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FLEXURAL STRENGTH BEHAVIOUR OF FIBRE CEMENT BOARD REINFORCED BY BLAST FURNACE SLAG FIBRES

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ABSTRACT

This paper presents an experimental study on fibre cement composite board (CCB) reinforced by Kraft and Blast Furnace Slag Fibres (BFSF) powder. Three different types of BFSF were used with Kraft pulp fibres extracted from waste cardboard. Three types of slag fibres including SLL (Slag fibre, long length), SLW (slag fibre, white colour) and SLY (slag fibre, yellow colour) in the range of 1-3% were used in this research.

This investigation provides an important insight into the study of the effect of blast furnace slag powder on the property of CCB reinforced by cellulose fibres; as no previous literatures has investigated the use of BFS fibres. The results show that SLL does not have enough consistency with Kraft pulp fibre and degrades the flexural properties of cement board over time. The results of modulus of rupture (MOR) for 7 to 28 days dropped from 11 to 7.5 MPa, respectively. On the other hand, SLW and SLY are much more compatible with hydrated cement products and Kraft pulp fibre giving MOR values of up to 17.5 MPa at 28 days.

KEYWORDS

Cement composite boards; Blast Furnace Slag Fibres; Waste cardboard Kraft; Natural cellulose fibres; BFSF powder.

INTRODUCTION

Natural fibres, such as cellulose fibres, are normally used in the production of cement boards, but when waste cardboard is incorporated, the flexural strength of the boards cannot meet the standards requirements; such as the Class 2 classification of BS EN 12467 standard. In order to improve the flexural behaviour of the cement board, slag fibres are used in combination with Kraft pulp fibres obtained from waste cardboard.

The replacement of hazardous asbestos fibres with alternative natural fibres as agricultural by-products was the initial endeavour in this area as they offer distinct advantages; such as being readily available, low cost, renewable, and comply with current manufacturing technologies (Coutts 2005, Agopyan, Savastano Jr. et al. 2005, Savastano Jr., Agopyan et al. 1999, Agopyan, John 1992) or can be found with negative value from industrial wastes (Savastano Jr, Warden et al. 2001).

The use of agricultural by-products such as bagasse, wheat etc. in manufacturing cement composite board (CCB) provides advantages for the development of low-cost environmentally friendly construction materials within construction industry. Nevertheless, there are still important challenges remaining that must be solved before these fibres can be implemented in cement composite products and provide the required long term durability of fibre cement board. The presence of lignin and extractives remaining in the fibres may cause an interruption within the cement-fibre interface and prevent appropriate bonding within cement particles as well as cement-fibre bonding.

The durability of the fibre-cement board is largely associated with the behaviour of fibres. Lignin and hemicellulose is present in most natural vegetable fibres that react with available hydrated cement matrices. Based on existing literature, within the fibre-cement interfacial zone, significant degradation occurs (Mohr, Biernacki et al. 2007, Tonoli, Santos et al. 2010, Savastano Jr., Agopyan et al. 1999). In order to overcome this issue, lignin content should be reduced, or an alternative method should be used to coat the lateral surface areas in order to improve the fibre-cement interface reactions.

No literature was found on the use of blast furnace slag fibres in the production of fibre-cement board by the authors. Research was only found relating to the use of blast furnace slag as an additive or a replacement of Portland cement in normal concrete.

Currently, many countries, including developing countries, are able to produce Blast Furnace Slag (BFS). These glassy granulated materials are derived from pig-iron manufactured as a by-product (Bentur 2007). In spite of consumption of BFS by the cement production factories, a considerable amount of this material is stockpiled every year. Substitution of granulated blast furnace slag (BFS) in place of ordinary Portland cement (OPC) brings many advantages, such as; lower CO_2 emissions, energy savings and cost reductions (John, Zordan 2001). Although for using BFS as a hydraulic binder it should be ground to comply with the standard requirement in fineness. This process may add further cost but considering that fact that the procedure produces BFS as a cheap substitute to cement in fibre cement production the extra cost can be justified. In addition to this advantage, it can also improve some physical and mechanical characteristics of fibre cement boards (Savastano Jr, Warden et al. 2001). At ambient temperatures, BFS hydration occurs very slowly and thermal or chemical activations either in tandem or individually, is necessary to stimulate acceptable dissolution rates (Escalante, Gomez et al. 2001).

