-crete and the densities of individual wood species used in this study which include beech, oak, pine and cedar. The percentage of tradical lime was two-third in mix while sawdust was one-third in mix. The density of tradical lime is 1201kg/m^3. Therefore, the calibrated density of wood-crete = 1201 (2/3) + ρ (1/3)

Where, ρ = density of individual wood specie. This means that if the wood-crete has had the same compact, the density of the wood-crete would have been equal to the calibrated density. Therefore, the compressive strength is calibrated to those as the calibrated density (i.e. the same compact). The calibrated results are summarised in table 8.3.

Table 8.3 Calibrated density and compressive strength of wood-crete with experimental mixture design

Samples		**Particle size (mm)**	**Compressive Strength (mpa)**	**Calibrated Compressive Strength (mpa)**	**Density (kg/m^3)**	**Calibrated Density (kg/m^3)**
Hardwood						
HW_B	Beech	1	3.93 (8.4)	4.14	934	1041
		2	3.90 (7.0)	4.12	930	1041
		3	3.44 (6.9)	3.64	929	1041
HW_O	Oak	1	2.19 (3.7)	2.41	859	1048
		2	2.07 (10.1)	2.32	821	1048

		3	1.95 (9.2)	2.19	816	1048
Softwood						
SW_P	Pine	1	1.37 (6.8)	1.59	696	966
		2	1.30 (4.5)	1.53	672	966
		3	1.23 (9.2)	1.46	655	966
SW_C	Cedar	1	0.07 (2.3)	0.09	543	973
		2	0.20 (8.6)	0.25	561	973
		3	0.18 (3.3)	0.23	539	973

* Values in ( ) are cov in %. ***S = Sawdust, TL = Tradical Lime, HW_B = hardwood beech, HW_O = hardwood oak, SW_C = softwood cedar, SW_P = softwood pine***

It can be seen from Table 8.3 that if the wood-crete had been made with the same compact (i.e. with the calibrated densities), the compressive strength was 26.4% higher for beech wood-crete compared to hardwood oak and 45.7% for softwood pine compared to softwood cedar. On average, the wood-crete made from hardwood sawdust records a much higher strength value (49.9%) than those made of softwood sawdust. This gives an indication that other factors such as higher lignin content in hardwood than softwood may affect the strength of wood-crete composites. Lignin is a contributing factor to high performance concrete strength and improves compressive strength of cement paste. The combination of cellulose, hemicelluloses and extractives (sugar, fatty acid e.t.c) content is higher in softwood than hardwood which is another possible factor for the low compressive strength with wood-crete made from softwood. For example, a research on the effect of sugar content on the property of composites showed that extracting sugar content from wood dust help improve the bonding strength of composite materials which has an influence on compressive strength of sawdust composites [142] [160] [144].

8.3.3 Correlation of Compressive Strength and Density

Average measured densities for wood-crete for hardwood, softwood and mixed wood respectively are used to plot their relationship with compressive strength (Fig 8.3). It is observed that the compressive strength increases with an increase in the density of wood-crete regardless of wood species. For the wood-crete made from hardwood oak, compressive strength increased from 1.95 to 2.19 MPa (5.8%) when the density of wood-crete increased from 816 to 859 kg/m3 (2.6%) and for the pine wood-crete from 1.23 to 1.37 MPa (5.4%) when density of pine wood-crete increased from 655 to 696 kg/m^3 (3.0%). The results are in line with the normal expectation of increasing compressive strength with increasing density. As discovered in previous study [146], compaction in mould is one factor that may have resulted in a higher compressive strength. Apart from compaction factor, another reason for the difference in strength of wood-crete from different types of hardwood is a variation in the property of raw materials themselves, such as a little difference in the compressive strength and actual density of various types of wood themselves. Density of hardwood oak is slightly higher than that of beech hardwood and the density of softwood cedar is higher than that of softwood pine.

The correlation of compressive strength with average density of wood-crete seems to be linear with a good degree of fit, R^2=0.94 (Fig. 8.3). However, a further comprehensive design of density profile is required to achieve an accurate modelling result.

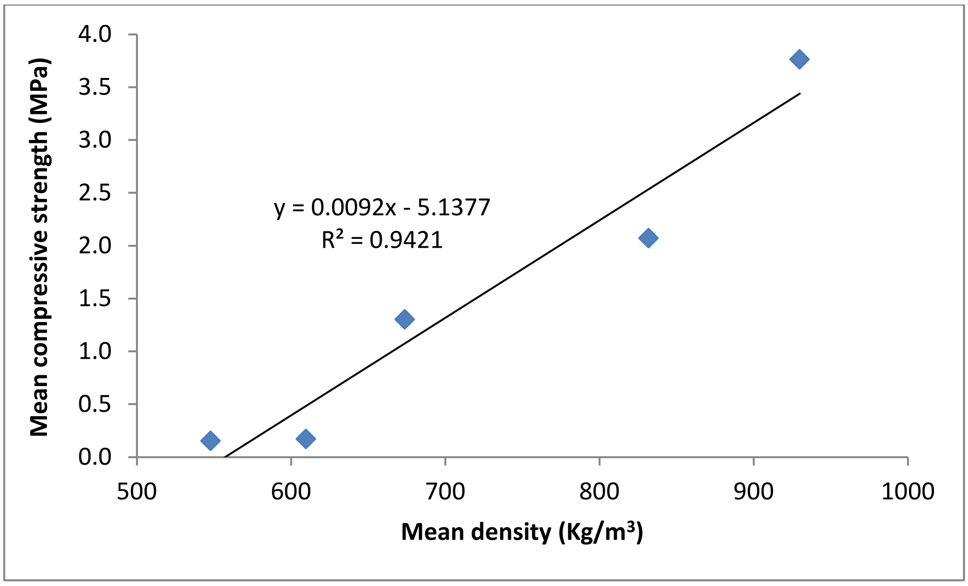


Figure 8.3 Mean compressive strength against density

8.3.4 Correlation of Particle Size and Compressive Strength

It was noticed that the geometry of sawdust used had a significant impact on the strength of wood-crete. Of important point to note here as shown in Fig 8.4 is that the blocks made with sawdust to tradical lime ratio of 1:1 both for 1mm, 2mm and 3mm particle sizes, were not subjected to compressive test because the samples did not bond together after demoulding period of 24hours. This is because the strength properties of composites strongly depend on the stress transfer between particles and binder and strength reductions occur by either adding a disproportion of particles or increasing particle size. While better bonding is achieved with sawdust to tradical lime ratio of 1:2 rather than sawdust to tradical lime ratio of 1:1 which clearly shows poor bonding (Fig 8.4), the wood-crete made with sawdust to tradical lime ratio of 1:2 with 1mm sieve size of sawdust achieved higher strength when compared to those made with 2mm and 3mm sieve size of sawdust of each type of wood used (Fig 8.5). It is also most interesting that the reduction of the compressive strength with the increase of the particle sizes is related to the density of wood species, i.e. the reductions in the compressive strength of hardwood-crete are more significant than those of softwood-crete. The reduction in compressive strength from 1mm to 3mm particle sizes is 5.8% for oak wood-crete, 6.6% for beech wood-crete, 3.4% for pine wood-crete and 27.9% for mixed wood. It was discovered that for cedar wood-crete, 2mm particle size achieved a higher compressive strength than 1mm particle wood-crete, while the strength is very similar between the wood-crete made with 2mm and 3mm particle.

The mean compressive strength of different particle size of hardwood, softwood and mixed wood are compared in Fig 8.5 likewise the mean density against particle size in Fig 8.6. It is evident that the compressive strength of wood-crete made with 1mm particle size hardwood had about 56% increase in strength properties when compared to same particle size of softwood. A 54% increase and 47% increase was also noticed in 2mm and 3mm particle sizes respectively. The effect of particle size on compression strength has been reported [161] where composite strength increased with decreasing particle size. Smaller particles have a higher total surface area for a given particle loading which indicates that strength increased with increasing surface area through a more efficient stress transfer mechanism [161]. Also, smaller particles can generally be well-bonded with binder compared to larger particles and such the applied stress can be effectively transferred to the particles from the binder and from the binder to particles, which improves the strength or load bearing capacity of the wood-crete under load. Much higher reduction in the compressive strength of wood-crete made from the mixed wood from 1mm to 3mm in comparison with those made from hardwood and softwood emphasizes an important consideration of the particle size distribution in manufacturing of wood-crete, because in practice it is very difficult to achieve a single wood species. This implies that sieve sizes should be controlled during manufacturing of wood-crete in order to avoid low strength while ensuring that only wood-crete with desirable mechanical characteristics is formed.

With density, it is seen that the density of wood-crete made with particle size 1mm is about 0.8 and 1.5% higher than those of wood-crete made with particle size 2mm and 3mm respectively (Fig 8.6). The wood-crete made with the small particle size may be more compact. Large particles not only retain the micro void within the sawdust, but may also create ‘bridging’ between particles.

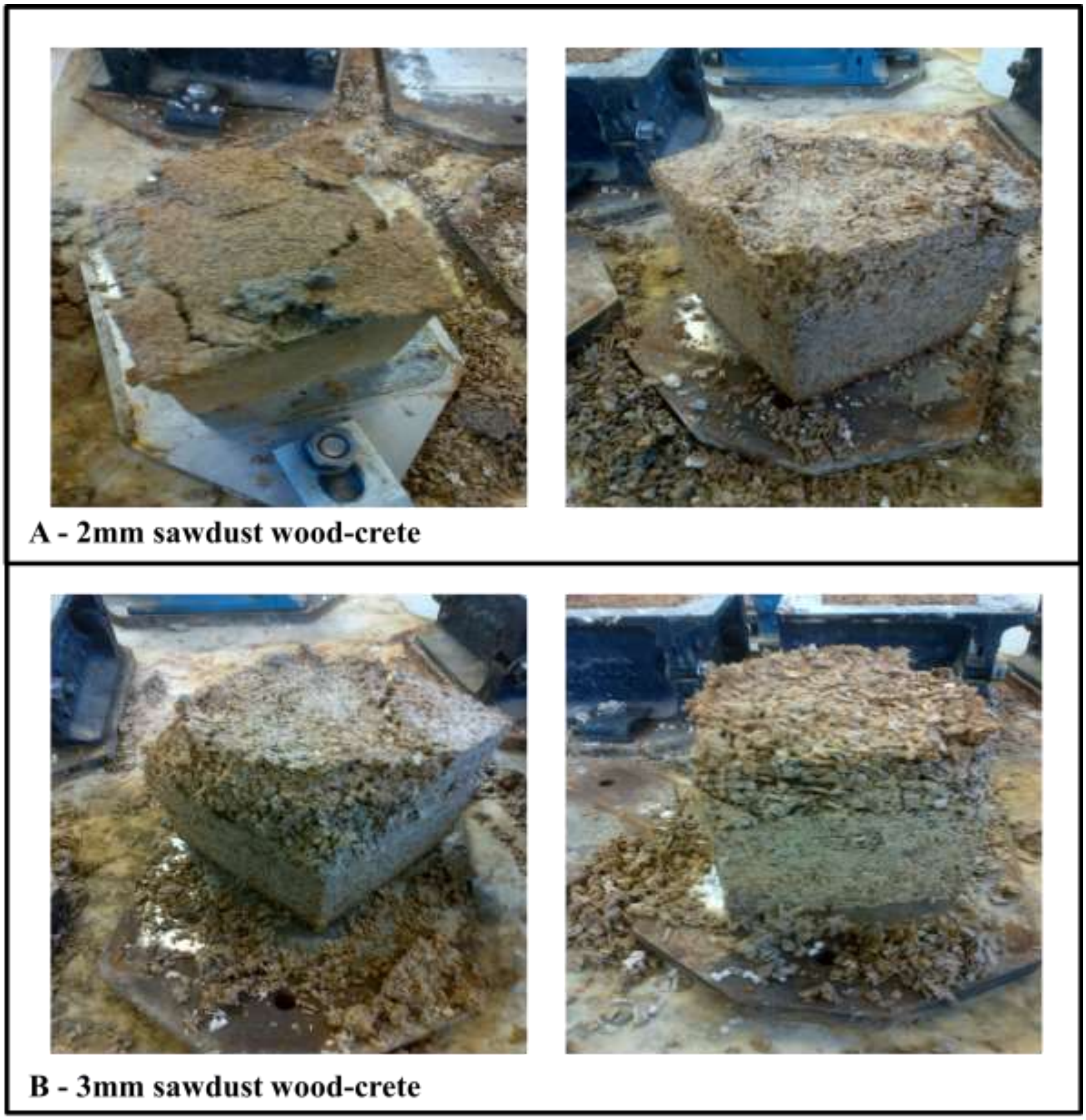


Figure 8.4 Poor bonding of wood-crete made with sawdust to tradical lime ratio 1:1 (demoulding after 24hours)

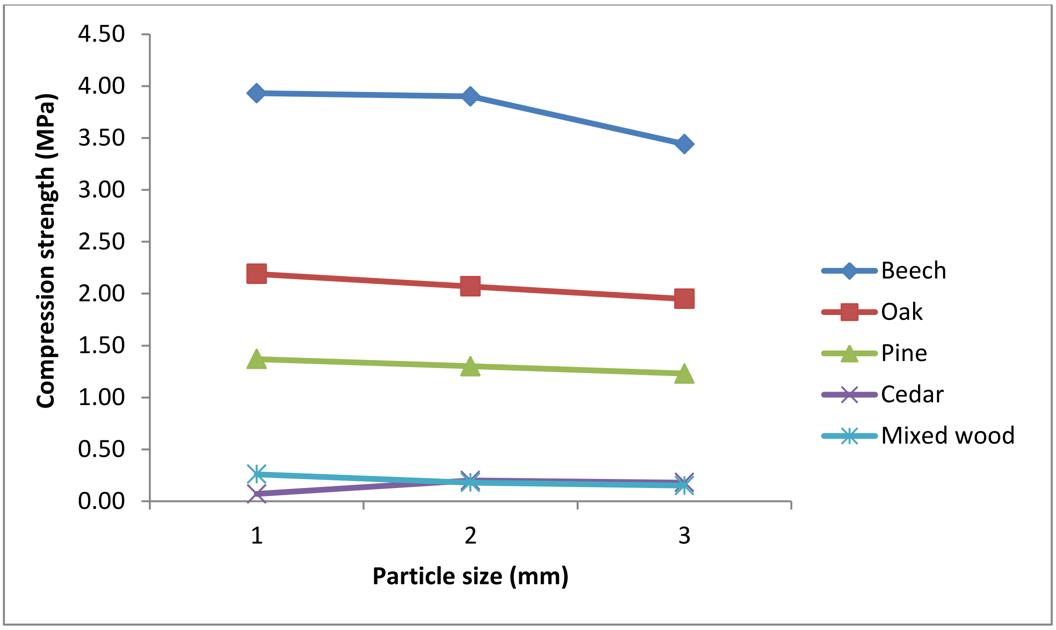


Figure 8.5 Mean compressive strength against particle size

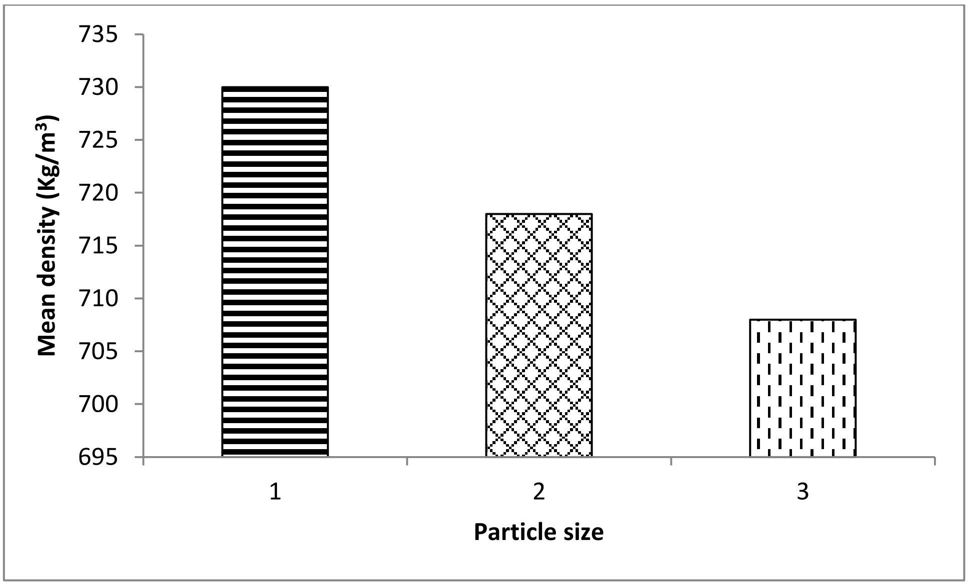


Figure 8.6 Mean density against particle size

8.3.5 Correlation of Wood Species with Thermal Conductivity

One of the main purposes for developing wood-crete as a building material is to evaluate its potential for thermal performance which is key parameters in low carbon sustainable building construction already highlighted in the development of wood-crete with sawdust and waste paper. Thermal conductivity depends on the composition, density, pore structure, moisture content and temperature of a material [162]. In wood, the main influencing factors are wood species, density, moisture content, direction of heat flow (anisotropy), inclination of grain and relation of volume or thickness to moisture content [163]. However, thermal conductivity is strongly influenced by density [162]. These have been reflected in the wood-crete developed in this study. It seems to be that wood-crete from softwood achieved a low thermal conductivity of 0.068 and 0.124 W/mK than wood-crete from hardwood of 0.114 – 0.171 W/mK (Table 8.4). However, a scrutiny of the data in Table 8.4 showed that the trend of change in thermal conductivity of the wood-crete follows that of the density and compressive strength of the wood-crete (Figs 8.7 and 8.8),

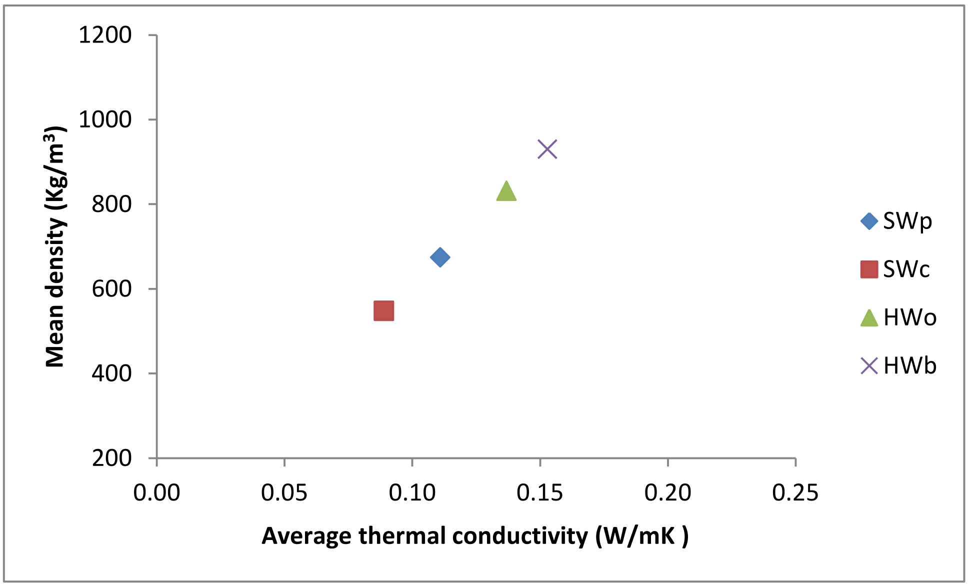


Figure 8.7 Mean density against mean thermal conductivity

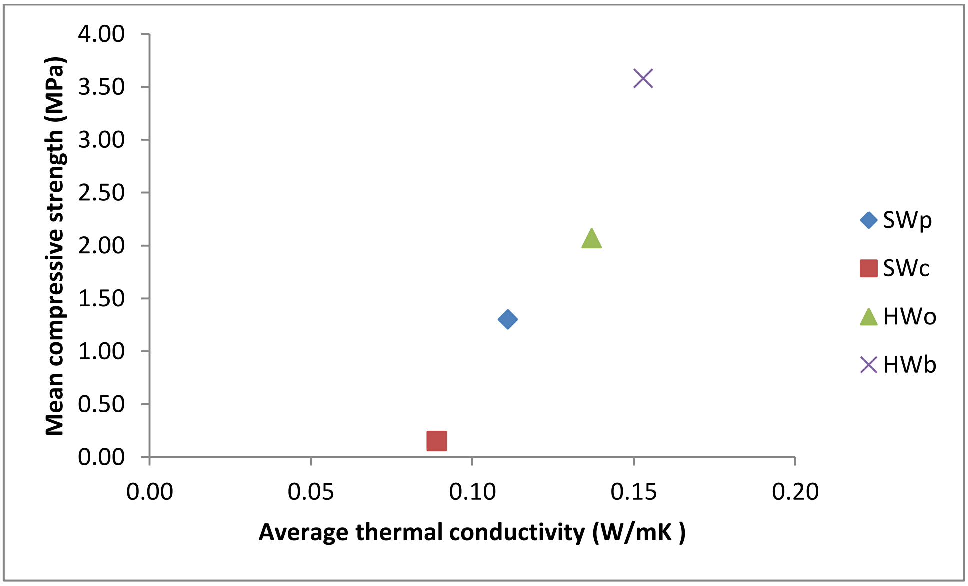


Figure 8.8 Compressive strength against mean thermal conductivity

i.e. the ranking of thermal conductivity = the ranking of density = beech wood-crete > oak wood-crete > pine wood crete > cedar wood-crete. The wood species may have little effect on the difference in the thermal conductivity of wood-crete. This may be true by considering the thermal properties of wood reported by previous worker [164], whose research on the thermal conductivity of five softwoods and five hardwoods showed that the average thermal conductivity for the former was 0.091 and for the latter 0.092 W/mK. Thermal conductivity of wood-crete from cedar sawdust was about 11% lower than wood-crete from pine wood while thermal conductivity of wood-crete from oak wood was about 5.6% lower than wood-crete from beech wood. These correspond to the fact that the density of cedar wood-crete is about 22% lower than that of pine wood-crete, while the density of oak wood-crete is about 8% lower than beech wood-crete. In general, wood-crete from softwood had about 18.3% lower in thermal conductivity than wood-crete from hardwood. The above result is also in agreement with results discovered in previous study [146], where reduced density resulted in a low thermal conductivity.

Also noticed here is that thermal conductivity reduced with a corresponding reduction in particle size of sawdust (Fig 8.9).

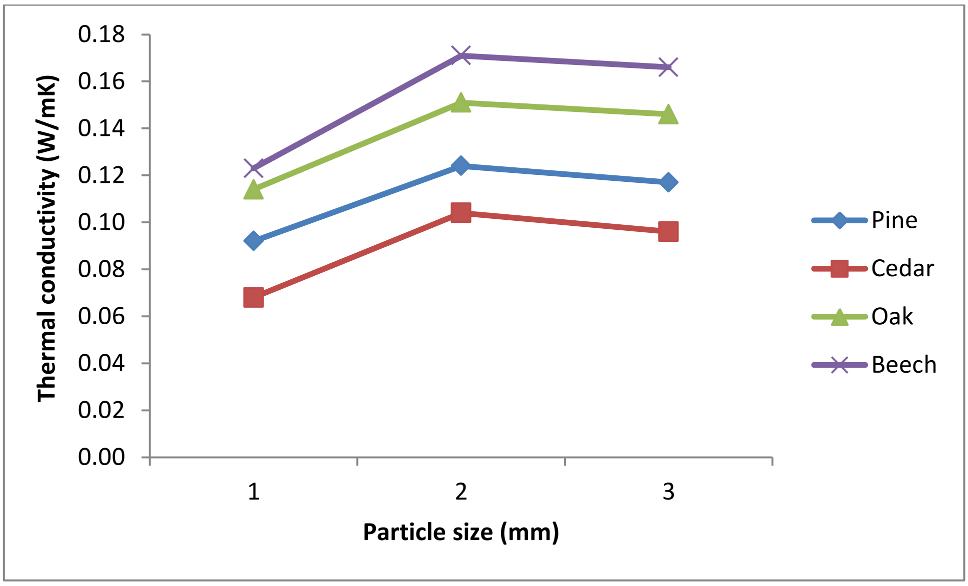


Figure 8.9 Mean thermal conductivity against particle size

Wood-crete made from 1mm particle size achieved a lower thermal conductivity than 2mm and 3mm particle size of sawdust. This again may be true when the thermal properties of wood particles by previous worker [165] whose research on the effect of particle size on the thermal conductivity of ZnS/diamond composites showed that thermal conductivity is increased by addition of large particles but lowered by the addition of sub-micron particles.

This effect is explained in terms of the interfacial thermal resistance which becomes increasingly dominant as the particles becomes smaller because that increased their surface to volume ratio [165].

Table 8.4 Thermal conductivity of wood-crete from various wood species.

Wood Species	**Particle size (mm)**	**Thermal Conductivity (W/mK)**	**Compressive strength (MPa)**	**Density (kg/m^3)**
Pine	1	0.092	1.37	696
	2	0.124	1.30	672
	3	0.117	1.23	655
Cedar	1	0.068	0.07	543
	2	0.104	0.20	561
	3	0.096	0.18	539
Oak	1	0.114	2.19	859
	2	0.151	2.07	821
	3	0.146	1.95	816
Beech	1	0.123	3.39	934
	2	0.171	3.90	926
	3	0.166	3.44	929

8.4 Interim Conclusions

The properties of wood-crete made from hardwood, softwood and mixed wood species has been developed and investigated. The compressive strength of wood-crete made from sawdust of softwood was similar and in some cases higher than that of hempcrete, while compressive strength of wood-crete made from hardwood was higher than that developed in chapters 6 and 7 of this thesis. This gives an indication that wood-crete can be made with various wood species resulting in different properties. In reality, it is not practicable to have sawdust from specific kinds of wood as most sawmills do not separate their sawdust during milling process. Hence, the wood-crete with the mixed wood species was specifically compared with single wood species of wood-crete. Specific outcomes from this chapter can be concluded as follows:

- Wood-crete made from hardwood resulted in higher strength compared to those made from softwood having a 53% difference in the compressive strength on average. Hardwood beech wood-crete recorded a 61% increase in compressive strength when compared to hardwood oak wood-crete; likewise softwood pine recorded a 79% increase in compressive strength when compared to softwood cedar wood-crete.
- The constituents of wood (lignin, cellulose, hemicelluloses and extractives) all contributed to the strength properties of wood-crete composites.
- To enable better bonding between sawdust and binder, a 1:2 of sawdust to binder ratio has been advisable.
- Wood-crete made with smaller particle size of 1mm achieved better compressive strength than those made with 2mm and 3mm particle sizes respectively. A reduction in compressive strength with an increase of particle size was strongly related to wood species.
- Wood-crete made from softwood has a lower thermal conductivity compared to wood-crete made from hardwood with a 19.4% reduction in thermal conductivity value.
- Mixing wood species for wood-crete production did not result in an average performance equivalent to the average performance of wood species, indicating an adverse effect of the mixing, such as ‘bridging’ between particles.

