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The Effects of SCMs on the Mechanical Properties and Durability of Fibre Cement Plates

Ceren Ince, Berkay Z. Erdem, Shahram Derogar, Nabi Yuzer

***Abstract*—**Fibre cement plates, often used in construction, generally are made using quartz as an inert material, cement as a binder and cellulose as a fibre. This paper, first of all, investigates the mechanical properties and durability of fibre cement plates when quartz is both partly and fully replaced with diatomite. Diatomite does not only have lower density compared to quartz but also has high pozzolanic activity. The main objective of this paper is the investigation of the effects of supplementary cementing materials (SCMs) on the short and long term mechanical properties and durability characteristics of fibre cement plates prepared using diatomite. Supplementary cementing materials such as ground granulated blast furnace slug (GGBS) and fly ash (FA) are used in this study. Volume proportions of 10, 20, 30 and 40% of GGBS and FA are used as partial replacement materials to cement. Short and long term mechanical properties such as compressive and flexural strengths as well as sorptivity characteristics and mass were investigated. Consistency and setting time at each replacement levels of SCMs were also recorded. The effects of using supplementary cementing materials on the carbonation and sulphate resistance of fibre cement plates were then experimented. The results, first of all, show that the use of diatomite as a full or partial replacement to quartz resulted in a systematic decrease in total mass of the fibre cement plates. The reduction of mass was largely due to the lower density and finer particle size of diatomite compared to quartz. The use of diatomite did not only reduce the mass of these plates but also increased the compressive strength significantly as a result of its high pozzolanic activity. The replacement levels of both GGBS and FA resulted in a systematic decrease in short term compressive strength with increasing replacement levels. This was essentially expected as the total rate of hydration is much lower in GGBS and FA than that of cement. Long term results however, indicated that the compressive strength of fibre cement plates prepared using both GGBS and FA increases with time and hence the compressive strength of plates prepared using SCMs is either equivalent or more than the compressive strength of plates prepared using cement alone. Durability characteristics of fibre cement plates prepared using SCMs were enhanced significantly. Measurements of sopritivty characteristics were also indicated that the plates prepared using SCMs has much lower water absorption capacities compared to plates prepared cement alone. Much higher resistance to carbonation and sulphate attach were observed with plates prepared using SCMs. The results presented in this paper show that the use of SCMs does not only support the production of more sustainable construction materials but also enhances the mechanical properties and durability characteristics of fibre cement plates.

Ceren Ince and Berkay Z. Erdem are with the Civil Eng. Dept. at Yeditepe University, Istanbul, Turkey, (Phone: 21605780000 -3212; fax: 216-5780400; e-mail: ceren.ince@yeditepe.edu.tr, berkayzafererdem@gmail.com).

Shahram Derogar is with the Architectural Dept. at Yeditepe University, Istanbul, Turkey (e-mail: derogar@yeditepe.edu.tr).

Nabi Yuzer is with the Civil Eng. Dept. at Yildiz Technical University, Istanbul, Turkey (nyuzer@yildiz.edu.tr).

***Keywords*—**Diatomite, fibre, strength, supplementary cementing materials.

I. Introduction

FIBRE cement is a composite material made using sand, cement and cellulose fibres invented in the late 19th century. Fibre-cement plates are generally used for various interior and exterior applications as smooth, flat surface for cladding, partitioning and edging. The use of fibre cement plates in construction industry is increasing due to its advantages over traditional materials. Their use significantly reduces the cost, space and time and they are also environmentally friendly and highly durable materials with high resistance to fire and water.

Originally the fibre of these plates were asbestos however, following it was discovered in 1970s that asbestos is extremely harmful to health [1] and the development of non-asbestos fibre cement products were industrialised. More recently, the effect of cellulose on the properties of cement based composites and the morphology of the fibres together with their mechanical and physical properties are studied [2], [3]. The scanning electron microscopy examination provided a homogenous distribution of fibres in the matrix when adequate water-cement ratio is used for various fibre contents [4].