The effect of weathering or ageing appears in cement composite in the form of loss in mechanical strength. This is due to carbonation of the matrix (Wang, Pu et al. 1995).

MATERIAL, MIX DESIGN AND LABORATORY PRODUCTION

The following materials were used in this research:

- **Waste cardboard**; The waste cardboard; which is normally used for packaging, was provided from local markets in the UK. The cardboard usually used for packaging is made out of unbleached Kraft pulp.
- **Blast Furnace Slag fibres**; The three types of slag fibres used in this research that were provided from Esfehan Steel maker Company (Iran) are listed as follows;
  a) Resin impregnated blast furnace slag fibre: the fibres were coated by yellow resin during the production. These fibres are called yellow slag fibres in this research.

b) White blast furnace slag fibres. Theses fibres are similar to yellow fibres but the resin were extracted so the intrinsic white colour of these fibres is observable.

c) Long blast furnace slag fibres. The procedure of production of these fibres is slightly different than that of white and yellow so that these fibres are much longer than the other two and there is no resin on the surface of these fibres. The intrinsic properties of these fibres are similar to the previous groups, but the length of these fibres was in the range of 5-8 mm whilst the range of the two other groups was in the range of 2-4 mm.

Some the most important properties of the slag fibres are summarised in table 1.

Table 0 1- Chemical composition of slag fibres using XRD test (ASTM C982-97)

Component	Mass (%)
Loss of ignition	3.76
SiO2	38
Cao	31.8
Al2O3	12.8
MgO	7.3
Tio2	2.5
K2O	1.8
Mno	0.93
Other	<1

The process for making slag fibres is as follows; the slag in the blast furnace floats on top of the iron and is transferred for classification. As the slag cools slowly, it results in an unreactive crystalline material consisting of an assembly of Ca-Al-Mg silicates. To gain a suitable slag, the melted slag needs to be rapidly cooled or quenched below 800 °C in order to prevent the crystallization of merwinite and melilite.

- **Portland cement**; The cement used was Portland cement CEM I 52.5; which complied with BS EN 197-1: 2000. The chemical composition and characteristics of the cement is shown in table 2.

Table 2- Composition and properties of the cement

Properties	Unit and compound	Standard range	The sample result
Surface area	(cm2/g)	3000-3200	3100
Setting time – initial	(mins)	160-180	165
3 days Compressive strength	(N/mm2)	27-31	29
7 days Compressive strength	(N/mm2)	38-42	39
28 day Compressive strength	(N/mm2)	>52.5	53.1
Sulphate	SO3 (%)	2.2-2.8	2.34
Chloride	Cl(%)	0.01-0.02	0.013

Alkali	Eq Na2O (%)	0.35-0.75	0.4
Tricalcium Silicate	C3s (%)	50-55	52
Dicalcium Silicate	C2S (%)	20-24	21
Tricalcium Aluminate	C3A (%)	6-8	6
Tetracalcium Aluminoferrite	C4AF (%)	10-12	12

- **Water**; Potable tap water was used.

Mix design

In this research, ten groups of mixes were designed, made and tested. In each group, six specimens were replicated. On the first three specimens flexural strength test was carried out on day 7. On the other three specimens density test and flexural strength test were conducted at 28 days. The mix quantities for each group are provided in the table below.

As seen in table 3, in all groups a cardboard waste Kraft fibre content of 3% by mass of the cement was used and different types of slag fibre in association with 1, 2 and 3 % fibre content (for the slag fibres) were designed and prepared.