CHAPTER 9 – CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

It has been established during the analysis of this research work that low-income housing existed primarily due to the problems around housing delivery caused by various factors including urban population growth. It has also been ascertained in the course of this thesis that low-cost materials helps achieves low-cost housing and as a result low-income earners or middle class in the society are able to afford to rent or buy homes without financial difficulties. Wood-crete produced in this study helps solve various problems raised in the course of this thesis which include: waste management and environmental problem – wood-crete construction products provides a solution to waste management through reuse of wood and paper waste thereby reducing cost of recycling and incineration. The production of wood-crete also stops sawdust and paper waste from going to landfill sites which has been seen from literature review of this study to cause pollution and contamination having significant impact of the health of residents within landfill sites. As part of the environmental benefits of the use of wood-crete, it provides those in the wood industry a means of discarding their waste whilst enabling the creation of a new commercial viable environmental friendly product for the construction industry. The use of wood-crete in light of this provides a potential solution for dealing with the increasing amounts of wood waste and promotes a waste management practice that helps mitigate the effect of waste on the environment, thus promoting sustainable and green environmental practices especially in developing countries.

With alternative building materials being considered that can achieve adequate strength properties, have good thermal performance and with less impact on the environment, an alternative material (wood-crete) needed to be developed. Wood-crete was produced by mixing sawdust, waste paper and tradical (which acts as a binder) to create a building materials. Not only does the use of locally sourced materials help to reduce cost of building projects, they contribute to the benefit of the local community and sustainability at large. Due to the vast problems associated with our environment, there is requirement for a bilateral and multilateral collaboration to facilitate creative innovations on how to curtail waste management practices by turning waste into value added products. With reference to the main waste considered for this study (sawdust and paper), turning these waste into value added products will help provide those in the wood and paper industries a means of discarding their wastes whilst enabling the creation of new commercial environmental friendly product for the construction industry. The merits associated with the use of local building materials are numerous to mention; ranging from environmental principles which includes renewable, energy efficient, affordable, recyclable potentials to social involvement which includes self-construction, family and community working together. Above all, local building materials have the potential to enhance a sustainable construction practice.

Wood-crete when compared with hempcrete is of similar thermal performance but most importantly has an improved strength property and focused on use of waste materials which has a positive effect to the environment. Just like cement-bonded wood composites (CBWC) and hempcrete, wood-crete with addition of structural support can be used in construction and most beneficial in developing countries because of their relatively low cost as wood used are waste products from sawmills, basic use of simple technology during production process, reduced weight of composites making handling easier and labour less tedious hence promoting the use of local materials.

Three different methods were used in the course of this study for the production of wood-crete. First method used in the development of wood-crete shows the suitability of making wood-crete from sawdust and paper waste achieving mechanical properties based on compressive strength and thermal conductivity. Based on this method, it is advisable to make wood-crete with sawdust and tradical lime at ratios 1:2 with addition of 75% waste paper as it achieved the best compressive strength of 0.80MPa.

Haven successfully made wood-crete out of sawdust and paper waste, second method which involved making wood-crete from treated sawdust solved the problem of poor bonding strength between sawdust and binder used (tradical lime) which was discovered to be the main reason for low compressive strength of wood-crete. Main conclusions and suggestions on the use and properties of wood-crete are centred on this second method. Wood-crete made with the second method should be based on the modification of sawdust by hot water boiling, alkaline treatment and the addition of different types of waste paper (de-fibred paper and paper strip) to achieve the highest compressive strength of 1.62MPa which involved treating sawdust by boiling at 140mins, addition of 4% of NaOH and 75% of paper strip with sawdust sieve size of 1mm and S/TL ratio of 1:2. This method is advised during production of wood-crete as it gives the best compressive strength properties of wood-crete.

The third method, based on investigating the effect of different wood-species on the property of wood-crete showed that extractives affect the strength of wood-crete. Based on this method, wood-crete should be made where possible with sawdust from hardwood. Highest compressive strength value of 3.93MPa was achieved with wood-crete made from beech wood. These three methods focused on the development of a new building material (wood-crete) made from sawdust, waste paper, and tradical lime with consideration for cheaper, locally and environmentally friendly materials to meet desired needs, enhance self-efficiency in construction thus enabling sustainable development. Across all three methods:

- ❖ The use of sawdust and binder had a direct effect on the strength properties of wood-crete, with 1:2 ratio of sawdust to binder having a better bonding between sawdust and binder and between sawdust particles than ratio 1:1.
- ❖ Highest strength of wood-crete was achieved with particle size 1mm compared to particle size 2mm and 3mm

Other significant findings include:

- ❖ Surface modification, processing of cellulosic fibril and the extraction of lignin and hemi-cellulosic compounds with alkali had an effect on compressive strength of wood-crete.
- ❖ Properties of wood-crete were closely related to the type of wood sawdust used for wood-crete with sawdust from hardwood giving rise to higher compressive strength
- ❖ Wood-crete composites had good thermal conductivity ranging from 0.046W/mK to 0.069W/mK and thus could be used for thermal insulating materials for building construction.
- ❖ Water absorption test and fire test interestingly showed that wood-crete meets with agreeable standards and like most building materials, suitable for non and semi-structural applications.

Taking a look at the results of compressive strength of wood-crete made from hardwood, it is fair to say that scientifically, treating hardwood beech sawdust with 4% NaOH at 140mins achieves a better strength. However, making wood-crete from only hardwood is not commercially viable to achieve as sawdust is not separated in sawmills during the sawing process of wood. If this has to be taken into account in reality, the cost implication of achieving wood-crete from hardwood sawdust would make wood-crete production unaffordable thus this study proposes the second methodology for the production of wood-crete.

Conclusively, results have shown that treating sawdust before use gives rise to a higher compressive strength of wood-crete which the second method used for the development of wood-crete clearly shows. Also studies have shown that treatment of wood fibres makes them immune to rot and insect damage. This is very important when considerations are made to the use of wood-crete in developing countries most prone to insects. From water absorption test and corresponding compressive test done on samples, it is advisable not to use wood-crete in areas of high percentage of dampness as this would have a huge effect on its structural application and impact strength. In all three methodologies used in this study, wood-crete was able to withstand considerable amount of impact load and considered, like hempcrete, most suitable for wall panelling or other non- and semi-structural applications with good thermal insulating properties.

9.2 Recommendations for Future Work

Results from development of wood-crete focused on the structural and thermal properties of wood-crete as an infill material. Future work should be undertaken to clearly define wood-crete performance as a structural in-fill and set design guidelines for wood-crete in-filled timber stud walls:

- Additional compressive tests on wood-crete in-filled walls
- Other combinations of wood-crete needs to be investigated to validate its full potentials to be used in load bearing walls and stand-alone structural application in the building industry.
- Full scale fire test
- Different high density wooe-crete infill walls can be tested to find out how wood-crete can perform as a load bearing material when used compositely with timber. This should lead to the development of a corresponding modelling.

BIBLIOGRAPHY

[1] T. Woolley, “The Role of Low Impact Building Materials in Sustainable Construction: The Potential of Hemp,” Queens University Belfast School of Architecture, UK, 2004.

[2] A. Behrensa, S. Giljuma, J. Kovandab and S. Niza, “The Material Basis of the Global Economy Worldwide Patterns of Natural Resource Extraction and their Implications for Sustainable Resource use Policies,” *Ecological Economics,* vol. 64, pp. 444 - 453, 2007.

[3] B. Kabir and S. Bustani, “A Review of Housing Delivery Efforts in Nigeria,” in *ISA Housing Conference, "Housing Assets, Housing People" Department of Urban Studies, University of Glasgow.*, Glasgow, 2009.

[4] A. G. Onibokun, “Environmental Issues in Housing Habitability,” *Environment and Planning,* vol. 5, pp. 461 - 476, 1977.

[5] O. T. Nubi, “Affordable Housing Delivery in Nigeria.,” in *The South African Foundation International conference and exhibition.*, Cape town, October, 2008.

[6] S. L. Rikko and D. Gwatau, “The Nigerian architecture: The Trend in Housing Development,” *Journal of Geography and Regional Planning,* pp. Vol. 4(5), pp. 273-278, 2011.

[7] O. F. J. Grimes, “Housing for Low Income Urban Families,” Washington International Bank for Reconstruction and Development, 1976.

[8] Atolagbe and M. O. Anifowose, “Architecture in Nigeria and Practice for Sustainable Environmental Development: A Comparative Study of Modern and Indigenous Housing Strategies.,” *AARCHES Journal,. Vol.,* pp. Pp 61-65., 2002.

[9] J. O. Fasakin, “Cooperative Housing; The Concept, Experience and applicability to Nigeria’s socio-economic millieu’,” in *Seminar paper presented at the Fedral University of Technology*, Akure, 1998.

[10] A. O. Oduwaye, “Urban Landscape Planning Experience in Nigeria. Landscape and Urban Planning,” pp. 43(1-3), 133-142, 1998.

[11] F. Omole, “Basic Issues in Housing Development,” Ondo, Nigeria, 2001.

[12] L. Okupe, “Private Sector Initiative in Housing Development in Nigeria – How feasible? Housing Today,” pp. 1 (6), 21 – 26, 2002.

[13] Federal Government of Nigeria, “National Housing Policy for Nigeria, Federal Ministry of Works,” Abuja, 2004.

[14] O. Oluwatuyi and S.-O. O. Olayemi, “Escalating Cost of Cement a threat to a Sustainable Housing Development in Nigeria,” *Journal of Research in International Business Management,* pp. 97 - 101, 2012.

[15] J. S. Ajanlekoko, “Sustainable Housing Development in Nigeria – The Financial and Infrastructural Implication,’,” in *International Conference on Spatial Information for Sustainable Development*, Nairobi, 2001.

[16] B. Oluwaseun, “Sustainable Development and Constitutionalism in Nigeria: Constitutional Design, Identity and Legitimacy in a deeply divided Society,” *Journal of Sustainable Developemtn in Africa Vol 13,* p. No. 8, 2011.

[17] Finmark Trust, “Overview of the Housing Finance Sector in Nigeria,” 2010.

[18] World Bank, World Development Indicators Database, “Annual Report,” 2008. [Online]. Available: www.worldbank.org. [Accessed 16 June 2010].

[19] United Nations, “The Millennium Development Goals Report,” New York, 2010.

[20] Building Design & Construction White Paper on Sustainability, November 2003. [Online]. Available: www.bdcmag.com. [Accessed 19 January 2010].

[21] United Nations, 2008. [Online]. Available: http://www.un.org/en/ecosoc/docs/pdfs/fina_08-45773.pdf. [Accessed April 2011].

[22] C. du Plessis, “Sustainable Development Demands Dialogue between Developed and Developing Worlds,” *Building Research and Information,* vol. 27, no. 6, p. 378 – 389, 1999.

[23] United Nations, “Agenda 21,” in *Department of Economic and Social Affairs*, Johannesburg, 2002.

[24] Building Research Establishment, “Report on the Construction of the Hemp Houses at Haverhill,” Suffolk, 2002.

[25] J. B. Falade, “The Future Environment: What Legacy?,” in *Paper presented at National Workshop on Nigerias Endangered Environment: Agenda for a New Millenum,* Lagos, 1999.

[26] S. Abumere, “Governing the City,” in *Paper presented at a National Confrerence on the City in Nigeria*, Ile Ife, 2002.

[27] Y. Odeyemi, “Urbanization and Gender Inequality in Nigeria,” in *Paper presented at a National Conference on the City in Nigeria*, Ile Ife, 2002.

[28] D. Olanrewaju, “Sustainable Environment and the Poor,” in *Paper presented at a National Conference on Challenges of Environmental Sustainability in a Democratic Government,* Akure, 2003.

[29] T. Agbola, “The Housing of Nigerians "A Review of Policy Development and Implementation,” Ibadan, Nigeria, 1998.

[30] A. D. Jiboye, “Achieving Sustainable Housing Development in Nigeria: A Critical Challenge to Governance,” *International Jouranl of Humanities and Social Science,* vol. 1, no. 9 Special Issue, July 2011.

[31] R. Liam, P. Hazel, B. Anne and D. Abigail, “Breaking Point - How Unaffordable Housing is Pushing us to the Limit,” England, 2008.

[32] Department for Communities and Local Government (DCLG), August 2006. [Online]. Available: www.communities.gov.uk.

[33] L. Okupe, “The Role of the Private Sector in Housing Delivery in Nigeria.,” in *National Serminar of the Nigerian Institute of Building,* Ibadan, 2000.

[34] B. Muhammad, “Cement Glut Saves Nigeria N300bn,” ThisDay Live, 29 May 2013. [Online]. Available: http://www.thisdaylive.com/articles/cement-glut-saves-nigeria-n300bn/148832/. [Accessed 28 June 2013].

[35] M. I. Udegbe, “Labour Force Output on Plastering Activity in Edo State, The Professional Builder,” *Journal of the Nigerian Instiuture of Building,* pp. 34 - 41, 2005.

[36] P. Malpass and A. Murie, *Housing Policy and Practice (Public Policy and Politics),* 1999.

[37] Shelter, “The Housing and Homelessness Charity,” [Online]. Available: http://england.shelter.org.uk. [Accessed 6 March 2010].

[38] O. Koenisgsberger, “ Housing in the National Development Plan: An example from Nigeria,” *Ekistics No. 180,* vol. 30, p. 393 – 397, 1970.

[39] O. E. Adeniyi, “Housing in Nigeria National Development.,” *The Nigerian Journal of Economic and Social Studies,* vol. XIV, no. 83 NISER Report Series, pp. 315 - 326, 1972.

[40] A. G. Onibokun, “A Critical Review of the Nigerian Government Housing Policy and Programmes,” in *Paper presented at the 2nd International Conference on Housing*, Ibadan, 1975.

[41] A. G. Onokerhoraye, “The Spatial Pattern of Residential Districts in Benin,” *Urban Studies,* vol. 44, pp. 291 - 302, 1977.

[42] D. Aradeon, “Regional assessment of human settlement policies in Nigeria,” *Habitat International,* vol. 3 & 4, p. 331 – 339, 1978.

[43] J. O. Abiodun, “Housing problem and policies: The Experience of a Tropical African Country, Nigeria,” in *Paper presented at the 50th Advance Summer Institute in Regional Science*, Amsterdam, 1980.

[44] S. Erguden, “Low-Cost Housing: Policies and Constraints in Developing Countries,” Nairobi, Kenya, 2001.

[45] A. L. Mobogunje, “Land Management in Nigeria: Issues, Opportunities and Threats,” in *National Conference on Land Management and Taxation, Department of Estate Management*, University of Lagos, 2002.

[46] A. D. Jiboye, “The Challenges of Sustainable Housing and Urban Development in Nigeria,” *Journal of Environmental Research and Policies,* vol. 4, no. 3, pp. 23 - 27, 2009.

[47] L. Ogunshakin and I. Olayiwola, “The Collapse of Official Housing Policy in Nigeria,” *Habitat International,* vol. 16, no. 1, pp. 41 - 53, 1992.

[48] K. A. Wahab, “Nigeria and her Housing Problems – Searching for Solutions,” *Construction in Nigeria,* vol. 6, no. 11, p. 20 – 25, November 1976.

[49] A. N. M. Afify, July 2011. [Online]. Available: www.cpas-egypt.com/pdf/Ayman_Afify/10th%20-%20Paper.pdf. [Accessed November 2011].

[50] S. A. Saka, “The Implementation of Low-Income Housing Programmes in Nigeria: 1980 – 1985 in Ilesanmi Adetokunbo. O - The Legacy and Challenge of Public Housing Provision in Lagos, Nigeria,” Hague, 1987.

[51] J. Yates and V. Milligan, “Housing Affordability: a 21st Century Problem,” 2007.

[52] J. Monzo, V. Borrachero, J. Paya, R. Barrionuevo, L. Soriano and N. D. Brito, “Morphology and Reactivity Studies of Peruvian Pozzolands,” in *11th International Conference on Non-conventional Materials and Technologies (NOCMAT 2009)*, Bath, 2009.

[53] R. A. d. M. Junior, S. P. Fucale, Y. V. Póvoas and A. D. Gusmão, “Research Characterizing the Physical Properties of Recycled Aggregate of Civil Construction Wastes,” in *11th International Conference on Non-conventional Materials and Technologies (NOCMAT 2009),* Bath, 2009.

[54] R. Taylor and A. Allen, *Waste disposal and landfill: Potential hazards and information needs World Health OrganizationProtecting Groundwater for Health: Managing the Quality of Drinking-water Sources. Edited by O. Schmoll, G. Howard, J. Chilton,* IWA Publishing, London. UK, 2006.

[55] M. Medina, “The Effect of Income on Municipal Solid Waste Generation Rates for Countries of Varying Levels of Economic Development: A Model,” *Journal of Solid Waste Technology & Management.,* pp. 149 - 155, 1997.

[56] M. Medina, *Solid Wastes, Poverty and the Environment in Developing Country Cities Challenges and Opportunities. Working Paper No. 2010/23,* March, 2010.

[57] J. Ferguson, N. Kermode, C. L. Nash, W. A. Sketch and R. P. Huxford, Managing and Minimizing Construction Waste : A Practical Guide, 1995.

[58] D. J. Craven, H. M. Okraglik and J. M. Eilenberg, "Construction Waste and a New Design Methodology, in Kilbert C J, (ed).Sustainable Construction, Centre for Construction and Environment, Gainsville, FL," pp. 89 - 98, 1994.

[59] M. J. Stokoe, P. W. Kwong and M. M. Lau, "Waste Reduction: A tool for Sustainable Waste Management for Hong Kong. In: Barrage A, Edelman Y,," in *Proceedings of R'99 World Congress*, Geneva.

[60] M. I. Obadan and E. O. Uga, "National Planning And Construction," in *17th Biennial Conference Of The Nigerian Institute Of Quantity Surveyors*, Nigeria, 1996.

[61] Federal Office of Statistics, *Review of Nigeria Economy, FOS,* Abuja, Nigeria, 1997.

[62] P. Olomolaiye, "Materials Management Practice and Waste on Nigerian Building Sites," *Building Research & Information,* vol. 19, no. 1, pp. 38 - 42, 1991.

[63] L. L. Ekanayake and G. Ofori, "Building Waste Assessment Score: Design-Based Tool," *Building and Environment,* vol. 39, no. 7, pp. 851 - 861, July 2004.

[64] A. B. Wahab and A. F. Lawal, "An Evaluation Of Waste Control Measures In Construction Industry In Nigeria," *African Journal Of Environmental Science And Technology,* vol. 5, no. 3, pp. 246 - 254, March, 2011.

[65] G. Jungmeier, B. Hillring, J. Hurley, M. Humar, A. Fruehwald and C. Gallis, "COST Action E31 – Management of Recovered Wood Proceedings of European COST E31 - Recycling, Bioenergy and other options," in *Management of Recovered Wood,* Thessaloniki, 2004.

[66] A. Grigoriou, "The Ecological Importance of Wood Products," *Scientific Annals of the Department of Forestry and Natural Environment,* vol. 39, no. 2, p. 703 – 714, 1996.

[67] B. Olufokunbi, "Entrepreneurship within the Nigerian Economy Today," in *Entrepreneurship within Nigerian Economy*, Obafeni Awolowo University, Ile-Ife, 1995.

[68] A. Dionco-Adetayo Erlinda, "Utilization of Wood Wastes in Nigeria: A Feasibility Overview," *Technovation,* vol. 21, no. 1, pp. 55 - 60, January 2001.

[69] F. H. Robert, "Building Products from Recycled Wood Waste," in *Energy Efficient Building Association: E1 - E6,* Dallas, TX: Wausau, 1994.

[70] Greater London Authority, " London Housing Market Report, Quarter 2," BERR, Monthly Bulletin of Building Materials and Components, London, 2012.

[71] R. F. Fellows, D. A. Langford, R. Newcombe and S. A. Urry, "Construction Management in Practice Longman. Harlow,," pp. 177; 224 - 231, 1983.

[72] Y. A. Sanusi, "Strategies for the Development and Use of Indigenous Building Materials for Low Cost Housing in Nigeria," in *In: Ike, E.C. (ed) Proceedings of the International Conference on Nigerian Indigenous Building Materials*, Zaria, Nigeria, 1993.

[73] T. C. Mogbo, "The Retail Trade and Building Materials in Nigeria," *The Quantity Surveyor,* vol. 29, pp. 42 - 45, 1999.

[74] K. Kern, "The Owner Built Home and Homestead," *Mother Earth News,* no. 15, pp. 8 - 11, May/June 2004.

[75] P. A. Okereke, “Construction Materials: Testing and Quality Control in Tropical Climate,” Owerri, Nigeria, 2003.

[76] P. N. C. Okigbo, “Nigeria’s Financial System. In: Mogbo, T.C. (2001) The Construction Sector and the Economic Growth of Nigeria, 1981–95,” *The Quantity Surveyor* , vol. 35, pp. 8 - 11 , 1982.

[77] T. C. Mogbo, “The Construction Sector and the Economic Growth of Nigeria, 1981–95,” *The Quantity Surveyor* , vol. 35, pp. 8 - 11, 2001.

[78] UNCHS, “Earth Construction Technology,” Nairobi, Kenya, 1992.

[79] UNCHS and CSC (Common Wealth Science Council), “Standards and Specifications for Local Building Materials in Ghana and Malawi,” *In: Ramachandran, A. (ed) Journal of the NETWORK of African Countries on Local Building Materials and Technology,* vol. 1, no. 2, pp. 8 - 9, 1990a.

[80] Y. Mahgoub, “Sustainable Architecture in the United Arab Emirates: Past and Present,” in *International Conference on Urbanisation and Housing.* , GOA, India, 2-5 October, 1997.

[81] M. M. Mourshed, W. M. Matipa, M. Keane and D. Kelliher, “Towards Interoperability: ICT in Academic Curricula for Sustainable Construction,” in *CIB W107 1st International Conference: Creating a Sustainable Construction Industry in Industry in Developing Countries*, Stellenbosch, South Africa, 11-13 November, 2000.

[82] M. T. Lilly and J. J. Wai, “Development and Manufacture of Roofing Tiles Using Local Available Raw Materials,” *The Quantity Surveyor,* vol. 35, pp. 14 - 19, 2001.

[83] UNCHS , “The Use of Selected Indigenous Building Materials with Potential for Wide Applications in Developing Countries,” Nairobi, Kenya , 1985.

[84] UNCHS and CSC (Common Wealth Science Council), “Workshop on Co-operation in the African Region on Technologies and Standards for Local Building Materials in Ghana and Malawi,” *In: Ramachandran, A. (ed) Journal of the NETWORK of African Countries on Local Building Materials and Technology,* vol. 1, no. 2, pp. 10 - 11, 1990b.

[85] K. Bala and I. K. Zubairu, “Detrimental Factors to Local Building Materials Utilisation in Nigeria. In: Ike, E.C. (ed),” in *Proceedings of the International Conference on Nigerian Indigenous Building Materials,* Zaria, Nigeria, 25-28 July 1993, pp 36 - 40.

[86] J. Turner, “Housing by People: Towards Autonomy in Building Environments,” *Pantheon, Random House,* pp. 1 - 169, 1977.

[87] D. F. Kere, “Sustainable Building for Africa,” in *RIBA,* London, 2010.

[88] B. Cather, “What’s New in Construction Materials? The Challenges of the Imagination,” *Construction Management and Economics,* vol. 19, pp. 335 - 336 , 2001.

[89] B. Kabir and S. A. Bustani, *A Review of Housing Delivery Efforts in Nigeria,* 2010.

[90] Nigeria Tribune: New Delivery Method and Mass Housing in Nigeria, October 2010. [Online]. Available: http://tribune.com.ng/index.php/tribune-business/12262-new-delivery-method-and-mass-housing-in-nigeria.

[91] V. I. Ogu and J. E. Ogbuzobe, “Housing Policy in Nigeria: Towards Enablement of Private Housing Development,” *Habitat Internationals,* vol. 25, pp. 473 - 492, 2001.

[92] C. Pugh, “The Changing Roles of Self-help in Housing and Urban Policies, 1950 - 1996: Experience in Developing Countries,” *Third World Planning Review,* vol. 1, pp. 91 - 109, 1997.

[93] R. Bevan and T. Woolley, "Constructing a Low Energy House from Hempcrete and other Natural Materials," in *11th International Conference on Non-conventional Materials and Technologies (NOCMAT 2009)*, Bath, 2009.

[94] M. Evernden and T. Mottram, "A case for Houses in the UK to be Constructed of Fibre Reinforced Polymer Components," in *11th International Conference on Non-conventional Materials and Technologies (NOCMAT), 2009-09-06 – 2009-09-09,* University of Bath, 2009.

[95] M. Evernden and T. Mottram, "A Case for Houses in the UK to be Constructed of FRP Components," in *ICE Construction Materials, 165 (CM1), 1000002,* 2012.

[96] P. D. Bruijn, *Hemp Concretes Mechanical Properties Using Both Shives And Fibres,* Sweden, 2008.

[97] A. K. Afuwape, "Design and Testing of Sawdust Compactors," Ile-Ife, Nigeria, 1983.

[98] L. Arnaud, V. Cerezo and C. Boutin, "Physical Properties of Concrete and Vegetable Particles. In Boutin C, Lefik M, editors. Experimental Knowledge versus Theoretical Models, Soils and Composites Materials.," 2004.

[99] L. O'Dowd and D. Quinn, "Investigating Properties of Concrete of Hemp and Lime Construction," Dublin, 2005.

[100] A. Mukherjee, *Structural Benefits of Hempcrete Infill in Timber Stud Walls,* Kingston, Ontario, Canada: A thesis submitted to the Department of Civil Engineering, Queen's University, Kingston, Ontario, Canada, 2012.

[101] The Limecrete Company LTD, "Sustainable Construction - Hempcrete Overview," 2012. [Online]. Available: www.limecrete.co.uk/docs/Hempcrete-Factsheet.pdf. [Accessed 2 February 2012].

[102] L. Arnaud and V. Cerezo, *Physical Evaluation of Construction Materials based on Hemp,* 2001.

[103] C. D. Gross, "Structural Enhancement of Timber Framing using Hemp-Lime," Thesis (Doctor of Philosophy (PhD)), University of Bath, 2013.

[104] P. I. Peev and J. Saxgren, "Is Hemp a Sustainable Construction Material?," University College Horsens Denmark, Denmark, 2012.

[105] S. Goodhew, J. Carfrae and P. De Wilde, "Briefing: Challenges related to Straw Bale Construction," *Engineering Sustainability,* vol. 163, no. ES4, pp. 185 - 189, 2010.

[106] A. Sutton, D. Black and P. Walker, "Straw Bale - An Introduction to Low-Impact Building Materials," IHS BRE Press, Watford, 2011.

[107] C. Gross, "Structural Performance of Prefabricated Straw Bale Panels," Thesis (Master of Philosophy MPhil)), University of Bath, 2009.

[108] R. W. Wolfe and A. Gjinolli, "Cement-Bonded Wood Composites as an Engineering Material," in *USDA Forest Service and the Forest Products Society,* Madison, Wisconsin, 1996.

[109] P. D. Evans, "Wood–Cement Composites in Asia-Pacific Region," in *The Australian Centre for International Agricultural Research (ACIAR),* Canberra, Australia, 2000.

