THE INFLUENCE OF NEAR SURFACE MOISTURE AND SPECIMEN THICKNESS ON CONCRETE PROTECTION TREATMENT

Mazen J. Al-Kheetan, Corresponding Author
Department of Civil and Environmental Engineering
College of Engineering, Design and Physical Sciences
Brunel University London
Kingston Ln, Uxbridge, Middlesex, United Kingdom, UB8 3PH
Tel: 44-189-5267-590; Email: mazen.al-kheetan@brunel.ac.uk

Mujib M. Rahman
Department of Civil and Environmental Engineering
College of Engineering, Design and Physical Sciences
Brunel University London
Kingston Ln, Uxbridge, Middlesex, United Kingdom, UB8 3PH
Tel: 44-189-5267-590; Email: mujib.rahman@brunel.ac.uk

Denis A. Chamberlain
Department of Civil and Environmental Engineering
College of Engineering, Design and Physical Sciences
Brunel University London
Kingston Ln, Uxbridge, Middlesex, United Kingdom, UB8 3PH
Tel: 44-189-5267-590; Email: denis.chamberlain@brunel.ac.uk

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ABSTRACT:
Moisture content at the time of applying the protective material to concrete has the major influence on the success or failure of the treatment process. The code of practice, BD 43/03 and BS EN 1504-2, suggests a maximum moisture content of approximately 5.0% at the time of applying the treatment. However, this moisture content is the bulk moisture content which is not representative for the 'near surface' moisture content. A new idiom is presented in this study that represents the theoretical moisture content at the time of application. "Apparent moisture content" is the water present near the surface of concrete and has the major effect on the application of protective materials. In the second part of this research, the efficacy of two hydrophobic materials were tested in terms of water absorption protection. Also, results from the Scanning Electron Microscope (SEM) for the formation and distribution of the applied protective materials has been presented in this research.

Key words: Moisture content, Bulk moisture, Apparent moisture, Concrete, Hydrophobic treatment, Water absorption

INTRODUCTION

Concrete has been used as the major construction material in many transportation infrastructures like highways, bridges, airports, parking spaces, embankment and port (*1*). Concrete used for this purpose is known to have a higher-priced basic expenditure than asphalt pavement, nevertheless it has a longer lifespan and lower maintenance costs *(2)*. However, like any exposed infrastructures, concrete pavement encounters degradation due to traffic and environmental loading such as water ingress, freezing and thawing, chloride penetration, and sulphate attacks (*3, 4*). Accordingly, it is necessary to protect concrete from water and aggressive chemicals and enhance its durability.

Many chemical materials have been used to treat and to waterproof concrete, either when concrete is in its fresh state or in matured state. The most commonly used protections materials are silane and siloxane based materials, cementitious coatings, crystallising materials, polymers, acrylic coatings, polyurethanes, epoxy, etc. (*5-9*). Other natural materials were also investigated by researchers, as alternatives to chemical ones, to enhance concrete durability and waterproofing, and at the same time lower the risk of contamination that other chemical materials impose to environment. These natural materials include vegetable oils, animal blood, and animal fats (*9-12)*. Moisture content of concrete, at the time of applying the treatment, is believed to be the main factor that affects the performance of these protective materials (*13-16, and 5*).

Moisture content is governed mainly by the pores distribution on the surface of the concrete (*17*). When smaller sizes of the pores exist on the surface, smaller than 100 nm in diameter, the amount of the absorbed water will be fewer. Accordingly, the quantity of pores that have diameters larger than 100 nm will significantly affect the amount of absorbed water. Also, it was found that moisture content is highly influenced by the small amount of water that has already been confined inside pores with diameters less than 10 nm; when water exists in these pores, it is missed in pores with larger diameters.

The amount of absorbed water in concrete was found to decrease with increasing the initial moisture content, as a result to the diminution of the pressure inside the capillary pores, where pores with large diameters have the most significant contribution in water transport, along with the high viscous strength of absorbed water when entering the capillary pores that is already occupied with water (*18*).

In another study, where the fractal geometry theory was used to quantify the pore distribution in different concrete types, it was found that C30 concrete has the least ability to absorb water, when compared with C20 and C40 concrete. This refers to pores distribution in these concrete mixes, where C30 concrete devises the least pore structure distributed along its structure, which is reflected on the quantity of the absorbed water (*19*).