Fibre cement plates are usually made using quartz and authors suggest in this paper that diatomite, a lighter density inert material, should be used as a full or partial replacement material to quartz to produce light weight fibre cement plates. It was reported in the literature [5] that the use of diatomite as a partial replacement material to quartz for fibre cement plates has not been investigated yet.

Supplementary cementing materials (SCMs) and pozzolanic replacement materials are often used as replacement materials to the binder (generally cement) for improved mechanical properties and durability characteristics of cement based materials and concrete. Durability of concrete with ground granulated blast furnace slug (GGBS) and fly ash (FA) are widely reported in the literature. Recent studies generally focused on the durability of GGBS concrete against sulphate attack [6], flexural behaviour of reinforced concrete beams with GGBS [7], strength development of fly ash concrete [8] and the sustainable studies of concrete with GGBS and FA [9], [10].

Although SCMs are widely used in the concrete industry, their application in fibre cement plates is not extensively addressed. The aim of this paper therefore is to investigate the possible role of supplementary cementing materials on the mechanical properties and durability characteristics of fibre

cement plates. Two main types of SCMs namely GGBS and FA are used as partial replacement materials to cement in this study. Partial replacement levels were 10, 20, 30 and 40% by volume. Diatomite, a much lower density inert material, is either used as partial or full replacement material to quartz. Fresh state properties of the fibre cement plates are determined by the consistency and setting time experiments. Short and long term compressive and flexural strength measurements characterized the mechanical properties of fibre cement plates. Sorptivity experiments were also carried out and the ability of the plates to absorb water when in contact with water is investigated. Durability characteristics of the plates prepared using SCMs are determined by the measurements of carbonation depth and resistance to sulphate attack. Results presented in this paper have important practical consequences as the use of diatomite resulted in a significant reduction of the total mass of these plates. More importantly, the use of diatomite coupled with the use of SCMs enhanced the long term mechanical properties, improved durability and suggest more sustainable production of these plates

II. Experimental Work

A. Materials

Experiments were carried out on fibre cement plates using Portland cement CEM1 (PC) as binders. The constituents of the mixes examined were the binders (PC and/or SCMs), fine aggregate (quartz and/or diatomite), fibres (cellulose and polypropylene) and water. Portland cement was obtained from Entegre Ltd. In the case of SCM additions, varying volume fraction replacement levels of fly ash (FA) and ground granulated blast furnace slag (GGBS) were used. The FA, was produced by Akcim Mining and Cement Industry Ltd and complies with [11]. The FA used in this study conforms to the special fineness (S) category of [11]. The GGBS used in the experimental work, manufactured by Cimkul Ltd, complies with [12]. Diatomite and quartz are obtained from Asu Chemistry Ltd and Akcelik Mining respectively. All mixes were prepared using water: binder: fibre: sand ratio by volume. The mass of binder, SCMs, fibres and fine sand required to produce the desired mix proportions by volume were calculated from carefully determined values of density. The particle size range, specific surface area, relative particle density and loss on ignition of GGBS, FA and Portland cement (PC), are given in Table I.

TABLE I
The Physical Properties of GGBS, FA and PC from the Manufacturer's Data

Addition	GGBS	FA	PC
Particle size range (microns, μm)	3-100	0.5-120	0.2-120
Specific surface area (m^2/kg)	450-550	N/A	405
Relative particle density	2.75-3.00	1.80-2.40	3.08
Loss on ignition	N/A	5.2	3.03

B. Mixing Regime

The mixing regime described in [13] was followed. The required volume of water was placed into the bowl of an orbital paddle mixer and the binder material with SCMs were added and mixed for 1 minute. Mixing continually, fibres (cellulose or polypropylene) were then added and mixed for 2 more minutes. Sand (quartz and/or diatomite) was then added over the following one minute and the resultant product mixed for a further minute. Mixing was then stopped and all unmixed solids removed from the paddle and the sides of the bowl and incorporated into the mix. Mixing was then continued giving a total mixing time of 10 minutes. Fibre cement plates were cured under water for compressive and flexural strength tests. Samples were cured under laboratory conditions (approximately 25°C and 50% RH) and cured under 40°C water for the investigation of the cure conditions on strength development. Samples were also cured under CO2 concentration for the measurement of carbonation depth and cure under sulphate solutions for the measurement of sulphate attack.