[110] S. Frybort, R. Mauritz, A. Teischinger and U. Muller, "Cement Bonded Composites Review," *BioResources,* vol. 3, no. 2, pp. 602 - 626, 2008.

[111] M. H. Hachmi and A. A. Moslemi, "Correlation between Wood-Cement Compatibility and Wood Extractives," *Forest Products,* vol. 39, pp. 55 - 58, 1989.

[112] M. Singh and M. Garg, "Retarding action of various Chemicals on Setting and Hardening Characteristics of Gypsum Plaster at different pH," *Cement and Concrete Research,* vol. 27, pp. 947 - 950, 1997.

[113] Q. Xu and J. Stark, "Early Hydration of Ordinary Portland Cement with an Alkaline Shortcrete Accelerator," *Advanced Cement Reseach,* vol. 17, pp. 1 - 8 , 2005.

[114] M. Z. Fan, P. W. Bonfield, J. M. Dinwoodie, J. Boxall and M. C. Breese, "Dimensional Instability of Cement-Bonded Particleboard: The Effect of Surface Coating," *Cement Concrete Research,* vol. 34, pp. 1189 - 1197, 2004a.

[115] M. Z. Fan, J. M. Dinwoodie, P. W. Bonfield and M. C. Breese, "Dimensional Instability of Cement-Bonded Particleboard: Behaviour of Cement Paste and its Contribution to the Composite," *Wood Fibre Science,* vol. 31, pp. 306 - 318, 1999b.

[116] M. Fan, M. K. Ndikontar, X. Zhou and J. N. Ngamveng, "Cement-bonded Composites made from Tropical Woods: Compactibility of Wood and Cement," *Construction and Building Materials,* vol. 36, pp. 135 - 140, 2012.

[117] L. Zhengtian and A. A. Moslemi, "Influence of Chemical Additives on the Hydration Characteristics of Western Larch Wood-Cement-Water Mixtures," *Forest Products Journal,* vol. 35, pp. 37 - 43, 1985.

[118] M. Z. Fan, J. M. Dinwoodie, P. W. Bonfield and M. C. Breese, "Dimensional Instability of Cement-Bonded Particleboard: Behaviour of Wood Chips from various stages of Manufacture of CBPB," *Journal of Material Science,* vol. 34, pp. 1729 - 1740, 1999c.

[119] M. Z. Fan, J. M. Dinwoodie and M. C. Breese, "Dimensional Instability of Cement-Bonded Particleboard: Mechanisms of Deformation of CBPB," *Cement Concrete Research,* vol. 29, pp. 923 - 932, 1999a.

[120] A. A. Moslemi and S. C. Pfister, "The Influence of Cement/Wood Ratio and Cement type on Bending Strength and Dimentional Stability of Wood-Cement Composite Panels," *Wood Fibre Science,* vol. 19, pp. 165 - 175, 1987.

[121] S. Poopathi and S. Abidha, "Use of Feather-Based Culture Media for the Production of Mosquitocidal Bacteria," *Biological Control,* vol. 43, no. 1, pp. 49 - 55, 2007.

[122] W. F. Schmidt and J. R. Barone, "New uses for chicken feathers keratin fiber," *Poultry Waste Management Symposium Proceedings,* p. 99 – 101, 2004.

[123] F. Casarin and F. C.-O. A. Brandelli, "Use of Poultry By-product for Production of Keratinolytic Enzymes"," *Food and Bioprocess Technology,* vol. 1, no. 3, p. 301 – 305, 2008.

[124] C. E. Reynolds, J. C. Steedman and A. J. Threlfall, Reynolds's Reinforced Concrete Designer's Handbook - 11th Edition, Abingdon, Oxon: Taylor and Francis, 2008.

[125] A. M. Othman, "Experimental Investigations of the Effect of Some Insulating Materials on the Compressive Strength, Water Absorption and Thermal Conductivity of Building Bricks," *Jordan Journal of Mechanical and Industrial Engineering,* vol. 4, no. 4, pp. 443 - 450, 2010.

[126] L. Cox and S. van Dijk, "Foam Concrete Limited - Low Density and High Strength," 29 July 2011. [Online]. Available: http://www.foamconcrete.info/page37.html. [Accessed 8 April 2012].

[127] F. A. Olutoge, "Investigations on Sawdust and Palm Kernel Shells as Aggregate Replacement," *ARPN Journal of Engineering and Applied Sciences,* vol. 5, no. 4, pp. 7 - 13, April 2010.

[128] B. A. Richard, “Waste Paper,” theguardian, February 2008. [Online]. Available: http://www.guardian.co.uk/environment/ethicallivingblog/2008/feb/15/wastepaper. [Accessed 19 May 2008].

[129] R. Srinivasan, K. Sathiya and M. Palanisamy, “Experimental Investigation in Developing Low Cost Concrete from Paper Industry Waste,” *The Bulletin of the Polytechnic Institute of Jassy, Construction Architecture Section (Romania),* pp. 44 - 56, 2010.

[130] S. A. Balwaik and S. P. Raut, “Utilization of Waste Paper Pulp by Partial Replacement of Cement in Concrete,” *International Journal of Engineering Research and Applications,* vol. 1, no. 2, pp. 300 - 309.

[131] R. Barrett-Evans, “Pointing with Lime Mortars,” Pembrokeshire County Council, November 2006.

[132] C. F. Ferraris, “Concrete Mixing Methods and Concrete Mixers: State of the Art,” *National Institute of Standards and Technology,* vol. 106, no. 2, pp. 391 - 399, 2001.

[133] British Standard BS EN 12390-2:2009, “Making and Curing Specimens for Strength Test,” BSI, United Kingdom.

[134] A. Zziwa, S. Kizito, A. Y. Banana, J. R. S. Kaboggoza, R. K. Kambugu and O. E. Sseremba, “Production of Composite Bricks from Sawdust using Portland Cement as a Binder,” 2006.

[135] M. H. Simatupang and R. L. Geimer, “Inorganic Binder for Wood Composites: Feasibility and Limitations. In: Proc. of the Wood Adhesive Symposium. Madison W I,” pp. 169 - 176, 1990.

[136] D. D. L. Chung, “Dispersion of Short Fibers in Cement,” *Journal of Materials in Civil Engineering,* vol. 17, pp. 379 - 383, July / August 2005.

[137] L. Dzurenda, *Effect of Thermal Modification of Oak Wood on Saawdust Granularity,* 2010.

[138] Y. M. Wei and B. Tomita, “Effects of five Additive Materials on Mechanical and Dimensional Properties of Wood Cement-Bonded Boards,” *Journal of Wood Science,* vol. 47, pp. 437-444, 2000.

[139] M. N. Al-khalaf and H. A. Yousift, “Compactibility of No-Fines Concrete,” *International Journal of Cement Composites and Lightweight Concrete,* vol. 8, no. 1, pp. 45 - 50, 1986.

[140] R. David, “Materials Selection Guidelines for Low Thermal Conductivity Thermal Barrier Coatings,” Santa Barbara, CA 93106-5050.

[141] G. A. Zaikov and A. Jimenez, Polymer Analysis, Degradation and Stabilization, New York: Nova Science Publishers, Inc, 2004.

[142] X. Li, L. G. Tabil and S. Panigrahi, “Chemical Treatments of Natural Fiber for Use in Natural Fiber-Reinforced Composites,” *Journal of Polymers and the Environment,* vol. 15, pp. 25 - 33, 2007.

[143] N. Lopattananon, K. Panawarangkul, K. Sahakaro and B. Ellis, “Performance of Pineapple Leaf Fiber–Natural Rubber Composites: The Effect of Fiber Surface Treatments,” *Journal of Applied Polymer Science,* vol. 102, pp. 1974 - 1984, 2006.

[144] A. Prompunjai and W. Sridach, “Preparation and Some Mechanical Properties of Composite Materials Made from Sawdust, Cassava Starch and Natural Rubber Latex,” *World Academiy of Science, Engineering and Technology,* pp. 930 - 934, 2010.

[145] A. K. Bledzki and J. Gassan, "Composites reinforced with cellulose based fibres," *Progress in Polymer Science,* vol. 24, p. 221, 1999.

[146] E. P. Aigbomian and M. Fan, "Development of Wood-Crete Building Materials from Sawdust and Waste Paper," *Construction and Building Materials,* vol. 40, pp. 361 - 366, 2013.

[147] G. Vaickelionis and R. Vaickelioniene, "Cement Hydration in the Presence of Wood Extractives and Pozzolan Mineral Additives," *Ceramics − Silikáty,* vol. 50, no. 2, pp. 115 - 122, 2006.

[148] M. Borrega, K. Nieminen and H. Sixta, "Effects of Hot Water Extraction in a Batch Reactor on the Delignification of Birch Wood," *BioResources*, vol. 6, no. 2, pp. 1890 - 1903, 2011.

[149] H. Kinoshita, K. Kaizu, M. Fukuda, H. Tokunaga, K. Keisuke and K. Ikeda, "Development of Green Composite consists of Woodchips, Bamboo Fibers and Biodegradable Adhesive," *Composites,* pp. 607 - 612, 2009.

[150] S. Migneault, A. Koubaa, F. Erchiqui, A. Chaala, K. Englund, C. Krause and M. Wolcott, "Effect of Fiber Length on Processing and Properties of Extruded Wood-Fiber/HDPE Composites," *Journal of Applied Polymer Science,* pp. 1086 - 1092, 2008.

[151] A. K. Bledzki, M. Letman, A. Viksne and L. A. Rence, "Comparison of Compounding Processes and Wood type for Wood Fibre-PP Composites," *Composites Part A: Applied Science and Manufacturing,* vol. 36, no. 6, pp. 789 - 797, 2005.

[152] G. Lulianelli, M. B. Tavares and L. Luetkmeyer, "Water Absorption Behabior and Impact Strength of PVC/Wood Flour Composites," *Chemistry and Chemical Technology,* vol. 4, no. 3, pp. 226 - 299, 2010.

[153] R. C. Pettersen, "'The Chemistry of Solid Wood In: ' R. Rowell (ed.)," *Journal of the American Chemical Society,* pp. 57 - 127, 1984.

[154] J. H. Grabber, "How do Lignin Composition, Structure and Cross-linking affect Degradability? A review of Cell Wall Model Studies," *Crop Science,* vol. 45, no. 3, pp. 820 - 831, 2005.

[155] J. Pourchez, P. Grosseau, R. Guyonnet and B. Ruot, "HEC Indluence on Cement Hydration measured by Conductometry," *Cement and Concrete Research,* vol. 36, no. 9, pp. 1777 - 1780, 2006.

[156] K. Wilson and D. J. B. White, The Anatomy of Wood: Its Diversity and Variability, London: Stobart & Son Ltd, 1986.

[157] Forest Products Laboratory USDA Forest Service, "Wood Handbook - Wood as an Engineering Material," Madison, Wisconsin, 1999.

[158] A. Mitani and I. Barboutis, *Tensile Strength by Compression Loading of some Hardwoods Bonded with PVAc and Casein Adhesives,* Aristotle University of Thessaloniki, Faculty of Forestry and Natural Environment,Department of Harvesting and Forest Products Technology, pp. 1352 - 1360.

[159] D. J. Cown and M. L. Parker, " Comparison of Annual Ring Density Profiles in Hardwoods and Softwoods by X-ray Densitometry," *Canadian Journal of Forestry Research,* vol. 8, pp. 442 - 449, 1978.

[160] T. A. Plekhanoca, J. Keriene, A. Gailius and G. I. Yakovlev, "Structural, Physical and Mechanical properties of Modified Wood-Magnesia Composite.," *Building Construction and Materials,* vol. 21, pp. 1833 - 8, 2007.

[161] S.-Y. Fu, X.-Q. Feng, B. Lauke and Y.-W. D. Mai, “Effects of Particle Size, Particle/Matrix interface adhesion and Particle Loading on Mechanical Properties of Particulate–Polymer Composites,” *Composite B - Engineering,* 2008.

[162] W. Sonderegger, P. Niemz, H. Bader and A. Weber, “Comparative Study on the Thermal Conductivity of Wood and Wood-Based Materials,” in *Wood Structure and Properties,* Zvolen, Slovakia, Arbora Publishers, 2006, pp. 391 - 394.

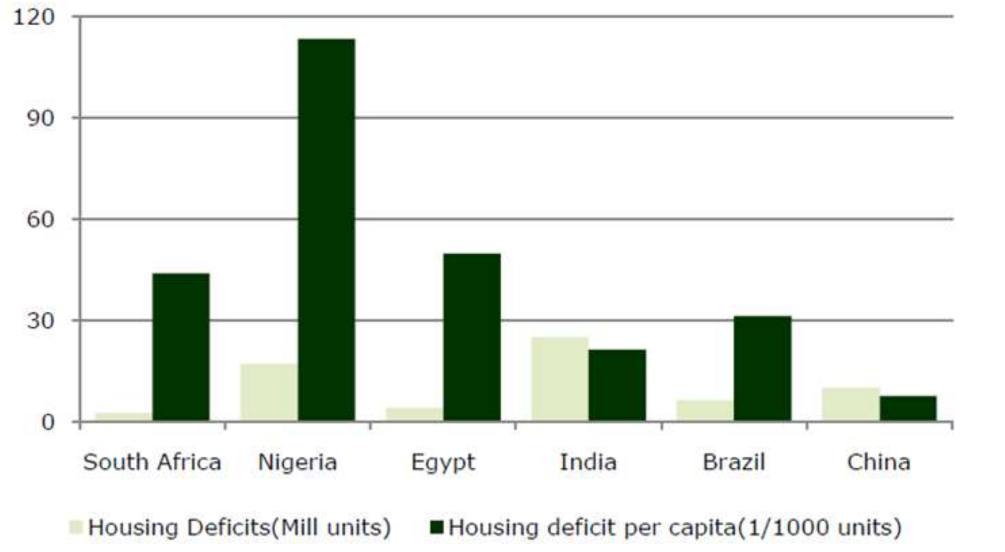
[163] B. M. Suleiman, J. Larfedt, B. Leckner and M. Gustavson, “Thermal Conductivity and Diffusivity of Wood,” *Wood Science,* vol. 33, pp. 465 - 473, 1999.

[164] Z.-T. Yu, X. Xu, L.-W. Fan, Y.-C. Hu and K.-F. Cen, “Experimental Measurements of Thermal COnductivity of Wood Species in China: Effects of Density, Temperature, and Moisture Content,” *Forest Products Journal,* vol. 61, no. 2, pp. 130 - 135, 2011.

[165] A. G. Every, Y. Tzou, D. P. H. Hasselman and R. Raj, “The Effect of Particle Size on the Thermal Conductivity of ZnS/diamond Composites,” *Acta Metallurgica et Materialia,* vol. 40, no. 1, pp. 123 - 129, 1992.

LIST OF APPENDICES

Appendix 1: Comparison Of Nigeria's Housing Deficit



Sources: Nationsencyclopedia, National housing ministries websites, Vetiva Research estimates

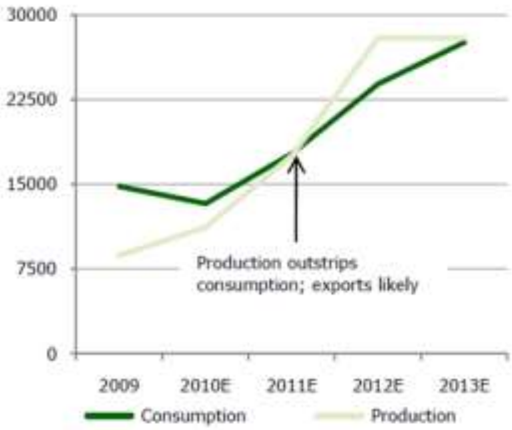
Appendix 2: Dominant Cement Producers in Some African Countries

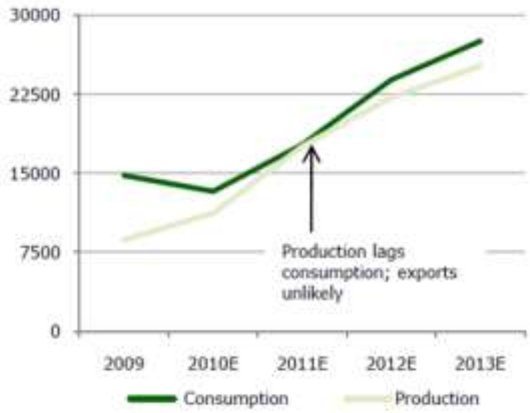
Country	Company	Parent	Production[1] Capacity
Egypt	Suez	Italcementi	12.0
Morocco	Lafarge Ciment	Lafarge	7.0
South-Africa	PPC**	Barloworld	8.0
Kenya	Bamburi	Lafarge	2.5
Ghana	Ghana Cement	Heidelberg	2.4
Nigeria	Dangote Cement	Dangote	8.0

Source: *Vetiva Research*

** PPC - Pretoria Portland Cement, [1]Current Production Capacity only

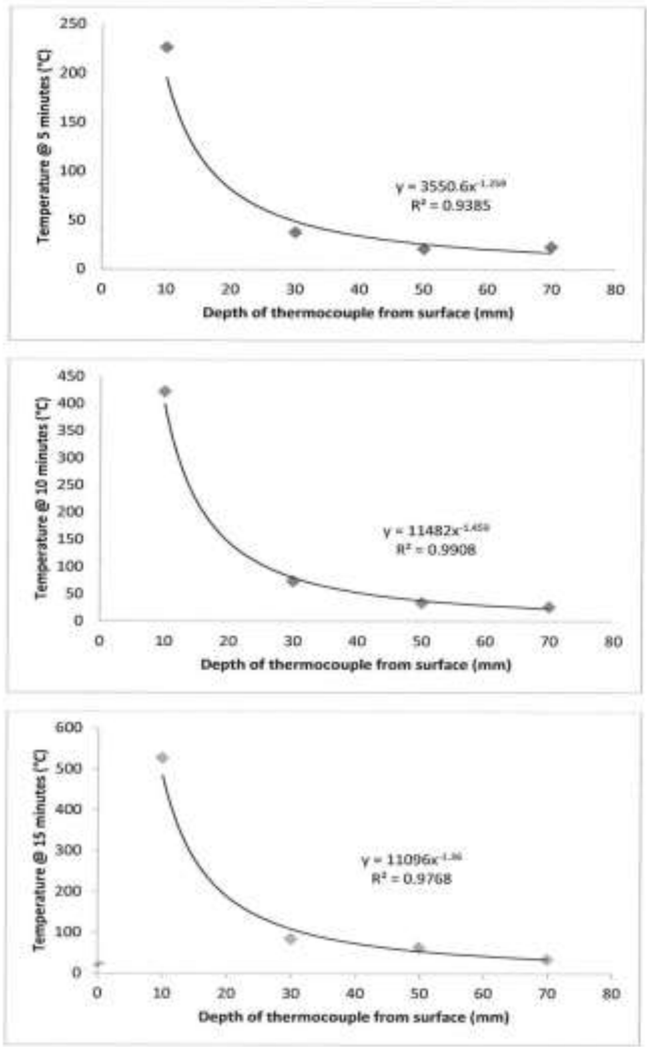
Appendix 3: Aggressive Case and Normal Case: Cement Production Vs Consumption (Million Tonnes)



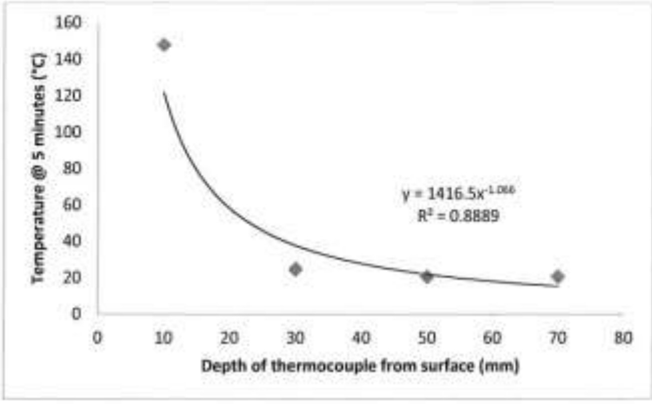


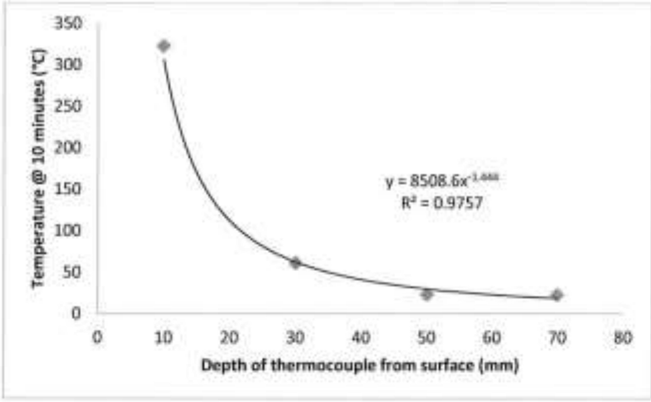
Sources: Industry, Vetiva Research estimates

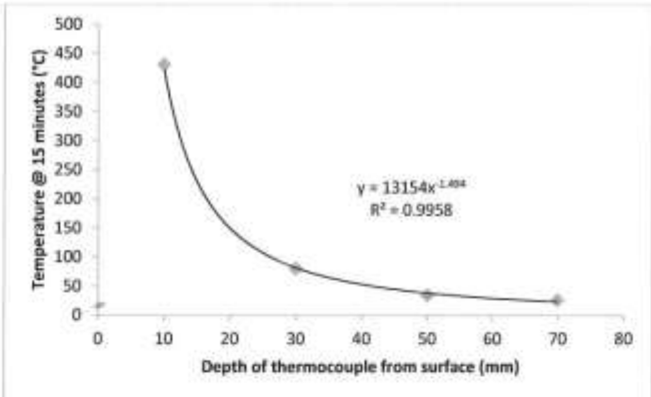
Appendix 4: Fire Test Samples



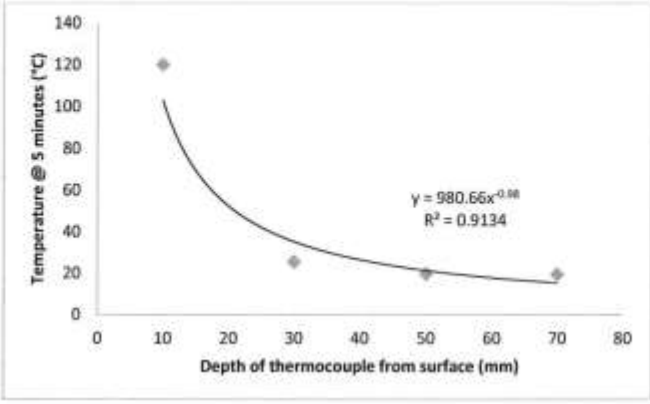
Sample A1

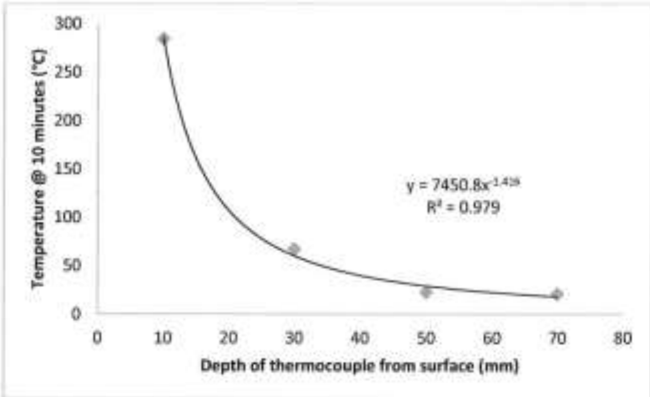

y = 1416.5x^-1.066
R² = 0.8889
Temperature @ 5 minutes (°C)
Depth of thermocouple from surface (mm)

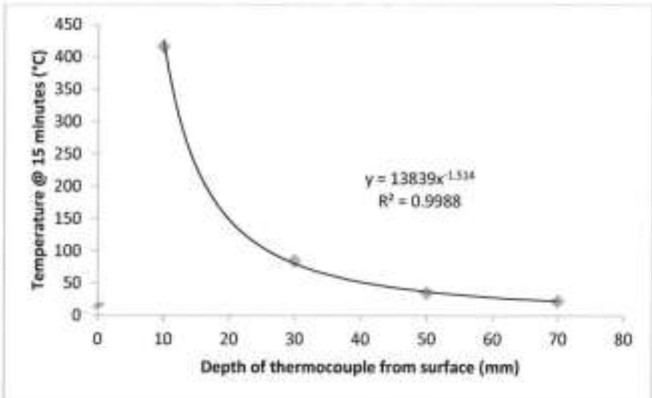

y = 8508.6x^-1.446
R² = 0.9757
Temperature @ 10 minutes (°C)
Depth of thermocouple from surface (mm)


y = 13154x^-1.494
R² = 0.9958
Temperature @ 15 minutes (°C)
Depth of thermocouple from surface (mm)

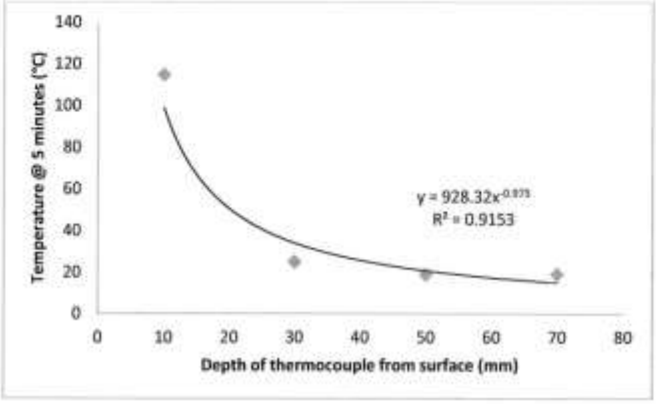
Sample B1

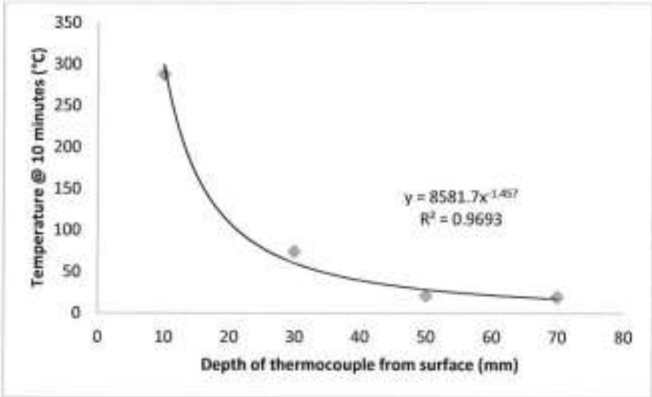

140
120
100
80
60
40
20
0
Temperature @ 5 minutes (°C)
$y = 980.66x^{-0.98}$
$R^2 = 0.9134$
0
10
20
30
40
50
60
70
80
Depth of thermocouple from surface (mm)