Moisture content in the pores of concrete has a great effect on the behaviour and properties of tested concrete samples (*20*). According to the design manual for roads and bridges BD 43/03, moisture content of concrete should be equivalent to 5.0 ±0.5% at the time of applying protective treatment (*21*). In addition, it is recommended that the application of protection material should take place on a “dry surface” to allow correct penetration of the product and hence maximum effectiveness. However, a dry surface does not necessarily mean the concrete has low internal moisture content especially after a prolong period of wet weather. Recently, there have been growing concern regarding the on-site performance of all hydrophobic impregnation materials, traditional and alternative (*22*). It seems that there is a marked discrepancy between outcomes of laboratory testing and apparent defence of actual treated structures.

It is probable that climatic conditions and moisture content prevailing at material application time are extremely influential in this. They bear directly on the achievable dosage with protection materials and thus the starting level of production provided. Research has shown that the effective dosage of the material largely related on the moisture content of the substrate (*23*). This may cause to a waste in the amount of protective materials applied to concrete and potentially become less protected. Accordingly, some questions have emerged, during time, therefore to results obtained in the previous researches of the authors of this paper, which led to the validity of the recommendation of 5.0% moisture content specified in the BD 43/03 and BS EN 1504-2. This moisture content is believed to be higher at the vicinity of the surface than what it is stated in the BD 43/03. In other words, authors believe that the recommended 5.0% moisture content is not the true representation of the actual near surface moisture which significantly impact the performance of protection material. The near surface moisture content is likely to significantly higher than 5%. It is therefore important to understand how moisture content varies across the depth of the specimen and develop a relationship between the near surface moisture and bulk moisture, and it is rather to be near the surface of the concrete, not within the concrete as a bulk. This approach will to determine a relationship between near surface moisture and effective dosage, which ultimately leads to more reliable performance from the protection materials.

RESEARCH OBJECTIVES

The work presented in this paper has three specific objectives:

(1) Investigate the influence of specimen geometry on the water absorption over a period and determine how moisture content changes with geometry of the specimens.

(2) Develop a relationship between near surface moisture content (apparent moisture content) and bulk moisture content (overall) of the concrete, and to determine the discrepancy of bulk moisture content and apparent moisture content.

(3) Investigate the efficacy of protective materials in terms of water absorption when applied in concrete with different thickness.

EXPERIMENTAL WORK

The experimental program is divided into two major parts. In part one, the concentration is given to establish a relationship between near surface moisture and bulk moisture; distinguish between the apparent and the bulk moisture content of concrete before applying the hydrophobic treatment, and determine the water absorption of treated and untreated concrete to evaluate the efficacy of two hydrophobic impregnants.

Mixture design

A C40 concrete mix with a w/c ratio of 0.46 was produced in this research, following the British Standard BS 1881-125 (*24*). The composition and proportions of the tested concrete is shown in Table 1. Slump value of this concrete mix was determined to be 70 mm.

TABLE 1 Adopted Mix Design (*24*)

Component	Quantity (Kg/m^3)
Cement	457
Water	210
Fine aggregate	660
Coarse aggregate	1073
Total	2400
Water/Cement ratio	0.46

Specimens manufacture

A total of 75 slabs, with five different thicknesses, were produced and cured in a water bath, at a temperature 20 °C, for 28 days. Slabs were divided into three groups; 25 slabs were treated with Fluoropolymers, 25 slabs treated with silicate resins, and 25 slabs were used as a control. Each group consisted of 5 different geometry; 150 mm x 150 mm x 150 mm, 150 mm x 150 mm x 120 mm, 150 mm x 150 mm x 90 mm, 150 mm x 150 mm x 60 mm, and 150 mm x 150 mm x 30 mm. Protective materials were brushed to all the sides of the concrete slabs, following manufacturer guidelines and the related standards BS EN 1504-2 (*22*).

Hydrophobic treatment

Two widely used hydrophobic protective materials, an aqueous fluoropolymer and an aqueous silicate resin, were applied on mature concrete to monitor their interaction with water. Materials were applied with a rate of 200 ml/m^2, following manufacture's guidelines, to concrete.