III. Experimental Work

A. Measurement of Consistency

The consistency of each mix is measured using a flow table. The mix is placed into a standard brass mold at the center of the flow table top. Mold is filled in two layers following tamping each layer 20 times with a tamper. The excess mix is removed from the top of the mold using the palette knife and the area around the base of the mold cleaned prior to the experiment. A period of approximately 15 seconds is allowed to elapse and the mold is then removed gradually. The table is jolted 15 times at a rate of approximately one jolt per second. The diameter of the spread mix is measured in two directions at right angles to each other using callipers and both results are reported [14].

B. Measurement of Setting Time

Initial and final setting times were determined using Vicat method described in [15]. The time elapsed since the mixing water was added to the binder to when the needle penetration is 4 mm from the base of the mold defines the initial setting time of the mix. The time when there is less than 0.5 mm penetration of the needle into the mix defines the final setting time.

C. Measurement of Sorptivity

The sorptivity, S, is the ability of a porous material to absorb water by capillarity. Prior to the sorptivity experiments the individual samples are dried to constant weight at 105˚C in an air oven and the area of the bed face of each sample was measured. The sorptivity of each sample was measured by placing the bed face in contact with a shallow layer of water and removing and weighing at intervals. The sorptivity is defined as the gradient of a plot of the cumulative absorbed volume of water per unit area of absorbing surface versus the square root of time.

D. Measurement of Compressive and Flexural Strength

Compressive strength testing was carried out on fibre cement plates prepared using SCMs as partially replacement

materials to the binder. Six samples of each mix were tested using a compressive testing machine. Measurements were carried out at a constant stroke rate of 5 µms-1.

E. Measurement of Carbonation Depth

Carbonation depth is measured using a solution of phenolphthalein indicator. Indicator appears pink in contact with alkaline cement plates with pH values in excess of 9 and colourless at lower levels of PH. Carbonation depth is measured 28 days after the plate samples were cast. Samples were cured in a closed desiccator at a constant temperature of 24 °C and RH of 60%, as well as an effective concentration of 10% CO2. Average carbonation depth is then determined based on the measurements taken from each of the four faces of every specimen [16]. Compressive strength was also determined according to the procedure given in Section III *D*.

F. Measurement of Resistance to Sulphate Attack

Measurement of the resistance to sulphate attack is determined following the fibre cement plates were cured under $NaSO_4$ solution for 28th days. Compressive strength tests were then performed according to the procedure given in Section III *D*.

IV. Experimental Work

A. Consistency

Consistency of each mix has been determined using the procedure described in Section III *A*. It must be noted that the consistency of each mix was deliberately kept constant to ensure constant consistency of all fibre cement plates examined and this is demonstrated in Fig. 1 (a). It must, however, be reported that to ensure constant consistency, the volume fractions of water was increased with the increase replacement levels of both GGBS and FA in plates as the replacement materials had much finer particle size than that of cement. Fig. 1 (a) shows that the consistency of all fibre cement plates prepared using increased volume fractions of GGBS are kept constant and an increasing amount of volume proportions of water is thus used to achieve constant consistency of all plates examined. Volume fractions of water with the increased replacement levels of GGBS of fibre cement plates are shown in Fig. 1 (b).