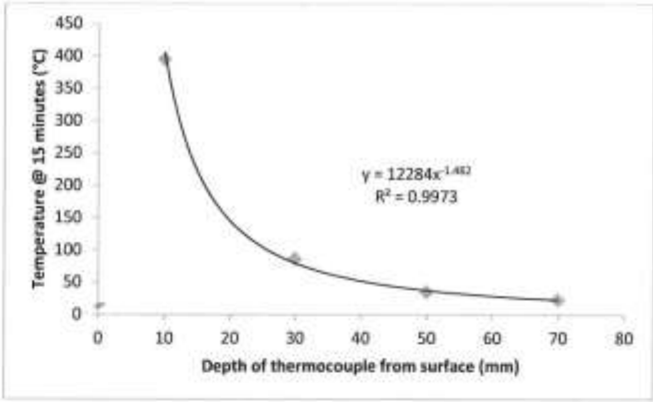

300
250
200
150
100
50
0
Temperature @ 10 minutes (°C)
$y = 7450.8x^{-1.436}$
$R^2 = 0.979$
0
10
20
30
40
50
60
70
80
Depth of thermocouple from surface (mm)


450
400
350
300
250
200
150
100
50
0
Temperature @ 15 minutes (°C)
$y = 13839x^{-1.534}$
$R^2 = 0.9988$
0
10
20
30
40
50
60
70
80
Depth of thermocouple from surface (mm)

Sample C1


Temperature @ 5 minutes (°C)
140
120
100
80
60
40
20
0
y = 928.32x-0.975
R² = 0.9153
0
10
20
30
40
50
60
70
80
Depth of thermocouple from surface (mm)


Temperature @ 10 minutes (°C)
350
300
250
200
150
100
50
0
y = 8581.7x-1.457
R² = 0.9693
0
10
20
30
40
50
60
70
80
Depth of thermocouple from surface (mm)


Temperature @ 15 minutes (°C)
450
400
350
300
250
200
150
100
50
0
y = 12284x-1.482
R² = 0.9973
0
10
20
30
40
50
60
70
80
Depth of thermocouple from surface (mm)

Sample C2

Appendix 5: Publications and Conferences

Publications

1. Title: Development of wood-crete Building Materials from Sawdust and Waste Paper
   Journal Name: Construction and Building Materials Journal - 40 (2013) 361 – 366
   Authors: Eboziegbe Patrick Aigbomian and Mizi Fan
2. Title: Development of wood-crete Building Material from Hardwood and Softwood Sawdust.
   Authors: Eboziegbe Patrick Aigbomian and Mizi Fan
   Journal Name: Construction and Building Technology Journal
   (Accepted for publication)
3. Title: Development of wood-crete from treated sawdust
   Journal Name: Construction and Building Materials Journal
   Authors: Eboziegbe Patrick Aigbomian and Mizi Fan
   (Awaiting publication – under review)

Conferences

1. Review on the use of sustainable material and designs for affordable housing in developing countries. Presented at research students conference 2010.
2. Development of wood-crete presented at research students conference 2012
3. Development of wood-crete using wood-waste and low cost inorganic binders. Poster presentation at Brunel Graduate School, 2012.
4. Development of wood-crete using wood-waste and low cost inorganic binders. 3rd Annual International Conference on Architecture, Athens, Greece. (Presented 10 – 13 June, 2013

Development of Wood-Crete Building Materials from Sawdust and Waste Paper

Eboziegbe Patrick Aigbomian and Prof Mizi Fan

Civil Engineering, School of Engineering and Design, Brunel University, Uxbridge, Middlesex, UK
Email - eboziegbe.aigbomian@brunel.ac.uk

ABSTRACT

This study was to develop a new building material, wood-crete, using sawdust, waste paper and tradical lime. The paper presents the processing technologies, factors which affect the performance of the developed composites and properties of wood-crete. The results showed that lightweight sustainable blocks can be produced with good insulating and other relevant properties for building construction. The composition of mix (addition of waste paper), had a dominant influence on both strength and thermal conductivity, reflecting its effect on the structure of composite and contribution of self strength of paper fibres. The combined effect of sawdust, waste paper and tradical lime had a direct effect on the strength properties of wood-crete. Of significant importance was the contribution of self strength of wood-crete due to the influence of the size of sawdust particles used. The developed wood-crete was able to withstand considerable amount of impact load and considered, like hempcrete, most suitable for wall panelling or other non- and semi-structural applications with good thermal insulating properties.

Keywords: Wood-Crete; tradical Lime, sawdust, compressive strength, thermal conductivity.

1 INTRODUCTION

Wood-Crete is a new material made from sawdust or other wood wastes, waste paper and Tradical Lime with consideration for cheaper and locally available materials to meet desired needs, enhance self-efficiency, and lead to an overall reduction in construction cost for sustainable development.

Wood waste, a major constituent of Wood-Crete, may be sawdust from the sawing of wood or any other wood wastes. Since wood is used in large quantities in many different sectors and is a part of our everyday lives, the volumes of sawdust and other recovered wood available are also large. Sawdust could be loose particles or wood chippings obtained as by-products from sawing of timber into standard useable sizes. The size of sawdust particles depends on the kind of wood from which the sawdust is obtained and also on the size of the teeth of the saw [1]. Between 10% and 13% of total content of log is reduced to sawdust in milling operations, depending largely on the average width of the blade, thickness of the timber sawed and technology of the sawing process [2]. Other wood wastes may include 1) solid or chipped wood in its natural stage without chemical contamination, 2) glued, coated lacquered wood without halogenic materials as timber preservative, 3) wood with halogenic materials (i.e. PVC) but no timber preservatives and 4) wood with timber preservatives [3]. According to COST Action E31 [4], the annual quantities of recovered wood in Europe reach about 30 million tonnes.

Waste paper and Tradical Lime are the other components of Wood-Crete. Waste paper is added to enhance material characteristics of lightweight and insulating properties while Tradical Lime, a specially designed binder, pre-formulated air lime based binder for making low energy, high carbon capture, durable and high quality products, is used as a binder.

Wood-Crete has been developing in this study, intending to achieve similar properties but more cost effective as those of Hempcrete. Hempcrete is the term used for the light weight, insulating and breathable material produced after mixing Hemp shive with a lime based binder and water. It can be cast around a load bearing frame (such as a timber frame) within temporary formwork or can be spray applied. It is left to set, after which time a variety of finishes can be applied.

Lime requires less energy to produce than cement, with much lower carbon emissions, because it uses kilns at a lower temperature [5-6]. It has been reported that approximately 110kg of CO_2 per m^3 of Tradical Hemcrete walling material is sequestrated – more for roof insulation. This carbon is then locked into the fabric of the buildings constructed with the

Tradical Hemcrete products thus having beneficial effects through reversing the carbon debt [7]. It is estimated that one square metre of lime hemp concrete wall stores between 14 and 35 kg CO_2 over its life span of 100 years.

The use of hemp shives were introduced in the early 1990s in France in a bid to make concrete lightweight [3]. Mixture of hemp shives and cementitious binder creates a building material with different properties including mechanical, thermal and acoustic properties that differ from those of conventional concrete. With a low density, thermal conductivity and better acoustic insulation properties, such material is advantageous for use in construction [1, 7, 8]. Amongst these material properties, hemp concrete when used for wall application is not load-bearing. Table 1 summarises some material properties of a lime hemp concrete mixture for wall application in comparison with those of other building materials [9].

Table 1 Material properties of lime-hemp concrete with other building materials

Material	**Young Modulus (MPa)**	**Compressive Strength (MPa)**	**Density (kg/m^3)**	**Thermal Conductivity ($W/M.^0C$)**
Steel	210000	350-1000	7500-8500	52.00
Concrete	20000	12-80	20000	1.50
Cellular Concrete	1000-2500	5	420-1250	0.14-0.23
Brick	10000-25000	25 – 60	1300-1700	0.27-0.96
Wood	230–20000	4 – 34	350-900	0.12-0.3
Lime Hempcrete	24	0.4	445	0.17

The ratio of mix of hemp concrete determines the compressive strength of the material. Compressive strength values for Hemp-Crete vary from 0.02 to 1.22MPa [3, 10], depending on the composition of the mixture. This is not strong enough for the material to be load-bearing and an additional load-bearing structure is needed. It is also reported that the hemp lime ratio of 3:1 is similar in strength to a 4:1 and 5:1 mix [8]. In addition, depending on the amount of hydrated lime in the binder mix, the maximum compressive strength is obtained after a period of time ranging from several months up to several decades [10]. Splitting tensile strengths, depending on the mixture, vary from 0.12 to 0.23 MPa [8]. Thermal conductivity was reported ranging from 0.07 to 0.11 W/mK [3, 10].

This study aims at developing a novel sustainable building material (Wood-Crete) which is lightweight, has good insulating properties and is able to withstand considerable amount of impact load. The study is part of a large project investigating the use of waste materials (e.g. wood wastes and waste paper) in the production of low cost and durable building materials, and this is the first paper of this series to present the manufacturing technologies and characteristics of the developed novel building material, Wood-Crete, made from sawdust, which is comparable to Hemp-Crete

2 MATERIALS AND METHODS

Binders (Tradical lime HB) was sourced from Lime Technology Ltd. UK and commercial Ordinary Portland cement (OPC) was mixed with sawdust sourced from the Wood Workshop at Brunel University, London. The sawdust particles were refined to 1mm mesh size. Waste paper (newspaper) also a constituent in this experiment was de-fibred firstly by soaking in water. The average microscopic measurement taken for 50 fibres was 1211.79µm in length and 25.97µm in breadth. The de-fibred waste paper was then mixed with sawdust and Tradical lime to improve the insulating properties and reduce the density of block samples.

Preceding block formation, the wood particles were dried in the oven at 100^0C for 24 hours to reduce the amount of water and then mixed with Tradical lime and cement at the designed ratios, as summarised in Table 2. The de-fibred waste paper added was calculated in percentage ratio of sawdust by weight. These various ratios of sawdust to Tradical lime to cement were designed with the intension of ascertaining the effect of lime and cement compositions on the strength of Wood-Crete. The ratios of sawdust to lime and cement used were based on economic considerations and permissible impact on the strength ascertained using the dropping method, as explained by Zziwa, et al. [11], where preliminary trial specimens of varying compositions of sawdust and cement were made, dried and dropped from waist height (approximately 1m) to assess their structural integrity.

Wood-Crete blocks were made by mixing waste paper in water before the required amount of sawdust and lime were added in the mixer. This method is advised so that the waste paper can be thoroughly wetted. Amount of water added for every sample was 750ml per every 400kg of sample. The mix was uniformly distributed into the square moulds which were treated with a mould release agent. The mixtures were placed in a forming mould for 24 hours before de-moulding while maintaining a relative humidity between 46% - 49% for all samples. Preparation of specimens for testing strength properties was based on BS EN12390-2 [12]. Wood-Crete blocks were moulded in the dimension of 100mm x 100mm x 100mm. The actual volume of the blocks was taken from the measurement of samples after drying. Samples were sandpapered for evenness and flatness in all sides while sample mass was determined using a weighing scale. The density of the blocks was calculated from mass and volume. Three replicates were taken for each type of Wood-Crete blocks.

The de-moulded Wood-Crete blocks were further cured for 32 days and tested for compressive strength at 20°C/65% relative humidity by applying a gradually increasing load under an universal Instron. The test pieces were placed between a supporting base and a flat steel plate. The machine applied a uniform load at a rate of 6mm/min until the maximum failure load was reached. The maximum load (in Newton) was automatically recorded and the compressive strength was calculated as maximum failure stress per unit area. The thermal conductivity was determined by using TCi Thermal Conductivity analyser which uses a novel analysis NDT technique. Samples were placed on a sensor which produces an amount of heat on application of current. The heat provided results in a rise in temperature at the interface between the sensor and the sample – typically less than 2ºC. This temperature rise at the interface induces a change in the voltage drop of the sensor element. Both thermal conductivity and effusivity are measured directly and rapidly, providing a detailed overview of the thermal characteristics of the sample material. The results are then displayed on the system's computer.

Table 2 Experimental mixture design

Samples	Sawdust / Binder ratio	% of Waste Paper
X1	S/TL (1:2)	75
X2	S/TL (1:2)	50
X3	S/TL (1:2)	30
X4	S/TL (1:2)	15
X5	S/TL (1:2)	10
X	S/TL (1:2)	0
Y1	S/TL (1:1)	50
Y2	S/TL (1:1)	25
Y3	S/TL (1:1)	10
Y4	S/TL (1:1)	5
Y5	S/TL (1:1)	0
W1	S/TL/C (2:1:1)	20
W2	S/TL/C (2:1:1)	15
W3	S/TL/C (2:1:1)	10
Z1	S/C (1:2)	0
Z	S/C (1:1)	0
XX1	S/TL (1:1) – 2mm sieve	25
XX2	S/TL (1:1) – 2mm sieve	10
XXX1	S/TL (1:1) – 3mm sieve	25
XXX2	S/TL (1:1) – 3mm sieve	10

3 RESULTS AND DISCUSSION

3.1 Density of Wood-Crete

It is observed that the density of Wood-Crete blocks was closely related to the composition of sawdust, waste paper, Tradical lime and cement (Table 3). Overall the density of Wood-Crete decreases with the increase of the waste paper added. For X-series of Wood-Crete, an increase in waste paper from 10 to 75% weight of sawdust resulted in a consistent reduction in the density of Wood-Crete from 713 to 473 kg/m3, about 1/3 reduction in density. This trend is also observed in the Y series of Wood-Crete composites made, with a reduction from 640 to 411 kg/m3 when waste paper was increased from 0 to 50% weight of sawdust. The reason for the lower density of pure sawdust and tradical lime composites compared with those of composites with 10 and 15% waste paper in the X-series experiment is still unknown. The only suspicion is the experimental deviation for some of the specimen made in this group as the cov is also abnormally high (Table 3).

Table 3 Mean density and compressive strength of Wood-Crete

Samples	**Waste paper (%)**	**Density (kg/m^3)**	**Compressive strength (N/mm^2)***	**Overall Mean**
S:TL=1:2				9.02
X1	75	473	0.80 (2.0)	
X2	50	526	0.61 (15.1)	
X3	30	604	0.48 (6.4)	
X4	15	702	0.41 (5.5)	
X5	10	713	0.35 (5.7)	
X	0	616	0.26 (19.4)	
S:TL=1:1				5.88
Y1	50	411	0.49 (2.9)	
Y2	25	485	0.41 (10.3)	
Y3	10	530	0.31 (11.6)	
Y4	5	549	0.22 (4.6)	
Y5	0	640	0.21 (0.0)	
S:C=1:1				37.33
Z	0	424	0.06 (37.3)	
S:C=1:2				10.00
Z1	0	543	0.10 (10.0)	

S:TL:C=2:1:1				18.33
W1	20	397	0.27 (15.7)	
W2	15	404	0.22 (19.3)	
W3	10	416	0.18 (20.0)	
S:TL=1:1 (2mmSieve size)				18.45
XX1	25	409	0.29 (14.6)	
XX2	10	376	0.19 (22.3)	
S:TL=1:1 (3mm Sieve size)				13.15
XXX1	25	364	0.20 (18.0)	
XXX2	10	356	0.12 (8.3)	
Hempcrete		445	0.4	
Concrete		20000	12 - 18	

A comparison of the density of X series and Y series shows that the density of Wood-Crete blocks made with 1:2 mix ratio of sawdust to tradical lime had a higher density than those made with 1:1 mix ratio of sawdust to tradical lime (Table 3). Theoretically, as the density of sawdust is lower than that of tradical lime (about 210kg/m3 to 1201kg/m3), it is expected that the densities of X series would be greater than those of Y series by more than 1.5 times. However, wood-crete blocks made with 1:1 ratio of sawdust to tradical lime showed a density difference of less than 1.1 times compared to similar ratio in the X series. It can thus be inferred that the sawdust may have more significant influence on the density of Wood-Crete than Tradical lime.

3.2 Correlation of density and size of sawdust

Wood-Crete made with 2mm sieve and 25% of waste paper, has higher density than that made with 3mm sieve at 25% waste paper, with the former being about 15% higher than the latter. A similar trend is found for the composites with 10% waste paper (Table 3). The density of Wood-Crete made with 2mm and 3mm sieve of sawdust was very low compared to the densities of all other samples made with 1mm sieve (Table 3). The smaller the size of particles of sawdust, the higher the density is achieved. The geometry of sawdust particles may be related to the structure of the final composites; large particles may limit the compaction of formatting composites, resulting in a reduction in density. Lower density of sawdust itself in comparison with Tradical lime can also contribute to a lower density of the final composites.

3.3 Compression strength of Wood-Crete

Compressive strength of Wood-Crete blocks are summarised in Table 3. It is very interesting that there was an increase in compression strength of blocks with the decrease of the density of the Wood-Crete. This may be due to the presence of waste paper in mix which acts as fibrous substance to network the materials and improve the bonding between sawdust and Tradical lime and among them whilst reducing density of blocks.

Another important property of Wood-Crete noticed during testing was the large deformation that can undergo after reaching the ultimate load. An example of the failure is given in Figure 1. Main failure mode of sawdust-Crete blocks was ductile followed by shear cracks in the core of blocks. This reveals that Sawdust-Crete has a quasi-ductile behaviour unlike the sudden brittle failure associated with concrete.

Figure 1 Behaviour of Wood-Crete under compressive loading

Considering that these developed lightweight materials, as other existing hempcretes, are intended to be used in combination with structural elements, such observed ductile behaviour may be attractive as it enhances the accommodation and adjustment between structural and non-structural elements which helps improve the absorption of small displacements and dumping, which always occur in houses and buildings [13].

The strength properties of Wood-Crete were not as good as those of normal concrete, but comparable to those of hemp lime composites, e.g. hempcrete. The compression strength values required for materials to be used as pavements ranges between 20 and 25 MPa while that for beams is between 20 and 35 MPa and up to 65 MPa for the reinforced concrete depending on the expected loads [11]. The compressive strength values of the Wood-Crete composites were incomparable with those of concrete bricks which mean that they are not fit for a direct or stand-alone application as structural elements. The strength values, ranging from 0.26 to 0.80 MPa for the Wood-Crete made, were rather comparable to compressive strength of hemp-Crete which is 0.4 MPa (Table 1).

The compressive strength achieved and various densities depended upon the ratio of sawdust to lime and cement used in addition to the percentage of waste paper. The Wood-Crete blocks with sawdust lime ratio of 1:2 showed higher compressive strength compared to those made with a ratio of 1:1. This suggests that higher proportion of tradical lime in the composite helps achieve stronger blocks. The composites did fail prematurely which again suggests that the sawdust:lime:cement matrix exhibited plasticity properties to some extent. This suggestion is, however, supported by previous work [11]. There is a strong probability that the mechanical properties and dimensional stability of composites can be improved with increasing amounts of the additives as reported previously for other lime based composites [14] and also with the treatment of sodium hydroxide at different temperatures [15].

3.3.1 Effect of waste paper on compression strength

There was an increase in compression strength of Wood-Crete blocks with an increase in the proportion of waste paper, whether for the 1:1 mix or 1:2 mix of Wood-Crete (Table 3). The compressive strength increased from 0.26 to 0.80MPa when the waste paper was increased from 0 to 75% sawdust for the ratio of 1:2 of sawdust to Tradical lime (X-series) and from 0.21 to 0.49 when the waste paper was increased from 0 to 50% for the ratio of 1:1 of sawdust to Tradical lime (Y-series) Wood-Crete blocks (Table 3). Overall, the compressive strength consistently increases with the increase of the waste paper (Figure 2), reaching 54% increase in compressive strength for 75% addition of waste paper. The test results also indicated that an inclusion of waste paper below 5% did not improve the compressive strength. These results are of importance for a mixture design: an inclusion of a small percentage of waste paper may not increase compressive strength of Wood-Crete due probably to the lower compressive strength of waste paper itself compared to the sawdust and Tradical lime. At this point, the waste paper simply acts as filler for the Wood-Crete. Waste paper may not affect the formation of Wood-Crete. However, a further increase of waste paper, such as from 5 - 75% in this study, could improve the structure of the Wood-Crete: a more consolidated bonding structure of the Wood-Crete may be established and hence give rise to a consistent increase in compressive strength of the Wood-Crete. The waste paper at this time acts as network links within the composites, improving bonding between waste paper with sawdust, between waste paper and Tradical lime and among them, and enhancing the stress transfer from one material to another within the composites.

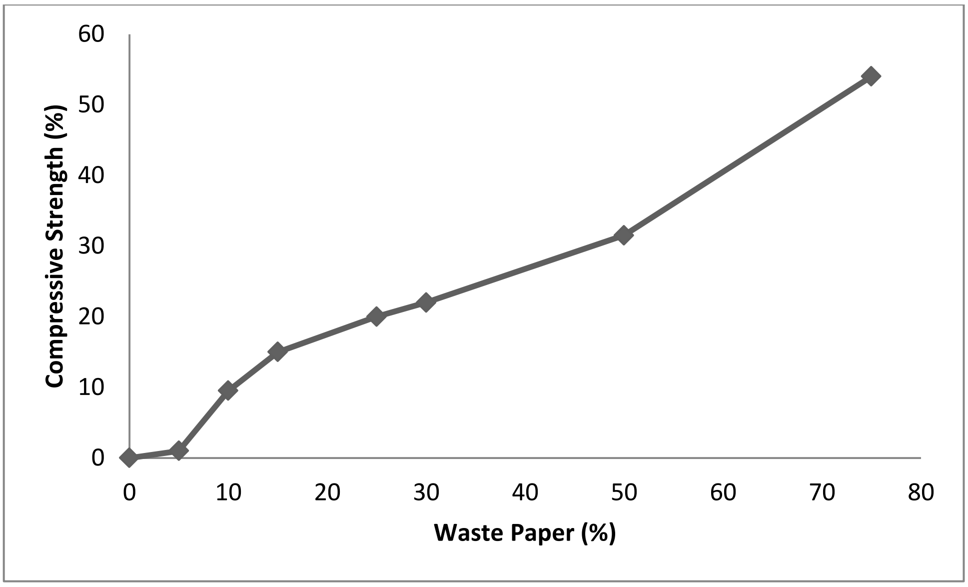


Figure 2 Increase in compressive strength with waste paper

3.3.2 Effect of sawdust and Tradical lime on compression strength

Figure 3 shows the difference of compressive strength of Wood-Crete made with different ratio of sawdust to Tradical lime: 1:2 for X series and 1:1 for Y series. Both X2 and Y1 have 50% waste paper (% sawdust), X5 and Y3 have 10%, and X and Y5 have 0% paper content. It is apparent that lower sawdust content gives rise to a higher compressive strength of Wood-Crete. The strength of Wood-Crete with a ratio of 1:2 (sawdust: tradical lime) is about 25% higher than that with 1:1 ratio comparing. The effect of tradical lime on compression strength of Wood-Crete has also been reflected in Figure 3. Wood-Crete made with higher sawdust means lower concentration of binder ratio achieving lower compressive strength. Without waste paper, an increase in tradical lime from 50% to 70% results in an increase in the compressive strength of 25%. With 10% waste paper, an increase of Tradical lime from 45% to 65% results in an increase of 14% compressive strength, and with 50% waste paper, an increase of Tradical lime from 40% -57% results in 25% increase of compressive strength of Wood-Crete.

Figure 4 shows the percentage of total sawdust and Tradical lime in relation to the compressive strengths for X and Y series. It is apparent that the strength linearly decreases with the increase of total sawdust and tradical lime. The bonding between sawdust and binder and between sawdust particles may be more comprehensive and stronger for the Wood-Crete with ratio of 1:2 than those of 1:1. The interface between particles may be more compact. This is also reflected with a higher density of X series Wood-Crete. Wood-Crete blocks made with ratio 1:1 were fragile due to their low density which indicates poor bonding between the binder and sawdust.

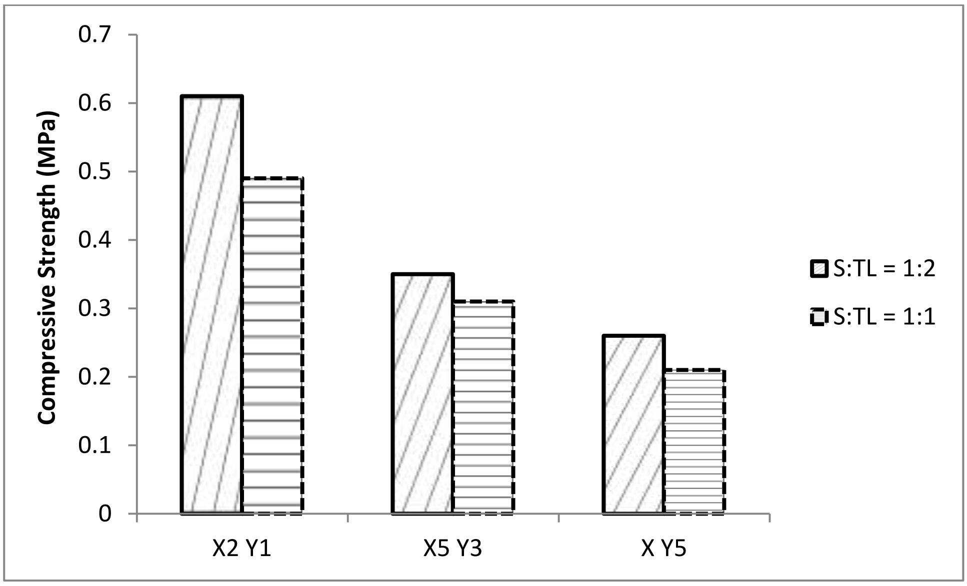


Figure 3 Compressive strength with different ratios of sawdust and waste paper

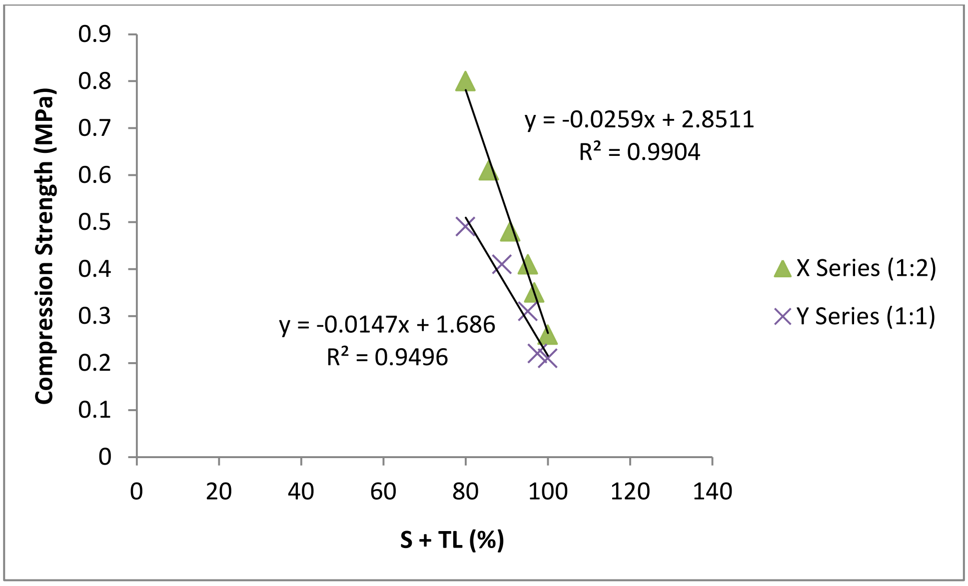


Figure 4 Effect of total sawdust and tradical lime on compressive strength

3.3.3 Combined effect of sawdust and waste paper on compressive strength

It is evident that the combined effect of sawdust and waste paper had a significant effect on the compressive strength of Wood-Crete. With the total sawdust and waste paper increased from 33.3% to 46.7%, the compressive strength increased about 3.5 times, see Figure 5 (X-series) as an example. The combined effect reflects the compaction of sawdust and waste paper: relatively small particles and paper fibres at this point may have filled many gaps between and within them each other, thus enhancing stress transfer between both materials.