Water absorption resistance

All slabs, treated and control, were fully immersed in water for one week to achieve the stated objectives of this study. The saturated surface dry weight of control slabs was measured after immersion in 1 hour, 3 hours, 24 hours, 48 hours, and 1 week. Treated concrete slabs were weighed after 10 minutes, 30 minutes, 1 hour, 2 hours, 3 hours, 4 hours, 24 hours, 48 hours, 72 hours, and 1 week of immersion in water, to get their saturated surface dry weights as well. The average absorption rate, for both treated and untreated slabs, was determined at each time interval, as a percentage of the absorbed water to the original dry weight of concrete.

Bulk and Apparent Moisture Content

Slabs were fully immersed under water for 1 week and they were weighed using the same intervals as the water absorption test described in previous section. The following formula was used to determine bulk moisture content:

$$\text{Moisture content (\%)} = \frac{M_{wet}-M_{dry}}{M_{dry}} x100\% \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

Where, M_{dry}: Mass of dry concrete (g), M_{wet}: Mass of wet concrete (g)

All parameters that from equation 1 were calculated by considering the full size of the specimens. For example, if the moisture content was calculated for a slab with dimensions of 150 mm x 150 mm x 150 mm, then

M_{dry} will be the full mass of the slab, and M_{wet} will be the whole mass of the slab and the absorbed water, assuming that water has fully penetrated to the slab and distributed evenly across its volume.

As the primary water transport mechanisms in concrete are capillary absorption and permeability, it can be assumed that water enters at the surface and then gradually penetrates to the depth of concrete. However, the capillary action is more significant near the surface than the permeability of concrete. Therefore, in this research, the apparent moisture (near surface) content was theoretically determined at different depths of 1 mm, 2 mm, 5 mm, and 10 mm from the surface of the slab from equation 1, by assuming that for same density material, all absorbed water was initially concentrated at 1mm depth and then gradually moves to 2mm and so on. The process is schematically shown in Figure 1.

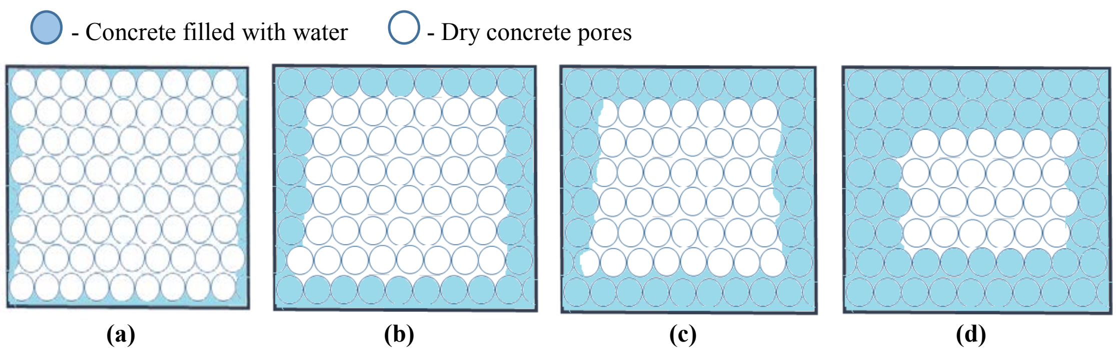


FIGURE 1 Idealised schmematic diagram for the presence of moisture in the near surface area of a concrete sample at: (a) 1 mm depth, (b) 2 mm depth, (c) 5 mm depth, and (d) 10 mm depth.

In this way, the water intake per surface area (ml/m²) and water intake per volume (ml/m³) were measured at different intervals for up to one-week. By rearranging equation 1 and utilising mass volume relation, the apparent moisture content was derived and is presented in equation 2.

$$\text{Moisture content (\%)} = \frac{M_{wet} - M_{dry}}{M_{dry}} x100\%$$

$$M_w = M_{wet} - M_{dry}$$

$$\rho_d = \frac{M_{dry}}{V_d}$$

$$\text{Apparent moisture content (\%)} = \frac{M_w}{\rho_d x V_d} x100\% \ldots\ldots\ldots\ldots (2)$$

Where, M_w: Mass of the absorbed water (g) ρ_d,: Density of dry concrete (g/cm³), and V_d: Volume of the layer with depth d from the surface (cm³).

Dry density of concrete slabs was calculated for each slab thickness and they were found very similar despite different geometry. Table 2 shows dry densities of all specimens.