Table 0- Mix design for making laboratory specimens

Mix number	Mix code	cement	Kraft fibre (dry)	(SL,Y) Slag fibre, Yellow	(SL,W) Slag fibre, White	(SL,L) Slag fibre, Long
1	K3	130	3.9	0	0	0
2	K3-SLY1	120	3.6	1.2	0	0
3	K3-SLY2	110	3.3	2.2	0	0
4	K3-SLY3	100	3	3	0	0
5	K3-SLW1	120	3.6	0	1.2	0
6	K3-SLW2	110	3.3	0	2.2	0
7	K3-SLW3	100	3	0	3	0
8	K3-SLL1	120	3.6	0	0	1.2
9	K3-SLL2	110	3.3	0	0	2.2
10	K3-SLL3	100	3	0	0	3

As can be seen, the only differences that can be noted for each specimen within the groups is related to the type and quantity of slag fibre used.

The symbols applied in table 3 are nominated based on the first letter of the fibres. For example: K stand for Kraft pulp fibre, SL Slag fibres, Y yellow slag fibre, W: white slag fibres.

Making specimens and curing

The method applied to make fibre-cement board in the laboratory is explained in a previous publication by the authors Khorami et al. 2011. The equipment used for making the specimen included, a drainage cubical mould (measuring 180* 82 mm plain and 150mm height), four perforated plates (two thin and two thick plates), two filter papers, mixer, vacuum pump, compression testing machine, 500 ml filter flask.

The specimens were kept in an incubator at 20°C and 95% relative humidity until tested.

RESULTS, ANALYSIS AND DISCUSSION

One of the most important mechanical performances of cement board is associated with flexural behaviour. The flexural strength test was conducted complying BS EN 12467: 2004. It was done based on the principal of 3-point flexural test spanning 160mm.

To clarify the symbols applied in this paper, an example is presented. Taking K3-SlW2-D7 as example;

K: stands for Kraft pulp fibres obtained from waste cardboard. And digit 3 shows the percentage of Kraft fibres by weight of the cement.

SLW2: stand for white slag fibre and the percentage of fibre content is 2 percent of the cement weight.

D7: shows the age of the specimen; for example this shows that the specimen was tested 7 days after casting and curing.

Modulus of rupture (MOR) for all groups

To compare the flexural behaviour of the specimens, one of the flexural stress-deflection results was chosen from each group to be considered as the representative of that group and compared with other groups.

Figure 1 presents the MOR (Modulus of Rupture) obtained from all specimens aged 7 and 28 days for each group:

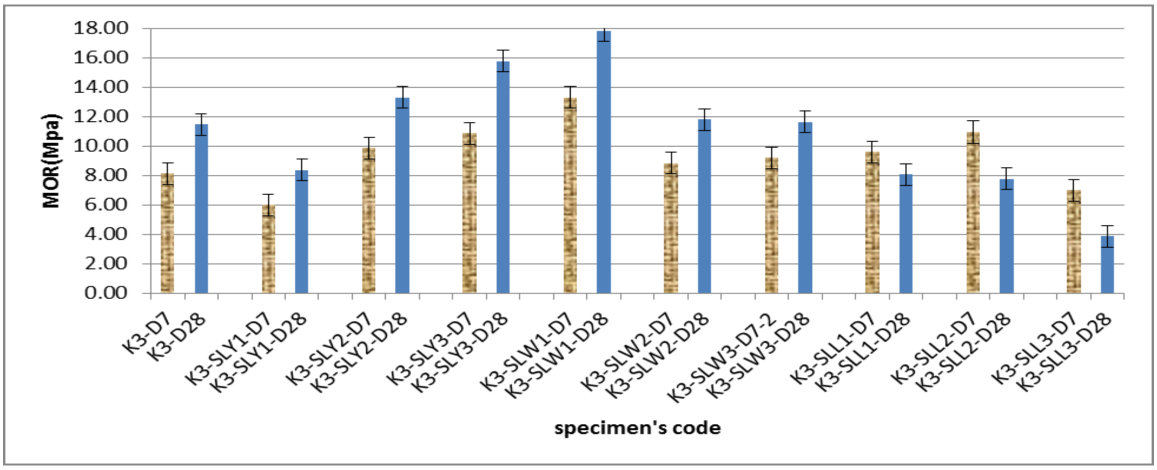

Figure 1- flexural strength of specimens at age of 7 & 28 days for all groups

The following points can be extracted from figure 1:

- In all groups, excluding K3-SLL, the flexural strength of the 7 day specimens are lower than the 28 day specimens as expected.
- The highest flexural strength is associated with K3-SLW1-D28.
- After K3-SLW1, the highest flexural strength is K3-SLY2 and K3-SLY3.
- The 28 days flexural strength of the specimens reinforced by SLL (i.e. K3-SLL) is even lower than K3.