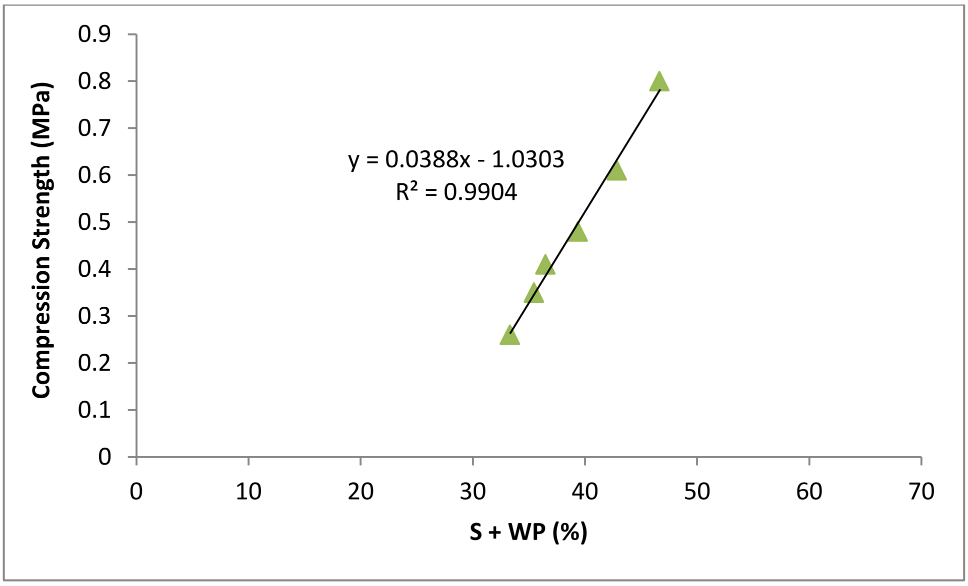


Figure 5 Compressive strength against total sawdust and waste paper

3.3.4 Correlation of density and compressive strength

The average measured densities for Wood-Crete for X and Y series are plotted against compressive strength in Figures 6. It is interesting that for both X and Y series Wood-Crete blocks, the compressive strength increases linearly with the decrease of density of Wood-Crete. The compressive strength increased from 0.35 to 0.80 MPa when the density decreased from 713 to 473 kg/m3 for X series Wood-Crete blocks and from 0.20 to 0.50 MPa when density decreased from 640 to 411 kg/m3 for Y-series Wood-Crete blocks. This result defies the normal expectation of increasing density with increasing compressive strength. The addition of waste paper may have added to the improvement of strength and a reduction in the density of Wood-Crete.

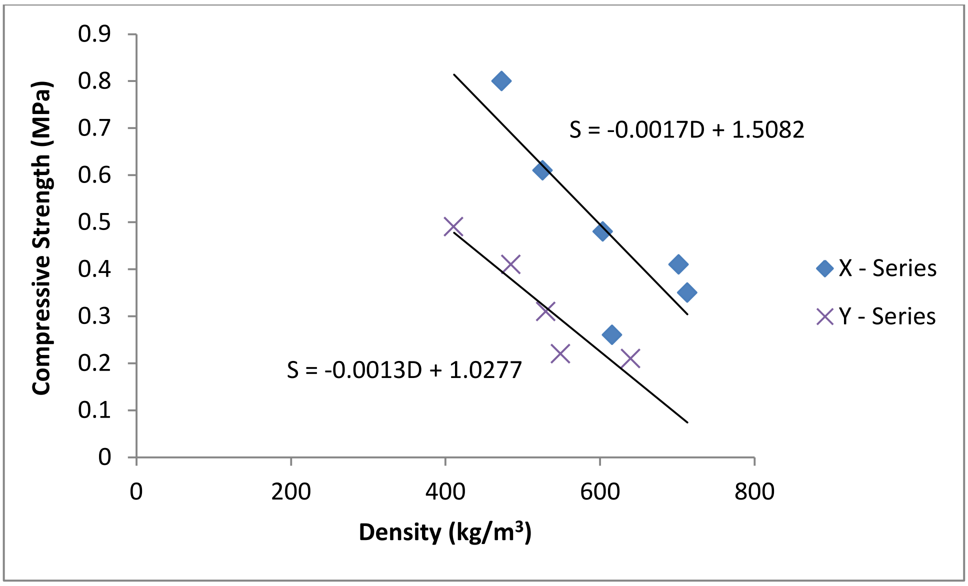


Figure 6 Compressive strength against density

3.3.5 Combined effect of cement and Tradical lime on Wood-Crete

The test results show that Wood-Crete made with the combined binder of cement and Tradical lime (W2 and W3) has a lower compressive strength compared to Wood-Crete made with only Tradical lime as the binder (Table 3). Comparing samples W3 and Y3 made with same ratio of sawdust and percentage of waste paper, W3 has the compressive strength of 0.18MPa in comparison of 0.31MPa for Y3. The rationale behind this may be the different hydration processes of two different binders. Different hydration schedules between binders may result in 1) inconsistent structure of the cured products because of local curing process of one binder, 2) incompact structure because if one binder hydrates first, the hydrated product may be damaged during the curing process of the second binder, 3) insufficient bonding due to the lack of binder. This means the same amount of binder has been divided into two processes. When the first hydration takes place, the limited binder may not be distributed and cover the whole surface area of sawdust and paper. However, when the second hydration takes place, the hydrated products and sawdust and waste paper all work as aggregates. It is thus suggested that single binder should be used whilst making Wood-Crete and if the binders are to be combined, the hydration process of individual binders should be worked out for careful analyses before mixing.

3.3.6 Effect of size of sawdust on compressive strength of Wood-Crete

The compressive strength of Wood-Crete with 2mm sieve size of sawdust is higher than that with 3mm sieve size of sawdust: at both 10 and 25% waste paper, the former is about 50% higher than the latter (Table 3). Although the strength is relatively low, the result proves that with smaller particles of sawdust at a higher percentage of waste paper, better strength is obtainable. The size of sawdust may have influenced the penetration of the Tradical lime into the particles, that is, the larger particle may prevent a thorough penetration of Tradical lime, resulting in inconsistent structure of Wood-Crete and hence reduction in the compressive strength.

4. THERMAL CONDUCTIVITY

The test results showed that Wood-Crete blocks have a good thermal insulation property. Thermal conductivity of the Wood-Crete blocks tested (X1 – X4) has a thermal conductivity ranging from 0.045 – 0.070 (Table 4). Thermal conductivity values achieved indicate that the Wood-Crete blocks can be used as in-fill wall panels since their strength is suitable for such applications with good thermal properties.

Table 4 Mean thermal conductivity of Wood-Crete: X-Series

%	**Mean density (kg/m^3)**	**Mean compressive strength (MPa)**	**Thermal conductivity (W/mK)**
75	473	0.80	0.046
50	526	0.61	0.069
30	604	0.48	0.063
15	702	0.41	0.052

4.3 Correlation of compressive strength with thermal conductivity

It is evident that an increase of compressive strength from 0.41 to 0.61 MPa, thermal conductivity increases from 0.052 to 0.069 W/mK. Further increase of the strength to 0.80 MPa, the thermal conductivity decreased from 0.069 to 0.046 W/mK. The increase in the strength of wood-crete means an improvement of both network and bonding systems of the materials which reflects in an improvement of heat conduction, i.e an improvement of thermal conductivity. However, much lower thermal conductivity (0.046W/mK) may be due to the dominated influence of nature of pores within the materials which is discussed in more details in next section.

4.4 Correlation of density with thermal conductivity

Overall thermal conductivity increased with a decrease in density (Table 4). Thermal conductivity increased from 0.046 W/mK with density of 473kg/m3 to 0.069W/mK with density of 526 kg/m3. However, further increase of density from 604kg/m3 to 702 kg/m3 resulted in a decrease of thermal conductivity from 0.063 to 0.052 W/mK. Thermal conductivity may be influenced by the degree of all processes of heat transfer such as heat conduction, convection and radiation. The efficiency of heat conduction is directly related to the density of material, i.e. with the increase of density, the conduction is improved, and hence, thermal conductivity increases. The convection may also play an important role in the thermal conductivity. The convection is related to the amount and geometry of pores and network system within the materials and this may be one of the reasons for the lower thermal conductivity of the wood-crete with a density of 702kg/m3 compared to that of 604kg/m3 because the pores may be too small for the formation of convection. The effect of porosity on the thermal conductivity of solids has also been reported by previous worker [16]. It was stated that the reduction in thermal conductivity depends on not only the volume fraction of pores but also their aspect ratio and their spatial distribution.

Both the correlation of compressive strength and density with thermal conductivity indicates that the addition of waste paper and composition of wood-crete and hence the structure of wood-crete may have played an important role on the thermal conductivity of the wood-crete blocks made. An increase in waste paper may have helped establish networks and bonding systems between sawdust particles and sawdust and binder, resulting in an increase of compressive strength. A high percentage of waste paper in general resulted in reduction in density, therefore, the thermal conductivity decrease.

5. CONCLUSIONS

A new building material has been developed by using waste wood, waste paper and tradical lime. Overall performance of wood-crete was very similar to that of hempcrete. The compressive strength of the developed wood-crete ranged from 0.06MPa to 0.80MPa indicating that like hempcrete, the new materials can be used as in-fills for wall panels and hollow blocks. The composites had good thermal conductivity ranging from 0.046W/mK to 0.069W/mK and thus could be used for thermal insulating materials for building construction. With some artistic designs and good wall finishes (e.g. wall papers), wood-crete blocks can be used for interior for non- or semi-structural panelling application. The properties of Wood-Crete composites were closely related to its composition with percentage of waste paper having an increasing effect on the compressive strength of wood-crete and ratio of sawdust to tradical lime having an effect on the bonding strength of wood-crete.

There is potential in the combined use of sawdust and waste paper as reinforcement in Wood-Crete composites for the building construction helping in reducing waste disposal costs and generating incomes from sales of sawdust by sawmills and waste paper to the building and construction industry.

The research programme is continued on how to improve the strength properties of Wood-Crete blocks for structural application and to develop the whole building systems by using Wood-Crete composites.

6. REFERENCES

[1] Afuwape A.K (1983) Design and Testing of Sawdust Compactors. BSc Thesis, Department of Agriculture and Engineering. Obafemi Awolowo University, Ile Ife, Nigeria.

[2] Chung Ddl. 2005. Dispersion of Short Fibers in Cement. J. Materials in Civil Engineering 17, 379-383.

[3] Evrard, A. (Ed.) (2003). Hemp Concretes, a Synthesis of Physical Properties.

[4] Ladislav Dzurenda (2010). Effect of Thermal Modification of Oak Wood on Sawdust Granularity.

[5] Elfordy. S., Lucas. F., Tancret. F., Scudeller. Y., Goudet. L., Mechanical and thermal properties of lime and hemp concrete ("hempcrete") manufactured by a projection process. Construction and Building Materials, 22 (2008) pp. 2116-2123.

[6] Wolfe R. and Gjinolli A.E, (1996). Assessment of Cement-Bonded Wood Composites as a Means of Using Low-Valued Wood for Engineered Applications. International Wood Engineering Conference 1996. USDA Forest Service, Forest Products Laboratory, USA.

[7] Arnaud L, Cerezo V, Boutin C (2004). Physical properties of concrete with vegetable particles. In: C Boutin, M Lefik (eds). Experimental knowledge versus theoretical models, soils and composite materials. American Concrete Institute Publications.

[8] O'Dowd, J. & Quinn, D. (2005). Investigating Properties of Hemp and Lime Construction. In Department Of Civil Engineering Vol. Bachelor of Engineering, University College Dublin. Dublin, 91 Pp.

[9] Paulien De Bruijn, Alnarp (2008). Hemp Concretes Mechanical Properties Using Both Shives And Fibres.

[10] Arnaud, L. & Cerezo, V. (2001). Physical Evaluation of Construction Materials Based On Hemp. Ph.D. Thesis.

[11] Zziwa A, S. Kizito, A. Y. Banana, J. R. S. Kaboggoza, R. K. Kambugu and O. E. Sseremba, (2006) Production of composite bricks from sawdust using Portland cement as a binder.

[12] BS EN12390-2: Making and curing specimens for strength tests.

[13] Tires, R. et al (2004) New Eco-Friendly Hybrid Composite Materials For Civil Construction

[14] Wei Y. M .and Tomita B. (2000). Effects of five additive materials on mechanical and dimensional properties of wood cement bonded boards. Journal of Wood Science. 47; 437-444.

[15] Pablo, A.A. (1989), Wood-cement boards from wood wastes and fast growing plantation species for low cost housing. Centre for advanced wood processing. University of British Columbia, Vancouver, V6T IZ4, Canada.

[16] Materials Selection Guidelines for Low Thermal Conductivity Thermal Barrier Coatings by David R. Clarke Materials Department, College of Engineering University of California, Santa Barbara, CA 93106-5050.

Development of Wood-Crete from Hardwood and Softwood Sawdust

Eboziegbe Patrick Aigbomian and Professor Mizi Fan*

Civil Engineering, Brunel University
London, UB8 3PH, UK

ABSTRACT

Wood-crete, a new building material has previously been developed from sawdust, inorganic binder and addition of waste paper, finding its use mainly for wall panelling or other non- and semi-structural applications with good thermal insulating properties.

In this study, the properties of wood-crete were investigated based on the type of wood sawdust – hardwood (beech and oak) and softwood (pine and cedar). The results showed that (1) the compressive strength of wood-crete was closely related to the wood species, with the compressive strength of 3.93MPa being for hardwood wood-crete compared to 1.37MPa and 0.26MPa of wood-crete from softwood and mixed wood respectively; (2) wood-crete from hardwood sawdust had a higher density than those made from softwood sawdust and mixed wood; (3) particle size had a significant influence on the strength properties and density of wood-crete with wood-crete made from 1mm particle size recording a higher compressive strength and density compared to 2mm and 3mm particle size. The optimum size for wood-crete was dependent on the wood species; (4) thermal conductivity of wood-crete was closely related to the chemical composition of various wood species, with softwood wood-crete having about 20% lower thermal conductivity compared to hardwood wood-crete; (5) a ratio of 1:2 of sawdust to binder was found advisable for the production of wood-crete for various wood species and particle sizes investigated. The compressive strength of wood-crete made from sawdust of both softwood and hardwood was similar to or higher than that of hempcrete, indicating their suitability for wall panelling or other non- and semi-structural applications. The results of this study provide an important foundation for choosing what wood species, particle sizes and combinations of sawdust to be used for the production of wood-crete.

Keywords: Wood-crete; tradical lime, sawdust, compressive strength, wood species; thermal conductivity.

* *Corresponding author: Professor Mizi Fan, Head of Research, Department of Civil Engineering, School of Engineering and Design, Brunel University, Uxbridge, London, UK*
Email: mizi.fan@brunel.ac.uk

1 INTRODUCTION

Wood-Crete is a new material made from sawdust or other wood wastes, and Tradical lime with consideration for low cost and locally available materials to meet desired needs, enhancing self-efficiency and leading to an overall reduction in construction cost for sustainable development. Wood-crete from different hard and soft wood is being developed in this study, intending to achieve similar properties to those of wood-crete in previous study [1] but most importantly to determine the different specific wood properties posed on strength properties of wood-crete. Wood waste, a major constituent of wood-crete, may be sawdust from the sawing of softwood or hardwood, or any other softwood and hardwood wastes (for instance, wood chips). Since wood is used in large quantities in many different sectors and is a part of our everyday lives, the volumes of sawdust and other recovered wood available are also large. Sawdust could be loose particles or wood chippings obtained as by-products from sawing of timber into standard useable sizes.

Wood-crete as developed in previous study [1] is intended to achieve similar properties but more cost effective as those of Hempcrete. The term used for the light weight, insulating and breathable material produced after mixing Hemp shive with a lime based binder and water is known as hempcrete [1]. Its use involves casting it around a load bearing frame (such as a timber frame) within temporary formwork or can be spray applied.

Sawdust has been used in combination with inorganic binders to produce wood-cement composites replacing sand and aggregate in concrete mix. There are a number of merits offered by wood and inorganic binders over some conventional building materials presently used. These composites combine the properties of both the wood fibre and matrix, which makes them more valuable to the building industry. Inorganic wood composite, such as wood-cement composite, has been studied in a great detail. It has been reported that the properties of wood-cement composites are dependent on wood species and other processing parameters (e.g. Blankenhorn et al) [2]: (1) as hydration time increased, the compressive strength of wood-cement composite increased; (2) mild chemical modification could provide some improvements in the compressive strength values for acetic acid and sodium hydroxide wood-cement composites compared to unmodified composites; (3) as the cement-to-wood ratio decreased, the compressive strength of the wood-cement composite decreased; (4) the effects of chemical modification on compressive strength depended on the hardwood species. Hardwoods have also been reported to have a lower compatibility with cement than softwood, partly due to the inhibitory properties of hydrolysable hemicellulose and other extractives present in hardwoods [3]. Experimentation with a group of four hardwoods and five softwoods from North America [4] revealed that hardwoods adversely affected tensile strength and exothermic behaviour of cement more than softwood.

Additionally, it has been reported that various chemical components of different wood species affects wood-cement composites [5]. Lignin has been reported to yield high performance concrete strength, set retarder for a cement composition and improve the compressive strength of cement pastes [6]. Furthermore, it has also been stated by Pourchez et al (2006) [7] that cellulose retards cement hydration process. The effect of cellulose is attributed to the increased viscosity of the water, which imparts the movement of ions, decreasing the dissolution rate of anhydrous phases and the precipitation of hydrates [7]. Likewise, it has been reported that water-soluble extractives of wood (hemicelluloses, starch, sugar, tannins, certain phenols and even lignin) can retard and sometimes inhibit the normal setting and strength development properties of cement during the production of wood/cement composites [8].

This study was to investigate the effect of wood species and other relevant experimental parameters on the properties of wood-crete. The composition and hence quality of sawdust may vary considerably from one to another resource, even of pure softwood or hardwood or a combination of various percentages of hardwood and softwood or various wood species within softwood and hardwood. A better understanding of raw materials and related influence on wood-crete production is highly desirable for the development of this new construction material.

1.1 2. MATERIALS AND METHODS

1.2 2.1 Materials

Table 1 show materials used for the production of wood-crete which includes sawdust, binder (tradical lime) and water including their composition and weight. Sawdust and binder were mixed in ratios 1:2.

Table 1: Material composition and weight

Materials		Density (kg/m3)	Weight
Sawdust	Cedar	530	120g
	Pine	510	
	Oak	750	
	Beech	730	
Tradical lime		1201	240g
Water		1000	450ml

2.1.1 Hardwood and Softwood

Softwood chosen for this study is pine and cedar. Pine sawdust was chosen due to its resistance to shrinkage and swelling [9]. Sawdust from cedar wood was chosen due to high shock resistance [9], good dimensional stability and pleasant scent of the wood which acts as a natural insect repellent which can add natural properties to wood-crete blocks [9].

Hardwood chosen for this study includes oak and beech. Oak wood was chosen for this study due to its common use for making furniture which leads to high availability of sawdust from sawmills. As well, oak wood is known for great strength and hardness, and is very resistant to insect and fungal attack because of its high tannin content. Beech wood sawdust was chosen as a result of good strength properties, abrasion resistance and high in resistance to shock associated with beech wood [9]. In general, oak wood and beech wood are the most used type of wood in production of furniture in European markets [10] which makes them well known and popular in sawmills. Other parameters of wood species used in this study can be summarised in Table 2 while the strength values of other building materials are stated in table 3.

Table 2 Composition of different wood species

	Beech	Oak	Pine	Cedar
Density (kg/m3)	730	750	510	530
Cellulose (%)	44.0	42.0	44.0	45.0
Hemicellulose (%)	24.5	29.0	28.5	13.2
Lignin (%)	22.4	25.0	28.1	29.3
Extractives (%)	2.0	4.4	3.8	10.2
Ash (%)	0.3	0.3	0.4	0.2

Table 3 Material properties of lime-hemp concrete and some other building materials

Material	Young Modulus (MPa)	Compressive Strength (MPa)	Density (kg/m^3)	Thermal Conductivity ($W/M.^0C$)
Steel	210000	350-1000	7500-8500	52.00
Concrete	20000	12-80	20000	1.50
Cellular Concrete	1000-2500	5	420-1250	0.14-0.23
Brick	10000-25000	25 – 60	1300-1700	0.27-0.96
Wood	230–20000	4 – 34	350-900	0.12-0.3
Lime Hempcrete	24	0.4	445	0.17

2.1.2 Binder

The binder used for wood-crete production is tradical lime. Tradical lime is also referred to as pure air lime which fulfils the qualities of fineness and reactivity. Tradical lime binder is a substance that sets and hardens independently and can bind other materials together. They have been used in the production of tradical hemp lime products for natural high performing and sustainable construction materials. Tradical lime hardens due to hydration and hardens even underwater or when constantly exposed to wet weather. Tradical lime is used in the production of mortars used for building masonry, for rendering or plastering, for decorating in both renovation and new build constructions. Tradical lime is known for its elasticity, durability (long lasting quality mortars), workability, vapour permeability and healthy material (natural and solvent-free).

2.2 Method

The manufacturing of wood-crete from specific sawdust followed the same process as described in previous work [1]. This involved the mixing of binder (tradical lime) with sawdust. The process involved measuring the required amount of sawdust needed and binder at the designed ratios. The ratios of sawdust to tradical lime used were based on economic considerations and permissible impact on the strength ascertained using the dropping method, as explained by Zziwa, et al 2006 [11], where preliminary trial specimens of varying compositions of sawdust and cement were made, dried and dropped from waist height (approximately 1m) to assess their structural integrity.

Table 4 shows the trial making used to determine the workable mix ratio of water to lime. During trial making, the mix made with water to total mix weight less than 450ml was found unworkable while the trial mix of water above 450ml was found to be slurry. Only the mix with the amount of water of 450ml for every 360g of total mix weight was found workable. Therefore, this ratio is termed as the mix workability ratio.

Table 4 Mix ratio in trial making

Water (ml)	Total mix weight (g)	Workable mix
300	360	No
400	360	No
500	360	Yes (slurry)
480	360	Yes (Slurry)
450	360	Yes

The mix ratio developed is also important to ensure individual wood particles to be fully encased by the binder to attain acceptable properties. Sawdust and binder (tradical lime) were mixed together before the addition of water so as to attain consistency in the mix. Consistent and uniform mixing was carried out to allow for clumps to be broken down and binding powder (tradical lime) to be dispersed evenly throughout the sawdust. Continuous mixing was done for a further few minutes after the addition of all materials in the mix. The mix was then uniformly distributed into the square moulds which were treated with a mould release agent. Preparation of specimens for testing strength properties was based on BS EN12390-2 [12] (making and curing specimens for strength tests). Wood-crete blocks were moulded in the dimension of 100mm x 100mm x 100mm. It was noticed that due to the light weight of sawdust, there was almost no compaction under self-weight, hence the tendency to create larger voids in moulds which could lead to low density and low strength. For each mix combination, three replicates were made for each sawdust to tradical lime of ratios 1:2 and ratio 1:1. A total of 72 samples were made. Of significant note is that the degree of compaction has a great impact on the density of wood-crete. In a bid to ensure equal compaction in the mould, a minimum of eight tamps was performed on each mould with minor force before levelling. The importance and advantage of tamping help remove voids and fill gaps whilst creating a consistent end product. The mixtures were placed in a forming mould for 24 hours to allow for setting before de-moulding while maintaining a relative humidity between 46% and 49% for all samples. The setting of inorganic binders is the result of a series of chemical reactions causing a succession of crystallization stages [13]. The samples were left at open air cure in the lab for 32days to attain the required amount of strength before being subjected to various kinds of tests

2.3 Testing

Prior to testing, the actual volume of the blocks was taken from the measurement of samples after drying. Samples were sandpapered for evenness and flatness in all sides while sample mass was determined using a weighing scale. The density of the blocks was calculated from mass and volume. Three replicates were taken for each type of wood-crete blocks.
Wood-crete blocks were tested for compressive strength at 20°C/65% relative humidity by applying a gradually increasing load under a universal Instron. The test pieces were placed between a supporting base and a flat steel plate. The machine applied a uniform load at a rate of 6mm/min until the maximum failure load was reached. The maximum load (in Newton) was automatically recorded and the compressive strength was calculated as maximum failure stress per unit area.

Thermal conductivity was tested for various wood-species to investigate the difference in thermal conductivity of wood-crete made from both hardwood and softwoods. The thermal conductivity was determined by using Isomet Thermal Conductivity analyser. A sensor is placed on a sample which produces an amount of heat on application of current (Fig 1). The heat provided results in a rise in temperature at the interface between the sensor and the sample. Both thermal conductivity and effusivity are measured directly and rapidly, providing a detailed overview of the thermal characteristics of the sample material. The results are then displayed on the system’s computer. Thermal effusivity is a measure of a materials ability to exchange thermal energy with its surrounding while thermal conductivity is the ability of a material to conduct heat.

Figure 1: Thermal conductivity test

2 RESULTS AND DISCUSSION

3.1 Correlation of density and wood species (sawdust)

An important factor for the difference in densities of wood-crete composites is due to individual wood densities of hardwood and softwood and their composition (Table 5). The effect of wood density on the density of wood-crete may result from two different aspects: one is the density of wood itself as a higher density means that more amount of wood and cell materials per unit volume to the wood sawdust within the wood-crete made; the other is the structure of wood. The density of wood is in general related to wood anatomy and hence the relative proportions of cell types or tissues most especially in hardwood species (vessel, fibre, axial and radial parenchyma), along with also their dimensions and distribution, which have indications of the penetration and setting of the lime matrix [5]. The level of effect is dependent on the balance of effects between the former and the latter. In this study, the density of most hardwoods is higher than softwoods naturally and this was reflected in the density of wood-crete with the blocks made from hardwood sawdust recording an 18% increase when compared to the density of wood-crete blocks made from softwoods. Research however shows that most hardwoods have less air in them than softwoods which also affects wood density [14] [15].