TABLE 2 Dry Densities of C40 Concrete with Different Thicknesses

Slab Thickness (mm)	Dry Density (g/cm³)	Standard Deviation
150 mm	2.2114	0.01826
120 mm	2.2208	0.00894
90 mm	2.2504	0.02416
60 mm	2.1954	0.02858
30 mm	2.2104	0.10381

RESULTS AND DISCUSSIONS

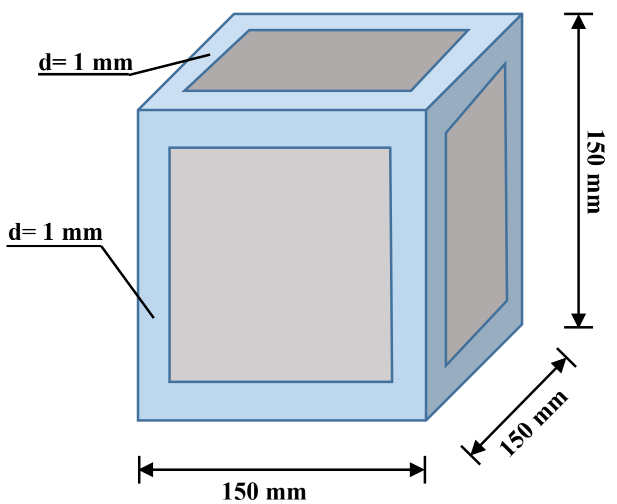
Part 1: Relationship between near surface moisture and bulk moisture

Bulk moisture content and surface moisture content (apparent) at different depths from concrete surface, during 1 week period, were measured for all slabs, and results are illustrated in Table 3. It is apparent from the table that near surface moisture content is significantly higher than the bulk moisture content.

TABLE 3 Moisture Content of Different Concrete Slabs Measured Near the Surface and as A Bulk

Slab thickness (mm)	Bulk moisture content (%)					Tested depth (mm)	Apparent moisture content (%)				
	1 hour	3 hours	24 hours	48 hours	168 hours		1 hour	3 hours	24 hours	48 hours	168 hours
150	1.5	1.6	1.9	2.0	2.3		38.5	41.8	47.1	51.8	57.7
120	1.7	1.8	2.0	2.2	2.5		40.3	42.4	47.0	50.7	58.6
90	1.5	1.7	1.9	2.1	2.3	1 mm	31.2	35.3	40.3	44.0	48.4
60	1.7	1.9	2.2	2.5	2.5		28.6	32.1	37.4	41.5	42.6
30	3.0	3.4	3.8	3.9	4.0		33.1	37.2	41.0	42.7	43.2
150	1.5	1.6	1.9	2.0	2.3		19.5	21.2	23.8	26.3	29.2
120	1.7	1.8	2.0	2.2	2.5		20.4	21.5	23.8	25.7	29.7
90	1.5	1.7	1.9	2.1	2.3	2 mm	15.8	17.9	20.5	22.3	24.6
60	1.7	1.9	2.2	2.5	2.5		14.5	16.3	19.0	21.1	21.7
30	3.0	3.4	3.8	3.9	4.0		16.9	19.0	21.0	21.8	22.1
150	1.5	1.6	1.9	2.0	2.3		8.1	8.8	9.9	10.9	12.2
120	1.7	1.8	2.0	2.2	2.5		8.5	9.0	10.0	10.8	12.4
90	1.5	1.7	1.9	2.1	2.3	5 mm	6.6	7.5	8.6	9.4	10.3
60	1.7	1.9	2.2	2.5	2.5		6.1	6.9	8.0	8.9	9.2
30	3.0	3.4	3.8	3.9	4.0		7.2	8.1	8.9	9.3	9.4
150	1.5	1.6	1.9	2.0	2.3		4.4	4.7	5.3	5.9	6.5
120	1.7	1.8	2.0	2.2	2.5		4.6	4.8	5.4	5.8	6.7
90	1.5	1.7	1.9	2.1	2.3	10 mm	3.6	4.1	4.7	5.1	5.6
60	1.7	1.9	2.2	2.5	2.5		3.5	4.0	4.6	5.1	5.3
30	3.0	3.4	3.8	3.9	4.0		4.0	4.5	5.0	5.2	5.3

For example, the moisture content, of a 150 mm^3 cube, after 1 week of immersion in water, is 2.3% according to the advices of the code of practice, whereas a 57.7% moisture content is what exists within 1 mm of the surface (Figure 2). This large difference between the two measured moisture contents will have impact on the dosage of surface treatments.