The aforementioned behaviour can be associated with some important parameters; such as types of fibre and fibre content.

As seen in figure 1, by increasing the fibre content of SLY from 1% to 3%, the flexural strength of the cement board increases from 8 MPa to 14 MPa. This shows that the interaction within the yellow slag fibres and Kraft increases as fibre-content increases. This may attributed to better performance of fibres in filling the pores and making the specimen denser so that the applied flexural load which can be transformed into tension and compression in the board, can be taken by dual action of the Kraft and yellow slag fibres.

The effect of longer slag fibres; which is associated with SLL, shows that the MOR of the specimen decreases over time; as illustrated in fig.1 for 7 and 28 days. In addition to this drawback, as fibre content was increased from 1% to 3% the 28 day MOR of the specimens decreases from 8 MPa to 3.8 MPa respectively.

While slag fibres showed better behaviour as the minimum fibre content (i.e. 1%) in combination with 3% Kraft pulp fibres resulted in the highest MOR; this may relate to the better performance of this fibre in hydrated cement. It seems that white slag fibres have better interlock connection and consistency in cement-fibre interface.

The weak performance of SLL incorporated with Kraft pulp fibres may relate to the length of the slag fibres that tie together and create a ball effect. If the fibres accumulate and tie with each other, it can lead to some weak points within the CCB and failure points will arise from this point when the CCB is under loading.

Flexural performance specimens reinforced by K3 solely

Figure 2 shows the 7 and 28 days flexural performance of the CCB reinforced by 3% Kraft pulp fibre. W/C stands for water : cement ratio used for each mix:

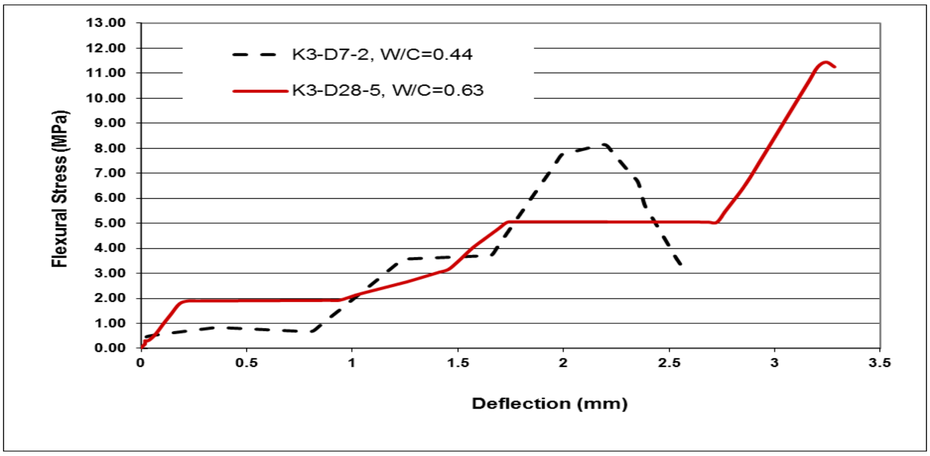

Figure 2- Flexural stress of specimens reinforced by 3% Kraft fibre at age of 7 & 28 days.

As can be seen in figure 2, the 28 days specimens performed better than 7 days specimens in terms of both MOR and ductility.

The maximum MOR experienced by 28 days specimen is about 11 MPa whilst the corresponding value for 7 days specimen is about 8 MPa, this shows about 40% increase in MOR over time from 7 to 28 days.

Ductility of the specimen increases from 7 to 28 days as the failure deflection for the 7days specimens occurs at 2 millimetres whilst the 28 days specimen elongation is about 3.5 millimetres in failure point.