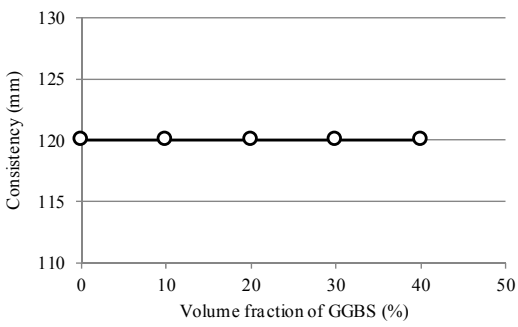

Fig. 1 (a) Consistency of plates with increasing volume fractions of GGBS (mm)

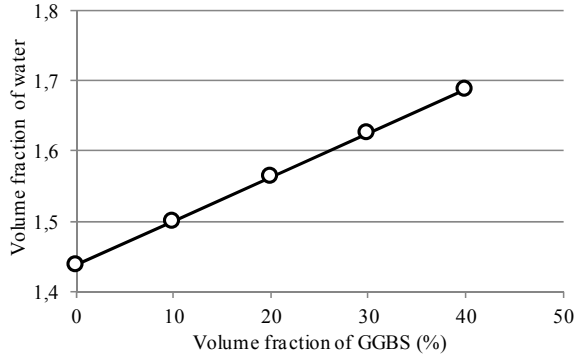

Fig. 1 (b) Volume fraction of water of plates with increasing volume fractions of GGBS

B. Setting Time

Determination of the initial setting time of the fibre cement plates prepared using SCMs (in this case GGBS and FA) is described in Section III *B*. The influence of the SCMs on the initial setting time is investigated in this section. Increasing volume fractions of GGBS is used as a replacement material to cement. Consistency of each mix was kept constant and hence the volume fraction of water is increased with increasing amounts of GGBS in Fig. 2 (○) and volume fraction of water was kept constant regardless of the amounts of GGBS used as partial replacement material to cement in Fig. 2 (□).

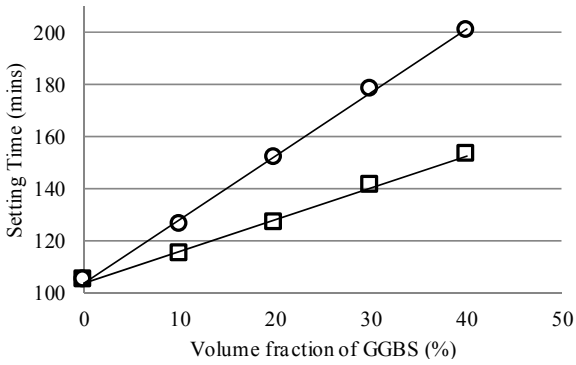

Fig. 2 Setting time of fibre cement plates prepared using GGBS. ○, constant consistency (increasing volume fraction of water); □, constant volume fraction of water

Results shown in Fig. 2 indicate that the initial setting time of the fibre cement plates are increased with the increasing volume proportions of GGBS. Higher amounts of setting times were observed in Fig. 2 (○) compared to Fig. 2 (□) as the increasing amounts of water content in Fig. 2 (○) also contributed in the increase in setting time of these plates. GGBS has much lower heat of hydration and is much less hydraulic in other terms has much slower rate of hydration compared to cement and this characteristics of GGBS is largely responsible from the increase in setting time of fibre cement plates prepared using GGBS.

C. Sorptivity

Experimental procedure of sorptivity is given in Section III

C. The influence of the use of diatomite as a partial and full replacement material to quarts on the sorptivity characteristics is investigated first. Results presented in Fig. 3 (a) show that increasing the volume fractions of diatomite decreased the sorptivity dramatically. This means in other terms that the ability of the plates prepared using diatomite to absorb water is reduced significantly. This result is expected as the finer particle size of diatomite results in a less porous and denser microstructure of the plates and hence results in a decrease in sorptivity.