Immersion period (hours)	*168*
M_w (g)	*170*
ρ_d (g/cm^3)	*2.4*
Slab thickness (mm)	*150*
d (mm)	*1*
V_d (mm^3)	*133208*
Apparent moisture content (%)	*57.7%*
Bulk moisture content (%)	*2.3%*

FIGURE 2 An illustration for apparent and bulk moisture contents for 150 mm x 150 mm x 150 mm slab after 1 week of immersion in water and at depth d= 1 mm from the surface.

Figures 3 a-d interpret the previous results into a more representative way, where a comparison between bulk and apparent moisture contents is made.

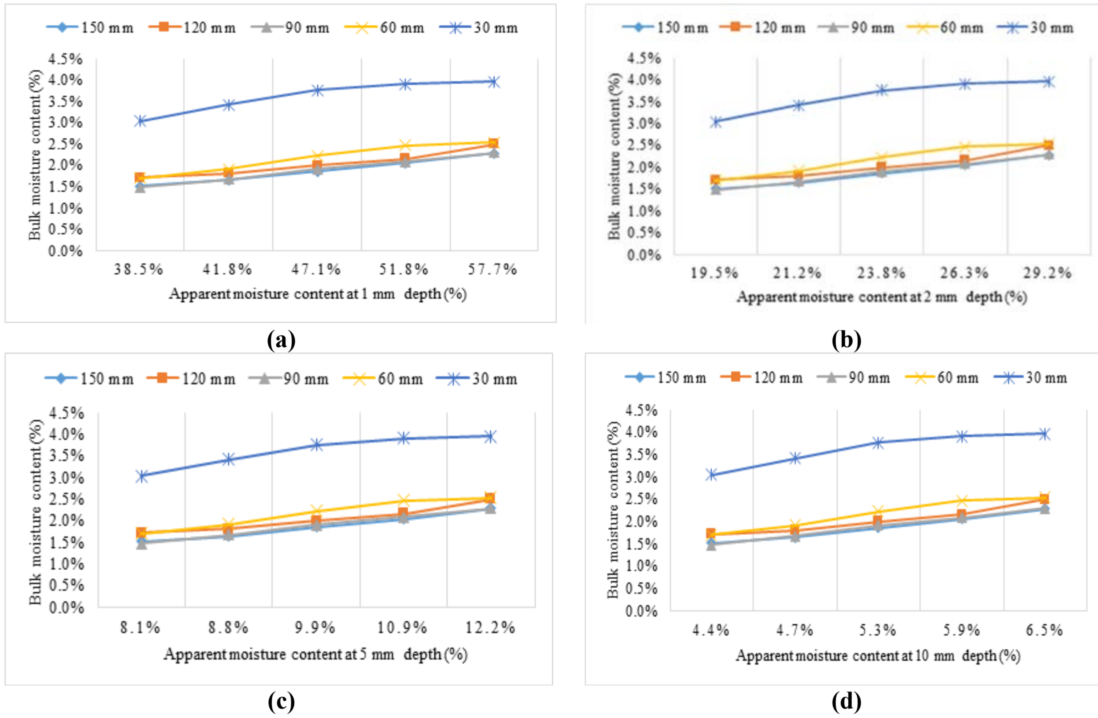


FIGURE 3 Concrete bulk moisture content and apparent moistuire content at: (a) 1 mm (b) 2 mm (c) 5 mm and (d) 10 mm from the surface of concrete.

The difference between the apparent and bulk moisture contents continues to appear regardless the size of the slab. However, this difference is lower, still significant, in the case of 30 mm slabs, where the two values get closer to each other with increasing the depth of testing. It is clear from Figure 3 that slabs with 30 mm thickness have the least divergent values for apparent moisture contents from the bulk moisture contents, and, at the same time, they have diverged and performed differently from slabs with other sizes. All concrete slabs with thicknesses range from 60 mm to 150 mm have shown similar performance to each other and a more clustered behaviour, as their moisture content values are close to each other. This behaviour could be noticed through all the tested depths.

All of that refer to the thickness of the slab, as decreasing the thickness to a very small value makes water absorption faster and easier than that in concrete with large thickness, which results in a very close value for moisture contents either on the surface or inside the slab.