Flexural performance of specimens reinforced by SLL fibre

The results of K3-SLL1, K3-SLL2 and K3-SLL3 are shown in figure 3. The figure shows that as fibre content of the long slag fibre in the cement board reinforced by the Kraft fibre increases, the flexural performance drops dramatically. This may be associated with the fibre-content of these long fibres. As fibre content increases, pores and voids may increase in the specimens because these long fibres cannot mix homogenously with Kraft fibres and hydrated cement products.

As seen in figure 3 the best performance belongs to K3-SLL1.

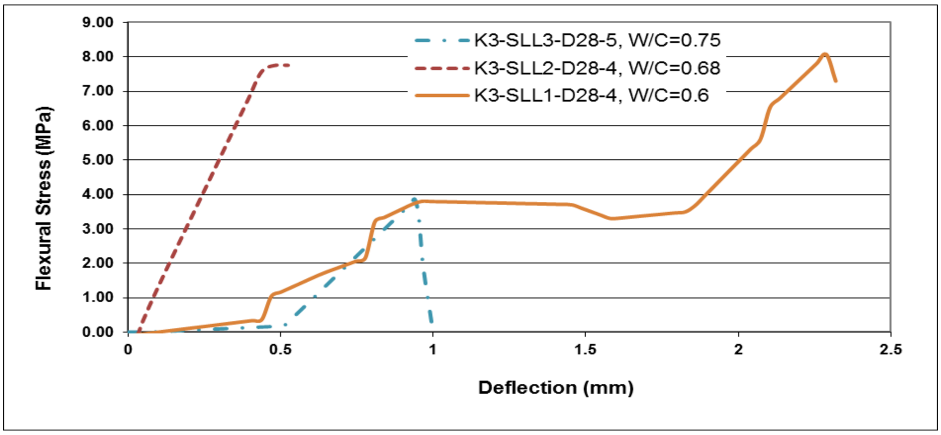

Figure 3- Comparison of specimens reinforced by 1%, 2% and 3% SLL at age of 28 days.

However, even though K3-SLL1 showed better performance in figure 3, it cannot meet the required expectations from the cement board because the flexural strength of the specimens for this group (i.e. K3-SLL1) decreases from 7 to 28 days after casting.

Flexural strength of specimens reinforced by SLY fibre

Figure 4 compares the representative groups including K3-SLY1, K3-SLY2 and K3-SLY3 in terms of flexural performance at 28 days. As can be seen in figure 4, as fibre-content of yellow slag fibre increases, all important parameters of flexural behaviour including modulus of rupture, toughness and ductility improved.

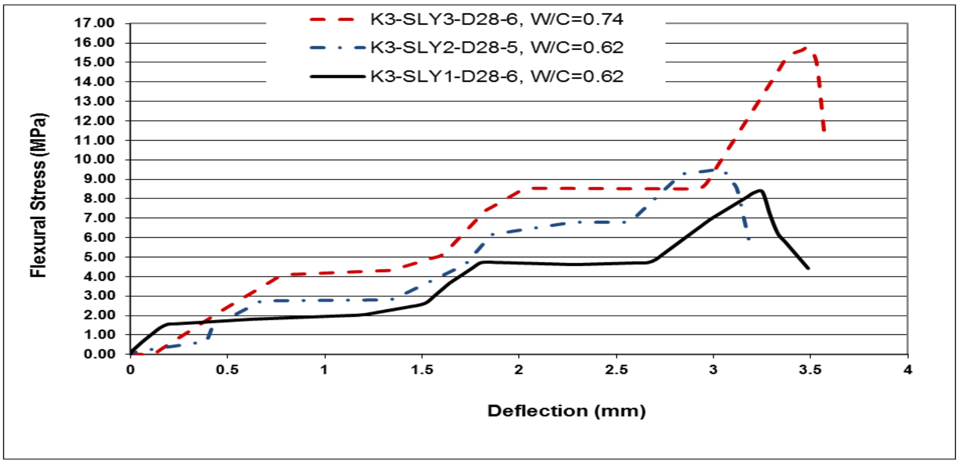

Figure 4- Comparison of flexural performance of the specimens reinforced by 1%, 2% and 3% SLY at age of 28 days.