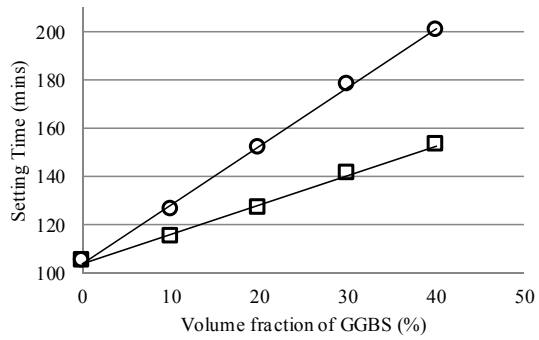

Fig. 3 (a) Sorptivity of fibre cement plates prepared using ●, 100% Quartz; ●, 50% Quartz with %50 Diatomite; ○, 100% Diatomite

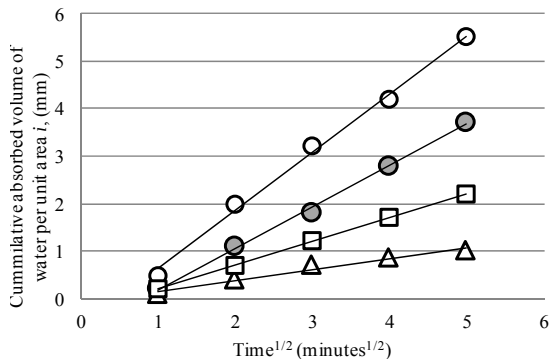

Fig. 3 (b) Sorptivity of fibre cement plates prepared using ○, 10% GGBS; ●, 20% GGBS; □, 30% GGBS; Δ, 40% GGBS

The influence of the effect of using GGBS as a partial replacement material on the sorptivity of fibre cement plates is also investigated. The increasing volume fraction of GGBS is used as a replacement material to cement and their sorptivity is measured. The results shown in Fig. 3 (b) indicated that the increasing volume fractions of GGBS resulted in a decrease in sorptivity characteristics of fibre cement plates. GGBS has much smaller particle size than that of cement and hence the use of GGBS as a replacement material to cement resulted in a less porous microstructure that resulted in a decrease in sorptivity.

D.Mass

One of the major aims of this paper is to investigate the possible role of diatomite either as a partial or full replacement material to quarts to produce light weight fibre cement plates. Quartz therefore is replaced with diatomite, a much lower density material. Increments of the replacement levels were 10% by volume. Results shown in Fig. 4 indicated that the increasing volume proportions of diatomite, used as a replacement material to quartz, resulted in a systematic decrease in total mass of the plates. It must be noted that the plates prepared using 100% diatomite is %16.5 lower in total mass than that prepared using 100% quartz.

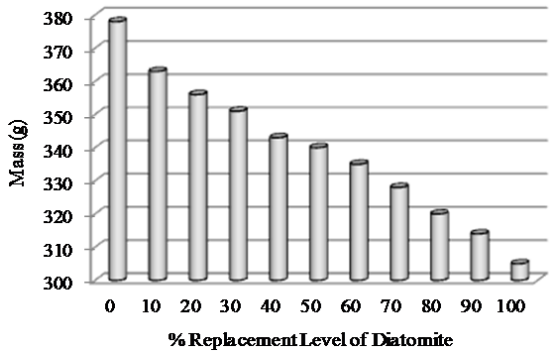

Fig. 4 Total mass of the fibre cement plates prepared using diatomite (%)

Bulk density of GGBS used as a partial replacement material to cement was equivalent to the bulk density of the binder (cement) and therefore, no significant change is observed in the total mass of the plates prepared using GGBS.

E. Compressive Strength

1. Influence of the Use of Diatomite

As discussed in Section IV *D*, the increase in the volume proportions of diatomite resulted in a significant reduction of the total mass of fibre cement plates. Diatomite is used as a replacement material to quartz and its influence on the short-term compressive strength is examined. The results shown in Fig. 5 demonstrated that the increasing amounts of diatomite resulted in a systematic increase in compressive strength of fibre cement plates. Diatomite has high pozzolanic activity index especially when compared to quartz and therefore is largely responsible from the increase in compressive strength of these plates.