Water intake per surface area vs. water intake per volume

Water intake for concrete has also been studied to check the amount of water that penetrates through the surface area of concrete, and the amount that goes per volume. Figures 4a and 4b show the water absorption per surface area against per volume, respectively, of untreated concrete during 1-week period.

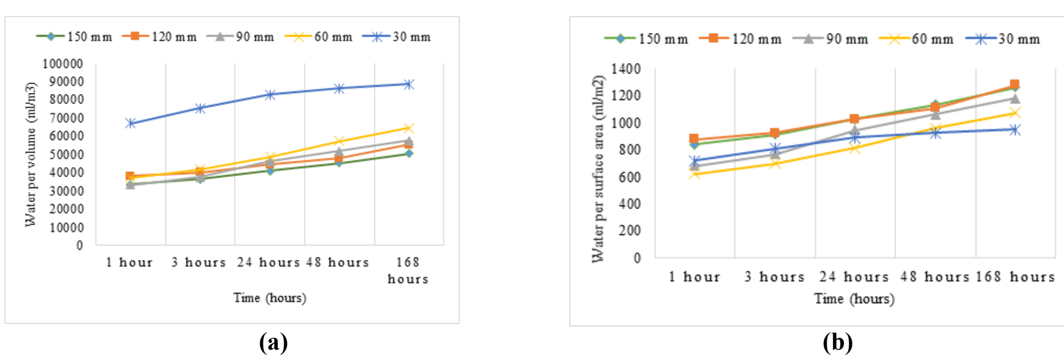


FIGURE 4 Water absorption of different concrete slabs with varying sizes: (a) per volume, and (b) per surface area.

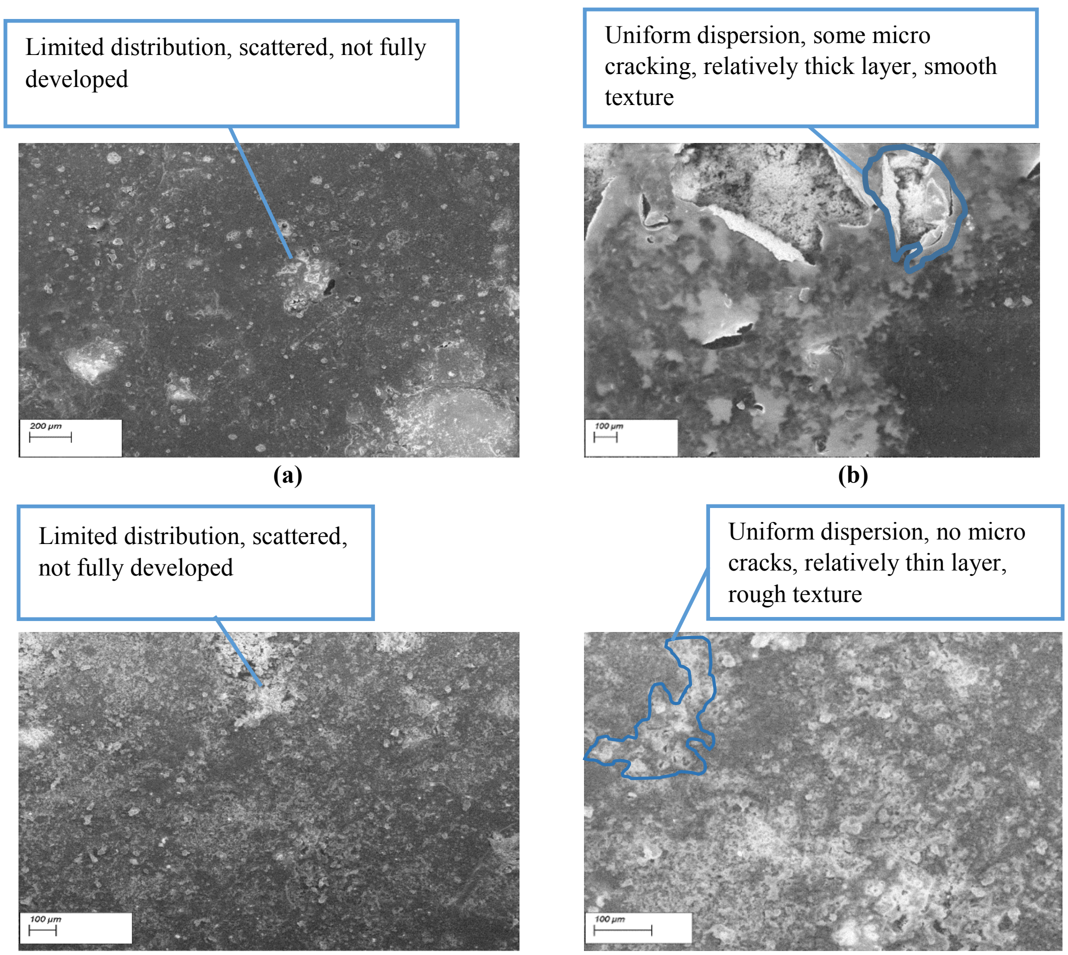
Water absorption per surface area, in general, is noticed to be increased with increasing the thickness of slabs, as the 150 mm and 120 mm thick slabs have the higher absorption rates between all the other slabs. Latter slabs have higher surface areas than the other slabs, which make them more susceptible to absorb water through their surfaces. On the other hand, and when referring to results from the water absorption per volume, 30 mm slab showed the highest absorption rate among all the slabs. This is caused by small thickness of the slab that makes water penetrates to the internal parts of it and not to stay on the near surface.