Furthermore, it was also noticed during wood-crete manufacturing that the softwood sawdust was lighter in texture than those of hardwood which made compaction in the mould more difficult than when using sawdust from hardwood which was finer and dense thus making compaction more compact. Wood-crete made from the mixed wood sawdust showed 18% reduction in density compared to wood-crete made from hardwood and 0.08% increase in density compared to wood-crete made from softwood (Table 5). The term mixed sawdust refers to wood waste from the sawing of wood of various types of both soft and hard woods without making reference to the percentage of hardwood or softwood in the mix. It is important to make use of this type of wood waste because in reality, sawmills do not separate their wood waste by wood species or wood type. Much more reduction in density compared to hardwood blocks and only slight increase in density compared to softwood blocks infers that the composition of the mixed wood sawdust may contain more softwood than hardwood, or the composition of the mixed wood may result in 'bridging' due to the different stiffness between hardwood and softwood. Fig 2 also shows that density of wood-crete made from hardwood beech is 5.7% higher than density of wood-crete made from hardwood oak, likewise density of wood-crete from softwood pine is 10.3% higher than density of wood-crete made from softwood cedar. The highest density of wood-crete made in this study is about 70% higher than the lowest one (Table 5), showing a significant effect of wood species for the production of wood-crete (Table 2).

Table 5 Mean density and compressive strength of wood-crete with experimental mixture design

Samples		**Particle size (mm)**	**Compressive strength (MPa)**	**Density (Kg/m3)**
Hardwood				
HW_B	Beech	1	3.93 (8.4)	934
		2	3.90 (7.0)	926
		3	3.44 (6.9)	929
HW_O	Oak	1	2.19 (3.7)	859
		2	2.07 (10.1)	821
		3	1.95 (9.2)	816
Softwood				
SW_P	Pine	1	1.37 (6.8)	696
		2	1.30 (4.5)	672
		3	1.23 (9.2)	655
SW_C	Cedar	1	0.07 (2.3)	543
		2	0.20 (8.6)	561
		3	0.18 (3.3)	539
Mixed				
MW		1	0.26 (19.4)	616
		2	0.18 (12.1)	610
		3	0.15 (8.1)	603

Values in ( ) are cov in %. ***S = Sawdust, TL = Tradical Lime, HW_B = hardwood beech, HW_O = hardwood oak, SW_C = softwood cedar, SW_P = softwood pine, MW = mixed wood***

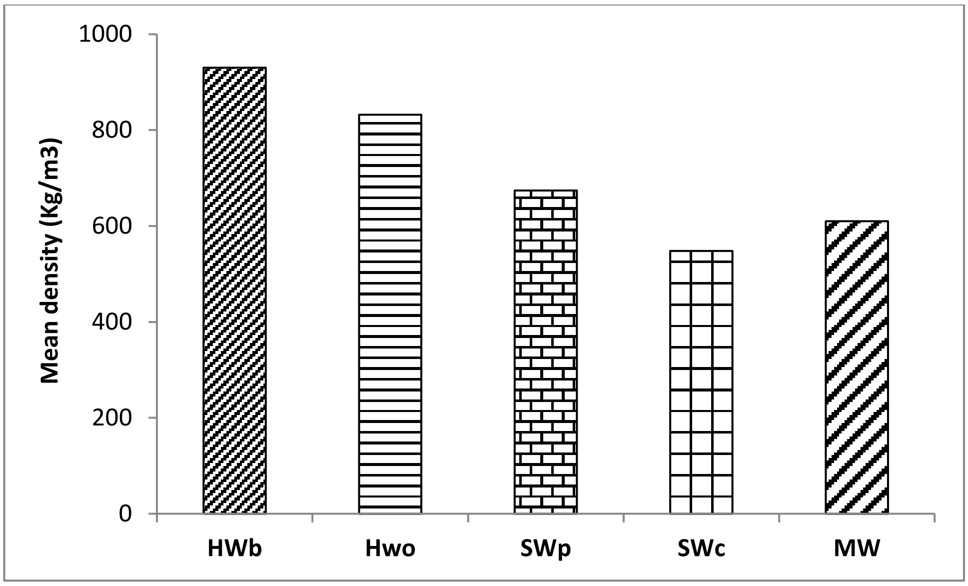


Figure 2: Comparison of overall density among various wood specie

3.2 Correlation of compressive strength and wood species

Fig 3 shows the correlation of compressive strength and wood species. It can be seen that the compressive strength of wood-crete beech is 29.1% higher than the compressive strength of oak and compressive strength of wood-crete pine is 79.3% higher than the compressive strength of wood-crete cedar. Overall, wood-crete made from hardwood had a much higher compressive strength than wood-crete made from softwood, on average 60.2% higher for the former compared to the latter. This may be due partly to the difference in the density (17.5%) between hardwood and softwood. A higher density of wood generally gives rise to a higher compressive strength and such the wood-crete would have a higher compressive strength due to the contribution of wood itself. It has also been reported that hardwoods are usually strong in compression, tension and shear while softwoods are strong in tension but weak in shear [15]. However, softwoods are generally strong along the grains while hardwoods are strong both along and across the grains. This difference may also contribute to the higher compressive strength of hardwood wood-crete made.

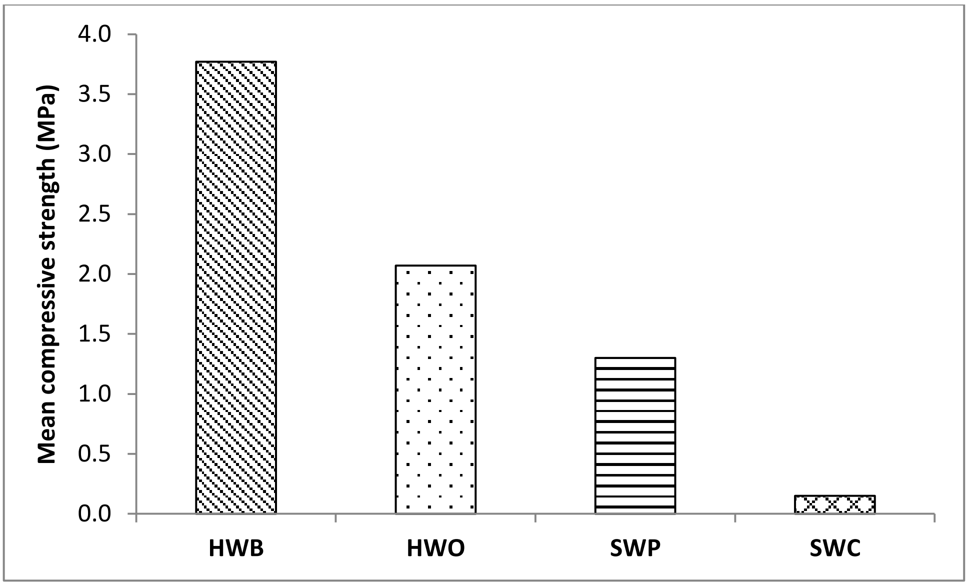


Figure 3: Mean compressive strength vs wood species

The property of composite is in general closely related to its density because the higher density means more compaction of the composite. In order to determine the degree of compression of wood-crete made with various densities of wood species, i.e. hardwood and softwood species in this study, it is necessary to calibrate the density of blocks by taking into account the ratio of mix of wood-crete and the densities of individual wood species used in this study which include beech, oak, pine and cedar. The percentage of tradical lime was two-third in mix while sawdust was one-third in mix. The density of tradical lime is 1201kg/m3. Therefore, the calibrated density of wood-crete = 1201 (2/3) + ρ (1/3)

Where, ρ = density of individual wood specie. This means that if the wood-crete has had the same compaction, the density of the wood-crete would have been equal to the calibrated density. Therefore, the compressive strength is calibrated to those that would have been the densities the same as the calibrated density (i.e. the same compaction). The calibrated results are summarised in table 6.

Table 6 Calibrated density and compressive strength of wood-crete with experimental mixture design

Samples		Particle size (mm)	Compressive Strength (mpa)	Calibrated Compressive Strength (mpa)	Density (kg/m3)	Calibrated Density (kg/m3)
Hardwood						
HW_B	Beech	1	3.93 (8.4)	4.14	934	1041
		2	3.90 (7.0)	4.12	930	1041
		3	3.44 (6.9)	3.64	929	1041
HW_O	Oak	1	2.19 (3.7)	2.41	859	1048
		2	2.07 (10.1)	2.32	821	1048

		3	1.95 (9.2)	2.19	816	1048
Softwood						
SW_P	Pine	1	1.37 (6.8)	1.59	696	966
		2	1.30 (4.5)	1.53	672	966
		3	1.23 (9.2)	1.46	655	966
SW_C	Cedar	1	0.07 (2.3)	0.09	543	973
		2	0.20 (8.6)	0.25	561	973
		3	0.18 (3.3)	0.23	539	973

Values in ( ) are cov in %. ***S = Sawdust, TL = Tradical Lime, HW_B = hardwood beech, HW_O = hardwood oak, SW_C = softwood cedar, SW_P = softwood pine***

It can be seen from the Table 6 that the wood-crete had been made with the same compaction (i.e. with the calibrated densities). The compressive strength was 26.4% higher for beech wood-crete compared to hardwood oak and 45.7% for softwood pine compared to softwood cedar. On average, the wood-crete made from hardwood sawdust records a much higher strength value (49.9%) than those made of softwood sawdust. This gives an indication that other factors such as higher lignin content in hardwood than softwood may affect the strength of wood-crete composites. Lignin has been reported by researchers to be a contributing factor to high performance concrete strength and improve compressive strength of cement paste. The combination of cellulose, hemicelluloses and extractives (sugar, fatty acid e.t.c) content is higher in softwood than hardwood which is another possible factor for the low compressive strength with wood-crete made from softwood. For example, research on the effect of sugar content on the property of composites showed that extracting sugar content from wood dust helps improve the bonding strength of composite materials which has an influence on compressive strength of wood-crete [16] [17] [18].

3.3 Correlation of compressive strength and density

Average measured densities for wood-crete for hardwood, softwood and mixed wood respectively are used to plot their relationship with compressive strength (Fig 4). It is observed that the compressive strength increases with an increase in the density of wood-crete regardless of wood species. For the wood-crete made from hardwood oak, compressive strength increased from 1.95 to 2.19 MPa (5.8%) when the density of wood-crete increased from 816 to 859 kg/m3 (2.6%) and for the pine wood-crete from 1.23 to 1.37 MPa (5.4%) when density of pine wood-crete increased from 655 to 696 kg/m3 (3.0%). The results are in line with the normal expectation of increasing compressive strength with increasing density. As discovered in previous study [1], compaction in mould is one factor that may have resulted in a higher compressive strength. Apart from compaction factor another reason for the difference in strength of wood-crete from different types of hardwood is a variation in the property of raw materials themselves, such as a little difference in the compressive strength and actual density of various types of wood themselves. Density of hardwood oak is slightly higher than that of beech hardwood and the density of softwood cedar is higher than that of softwood pine.

The correlation of compressive strength with average density of wood-crete seems to be linear with a good degree of fit, R^2=0.94 (Fig. 4). However, a further comprehensive design of density profile is required to achieve an accurate modelling result.

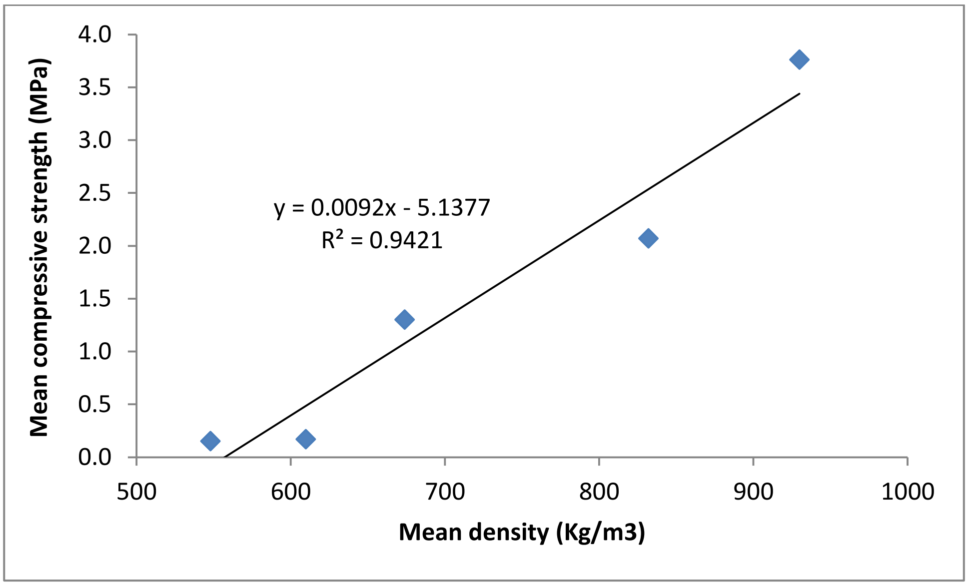


Figure 4: Mean compressive strength against density

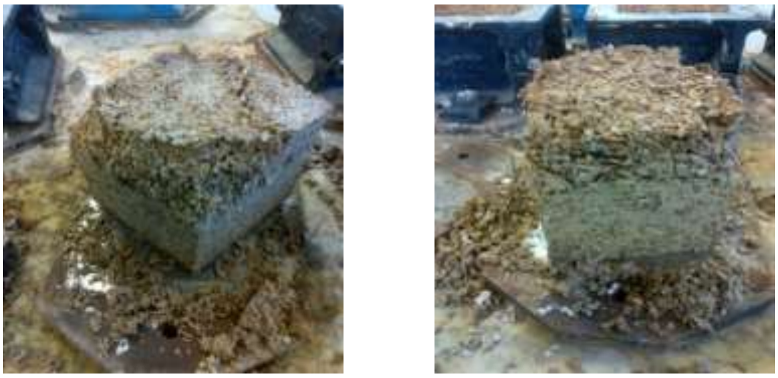
3.4 Correlation of particle size and compressive strength

It was noticed that the geometry of sawdust used had a significant impact on the strength of wood-crete. Of important point to note here as shown in Fig 5 is that the blocks made with sawdust to tradical lime ratio of 1:1 both for 1mm, 2mm and 3mm particle sizes, were not subjected to compressive testing because the samples did not bond together after demoulding period of 24hours. This is because the strength properties of composites strongly depend on the stress transfer between particles and binder and strength reductions occur by either adding a disproportion of particles or increasing particle size. Wood-crete made with sawdust to tradical lime ratio of 1:2 with 1mm sieve size of sawdust achieved higher strength when compared to those made with 2mm and 3mm sieve size of sawdust of each type of wood used (Fig 6). In addition to the increase in strength associated with short fibres, it has also be discovered in a previous study by Migneault [19], that short fibres are the easiest to mix which enables fibres to be properly coated with matrix thus having effect on mechanical properties. It is also most interesting that the reduction of the compressive strength with the increase of the particle sizes is related to the density of wood species, i.e. the reductions in the compressive strength of hardwood-crete are more significant than those of softwood-crete. The reduction in compressive strength from 1mm to 3mm particle sizes is 5.8% for oak wood-crete, 6.6% for beech wood-crete, 3.4% for pine wood-crete and 27.9% for mixed wood. It was discovered that for cedar wood-crete, 2mm particle size achieved a higher compressive strength than 1mm particle wood-crete, while the strength is very similar between the wood-crete made with 2mm and 3mm particle.

The mean compressive strength of different particle size of hardwood, softwood and mixed wood are compared in Fig 6, likewise the mean density against particle size in Fig 7. It is evident that the compressive strength of wood-crete made with 1mm particle size hardwood had about 56% increase in strength properties when compared to same particle size of softwood. A 54% increase and 47% increase was also noticed in 2mm and 3mm particle sizes respectively. The effect of particle size on compression strength has been reported [20] where composite strength increased with decreasing particle size. Smaller particles have a higher total surface area for a given particle loading which indicates that strength increases with increasing surface area through a more efficient stress transfer mechanism [20]. Also, smaller particles can generally be well-bonded with binder compared to larger particles and such the applied stress can be effectively transferred to the particles from the binder and from the binder to particles, which improves the strength or load bearing capacity of the wood-crete under load [19]. Much higher reduction in the compressive strength of wood-crete made from the mixed wood from 1mm to 3mm in comparison with those made from hardwood and softwood emphasizes an important consideration of the particle size distribution in manufacturing of wood-crete, because in practice it is very difficult to achieve a single wood species. This is because sawmills do not separate their wood waste during the sawing or milling process of wood. This implies that sieve sizes should be controlled during manufacturing of wood-crete in order to avoid low strength while ensuring that only wood-crete with desirable mechanical characteristics is formed.

It is seen that the density of wood-crete made with particle size 1mm is about 0.8 and 1.5% higher than those of wood-crete made with particle size 2mm and 3mm respectively (Fig 7). The wood-crete made with the small particle size may be more compact while large particles not only retain the micro void within the sawdust, they may also create ‘bridging’ between particles.

a) 2mm sawdust wood-crete



b) 3mm sawdust wood-crete

Figure 5: Poor bonding of wood-crete made with sawdust to tradical lime ratio 1:1 (demoulding after 24hours)

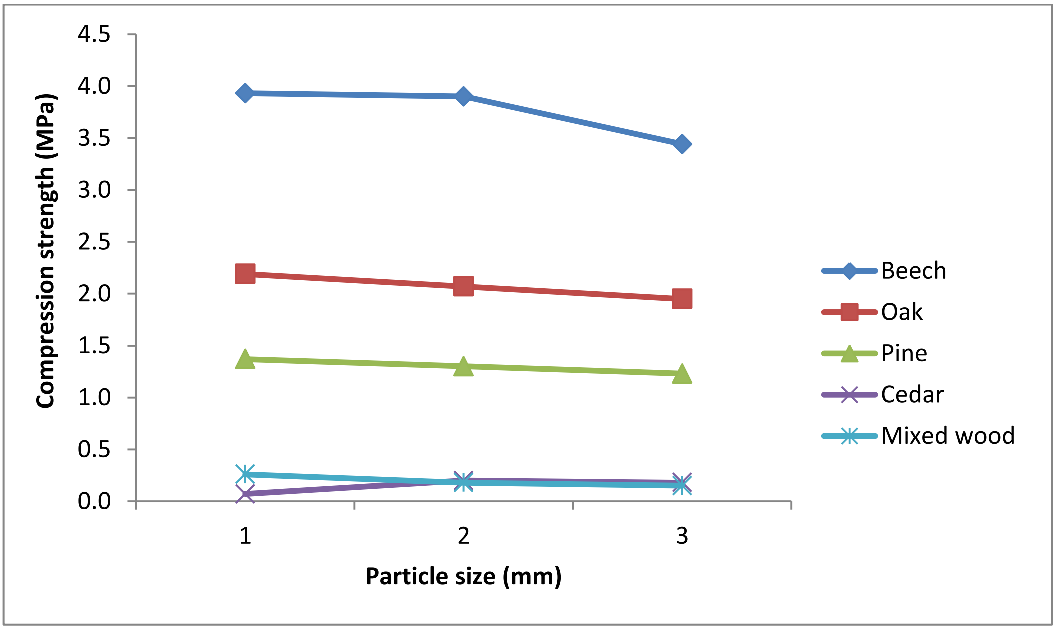


Figure 6: Mean compressive strength against particle size

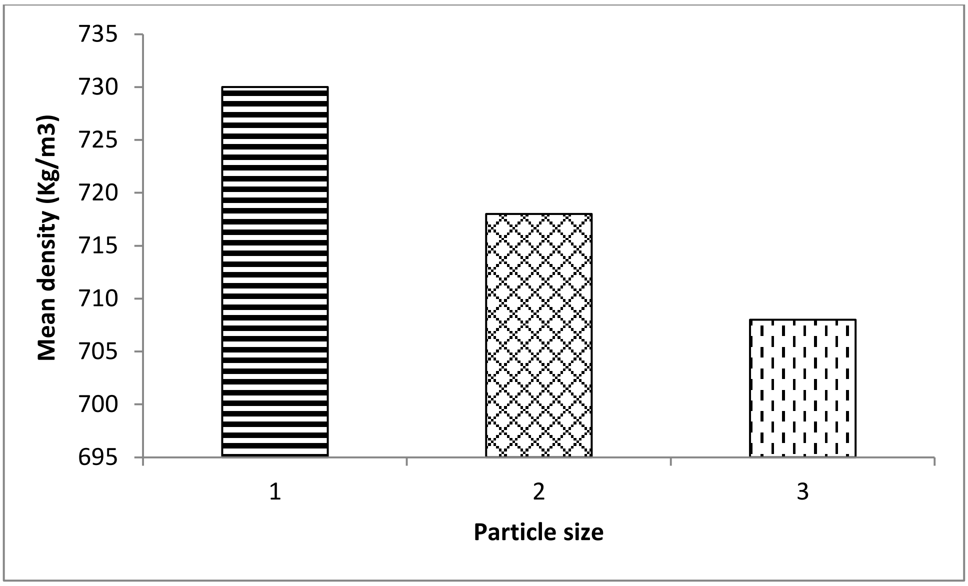


Figure 7: Mean density against particle size for all wood species

3.5 Correlation of wood species with thermal conductivity

One of the main purposes for developing wood-crete as a building material is its thermal performance which is a key parameter in low carbon sustainable building construction. Thermal conductivity depends on the composition, density, pore structure, moisture content and temperature of a material [21] [22] . In wood, the main influencing factors are wood species, density, moisture content, direction of heat flow (anisotropy), inclination of grain and relation of volume or thickness to moisture content [23]. However, thermal conductivity is strongly influenced by density [21]. These have been reflected in the wood-crete developed in this study. It seems to be that wood-crete from softwood achieved a low thermal conductivity of 0.068 and 0.092 W/mK and wood-crete from hardwood achieved 0.114 – 0.123 W/mK (Table 7). However, a scrutiny of the data in Table 7 showed that the trend of change in thermal conductivity of the wood-crete follows that of the density of the wood-crete, i.e. the ranking of thermal conductivity = the ranking of density = beech wood-crete > oak wood-crete > pine wood crete > cedar wood-crete. The wood species may have little effect on the difference in the thermal conductivity of wood-crete. This may be true by considering the thermal properties of wood reported by a previous worker [24], whose research on the thermal conductivity of five softwood and five hardwood showed that the average thermal conductivity for the former was 0.091 and for the latter 0.092 W/M.^{0}C. Thermal conductivity of wood-crete from cedar sawdust was about 15% lower than wood-crete from pine wood while thermal conductivity of wood-crete from oak wood was about 3.8% lower than wood-crete from beech wood. These correspond to the fact that the density of cedar wood crete is about 22% lower than that of pine wood-crete, while the density of oak wood-crete is about 8% lower than beech wood-crete. The above result is also in agreement with results discovered in the previous study [1], where reduced density resulted in a low thermal conductivity.

Table 7 Thermal conductivity and effusivity of wood-crete from various wood species.

Wood Species	**Thermal Conductivity (W/M.^{0}C)**	**Thermal Effusivity (Ws½/m²K)**	**Compressive strength (MPa)**	**Density (kg/m3)**
Pine	0.092	113.582	1.37	696
Cedar	0.068	106.156	0.07	543
Oak	0.114	115.277	2.19	859
Beech	0.123	116.014	3.39	934

4 CONCLUSION

The wood-crete made with hardwood, softwood and mixed wood species has been developed and the properties of the made wood-crete composites have been analysed. The compressive strength of wood-crete made from sawdust of softwood was similar to that of hempcrete and in some cases higher while compressive strength of wood-crete made from hardwood was higher than that developed in previous series of wood-crete [1]. This gives an indication that wood-crete made from specific types of wood can as well be used as in-fills in construction. However, the compressive strength of wood-crete were not comparable to those of normal concrete as the strength values were lower than those of concrete and some other building materials (table 3). Nevertheless, the compressive strengths were higher than those of hempcrete which is currently used in construction.

The properties of wood-crete were related to its composition and type of sawdust from different kinds of wood species. Conclusively,

- Wood-crete made from hardwood resulted in higher strength compared to those made from softwood having a 53% difference in the compressive strength on average. Hardwood beech wood-crete recorded a 61% increase in compressive strength when compared to hardwood oak wood-crete; likewise softwood pine recorded a 79% increase in compressive strength when compared to softwood cedar wood-crete.

- ❖ The constituents of wood (lignin, cellulose, hemicelluloses and extractives) all contributed to the strength properties of wood-crete composites.
- ❖ To enable better bonding between sawdust and binder, a 1:2 of sawdust to binder ratio has been advisable.
- ❖ Wood-crete made with smaller particle size of 1mm achieved better compressive strength than those made with 2mm and 3mm particle sizes respectively. A reduction in compressive strength with an increase of particle size was strongly related to wood species.
- ❖ Wood-crete made from softwood has a lower thermal conductivity compared to wood-crete made from hardwood with a 19.4% reduction in thermal conductivity value.
- ❖ Mixing wood species for wood-crete production did not result in an average performance equivalent to the average performance of wood species, indicating an adverse effect of the mixing, such as ‘bridging’ between particles.

5 BIBLIOGRAPHY

[1] E. P. Aigbomian and M. Fan, “Development of Wood-Crete Building Materials from Sawdust and Waste Paper,” *Construction and Building Materials,* vol. 40, pp. 361 - 366, 2013.

[2] P. R. Blankenhorn, P. J. Labosky, M. Dicola and L. R. Stover, “Compressive Strength of Hardwood-Cement Composites,” *Forest Products,* vol. 44, no. 4, pp. 59 - 62 , 1994.

[3] Y. M. Wei, Y. G. Zhou and B. Tomita, “Hydration Behavior of Wood Cement-Based Composites I: Evaluation of Wood Species Effects on Compatibility and Strength with Ordinary Portland Cement,” *Wood Science,* vol. 46, pp. 296 - 302, 2000.

[4] F. C. Jorge, C. Pereira and J. M. F. Ferreira, “Wood-Cement Composites: A Review,” *Published Online,* vol. 62, no. 5, pp. 370 - 377 , 2004.

[5] R. C. Pettersen, “‘The Chemistry of Solid Wood In: ’ R. Rowell (ed.),” *Journal of the American Chemical Society,* pp. 57 - 127, 1984.

[6] J. H. Grabber, “How do Lignin Composition, Structure and Cross-linking affect Degradability? A review of Cell Wall Model Studies,” *Crop Science,* vol. 45, no. 3, pp. 820 - 831, 2005.

[7] J. Pourchez, P. Grosseau, R. Guyonnet and B. Ruot, “HEC Indluence on Cement Hydration measured by Conductometry,” *Cement and Concrete Research,* vol. 36, no. 9, pp. 1777 - 1780, 2006.

[8] L. K. Aggarwa and J. Singh, “Effect of Plant Fibre Extractives on Properties of Cement,” *Cement and Concrete Composites,* vol. 12, pp. 103 - 108, 1990.

[9] Forest Products Laboratory USDA Forest Service, “Wood Handbook - Wood as an Engineering Material,” Madison, Wisconsin, 1999.

[10] A. Mitani and I. Barboutis, *Shear Strength by Compression Loading of some Hardwoods Bonded with PVAc and Casein Adhesives,* pp. 1352 - 1360 2010.

[11] A. Zziwa, S. Kizito, A. Y. Banana, J. R. S. Kaboggoza, R. K. Kambugu and O. E. Sseremba, “Production of Composite Bricks from Sawdust using Portland Cement as a Binder,” 2006.