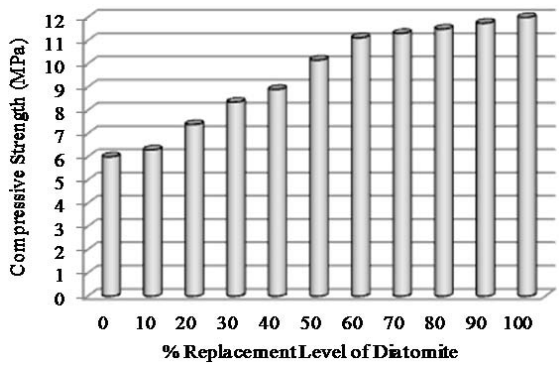

Fig. 5 Compressive strength of fibre cement plates prepared using diatomite (%)

Supplementary cementing materials such as GGBS and FA are used as partial replacement material to cement and their influence on the 28th days compressive strength of fibre cement plates is investigated in this section.

2. Short-Term Compressive Strength

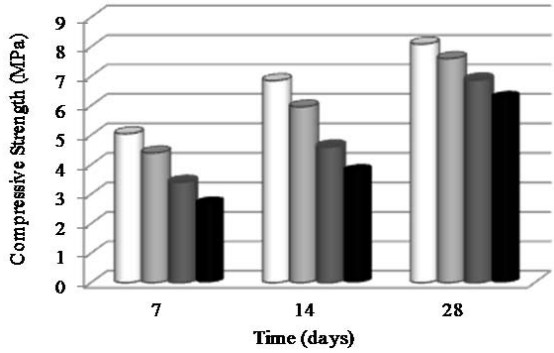

Fig. 6 (a) Compressive strength of fibre cement plates prepared using ○, 10% GGBS; ●, 20% GGBS; ●, 30% GGBS; ●, 40% GGBS

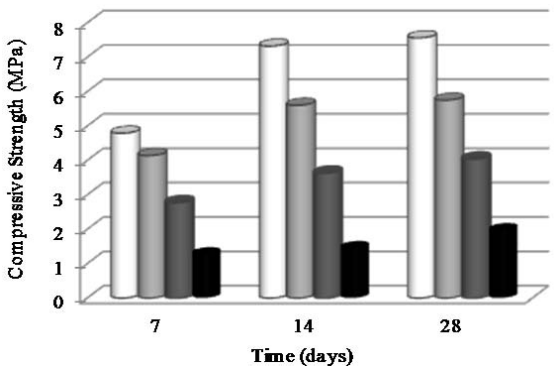

Fig. 6 (b) Compressive strength of fibre cement plates prepared using ○, 10% FA; ●, 20% FA; ●, 30% FA; ●, 40% FA

Both replacement levels were 10, 20, 30 and 40% by volume. Compressive strength measurements of fibre cement plates prepared using GGBS and FA were carried out on the 7th, 14th and 28th days and are shown in Figs. 6 (a) and (b) respectively.

Results have shown that the increasing replacement levels of both GGBS and FA resulted in a systematic decrease in compressive strength of plates. It must be noted that the rate of hydration of both GGBS and FA is much slower than that of cement. As oppose to cement that gains its full compressive strength in 28th days, supplementary cementing materials, such as GGBS and FA, require longer period of time to complete hydration reaction and gain full compressive strength. Since the rate of hydration is relatively slow in SCMs, higher then amount of SCMs, used as a partial replacement material to cement, lower the short-term compressive strength.

3. Long-Term Compressive Strength

It is discussed in Section IV *E* 2 that the rate of hydration of SCMs is much slower than that of cement. It was therefore crucial to perform long-term compressive strength measurements to investigate the actual influence of SCMs on the mechanical properties of fibre cement plates. Fibre cement plates prepared using 10, 20, 30 and 40% GGBS were therefore cured under water at 20°C for a period of 6 months.

