

Manufacturing cement-based materials and building products via extrusion: from laboratory to factory

1 **Xiangming Zhou** BEng, MEng(Res), PhD, PGCert
Senior Lecturer in Civil Engineering, Brunel University, Uxbridge, UK

2 **Zongjin Li** BEng, MSc, PhD, PE, MHKIE
Professor in Civil Engineering Materials, Hong Kong University of
Science and Technology, Hong Kong



Manufacturing is critical to the economies of the UK and many other countries in the rest of the world. However, manufacturing of cement-based materials and building products predominantly remains based on old batch-processing techniques such as casting and pressing, and this may limit the applications and performance of the materials and products formed. This paper reports on research into transforming the manufacturing of precast cement-based materials and building products from in batches to continuous processes by way of extrusion. Techniques used for producing plastic products are transferred into manufacturing cement-based building products, such as flat and corrugated sheet tiles, downpipes, door and window frames, door panels, solid wall and facade panels, and honeycomb wall and facade panels, both at laboratory and factory scales. In combination with sustainable cementitious materials with low carbon dioxide emissions and low energy consumption as the matrix, this enables sustainable building products to be manufactured by way of extrusion.

1. Introduction

Manufacturing is critical to the economy of the UK and many other countries. Manufacturing directly accounts for 10% of the UK's gross domestic product and employs 2.5 million people, 9% of the employed labour force (Lavery *et al.*, 2013). However, the UK manufacturing industry is facing rising labour, material and energy costs and tightening environmental restrictions.

The UK government is committed to reducing the country's greenhouse gas emissions by 80% compared with 1990 levels by 2050. It is also committed to improving the capability and competitiveness of the manufacturing industry. Therefore, more efficient and greener manufacturing methods that can make significant contributions to the economy are urgently needed. Considering the huge volume of building products manufactured every year in the UK, a significant contribution to reaching national carbon dioxide emissions reduction targets could be achieved by enhancing the efficiency and sustainability of manufacturing methods for building products.

Cement-based materials are the most widely used construction materials and building products. However, their manufacture is predominantly based on old batch-processing techniques such as

casting and pressing technologies, which limits the application and performance of the products formed. Batch processing is also labour and energy intensive.

Advanced manufacturing techniques could enhance material properties, reduce carbon dioxide emissions and energy consumption, generate less waste, make more efficient use of raw materials, generate additional profits and create new manufacturing jobs. Though the added value to a single unit may not be great, by considering the amount of Portland cement produced in the UK and in the world (10 Mt/y and 4 Gt/y respectively), the added economic, environmental and social benefits of advancing manufacturing techniques of cement-based materials and building products could be huge.

Many cement-based building products are reinforced with short discrete fibres. The performance of cementitious composites reinforced with short discontinuous fibres is comparable to that obtained with continuous aligned fibres or mats (Aldea *et al.*, 1998). However, the fibre-cement industry is still using a traditional processing technique, the Hatschek process, which was invented more than 100 years ago. Since then, this process has been the main commercial production method for fibre-reinforced cementitious roofing and cladding products, and has undergone little change.

Although the Hatschek method is a continuous process, composites made by this method are usually brittle (Li and Mu, 1998). The process generates a high level of wastewater and delamination of layers has been found in cement-based products made by this method during freeze–thaw cycles (Shao and Qiu, 2002). Products also exhibit a relatively high sorption and permeability (Shao and Qiu, 2002). An alternative processing method for fibre-cement building materials and products is thus needed – and extrusion could be the answer.

Extrusion is a commonly used material processing method throughout the ceramic, mechanical, chemical and pharmaceutical industries. This plastic-forming process consists of forcing a highly viscous, semi-solid, dough-like plastic mixture through a shaped die of desirable section. The process is continuous and simpler to use than many other conventional methods, and is therefore highly suited for industrial-scale mass production. Extrusion technology has begun to be employed by the fibre-cement industry as an alternative method for manufacturing high-performance fibre-cement building materials for traditional products such as bricks, tiles and pipes as well as advanced products such as honeycomb panels.

The advantage of introducing extrusion into fibre-cement products processing is that the materials are formed under high shear and compression during the extrusion process. This results in formed composites with improved performance. For the fibre-cement manufacturing industry, the extrusion technique enables flexibility in fast fabrication of building products with regular or complicated shapes (e.g. finely structured honeycomb panels, window and door frames, and wave-shaped roof tiles) without the need for moulds, which can reduce labour costs and, consequently, production costs.