Part 2: Hydrophobic resistant treatments

Dispersion of surface applied material

Treated concrete was observed under the Scanning Electron Microscope (SEM) to investigate the behaviour of the two applied impregnants. Silicate resins and Fluoropolymers were monitored under a magnification of 500X after they were applied to concrete in day one, to check their distribution and uniformity over concrete. Further SEM testing is under way, with higher magnifications, to check the structure and size of polymers and crystals formed.

Figures 5 a-d show the distribution of the protective material over the concrete sample after 1 day and 4 days of application. The presence of the polymers and resins of the materials is recognisable in the figures as they cover a wide area of the concrete sample. After 1 day of application, both Fluoropolymer and Silicate Resin, as shown in Figures 5a and 5c, presented a limited distribution over the concrete surface with little dispersion. However, after 4 days of application both materials, as shown in figures 5b and d, have developed and covered most of the concrete surface with a smooth texture in the case of Fluoropolymer and a rough texture in the case of Silicate Resin.



(a) **(b)** **(c)** **(d)**

FIGURE 5 A 500X SEM results for (a) Fluoropolymer material after 1 day of application, (b) Fluoropolymer material after 4 days of application, (c) Silcate resin material after 1 day of application, and (d) Silcate resin material after 4 days of application

Efficacy of impregnation

Water absorption for concrete treated with fluoropolymers and silicate resins was evaluated for all concrete slabs with different thicknesses by following a non-standardised method. Figure 6 shows the water content relation to concrete thickness at 2 mm testing depth, for treated and untreated concrete, during an immersion period of 1 week.