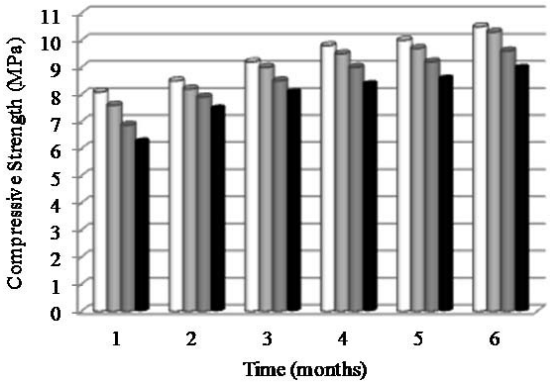

Fig. 7 Long-term compressive strength of fibre cement plates prepared using ○, 10% GGBS; ●, 20% GGBS; ●, 30% GGBS; ●, 40% GGBS

Compressive strength results of fibre cement plates prepared using increasing volume proportions of GGBS are shown in Fig. 7. Results shown in Fig. 7 indicated that the compressive strength of fibre cement plates at each volume proportions of GGBS is increasing with time. Higher compressive strength values are observed in plates that contain lower volume proportions of GGBS. As discussed previously, SCMs have lower rate of hydration and therefore, plates prepared with high volume proportions of SCMs take longer periods of time to complete full hydration. It must however be noted that compressive strength of 6 months old fibre cement plates prepared using 10% GGBS is equivalent to the 88% of the compressive strength of plates prepared cement alone.

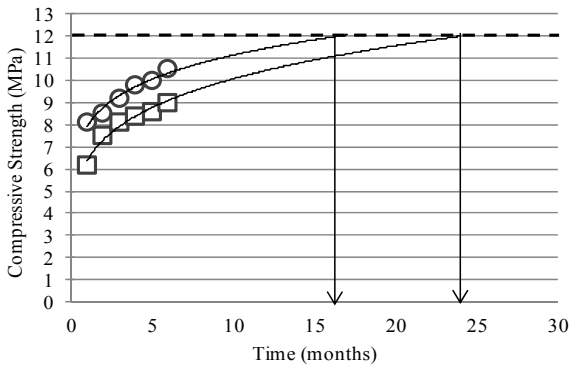

Fig. 8 Compressive strength development of fibre cement plate prepared using ○, 10% GGBS; □, 40% GGBS

Long-term compressive strength of fibre cement plates prepared using 10 and 40% replacement levels of GGBS are shown in Fig. 8. Dash-line in Fig. 8 represents the compressive strength values of fibre cement plates prepared cement alone (control specimen). When the best fit cures are

drawn to the data, it was observed that plates prepared using 10% of GGBS reach the compressive strength of control specimen in 16 months while plates prepared using 40% GGBS reach the same compressive strength value in 24 months.

F. Carbonation

Durability characteristics of fibre cement plates prepared using GGBS are investigated with the measurements of the depth of carbonation and resistance to sulphate attack. Carbonation depth of fibre cement plates are measured using the procedure given in Section III *E*.

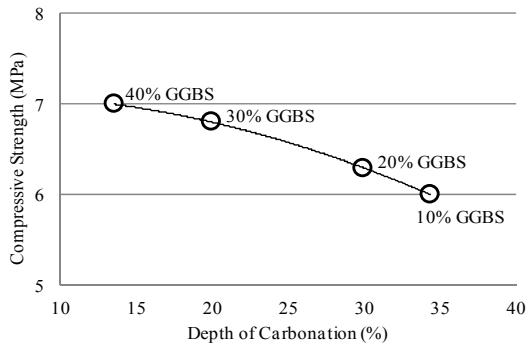

Fig. 9 Compressive strength of fibre cement plates prepared using GGBS

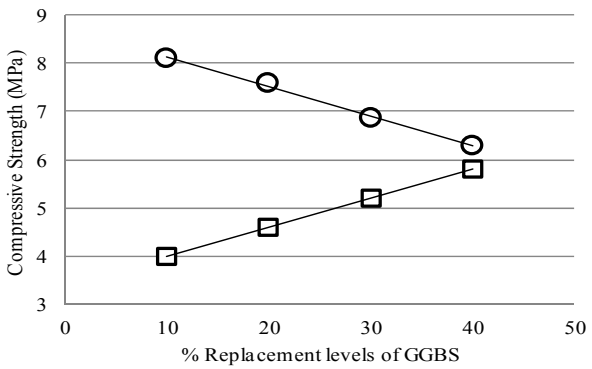

Fig. 10 Compressive strength of fibre cement plates prepared using GGBS; ○, cured under water; □, cured under sulphate solution for 28th days

Results shown in Fig. 9 indicated that increasing volume proportions of GGBS resulted in a decrease in the carbonation depth of fibre cement plates. Results also showed that increasing volume proportions of GGBS resulted in a smaller decrease compressive strength of these fibres. This means in other words that the resistance to carbonation is much higher in plates prepared using GGBS than that of plates prepared using cement alone.