The semi-solid nature of the extruded materials means that the curing time for cement-based products can be significantly reduced. Qian *et al.* (2003) found that short discrete fibres can be aligned along the extrusion direction, so that the extrusion technique can also substantially improve the mechanical performance of fibre-cement composites and products. Extrusion can produce fibre-reinforced cement composites with a well-consolidated matrix and good fibre packing, resulting in low porosity and a strengthened fibre–matrix bond, which in turn leads to enhanced mechanical properties and durability (Peled and Shah, 2003; Teixeira *et al.*, 2012).

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There are, however, disadvantages to employing extrusion in manufacturing fibre-cement materials and building products. Generally, the extrusion of fibre-cement materials requires compositional changes and relatively costly specialist processing additives, such as hydroxypropyl methylcellulose (Methocel, Dow Chemical Company), to facilitate extrusion. The degree of compaction in the extrusion process also decreases with increasing fibre content.

2. Key factors to the extrusion of cement-based materials

A successful and successive extrusion process largely depends on the rheology of the ‘green’ material during extrusion, the extrusion system and the interface between the green material and the extruder (including extruder screw, die-land and die-exit) during the process. Fresh cement-based materials suitable for extrusion (see Figure 1) exhibit semi-solid, dough-like rheological properties (Srinivasan *et al.*, 1999) that are quite different from traditional fresh cement paste or mortar, which usually possesses a much higher water to cement ratio and flowability.

Cement-based dough-like fresh materials suitable for extrusion exhibit almost no fluidity but high cohesion under normal conditions. Only during extrusion are these fresh paste-like materials forced to flow in an extruder until being extruded out of the die-exit. Differing from polymeric materials that exhibit mainly viscous properties and become solid after being extruded out of the die-exit due to a phase change, cement-based dough-like materials tailored for extrusion exhibit coupled elastic, viscous and plastic rheological properties.

In the materials processing industry, rheological properties of materials are important for selecting processing conditions that enable a smooth extrusion process. However, it is not possible to use one single test to characterise the coupled elasto-visco-plastic rheological properties of cement-based materials tailored for extrusion (Zhou *et al.*, 2013).

Alfani and Guerrini (2005) reviewed the most promising ‘non-traditional’ rheology test methods for concentrated and cohesive extrudable fresh cement-based materials and found that those ‘promising’ test methods were initially developed for materials such as plastics, rubber, clays, soils and metals, rather than traditional cement pastes or mortars with high flowability. Zhou *et al.* (2013)



Figure 1. Semi-solid, dough-like fresh cement-based materials for extrusion: (a) during mixing not suitable for extrusion; (b) suitable for extrusion

provide a summary of the non-traditional rheology test methods for semi-solid, dough-like fresh cement-based materials for extrusion, which include ram extrusion (Srinivasan *et al.*, 1999; Zhou and Li, 2005a), capillary extrusion (Zhou and Li, 2005b), orifice extrusion (Zhou *et al.*, 2013), upsetting and squeezing flow (Li and Li, 2007; Toutou *et al.*, 2005; Zhou and Li, 2006).

An elasto-visco-plastic constitutive model was proposed by Zhou and Li (2011) for simulation of the coupled elasto-visco-plastic rheological properties of semi-solid, dough-like fresh cement-based materials for extrusion. The constitutive model was successfully employed in simulating the monotonic upsetting process (Zhou and Li, 2007) and the ram extrusion process (Zhou and Li, 2009) of semi-solid, dough-like fibre-reinforced fresh cement-based materials tailored for extrusion. On the other hand, Perrot *et al.* (2009) proposed linking the rheological concepts of firm cement-based materials and soil mechanics and established a simple criterion to predict the extrusion ability of a mortar.

Zhou and Rong (2014) employed a direct shear box test from soil mechanics and characterised the rheological properties of semi-solid, dough-like fresh fibre-cement composites for extrusion. The results were interpreted by a Mohr–Coulomb failure envelope. The effects of fibre volume and water content on the overall rheological properties of the materials for extrusion were characterised, which is helpful in selecting material compositions. They concluded that the direct shear box test is a simple but efficient test method for characterising the rheology of semi-solid, dough-like fresh cement-based materials for extrusion. Nevertheless, trial-and-error is always helpful in tailoring material formulations.