The trend shown in figure 4 illustrates that the yellow slag fibres are compatible with Kraft fibres and have good consistency with hydrated cement products. It seems that for the last group (i.e. K3-SLY3), fibre-cement interface has better interlocking and this may make the cement board denser than other groups reinforced by yellow slag fibres.

Flexural strength of specimens reinforced by SLW fibre

Figure 5 compares three mixes reinforced by SLW with 1%, 2% and 3% white slag fibres at 28 days.

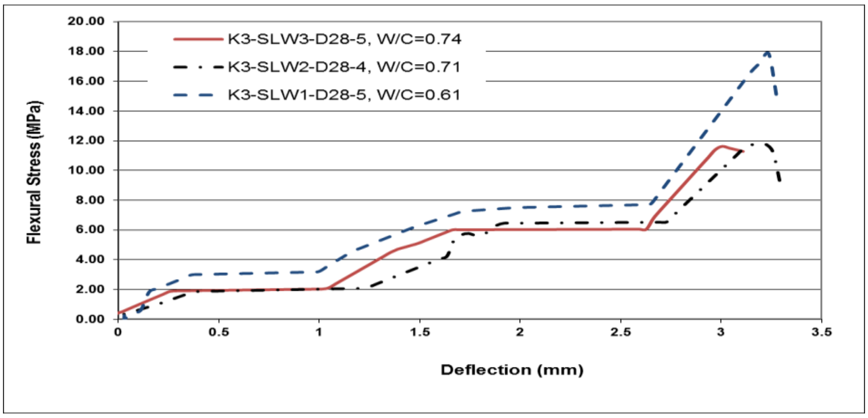

Figure 5- Comparing flexural behaviour of specimens reinforced by 1%, 2% and 3% SLW at age of 28 days.

As can be seen, as fibre content increases from 1% to 3%, modulus of rupture decreases. This may be associated with the type of slag fibre used; as white slag fibre does not have any coating agent; such as coupling or foaming agent. If there is no coating agent on the fibres, hydrated cement products can stick to the fibres better than coated fibres.

The best performance as seen in figure 5 is related to K3-SLW1 whilst the other two groups (i.e. K3-SLW2 and K3-SLW3) cannot reach 18 MPa.

Comparison of MOR for K3, SLY and SLW mixtures

Figure 6 compares K3, K3-SLW1 and K3-SLY3. In this comparison, K3-SLL is excluded; as using SLL in combination with K3 caused a reduction and defects in flexural performance of cement boards. Therefore, only fibres that improved the flexural behaviour of the cement board was compared in this section.

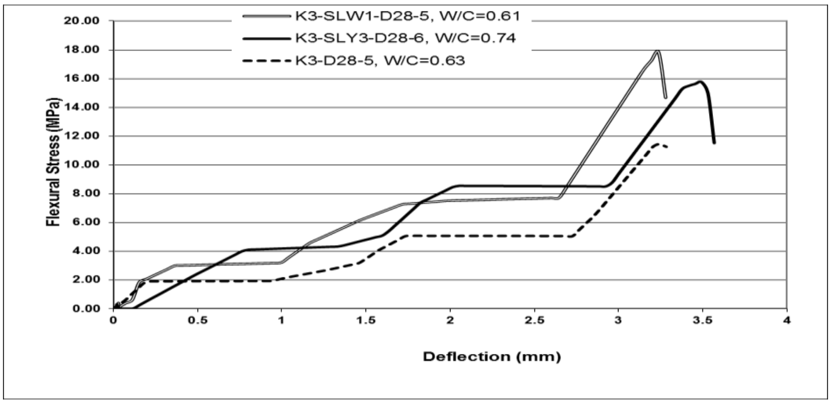

Figure 6- Comparison of flexural behaviour of the best representative of all groups at age of 28 days.