[12] British Standard BS EN 12390-2:2009, “Making and Curing Specimens for Strength Test,” BSI, United Kingdom.

[13] M. H. Simatupang and R. L. Geimer, “Inorganic Binder for Wood Composites: Feasibility and Limitations. In: Proc. of the Wood Adhesive Symposium. Madison W I,” pp. 169 - 176, 1990.

[14] D. J. Cown and M. L. Parker, “ Comparison of Annual Ring Density Profiles in Hardwoods and Softwoods by X-ray Densitometry,” *Canadian Journal of Forestry Research,* vol. 8, pp. 442 - 449, 1978.

[15] K. Wilson and D. J. B. White, The Anatomy of Wood: Its Diversity and Variability, London: Stobart & Son Ltd, 1986.

[16] X. Li, L. G. Tabil and S. Panigrahi, “Chemical Treatments of Natural Fiber for Use in Natural Fiber-Reinforced Composites,” *Journal of Polymers and the Environment,* vol. 15, pp. 25 - 33, 2007.

[17] T. A. Plekhanoca, J. Keriene, A. Gailius and G. I. Yakovlev, “Structural, Physical and Mechanical properties of Modified Wood-Magnesia Composite.,” *Building Construction and Materials,* vol. 21, pp. 1833 - 8, 2007.

[18] A. Prompunjai and W. Sridach, “Preparation and Some Mechanical Properties of

Composite Materials Made from Sawdust, Cassava Starch and Natural Rubber Latex," *World Academiy of Science, Engineering and Technology,* pp. 930 - 934, 2010.

[19] S. Migneault, A. Koubaa, F. Erchiqui, A. Chaala, K. Englund, C. Krause and M. Wolcott, "Effect of Fiber Length on Processing and Properties of Extruded Wood-Fiber/HDPE Composites," *Journal of Applied Polymer Science,* pp. 1086 - 1092, 2008.

[20] S.-Y. Fu, X.-Q. Feng, B. Lauke and Y.-W. D. Mai, "Effects of Particle Size, Particle/Matrix interface adhesion and Particle Loading on Mechanical Properties of Particulate–Polymer Composites," *Composite B - Engineering,* 2008.

[21] W. Sonderegger, P. Niemz, H. Bader and A. Weber, "Comparative Study on the Thermal Conductivity of Wood and Wood-Based Materials," in *Wood Structure and Properties,* Zvolen, Slovakia, Arbora Publishers, 2006, pp. 391 - 394.

[22] L. Dzurenda, *Effect of Thermal Modification of Oak Wood on Saawdust Granularity,* 2010.

[23] B. M. Suleiman, J. Larfedt, B. Leckner and M. Gustavson, "Thermal Conductivity and Diffusivity of Wood," *Wood Science,* vol. 33, pp. 465 - 473, 1999.

[24] Z.-T. Yu, X. Xu, L.-W. Fan, Y.-C. Hu and K.-F. Cen, "Experimental Measurements of Thermal COnductivity of Wood Species in China: Effects of Density, Temperature, and Moisture Content," *Forest Products Journal,* vol. 61, no. 2, pp. 130 - 135, 2011.

Development of Wood-Crete from Treated Sawdust

Eboziegbe Patrick Aigbomian and Prof Mizi Fan

Civil Engineering, School of Engineering and Design, Brunel University, Uxbridge, Middlesex, UK
Email - eboziegbe.aigbomian@brunel.ac.uk

ABSTRACT

The properties of wood-crete were investigated based on the modification of sawdust by hot water boiling, alkaline treatment and the addition of different types of waste paper. The results showed that (1) surface modification, processing of cellulosic fibril and the extraction of lignin and hemi-cellulosic compounds with alkali had an effect on the compressive strength of wood-crete, with treating sawdust with 4% NaOH at 140mins of boiling time achieving the highest increase of 260% compressive strength; (2) boiling sawdust from 100mins to 140mins saw a gradual increase in compressive strength but reduced at a higher boiling time; (3) the combined effect of enhanced sawdust and addition of waste paper had a direct effect on the compressive strength of wood-crete with paper strip recording a much higher strength of 1.62 MPa compared to 1.06 MPa of de-fibred paper; (4) the treating sawdust with NaOH more than 4% weakened the individual wood particles thus leading to poor strength of wood-crete; and (5) water soaking resulted in a little water uptake (about 0.1%) of wood-crete whether with 1:1 or 1:2 sawdust to tradical lime ratio, but significant decrease in compressive strength, showing that the wood-crete could be used in damp areas only if it is not for load bearing purpose. The findings of this study provide an important background and foundation for achieving better strength of wood-crete and for directing a better uses of this potential low carbon sustainable product in construction.

Keywords: Wood-Crete; tradical Lime; sawdust; waste paper; compressive strength; water absorption

* *Corresponding author: Professor Mizi Fan, Head of Research, Department of Civil Engineering, School of Engineering and Design, Brunel University, Uxbridge, London, UK*
Email: mizi.fan@brunel.ac.uk

1 INTRODUCTION

Wood-crete is a new material made from sawdust or other wood wastes or materials, and Tradical lime with consideration for cheaper and locally available materials to meet the desired needs, enhance self-efficiency and lead to an overall reduction in construction cost for sustainable development. Wood-crete has been developed in this research programme, intending to achieve similar properties but more cost effective than those of cement bonded composites and hempcrete. A number of advantages of wood-crete over other conventional wood composite materials include better insulation properties, resistance to water absorption, fire performance and strength properties [1] [2]. When compared with hempcrete, wood-crete can reduce material cost, reuse wood wastes, and has similar thermal performance and an improved strength. Just like cement-bonded wood composites (CBWC) and hempcrete, wood-crete with an addition of structural support can be used in construction and most beneficial in developing countries because of their relatively low cost as wood used are waste products from sawmills [1], the basic use of simple technology during production process, the reduced weight of composites making handling easier and labour less tedious [3], and the use of local materials. As part of the environmental benefits of the use of wood-crete, it provides those in the wood industry a means of discarding their waste whilst enabling the creation of a new commercially viable, environmentally friendly product for the construction industry [4]. It will provide a solution to the increasing amounts of wood waste and promote a waste management practice that helps mitigate the effect of waste on the environment, thus promoting a sustainable and green environmental practice most especially in developing countries. Wood-crete is produced with a binder known as tradical lime which is known for its elasticity, durability (long lasting quality mortars), workability, vapour permeability, and healthy material (natural and solvent-free) when compared to the use of cement.

The strength of wood-crete is directly related to the bonding strength between sawdust and tradical lime [5]. The chemistry between the bonding of sawdust and binders has been argued by a number of authors [6-8]: Wood contains a number of substances, including hemicelluloses, starches, sugars, phenols and hydroxylated carboxylic acids which could dissolve and affect lime crystallization. The major problems of wood composites are associated with the hydrophilic character of the cellulose structure of fibre [5]. Researchers have suggested some propounding solutions to the above problem by stating the necessities to modify cellulose fibre surface by scientific methods to reduce the hydrophilic nature of sawdust thereby improving the sawdust–matrix bonding [5] [6]. Research has shown that as a result of the enhancement through different surface modification of sawdust interface, there is a significant increase in the strength of composites [7] [8]. The partial removal of the components of sawdust which include cellulose, hemi-cellulose, lignin (the main components that contribute to the strength, flexural and impact properties of composites) and pectin, waxes, and water-soluble substances [5] with alkali solution and the modification of cellulose fibre was reported by Zaikov et al, 2004 [6]. Modification of sawdust as stated by Prompunjai and Sridach (2010) [5] include de-waxing, alkali treatment, cyanoethylation and benzolation. Several studies have noted that the reason for cohesion of matrix with the treated sawdust is that as lignin is removed, the middle lamella joining the ultimate cells becomes more plastic and homogeneous due to the gradual elimination of micro-voids [5]. It has also been stated that during modification by alkaline treatment, the hydrogen bonding in the network structure is disrupted, thereby increasing surface roughness [5]. The treatment removes a certain amount of lignin wax and oils covering the external surface of the fibre cell wall, depolymerises cellulose and exposes the short length crystallites [7] [9]. The bonding between sawdust and hydrophobic matrix has a direct effect on the mechanical properties of composite materials while studies have also shown that the removal of hemicelluloses produces less dense and less rigid inter-fibrillar region [5].

This paper presents the outcomes from an extensive research on the development of novel building materials, wood-crete. The paper focuses on the development of the wood-crete with the treated sawdust, which otherwise is burnt or landfilled. Various treatments were proposed to optimise the property of wood-crete and the performance of the developed wood-crete was assessed.

2 MATERIALS AND TREATMENT

2.1 Raw materials and treatments and wood-crete fabrication

Preceding block formation the sawdust sourced from wood workshop at Brunel University was refined to 1mm sieve size. The materials are then divided into three groups: the first group of the materials was treated with NaOH at various percentages, namely 0, 1, 2, 3, 4, 5 and 6% and boiled in water with duration of 100, 120, 140 and 160 minutes. This group of materials is used for the experiments of wood-crete without the addition of waste paper. The second group of the materials was treated with NaOH of 0, 2, 4, 6 and 8% and boiled in water for the duration of 80mins. The third group of materials was treated with NaOH of 2 and 4% and boiled in water for the duration of 40, 60, 100, 120 and 140 minutes. The second and third group of the treated materials was used for the experiments of wood-crete with the addition of waste paper (de-fibred and paper strip at 50% and 75%). More details of experimental designs is included in Tables 1 and 2. The treated sawdust solution was washed with distilled water to remove the adsorbed alkali and soluble like sugar which tends to inhibit hydration as noticed in wood-cement composites [5]. The treated sawdust was then dried in an oven at 100±3°C for 24hours and sealed in an airtight container before use.

Tradical lime HB sourced from Lime Technology Ltd. UK was used as binder and mixed with sawdust in ratio 2:1.

Two types of waste paper were used for purpose of comparison. The first type of waste papers (newspaper) was de-fibred firstly by soaking in water, dried and then blended. The average microscopic measurement taken for 50 fibres was 1211.79µm in length and 25.97µm in breadth. The second type of waste papers (paper strip) used is measured 279.4mm in length and 10.0mm in breath. The de-fibred and paper strip waste papers were then mixed with sawdust and Tradical lime to improve the insulating properties and reduce the density of block but most importantly contributing to self-strength of wood-crete [250].

The amount of water used for all blocks varied depending on the type of mix combination. The blocks made without the addition of waste paper used 80ml per every 100g of mix. The blocks made with paper strip (shredded paper) used 136ml per every 100g of mix while the blocks made with de-fibred paper used 193ml per every 100g of mix. This was determined by the mix workability during sample trial making. During sample trial making, the mix made with water to total mix weight less than the above stated for every combination was termed unworkable, while trial samples made with water higher than those stated above for every combination was termed to be slurry. This was important in other to be able to control the amount of water for every mix which has a direct effect on the density of sample.

The de-fibred paper and paper strips added were calculated in percentage ratio of sawdust by weight. Wood-crete blocks were made by mixing waste paper in water before the required amount of sawdust and lime were added in the mixer. This method is advised so that the waste paper can first be thoroughly wetted [250]. The mix was uniformly distributed into the square moulds which were treated with a mould release agent. Preparation of specimens for testing strength properties was based on BS EN12390-2 [11]. Three replicates of samples were made for each fabrication of wood-crete. The mixtures were placed in a forming mould for 24 hours before de-moulding while maintaining a relative humidity between 46% and 49% for all samples. Wood-crete blocks were moulded in the dimension of 100mm x 100mm x 100mm.

2.2 Testing

Actual volume of the blocks was taken from the measurement of samples after drying. Samples were sandpapered for evenness and flatness in all sides while sample mass was determined using a weighing scale. The density of the blocks was calculated from mass and volume. Three replicates were taken for each type of the wood-crete blocks and the mean value taken.

The de-moulded wood-crete blocks were further cured for 32 days and tested for compressive strength at 20°C/65% relative humidity by applying a gradually increasing load under an universal Instron. The test pieces were placed between a supporting base and a flat steel plate. The machine applied a uniform load at a rate of 6mm/min until the maximum failure load was reached. The maximum load (in Newton) was automatically recorded and the compressive strength was calculated as maximum failure stress per unit area.

Both the wet strength and water uptake of the developed wood-crete were also evaluated. Experimental set up was carried out according to long term water absorption by total immersion as described in BS EN1208:1997 [12]. Excess water adhering to surface, not absorbed by the test sample is removed by drainage or taken into account by deduction of the initial water uptake. For this test set up, excess water on the surface not absorbed by test sample was removed by deduction method. The method involved weighing the test sample to the nearest 0.1g to determine its initial mass, m_0. The test sample is then placed in the water tank in such a position that it is totally immersed in water with the top face of the test specimen (50 ± 2) mm below the water level. Sample is removed after 10s, holding it horizontally and placed within 5s, in a plastic tray of known mass. Test sample and tray are weighed together to determine the mass of the test specimen, m_1, including the initial water uptake. Test sample is then placed in the water tank and a sufficient load is applied to keep the sample totally immersed in water, with the top face of the test sample (50 ± 2) mm below the water level. After the 28day period of water absorption test, samples were subjected to compressive test and results were compared to samples made with the same conditions without being subjected to water absorption.

2.3 Experimental mix design

The detailed experimental designs are included in Tables 1, 2 and 3 in the section of results and discussion, including various boiling times and addition of NaOH, wood-cretes with and without waste papers. The sawdust to binder ratio remained 1:2 for all mix designs.

3 RESULTS AND DISCUSSION

3.1 Effect of water boiling treatment on the compressive strength of wood -crete

Table 1 shows that the compressive strength of wood-crete increased gradually as the water-boiling time increased from 80mins to 140mins and then decreased at 160mins. The average compressive strength of wood-crete without an addition of NaOH increased from 0.25 to 0.33 MPa and then decreased to 0.28MPa. These results are in agreement with the previous studies conducted by Aigbomian and Fan [250], a compressive strength of 0.26 MPa was achieved for the wood-crete made with sawdust without boiling treatment. It is apparent that the boiling time less than 120mins has little effect on the compressive strength but rather tends to weaken the bonding between sawdust and binder. This may also explain why, as boiling time increased from 140mins to 160mins, the strength of wood-crete decreased from 0.33 MPa to 0.28 MPa. This means that though the treatment helps to extract soluble from sawdust to create a better bonding between sawdust and binder, a prolong boiling time may weaken sawdust particles themselves, thereby creating weaker wood-crete. The boiling time for the sawdust to be used for wood-crete production should be 140mins if no NaOH is included in the boiling water.

Overall mean values of compressive strength with duration of boiling time, for all NaOH additions tested, are 0.41 MPa with duration of 100mins, 0.52 MPa at 120mins, 0.50 MPa at 140mins and 0.37 MPa at 160mins. This again indicates that the compressive strength increased at first and then decreased with the duration of boiling time. However, the boiling time of 120mins gives the highest compressive strength compared to other treating times.

There was an 11.8% increase in compressive strength when sawdust is boiled at 100mins to 120mins and a 14.9% decrease in compressive strength when sawdust is boiled from 140mins to 160mins. This illustrates the effect of NaOH on the soluble content of sawdust (Table 1).

Table 1 Experimental design and mean value of wood-crete property (without waste paper)

NaOH (%)	Boiling time (min)							
	100		120		140		160	
	CS (MPa)	Den (kg/m3	CS (MPa)	Den (kg/m3	CS (MPa)	Den (kg/m3	CS (MPa)	Den (kg/m3
0	0.25 (8.0)	640	0.27 (1.9)	627	0.33 (18.6)	610	0.28 (5.3)	629
1	0.15 (12.3)	617	0.39 (16.7)	641	0.41 (2.2)	640	0.29 (9.9)	628
2	0.15 (8.9)	639	0.16 (10.9)	632	0.63 (3.7)	640	0.59 (2.1)	635
3	0.73 (2.4)	622	0.78 (6.6)	622	0.79 (12.0)	603	0.57 (15.8)	614
4	0.67 (5.3)	609	0.75 (8.3)	615	0.87 (5.1)	619	0.39 (10.4)	611
5	0.65 (5.7)	602	0.68 (7.2)	611	0.26 (17.0)	623	0.24 (16.9)	631
6	0.30 (9.1)	610	0.58 (11.6)	605	0.24 (4.5)	610	0.24 (5.0)	614
MEAN	**0.41 (7.4)**	**620**	**0.52 (9.0)**	**622**	**0.50 (9.0)**	**621**	**0.37 (9.3)**	**623**

CS = Compressive Strength, Den = Density, NaOH = Sodium Hydroxide, Values in ( ) are cov. in %

3.2 Effect of NaOH treatment on compressive strength of wood-crete

Figure 1 shows that overall mean compressive strength of various treating durations of wood-crete gradually increased as the percentage of NaOH increased from 0 to 3% and then decreased as the percentage of NaOH continued to increase from 4 to 6%. It is apparent that an addition of NaOH is able to extract the soluble content of sawdust effectively. Proven here is that the treating sawdust to be used for wood-crete production should be 3% with boiling time of 130mins. Although there is only 3% decrease in compressive strength when NaOH increased from 3% to 4%, there is a drop of 33% in compressive strength when sawdust is treated further from 4% to 6%. Whilst the treatment of sawdust with NaOH helps form a good bond and promote the ionization of hydroxyl group, treating sawdust with more than 4% of NaOH tends to create a weaker bond and weakens individual wood particle fibres, hence results in low compressive strength of the wood-crete made from the treated sawdust.

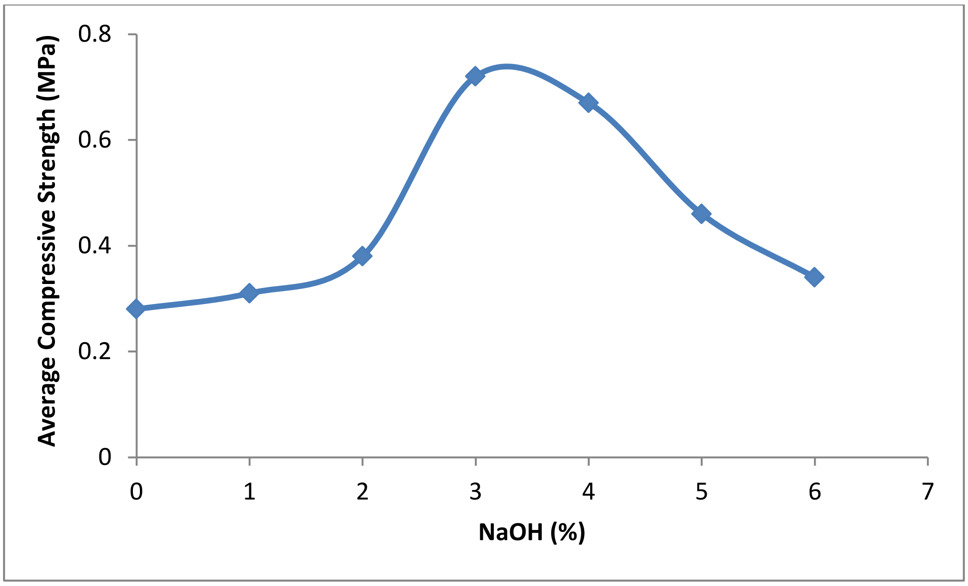


Figure 1 Mean compressive strength vs NaOH for all boiling times

The effect of NaOH treatment is also related to the boiling time (Table 1). With the 100 minute boiling time, there is a little effect between 0 to 2 % NaOH. However, from 2 to 3 %, this is a significant increase in the compressive strength. Changing NaOH from 5 to 6% resulted in an adverse effect, with compressive strength reducing from 0.65 to 0.30MPa. A similar trend was found for boiling time of 120 minutes. When boiling time was increased to 140 minutes, even a 1% or 2% NaOH can result in a substantial increase of compressive strength, which increased about 30% or 100% respectively although over 170% increase in the compressive strength was achieved at 4% NaOH. A comparison of the last two columns of Table 1 indicates that a long duration of boiling time may have resulted in significant effect on the strength of sawdust. The highest compressive strength was only 0.59MPa with the boiling duration of 160min in comparison to 0.87MPa with the boiling duration of 160min.

3.3 Combined effect of NaOH and boiling time

Observed is that there was an increase in the compressive strength of blocks as the percentage of NaOH increased as well as boiling time (Table 3 and Fig 2). High compressive strength areas on Figure 2 are indicated with red zone and as strength decreases, colour changes from yellow, to green and blue. As reported by Vaickelionis and Vaickelioniene 2006, a longer extraction time and a higher temperature (up to 100°C) afford a higher concentration of soluble materials [13]. Previous studies have shown that the major problems of wood composites are associated with the hydrophilic character of the cellulose structure of fibre and overcoming this problem means modifying the fibre surface by the physical and chemical methods to reduce the hydrophilic nature of sawdust which improves the sawdust–matrix bonding [5]. The treatment of wood fibre prevents sugar and tannins in the wood from reacting with the matrix which interferes with proper curing [13]. It can thus be inferred that the reason for the significant increase in strength of composite after treatment of sawdust is that there has been a change in the interface quality of sawdust which has consequently improved the bonding of sawdust and matrix resulting to better compressive strength. Figure 2 indicates that to achieve good compressive strength, the treating regimes for sawdust should be within the range of 3 to 4% with boiling duration between 135 and 140 minutes (red zone on Figure 2). It is interesting to see that low percentage of NaOH at boiling time between 110 to 130 minutes gives similar result to high percentage of NaOH with longer boiling time above 155 minutes (Figure 2). This gives an indication that during initial boiling state of sawdust, there is no significant indication of change in sawdust matrix. However, as boiling time increases, the structural behaviour of sawdust particles begin to change and then weaken with excessive heating time. This has been further confirmed from the results from the wood-crete with an addition of waste paper (Table 2). Table 2 shows that at a low boiling time of 80 minutes, a higher percentage of NaOH is needed to achieve better compressive strength, although there is a variation when sawdust was treated from 2% of NaOH to 4% of NaOH, which may be due to the variation of raw materials or experimental variation as much higher cov values of wood-crete treated with 4% of NaOH was observed in comparison with the cov values of wood-crete treated with 2% of NaOH.

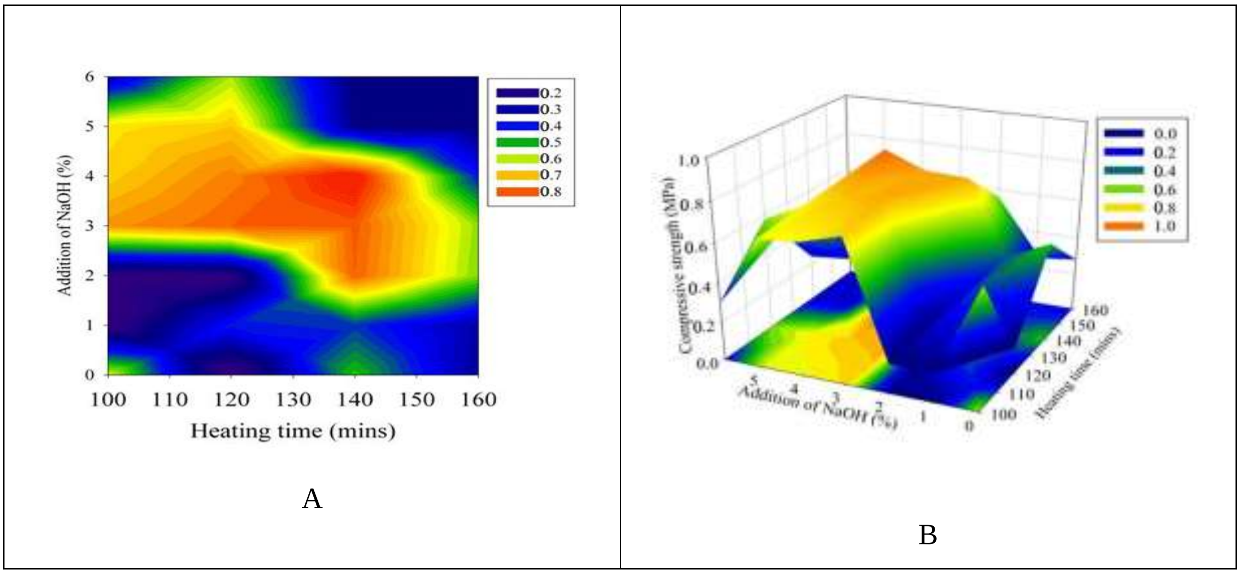


Figure 2 Combined effect of NaOH and boiling time: A=2D and B=3D images

Table 2 Experimental design and mean value of wood-crete property at various NaOH (Boiling time 80 minutes)

NaOH (%)	50%DF		75%DF		50%PS		75%PS	
	CS (MPa)	Den (kg/m3)	CS (MPa)	Den (kg/m3)	CS (MPa)	Den (kg/m3)	CS (MPa)	Den (kg/m3)
0	0.30 (3.2)	551	0.33(4.2)	532	0.44 (11.0)	650	0.58 (5.0)	596
2	0.62 (3.3)	539	0.72 (5.3)	520	0.81 (6.6)	642	1.03 (2.7)	591
4	0.36 (12.5)	547	0.38 (7.4)	518	0.42 (5.8)	638	0.48 (10.1)	587
6	0.73 (5.1)	536	0.80 (6.2)	513	1.06 (3.4)	641	1.01 (8.2)	583
8	0.82 (2.9)	544	0.81 (6.9)	535	0.95 (4.7)	644	1.25 (4.1)	595

CS = Compressive Strength, Den = Density, NaOH = Sodium Hydroxide, DF = de-fibred, PS = Paper Strip, Values in ( ) are cov. in %

3.4 Combined effect of NaOH treatment and waste paper on compressive strength of wood-crete

Table 2 shows the effect of treating sawdust at various percentages of NaOH on the compressive strength of wood-crete in combination with waste paper. It is observed that there was an increase in compressive strength of wood-crete with the type of paper used and in percentage of NaOH. Wood-crete made with 75% of paper strip at 4% of NaOH achieved higher compressive strength than those made with 75% of de-fibred at 4% of NaOH with about 16% increment in strength property. The same trend is noticed with wood-crete made with 50% of paper strip and 50% of de-fibred at 4% of NaOH and wood-crete made with 2% of NaOH both for 50% paper strip and 75% paper strip and 50% de-fibred and 75% de-fibred paper. Two significant evidences are confirmed here: the first is that the higher the percentage of NaOH, the better the compressive strength and the second is that the wood-crete with paper strip performs better in compressive strength than those with de-fibred paper. It is not clear why the treatment with 2% of NaOH has a better strength compared to 4% of NaOH, although there is a much higher cov for the results under 4% NaOH treatments, showing possible experimental operation variation.

3.5 Combined effect of boiling time and waste paper on compressive strength of wood-crete

Figure 3 shows overall mean compressive strength across different water boiling times of both de-fibered and paper strip. The results for each individual regime of treatment are given in Table 3. It can be seen that the strength consistently increases with the boiling time increase, from 0.40 to 1.22MPa when the boiling time from 40 to 140 minutes. The correlation can be established with a good fit of linear regression (Figure 3).