Practically, ram extrusion is a simple but promising method that can give an indication of rheological properties and, most importantly, the extrudability of fibre-reinforced fresh cement-based paste-like materials. The ram extrusion mechanism is illustrated well by the Benbow–Bridgwater model, which is based on the assumption of plastic deformation in die-entry and plug flow in die-land. As schematically presented in Figure 2(a),

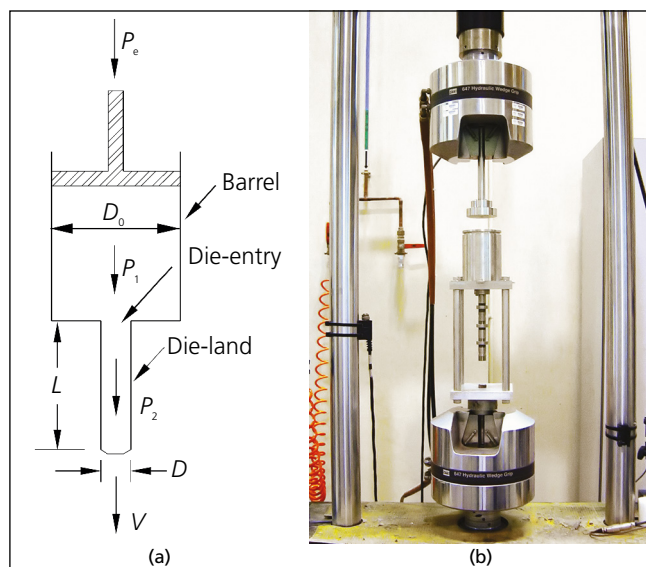


Figure 2. (a) Schematic illustration of ram extrusion. (b) Laboratory-scale ram extruder

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the total extrusion pressure drop (P_e) through a circular die with a die-entry angle of 90° can be calculated by the equation proposed by Benbow and Bridgwater (1993).

Ram extruders can therefore be employed as a form of rheometer to provide a means of characterising the bulk and interfacial rheology of paste-like materials tailored for extrusion. The total extrusion pressure P_e at the upstream of material flow gives an indication of the rheological properties and extrudability of the semi-solid, dough-like material being processed. A higher pressure is required to extrude a stiffer paste-like material in ram extrusion. It can also be used to study the effect of individual compositions (e.g. binder, fibre and water contents) on the overall rheology and extrudability of the composite materials during extrusion.

Ram extrusion can also be employed to investigate the effects of the extrude–extruder interface on the extrudability of fibre-cement fresh materials tailored for extrusion. A typical laboratory-scale ram extruder for tailoring the rheology and extrudability of fibre-cement dough-like fresh materials for extrusion is shown in Figure 2(b). Comprehensive studies on the effects of various compositions on overall rheology and extrudability of fresh cement-based materials for extrusion by way of ram extrusion have been presented by Srinivasan *et al.* (1999) and Zhou and Li (2005a), respectively. It should be noted, however, that the experience gained from ram extrusion cannot be directly applied to screw-based extrusion due to different materials flow in the two methods.



Figure 3. Screw extruder for pilot study of extrusion of fibre-cement building products

Ram extrusion is an intermittent process, whereas screw-based extrusion can be a continuous process with raw materials fed at the upstream and products obtained at the downstream of the extrusion flow. Nevertheless, ram extrusion can be regarded as an indicator of the extrudability of materials and trial-and-error is always helpful in scaling up laboratory research to industrial production.

In a few laboratories around the world, various fibre-cement building products have been successfully produced, mainly by pilot-scale screw extruders (such as the one shown in Figure 3). These extruded building products include

- high-performance fibre-reinforced cementitious composite pipes (Stang and Pedersen, 1996)
- fibre-reinforced cement pressure pipes (Aldea *et al.*, 1998)
- fibre-reinforced cement-based flat sheets (Li *et al.*, 2001)
- cement-based lightweight and high-temperature-resistant flat sheets with perlite as aggregate (Li *et al.*, 2004)
- geopolymer composite building products (Li *et al.*, 2005)
- nailable high-performance fibre-reinforced cement-based composites (Kuder and Shah, 2007)
- functionally graded fibre-reinforced cement composites (Shen *et al.*, 2008)
- lightweight wood–magnesium oxychloride cement composite building products, which are also nailable and can be machined like wood (Figure 4) (Zhou and Li, 2012).

Large partition wall panels with a honeycomb cross-section measuring 600 mm × 90 mm have already been continuously produced in a new extrusion factory in Hangzhou, China



Figure 4. Extruded wood–magnesium oxychloride cement composites: (a) door frame and panels made of extruded products; (b) corner of the door with frames connected by angle steel and nails

In addition, in the extruded building products, significant amounts of Portland cement were replaced by industry by-product supplementary cementitious materials (e.g. pulverised-fuel ash, ground granulated blast-furnace slag and metakaolin), which reduces embodied carbon dioxide and energy. The extrusion technique itself is regarded as a low-energy process. It is also a wet process, which can therefore reduce the troublesome issue of dust generation associated with the manufacture of cement-based products.