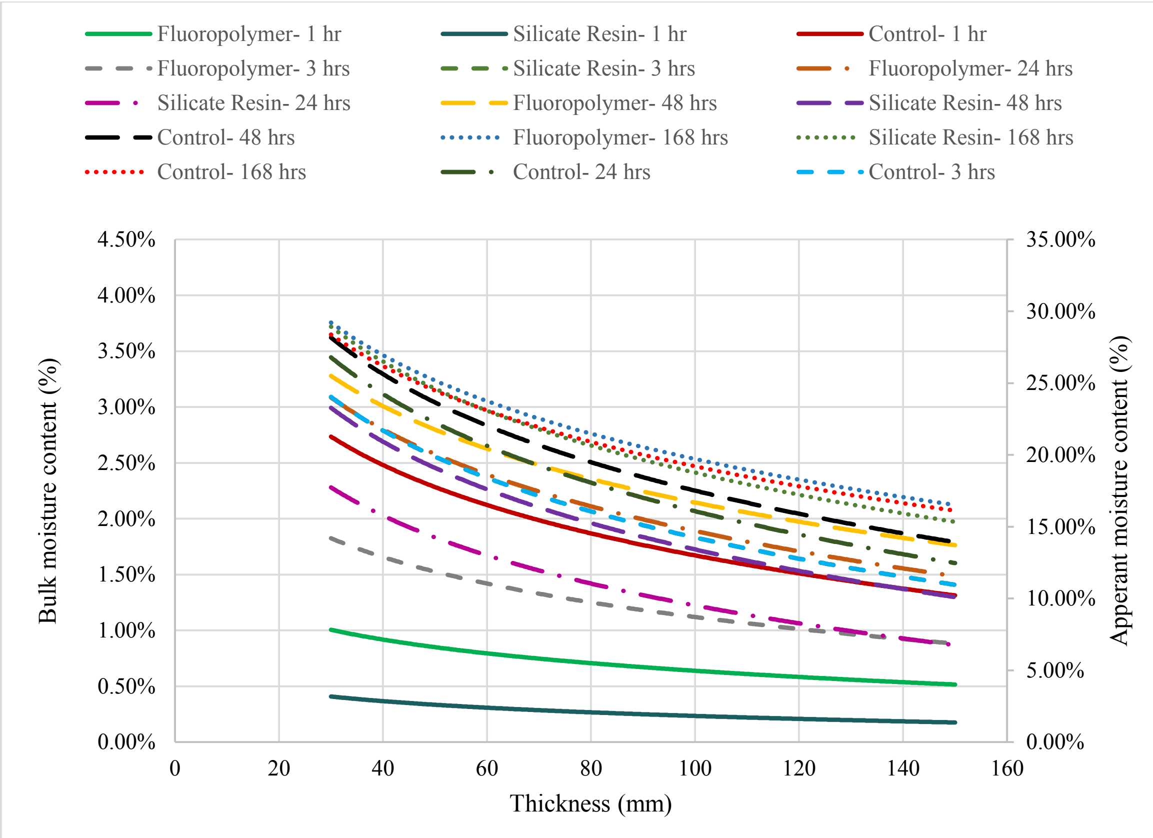


FIGURE 6 The bulk moisture content and its corresponding apperant moisture content change with concrete thickness during 1 week of testing period at 2 mm depth.

Water absorption for all the treated and untreated samples was noticed to be decreasing with increasing the thickness of the slabs. This behaviour was observed in all the slabs during all immersing times. Moreover, Figure 5 shows a great divergence between the values of the bulk and apparent moisture contents during the 1-week immersion time. This difference between the two water content values is less significant when the thickness of concrete slab increases, where both values start to converge with increasing the thickness. For example, 90 mm thick slabs treated with Fluoropolymers, after 1 hour of immersion, had a bulk moisture content of 0.7%, however their apparent moisture content was around 5%. This divergence in values leads to an improper application of treating materials.

On the other hand, concrete slabs treated with silicate resin material have shown the optimum performance in terms of water absorption resistance, followed with concrete treated with fluoropolymers.

CONCLUSIONS

A two-parts testing method was operated in this research in order to evaluate the representativeness of the moisture content described in the code of practice, and compare it with a more reliable apparent moisture content parameter. The second part of the research involved studying the influence of specimen geometry on the efficacy of two hydrophobic protecting materials; Silicate resins and Fluoropolymers, in terms of water absorption. The most important observations and conclusions from this research are:

(1) The theoretical near-surface moisture content (apparent) was found to have a higher value than the bulk moisture content, suggested by the code of practice, at the time of material application. This indicates that water presence on the surface is higher than its presence in the internal parts of concrete, which might influence the applied dosage of protective materials. It is appeared that the near surface moisture is better representation of moisture level when applying impregnants. Therefore, studies are underway to establish a relation between the amount of dosage and the apparent moisture content.

(2) The confusion and misinterpretation between the apparent and bulk moisture contents, leads to a higher rate of protective material refusal when applied to concrete, which affects the performance and economic benefits of protecting concrete.

(3) Increasing the thickness of concrete slabs reduced water absorption, either in treated or untreated concrete. Moreover, treatment was more useful in concrete with large thicknesses than small thicknesses, especially in the case of concrete exposed to water for long periods of time.

(4) Water intake per surface area was higher in slabs with larger sizes, and water intake per volume was higher in slabs with small thicknesses.

(5) SEM analysis for concrete treated with Fluoropolymers and Silicate Resins showed that both materials needed an average time of 4 days to develop and cover most of concrete's surface. Fluoropolymer has been developed into a thick and smooth layer, however Silicate Resin had a relatively rough and thin texture.

FUTURE WORK

Research is ongoing regarding apparent moisture content and its influence on the efficacy of protective materials. Studying the time of application, dosage, and optimum protection of hydrophobic materials at the most appropriate 'apparent moisture content' is under study.

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