Waste paper has also had an effect on the property of wood-crete (Figure 4). Overall the wood-crete with paper strips had a better compressive strength than those with de-fibred waste paper (Table 3 and Figure 4). A higher concentration of waste paper also gave rise to a better compressive strength. This is also in agreement with the results from previous study by the authors [250] which showed that 75% of de-fibred waste paper achieved a better strength than 50% of de-fibred waste paper. It is also evident that as the percentage of NaOH reduced, there was a corresponding reduction in the compressive strength of wood-crete (Table 3).

Figure 3 and 4 also shows that where there was an increase in percentage of waste paper and heating time, there was a corresponding increase in compressive strength of wood-crete. In general, it observed that there is 12% increase in average compressive strength when wood-crete is made with 50% paper strip compared to 50% de-fibred paper and an 18% increase when wood-crete is made with 75% paper strip compared to that when wood-crete is made with 75% de-fibred paper.

Table 3 Experimental design and mean value of wood-crete property at different heating times and NaOH

Boiling time (min)	NaOH (%)	50%DF		75%DF		50%PS		75%PS	
		CS (MPa)	Den (kg/m3)	CS (MPa)	Den (kg/m3)	CS (MPa)	Den (kg/m3)	CS (MPa)	Den (kg/m3)
40	2	0.26 (3.0)	547	0.32 (6.8)	522	0.45 (4.1)	652	0.58 (6.6)	594
40	4	0.35 (4.9)	549	0.47 (4.0)	529	0.59 (6.4)	658	0.69 (3.0)	591
60	2	0.62 (2.5)	554	0.63 (14.4)	521	0.64 (18.0)	656	0.74 (16.0)	593
60	4	0.63 (1.5)	545	0.69 (8.7)	516	0.74 (10.8)	648	0.77 (6.5)	588
100	2	0.63 (3.2)	550	0.80 (9.2)	511	0.97 (6.3)	649	1.32 (10.3)	580
100	4	0.70 (4.5)	546	0.83 (8.6)	509	0.10 (2.7)	645	1.33 (15.2)	582
120	2	0.87 (9.1)	540	0.91 (11.4)	502	0.99 (2.2)	648	1.27 (4.3)	590
120	4	0.90 (10.2)	539	0.98 (3.6)	498	1.04 (6.5)	642	1.16 (5.7)	584
140	2	0.94 (1.8)	536	1.04 (5.5)	503	1.11 (9.7)	644	1.56 (2.4)	576
140	4	1.01 (9.0)	535	1.06 (7.8)	508	1.17 (12.3)	630	1.62 (10.6)	562

CS = Compressive Strength, Den = Density, NaOH = Sodium Hydroxide, DF = de-fibred, PS = Paper Strip,
Values in ( ) are cov. in %

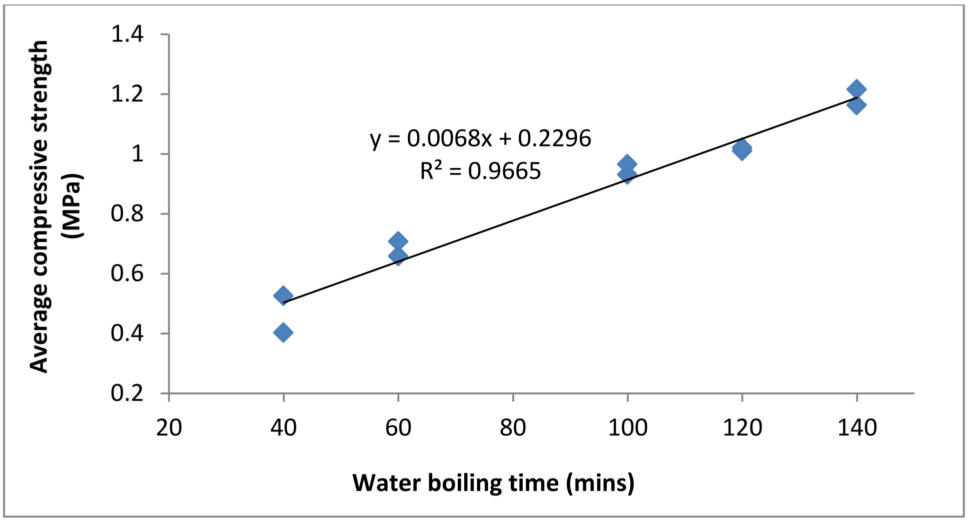


Figure 3 Average compressive strength vs boiling time

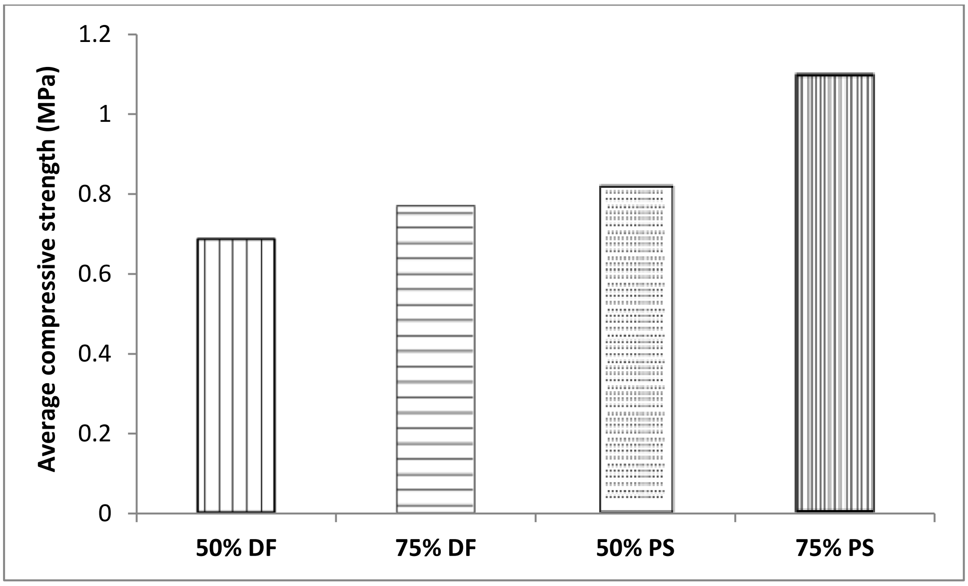


Figure 4 Average compressive strength vs waste paper

3.6 Effect of fibre length on compressive strength of wood-crete

Another factor to be considered here is the effect of fibre length on the compressive strength of wood-crete. With less information on the effect of length of paper fibre on composites, a few studies showed that generally impact strength is higher with longer fibres than shorter fibres [14]. It has been suggested that the mechanical properties of composites increase with increase in fibre length [15]. Both strength and stiffness increase can be realized with increasing fibre length if (1) adhesion between wood fibres and matrix is good, (2) fibres are uniformly dispersed in the matrix and (3) fibres are adequately oriented. This study shows that overall, there is an increase in strength of wood-crete blocks made of the same conditions with paper strip compared to those made with de-fibred paper (Tables 2 and 3). Taking wood-crete with 75% addition of paper fibre as an example (Figure 5), the change of compressive strength can be plotted as polynomial regression with a good fit. The difference (the higher for paper strip) in compressive strength Δy is $0.0002x^2$-0.0217x+0.8881, where x is the boiling time. For example, the strength value at 140mins boiling time is about 35% higher for the wood-crete with 75% of paper strip than that of the de-fibred waste paper. Very similar trend is observed across all treatments (Tables 2 and 3).

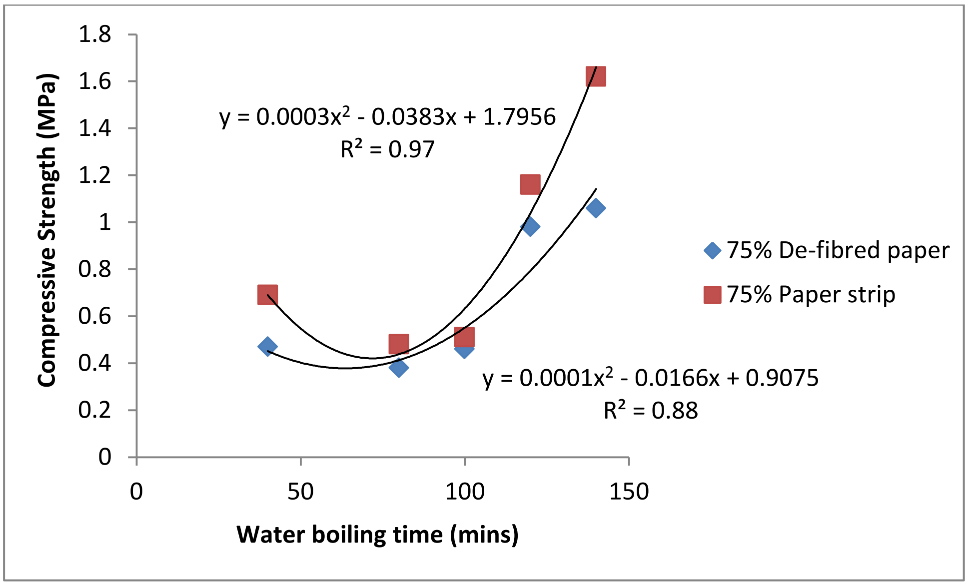


Figure 5 Effect of fibre length on compressive strength

3.7 Effect of de-fibred and paper strip on density of wood-crete

It was noticed that the density of blocks made with de-fibred paper was lower than those made with paper strip. Figure 6 shows two key points: 1) The density of wood-crete made with waste paper are almost the same for all different boiling times (Line 1) although the compressive strength is different between different boiling times; 2) The blocks made with 50% paper strip attained a higher mean density compared to those made with 50% de-fibred paper (Line 2) and the blocks made with 75% paper strip have a higher density than those with 75% de-fibred paper (Line 3). Comparing blocks made with 50% and 75% de-fibred paper, it is noticed that lower percentage of paper showed higher density. This trend is also noticed with blocks made with 50% and 75% paper strip (Table 2 and Figure 6). The reason for a higher density in blocks made with lesser percentage of paper compared to blocks made with higher percentage of paper may be due to compaction during making of wood-crete and loss of moisture.

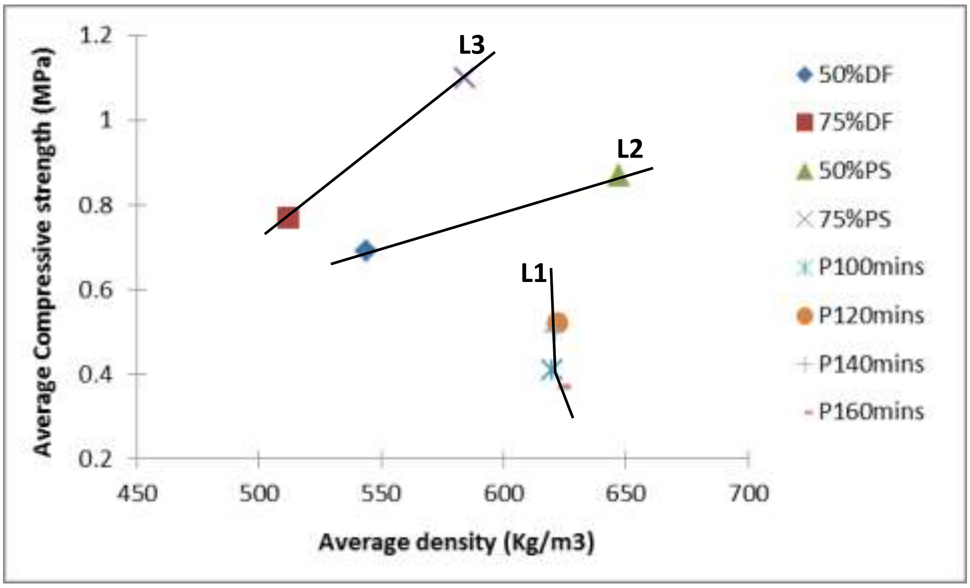


Fig 6 Average compressive strength vs density

The mechanical properties of wood composites generally increase with increasing density. However, in previous study [250], it was discovered that as the density of wood-crete blocks decreased, there was an increase in the compression strength of blocks. This is again confirmed in this study (Figure 6). Considering the results of blocks made with 50% DF and those made with 75% DF, it can be seen that compressive strength increased with decrease in density. The trend also applies to those of blocks with 50% and 75% paper strips (Figure 6). This only suggests that the effect of fibre on mechanical properties is more significant compared to the effect of density. According to Migneault et al 2008 [15], the classical theory of mechanics shows that the load applied to a fibre-reinforced composite material is transferred from matrix to fibres by shear stresses along the fibre-matrix interface, thus transferring efficiency may increase with increasing fibre L/D ratio. The mechanical results observed support the argument [15] and are in conformity with the classical mechanics theory.

Also proven here is that blocks made with PS showed compressive strength significantly higher than blocks made without paper. This is a proof that the presence of fibres contributes to the strength properties of composites. The highest strength property of the treated wood-crete was 1.62MPa but not as comparable as those of normal concrete, but comparable and higher than those of hemp lime composites, e.g. hempcrete. The compression strength value of hempcrete is reported to be between 0.4 and 0.7 depending on mix design [16]. The compressive strength values of blocks were incomparable with those of concrete bricks which have been reported to be in the range of 20 to 35MPa and even up to 65MPa. This means that the treated blocks are not fit for a direct or stand-alone application as structural elements but like hempcrete, can be used in combination with supporting wood structures.

Test results suggest that wood-crete is a ductile material that can sustain large deformations. This kind of deformation has also being noticed and discussed in previous series of wood-crete development [250].

3.8 Performance of wood-crete under water immersion

Water absorption behaviour has been intensively studied due to its important features as it determines end-user applications of most wood composites when are subjected to the environment where moisture conditions change rapidly. Poor resistance of wood to moisture absorption can cause dimensional instability and undesirable effects on the mechanical properties of composite materials [17] [18]. Experimental set up was in accordance with the long term water absorption by total immersion as described in EN1208:1997. After the 28 day period of water absorption, blocks were subjected to compressive strength assessment.

3.8.1 Water absorption

Water uptake of different blocks of wood-crete composites at different periods of immersion are shown in Table 4. The observation reveals the independent of the type of combinations used to make wood-crete. The water absorption increased with less amount of paper content in wood-crete. This was surprising because as expected, it was assumed that the presence of paper fibres in wood-crete would make absorption higher. The inference to this would be that the paper fibres were well coated with the matrix used and it has been reported that matrix absorbs little water [18]. This author also reported that the water absorption in composites is dependent on the presence of wood which interacts with water not only on the surface but also in bulk. The authors went further to explain that wood contains numerous hydroxyl groups (–OH), which are available for interaction with water molecules by hydrogen bonding. Three main regions where water can reside in composites may include: the lumen, the cell wall and the gaps between fibre and matrix in the case of weak interface adhesion. This thus explains the reason for high water absorption with samples made with sawdust to tradical lime ratio of 1:1 compared to those made with ratios 1:2 (Table 4).

Table 4 Effect of time of immersion on different samples of wood-crete composites

No	WP (%)	Density of samples before immersion (kg/m3)	Water absorption (%)		
			7days	14days	28days

All samples made with de-fibred paper and sawdust : tradical lime of 1:2					
A	75	473	0.089	0.092	0.094
B	50	526	0.090	0.095	0.098
C	30	604	0.094	0.099	0.102
D	15	702	0.101	0.105	0.108
E	10	713	0.099	0.102	0.103
F	0	616	0.088	0.089	0.089
All samples made with de-fibred paper and sawdust : tradical lime of 1:1					
G	50	411	0.094	0.097	0.099
H	25	485	0.097	0.103	0.104
I	10	530	0.093	0.098	0.101
J	5	549	0.087	0.091	0.094
K	0	640	0.090	0.091	0.092

Table 4 also shows that across all blocks, the rate of water intake was higher in the first 7 days. The blocks without waste paper also showed a saturation point (where no more water was absorbed and the water content in the blocks remained the same) after 14days of water immersion. However, all other blocks though continued to absorb water did not show great significance in absorption rate. Overall, water absorption is low, around 0.1% even after 28days of water immersion. Test results make a confirmation that the wood-crete can be used in damp areas including bathrooms due to low water absorption rate, if it is not for load bearing purpose. However, they perform better where minimal wetting application is required.

3.8.2 Compressive strength of wood-crete after water absorption

The compressive test results of samples after day 28 are shown in Table 5. Comparing block B with E, only 6% percentage difference is noticed in compressive strength likewise a 2% percentage difference when block E is compared with I (Figure 8 and Table 5). This is evident that the ratio of sawdust to tradical lime did not necessarily play a significant role in the compressive strength of wood-crete after water absorption but rather other factors like the constituent of wood-crete e.g. the addition of waste paper (Figure 8). However, a significant differences in compressive strength are observed in giving an insight of how well wood-crete behaves after being subjected to adverse weather conditions, although the water uptake was very low (Table 4).

Table 5 Compressive strength at day 28

No	WP (%)	Compressive strength (MPa)	Compressive strength (MPa)
		28days water soaked	Dry blocks
All samples made with de-fibred paper and sawdust : tradical lime of 1:2			
A	75	0.094	0.800
B	50	0.090	0.610
C	30	0.088	0.480
D	15	0.080	0.410
E	10	0.074	0.350
F	0	0.061	0.260
No.	**WP (%)**		
All samples made with de-fibred paper and sawdust : tradical lime of 1:1			
G	50	0.092	0.490
H	25	0.083	0.410
I	10	0.071	0.310
J	5	0.063	0.220
K	0	0.068	0.210

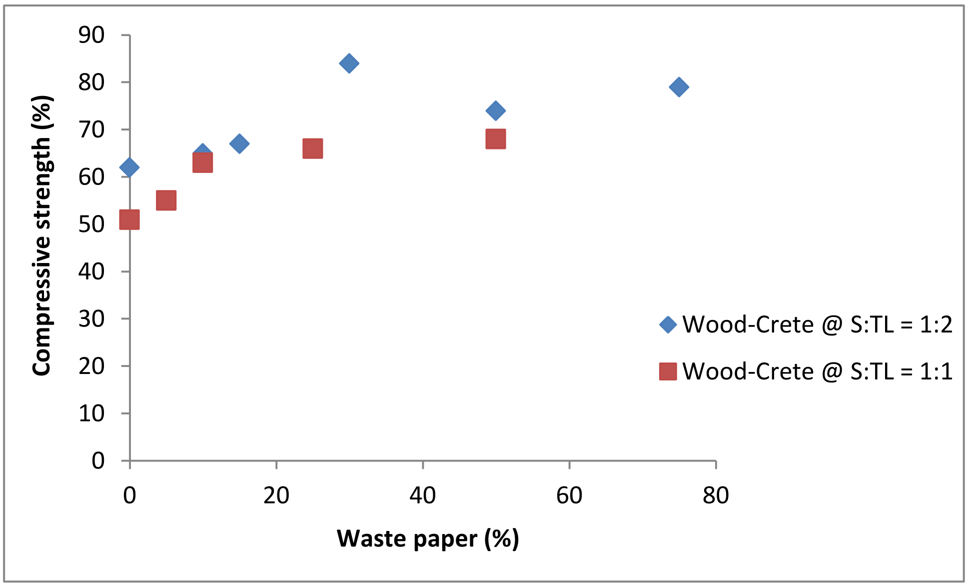


Figure 8 Compressive strength of wood-crete after water soaking

4 CONCLUSION

Improved wood-cretes have been developed with sawdust having various treating regimes and addition of waste papers. The performance of the developed wood-crete has also been assessed under both dry condition and after subjecting to 28 day water soaking. The following conclusions can be drawn:

i) Hot water treatment resulted in a significant improvement of wood-crete, with the compressive strength being increased by about 30% and 260% for hot water boiling treatment and hot water with 4% NaOH treatment respectively. The magnitude of increase was related to the treatment time;

ii) An addition of NaOH was able to extract the soluble content of sawdust effectively, resulting in a gradual increase of compressive strength of wood-crete, but excess NaOH tended to weaken individual wood particle fibres for an adverse effect on the strength of wood-crete;

iii) The combined effect of boiling time of sawdust and addition of waste paper on compressive strength of wood-crete was significant. The correlation of the waste paper reinforced wood-crete with boiling time of saw dust was linear from 0.40 to 1.23MPa for the blocks developed; a higher percentage of waste paper also gave rise to a higher compressive strength;

iv) The geometry of waste paper had an influence on the compressive strength of wood-crete with the treated sawdust, with paper strip being more effective than de-fibred waste paper;

v) The density of wood-crete made with waste paper was almost the same for all different treating times of sawdust although the compressive strength was different. However, the blocks made with paper strip attained a higher mean density compared to those made with de-fibred paper;

vi) 28% water soaking resulted in a little water uptake (about 0.1%) of wood-crete whether sawdust to tradical lime ratio of 1:1 or 1:2. However, the decrease in compressive strength was significant, showing that the wood-crete could be used in damp areas only if it is not for load bearing purpose.

Bibliography

[1] M. Fan, P. Bonfield and J. Dinwoodie, “Nature and Behaviour of Cement Bonded Particleboard: Structurem Physical Property and Movement.,” *Material Science,* vol. 41, no. 17, pp. 5666 - 5678, 2006.

[2] T. A. Plekhanoca, J. Keriene, A. Gailius and G. I. Yakovlev, “Structural, Physical and Mechanical properties of Modified Wood-Magnesia Composite.,” *Building Construction and Materials,* vol. 21, pp. 1833 - 8, 2007.

[3] M. Fan, M. K. Ndikontar, X. Zhou and J. N. Ngamveng, “Cement-bonded Composites made from Tropical Woods: Compactibility of Wood and Cement,” *Construction and Building Materials,* vol. 36, pp. 135 - 140, 2012.

[4] G. Jungmeier, B. Hillring, J. Hurley, M. Humar, A. Fruehwald and C. Gallis, “COST Action E31 – Management of Recovered Wood Proceedings of European COST E31 - Recycling, Bioenergy and other options,” in *Management of Recovered Wood,* Thessaloniki, 2004.

[5] A. Prompunjai and W. Sridach, “Preparation and Some Mechanical Properties of Composite Materials Made from Sawdust, Cassava Starch and Natural Rubber Latex,” *World Academiy of Science, Engineering and Technology,* pp. 930 - 934, 2010.

[6] G. A. Zaikov and A. Jimenez, Polymer Analysis, Degradation and Stabilization, New York: Nova Science Publishers, Inc, 2004.

[7] X. Li, L. G. Tabil and S. Panigrahi, “Chemical Treatments of Natural Fiber for Use in Natural Fiber-Reinforced Composites,” *Journal of Polymers and the Environment,* vol. 15, pp. 25 - 33, 2007.

[8] N. Lopattananon, K. Panawarangkul, K. Sahakaro and B. Ellis, “Performance of Pineapple Leaf Fiber–Natural Rubber Composites: The Effect of Fiber Surface Treatments,” *Journal of Applied Polymer Science,* vol. 102, pp. 1974 - 1984, 2006.

[9] A. K. Bledzki and J. Gassan, “Composites reinforced with cellulose based fibres,” *Progress in Polymer Science,* vol. 24, p. 221, 1999.

[10] E. P. Aigbomian and M. Fan, “Development of Wood-Crete Building Materials from Sawdust and Waste Paper,” *Construction and Building Materials,* vol. 40, pp. 361 - 366, 2013.

[11] British Standard BS EN 12390-2:2009, “Making and Curing Specimens for Strength Test,” BSI, United Kingdom.

[12] British Standard BS EN 12087:1997, “Thermal Insulating Products for Building Applications. Determination of Long Term Water Absorption by Immersion,” BSI, United Kingdom, 1997.

[13] G. Vaickelionis and R. Vaickelioniene, “Cement Hydration in the Presence of Wood Extractives and Pozzolan Mineral Additives,” *Ceramics − Silikáty,* vol. 50, no. 2, pp. 115 - 122, 2006.

[14] H. Kinoshita, K. Kaizu, M. Fukuda, H. Tokunaga, K. Keisuke and K. Ikeda, “Development of Green Composite consists of Woodchips, Bamboo Fibers and Biodegradable Adhesive,” *Composites,* pp. 607 - 612, 2009.

[15] S. Migneault, A. Koubaa, F. Erchiqui, A. Chaala, K. Englund, C. Krause and M. Wolcott, “Effect of Fiber Length on Processing and Properties of Extruded Wood-Fiber/HDPE Composites,” *Journal of Applied Polymer Science,* pp. 1086 - 1092, 2008.

[16] P. D. Bruijn, *Hemp Concretes Mechanical Properties Using Both Shives And Fibres,* Sweden, 2008.

[17] A. K. Bledzki, M. Letman, A. Viksne and L. A. Rence, "Comparison of Compounding Processes and Wood type for Wood Fibre-PP Composites," *Composites Part A: Applied Science and Manufacturing,* vol. 36, no. 6, pp. 789 - 797, 2005.

[18] G. Lulianelli, M. B. Tavares and L. Luetkmeyer, "Water Absorption Behabior and Impact Strength of PVC/Wood Flour Composites," *Chemistry and Chemical Technology,* vol. 4, no. 3, pp. 226 - 299, 2010.

[19] A. Zziwa, S. Kizito, A. Y. Banana, J. R. S. Kaboggoza, R. K. Kambugu and O. E. Sseremba, "Production of Composite Bricks from Sawdust using Portland Cement as a Binder," 2006.

Development of Wood-Crete Building Materials from Wood-Waste and Inorganic Binder

Development of Wood-Crete Building Materials from Wood-Waste and Inorganic Binder

Eboziegbe Patrick Aigbomian and Prof Mizi Fan

Civil Engineering, School of Engineering and Design, Brunel University, Uxbridge, Middlesex, UK
Email - eboziegbe.aigbomian@brunel.ac.uk

ABSTRACT

This study was to develop a new building material, wood-crete, using sawdust, waste paper and tradical lime. The paper presents the processing technologies, factors which affect the performance of the developed composites and properties of wood-crete. Properties of wood-crete were investigated based on; (1) the type of wood sawdust – hardwood (beech and oak) and softwood (pine and cedar); (2) modification of sawdust by hot water boiling, alkaline treatment and the addition of different types of waste paper. The results showed that; (1) lightweight sustainable blocks can be produced with good insulating and other relevant properties for building construction with compressive strength of up to 3.93MPa; (2) the compressive strength of wood-crete was closely related to the wood species, with the compressive strength of 3.93MPa being for hardwood wood-crete compared to 1.37MPa and 0.26MPa of wood-crete from softwood and mixed wood respectively; (3) surface modification, processing of cellulosic fibril and the extraction of lignin and hemi-cellulosic compounds with alkali had an effect on the compressive strength of wood-crete, with treating sawdust with 4% NaOH at 140mins of boiling time achieving the highest increase of 260% compressive strength. The properties were closely related to the composition of wood-crete with an addition of waste paper being a dominant influence on strength, reflecting its effect on the structure of composite and contribution of self strength of paper fibres. Of significant importance was the contribution of self strength of wood-crete due to the influence of the size of sawdust particles used. The developed wood-crete was able to withstand considerable amount of impact load and considered, like hempcrete, most suitable for wall panelling or other non- and semi-structural applications.

Keywords: Wood-Crete; tradical Lime, sawdust, compressive strength, thermal conductivity.