3. Transformation of the extrusion technique to the fibre-cement industry

The extrusion technique for manufacturing fibre-cement building products has recently been successfully applied in industry. A large extruder for processing fibre-cement composite building products has been invented (Figure 5) and a fibre-cement building products extrusion factory has been established in Hangzhou, China (Figure 6). Large partition wall panels with a honeycomb cross-section of dimensions 600 mm × 90 mm (Figures 7 and Figure 8) have been continuously produced in the factory to serve the needs of infrastructure development (e.g. residential buildings, offices and hotels) in Hangzhou. The extruder can be used for manufacturing fibre-cement building products with other cross-sections by just changing the shape of the die, indicating the flexibility of the extrusion system itself.

The European Commission has funded the project 'Nanotechnology enhanced extruded fibre reinforced foam cement based environmentally friendly sandwich material for building applications' (FIBCEM project) through the seventh research framework programme. One of the objectives of this project is to develop extrusion techniques for the commercial production of fibre-reinforced cement-based building products of various geometries, in particular roofing tiles and sidings. The project consortium consists of both research organisations and commercial enterprises, with the

latter providing the knowledge and capability of creating economic and safe products based on the extrusion technology developed. It is expected that the extrusion technology developed in the FIBCEM project will be exploited by industry partners for commercial production of fibre-cement building products.

4. Conclusions

After two decades of research and development into extrusion techniques for the manufacture of cement-based materials and building products, the following conclusions can be drawn.

Firstly, extrusion is a promising materials processing technique for short discrete fibre-reinforced semi-solid, dough-like cement-based fresh materials to be used in the manufacture of building products.

The extrusion technique developed for manufacturing cement-based materials and building products has been validated in the laboratory and by pilot-scale production. It has also been scaled up for industrial mass production and has great potential in the construction industry



Figure 5. Factory-scale extruder for manufacturing fibre-cement building products

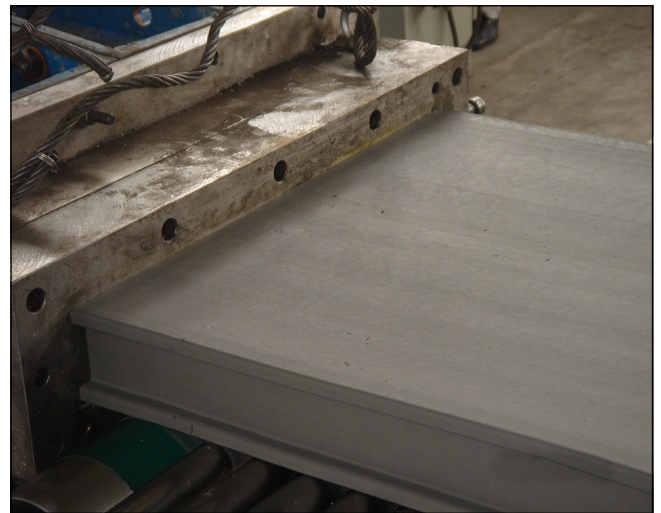


Figure 7. Fibre-cement extrudate just after die-exit



Figure 6. Overview of fibre-cement building products extrusion factory

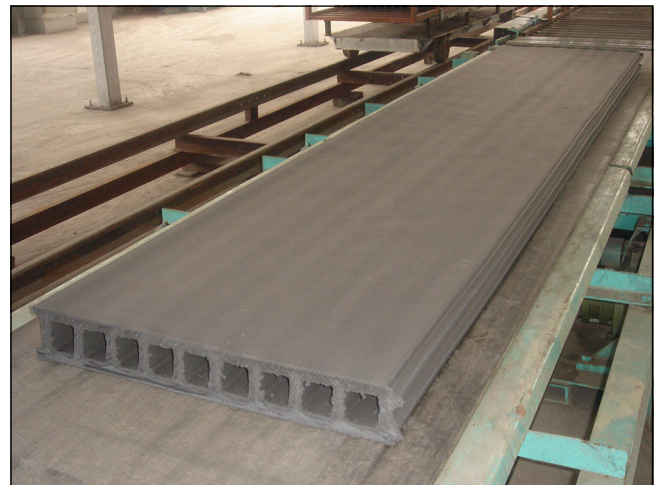


Figure 8. Extruded honeycomb fibre-cement partition wall panel of 600 mm x 90 mm cross-section and several metres long

Secondly, to achieve successive and successful extrusion of cement-based materials, appropriate rheological properties need to be attained and held during the process. Cement-based fresh materials suitable for extrusion exhibit coupled elastic, viscous and plastic rheological properties. Various test methods have been proposed for characterising the rheology of such semi-solid, dough-like fibre-reinforced fresh cement-based materials for extrusion.

Thirdly, the extrusion technique developed for manufacturing cement-based materials and building products has been validated in the laboratory and by pilot-scale production. It has also been scaled up for industrial mass production. The extrusion of cement-based materials for manufacturing building products has great potential in the construction industry.

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