G. Sulphate Attack

Resistance to sulphate attack of fibre cement plates prepared using SCMs are measured following the procedure described in Section III *F*. Results shown in Fig. 10 indicated that increasing volume proportions of GGBS resulted in an increase in compressive strength of fibre cement plates cured under sulphate solutions. This means in other words that the increased volume proportions of GGBS resulted in an increased resistance to sulphate attack of fibre cement plates.

H. Cure Conditions

Considering the slower rate of hydration of SCMs used as a partial replacement material to cement, it was vital to study the influence of the cure conditions on the mechanical properties of fibre cement plates prepared using SCMs. Fibre cement plates, containing 10, 20, 30 and 40% of GGBS by volume, were cured under three different conditions. First set of samples were cured under laboratory conditions at 24°C and 30% RH, then next set of samples were cured under water at ambient temperature (24°C) while the third set were cured under 40°C hot water for a period of 28th days. Compressive strength of fibre cement plates cured under all conditions is shown in Fig. 11. Experimental results have shown that fibre cement plates cured under hot water provided the highest compressive strength compared to the other cure conditions examined in this paper. Authors suggest that curing the samples under hot water increased the rate of hydration and hence enhanced the strength development of fibre cement plates prepared using GGBS.

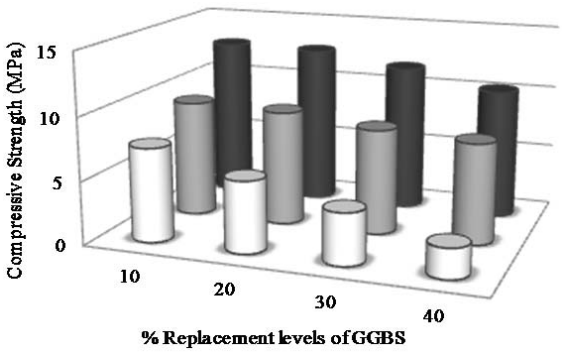

Fig. 11 Compressive strength of fibre cement plates, ○, cured under air; ●, cured under water; ●, cured under hot water at 40°C

V. Conclusion

This paper firstly investigates the possible role of diatomite as a replacement material to quartz on mechanical properties of fibre cement plates. The use of diatomite as a replacement material to quartz did not only result in a massive reduction of the final weight of fibre cement plates but also increased the compressive strength significantly. Experimental results showed that the increasing replacement levels of GGBS used as a replacement material to cement resulted in a decrease in the setting time of these plates. Sorptivity characteristics of these plates were enhanced with the use of increasing replacement levels of both diatomite and GGBS. Short and long-term mechanical properties of fibre cement plates prepared using GGBS are examined. Results showed that the increasing volume proportions of GGBS resulted in a decrease in compressive strength of the plates. This is mainly because of the slower rate of hydration of GGBS compared to cement.

Long term compressive strength measurements however, showed that the plates prepared using GGBS reach the compressive strength of control specimen in approximately 2 years' time. It should also be noted that the durability characteristics of these plates when GGBS is used as a replacement material is improved significantly. The increased volume fraction of GGBS used as a replacement material to cement resulted in an increased resistance to both carbonation and sulphate attack. Investigation of the cure conditions on the mechanical properties of the fibre cement plates relieved that the hot water curing was the most appropriate cure condition of the plates prepared using GGBS as it enhanced the heat of hydration of such plates considerably. Authors therefore strongly suggest that the results reported in this paper have important consequences in construction practice.

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