As illustrated in figure 6, the best performance belongs to K3-SLW1, then K3-SLY3 and the last one is K3. Modulus of rupture for specimens reinforced by only 3% Kraft fibre is about 11 MPa, whilst specimens reinforced by a combination of 3% Kraft and 3% yellow slag fibres is about 16 MPa and the corresponding value for the specimens reinforced by 3% Kraft and 1% white slag fibres reached 18 MPa.

Therefore, yellow slag fibres and white slag fibres could improve 45% and 65% of the specimens reinforced by 3% Kraft fibres, respectively.

It should be noted that the initial part of all graphs that contains a tail is related to the specimens setting onto the jaws of the compression machine.

Specific gravity of the specimens

Figure 7 shows the average specific gravity of the specimen's representative by each group.

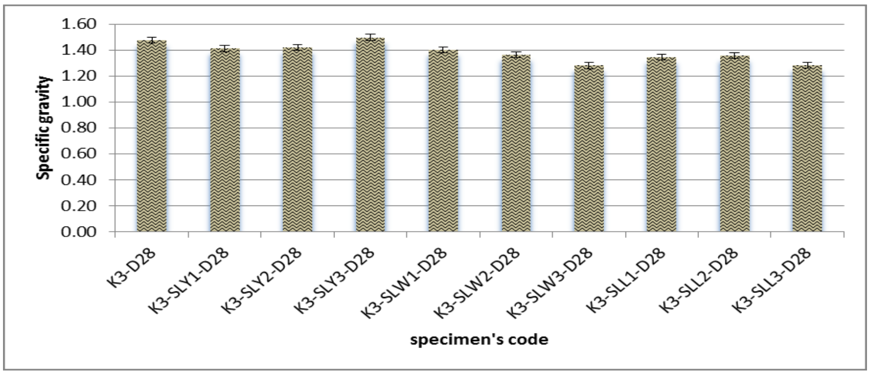

Figure 7- Density of specimens at age of 28 days

As shown in figure 7 there is no considerable difference within specific gravity of all groups. The values for all groups are approximately identical and vary between 1.3 to 1.5. It is obvious that the higher fibre content, the lower the specific gravity in the specimens. This is mainly due to lower SG of fibres than cement.

High fibre content may also associate with high porosity and this cause some voids within hydrated cement and fibres which lead to a decrease in density or specific gravity.

CONCLUSION

In this research, an attempt was made to investigate the feasibility of using slag fibres in combination with Kraft pulp fibres.

Three different types of slag fibre including SLW, SLY and SLL were applied in this research. Ten groups of specimens were made using constant 3% Kraft pulp fibres with 1%, 2% and 3% slag fibres. The procedure to manufacture samples and important conditions for curing the specimens were all identical. The two important parameters including; type of fibres and fibre-content were studied in this research.

Flexural performance; which is the most important mechanical property, water-cement ratio and specific gravity were investigated. The outcome of this study is as follows:

1. The cement board made out of 3% Kraft pulp fibre can experience about 8 MPa and 11 MPa at 7 days and 28 days, respectively; this illustrates that modulus of rupture increases during time as expected.
2. The long slag fibres (length 5-8 mm) cannot meet the required properties to gain the high flexural performance including MOR, toughness and ductility. Using this type of fibre caused a reduction in all aforementioned flexural properties. In addition to the weakness of these fibres in meeting the required needs for flexural performance, the characteristics of the cement board reinforced by SLL were weaker after 28 days in comparison with 7 day specimens.
3. The specimens reinforced by SLY, show two important properties including: 1) flexural performance of the specimens improved from 7 to 28 days and 2) with increasing fibre content from 1% to 3%, the modulus of rupture increased from 8 MPa to 15.5 MPa; which is much higher than the specimens made with Kraft fibres solely.

4. The specimens reinforced by SLW showed a suitable flexural performance when 1% SLW was used in combination with 3% Kraft fibres. In this case, modulus of rupture for K3-SLW1 increased to 18 MPa while the corresponding value for K3 was only 11.5 MPa. In addition, the flexural behaviour of specimens reinforced by 1, 2 and/or 3% SLW, were improved from 7 to 28 days.

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