Mechanical and Microstructural Properties of Self-Compacting Concrete Blended with Metakaolin, Ground Granulated Blast-furnace Slag and Fly Ash

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Abstract

The aim of this study is to investigate the mechanical and microstructural properties of self-compacting concrete (SCC) mixtures containing three supplementary cementitious materials (SCMs), namely metakaolin, ground granulated blast-furnace slag and fly ash. For the mixtures, cement was replaced by SCMs at different levels. The mechanical properties were evaluated against a control mixture (without SCM). The microstructural properties were examined using SEM and EDS on mixtures with high volume of SCMs. The utilisation of SCMs enhanced compressive strengths. Metakaolin gave the most enhancing effect as a replacement material to cement on mechanical and microstructural properties of SCC at all ages.

Keywords

Self-compacting concrete; Mixture design method; Metakaolin; Ground Granulated Blast-furnace Slag; Fly ash; Compressive strength; Modulus of elasticity; Scanning electron microscope (SEM); Energy Dispersive X-ray spectroscopy (EDS).

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1 Introduction

Self-compacting concrete (SCC) is a new type of high-performance concrete characterized by its ability to flow and compact under its own weight without the need of any external vibrations and also fill the formwork whilst maintaining homogeneity without any migration or separation of its large components even in the presence of congested reinforcement [1, 2]. Researchers [3-6] have defined SCC in almost the same terms as a highly flowable concrete that should meet the requirements of flow-ability, passing ability and segregation resistance.

In the last two decades, SCC has been developed further, utilising various supplementary cementitious materials (SCMs) such as metakaolin (MK) [7-14], fly ash (FA) [9, 11-14] and ground granulated blast-furnace slag (GGBS) [9]. The incorporation of different SCMs in concrete can have a considerable effect on both fresh and hardened phases [7-14]. All SCMs have two common features; their particle sizes are smaller than or the same as Portland cement (PC) and they exhibit pozzolanic behaviour involving in the hydration reactions. Pozzolans, which contain silica (SiO_2) in a reactive form, have little or no cementitious value by themselves. However, in a finely divided form and in the presence of moisture they chemically react with calcium hydroxide (CH) at ordinary temperatures to form cementitious compounds [15, 16].

GGBS is a by-product from the blast-furnaces used to make iron. It has been successfully utilised in many countries around the world achieving many technical benefits in construction industries [17, 18]. Adding GGBS to self-compacting concrete offers many advantages related to increasing its compactability, consistency and retaining it for a longer time, while protecting cement against both sulphate and chloride attack [19]. Because GGBS has about 10% lower density than PC, replacing an equal mass of cement by GGBS will result in a larger paste volume, which extensively increases the segregation resistance and flow ability. A study was carried out by Oner and Akyuz [20] on 32 different mixtures of SCC containing GGBS, indicated that as GGBS content increases, water to binder ratio decreases for the same consistency and thus GGBS has a positive effect on the consistency. They specified

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further that the compressive strength of concrete mixes containing GGBS increases with increase of GGBS replacement level.

Metakaolin is produced by heat-treating kaolin, one of the most abundant natural minerals at ascetically high temperatures, ranging from 650 to 800 °C [21, 22]. MK normally contains 50-55 percent SiO_2 and 40-45 percent Al_2O_3 [23, 24]. Other oxide particles exist in small quantities including Fe_2O_3, TiO_2, CaO, and MgO. MK particles are generally finer than cement and coarser than silica fume particles in an order of scale. Due to the controlled nature of the processing, MK powders are very consistent in appearance and performance [25]. Regardless of the reactivity of an SCM, if it is extremely fine, it will generally impart some benefit to mortars and concrete. Small particles, which can fit between cement grains, allow for more efficient paste packing, which in turn reduces bleeding, lowers the mean size of capillary pores, and may reduce water requirements due to a ball bearing effect (if the particles are round) [26]. Improved particle packing at the aggregate/paste interface results in a thinner transition zone with a denser, more homogeneous microstructure [27]. In addition, acting together, many small particles have a large total surface area, leading to an increase in reactivity. Typically, SCMs such as MK with higher volume of alumina substances, incline to have higher pozzolanic capacities. This is because of the formation of C-A-H which has a high CH demand. This is actually critical, as CH does not affect concrete strength significantly and can be disadvantageous to durability. The removal or reduction of CH particles can be satisfied by secondary reaction with MK. Therefore, MK can greatly enhance concrete performance [26, 28]. There is little existing literature regarding the effect of metakaolin on the modulus of elasticity. As it has been shown to increase compressive strength and to densify the microstructure, it follows that MK might also lead to increased elastic modulus, or stiffer concrete. From the literature, modulus of elasticity generally seems to increase with increasing MK content, although the rate of increase is lower than that for compressive strength [29].

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FA or pulverised fuel ash (PFA) in the UK is a by-product of coal fired electricity generating plants. It can be used as a partial replacement of cement in SCC, because of its pozzolanic properties. FA can generally improve both fresh and hardened properties of SCC and can be replaced up to 30 percent of PC by mass. However, FA reacts more slowly than conventional concretes made with PC and therefore the maximum strength needs more time to gain. Adding FA to SCC mixture can improve its rheological characteristics while reducing water demand, because of its small spherical shape [30]. Furthermore, additional studies showed that the effect of FA on the workability of super flowing concrete by replacing 30% of cement with FA can result in outstanding workability [31]. FA can also increase the reactivity of SCC. This effect can lead concrete to increased compressive strength, improved durability and reduced drying [32]. Fly ash can also decrease bleeding and develop constancy [33].

The main aim of this research work was to utilise three types of SCMs: metakaolin, fly ash and GGBS in SCC and to study its effect on hardened and microstructure at different replacement levels of cement (10 and 20 wt.% for MK and 10, 20 and 30 wt.% for FA and GGBS) because it was reported in the literature that in major cases concrete blended with SCMs exhibits better performance in strength and improvement in pore structure. The rheological properties were examined by conducting several tests as per The European Guidelines for Self-Compacting Concrete [34] specifications and proper mix proportion was achieved. To assess the mechanical properties of SCC mixes compressive strength and modulus of elasticity were evaluated. For the mixes with higher volume SCMs, the micro-analyses using scanning electron microscope (SEM) and energy-dispersive X-ray spectroscopy (EDS) were carried out to assess the Ca/Si ratio.

2 Experimental Work

2.1 Constituent materials

Portland cement CEM II/ B-V 32.5R, manufactured by Lafarge Company, was used throughout this study. Fly ash used in this experiment is classified as siliceous fly ash

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(alumino-silicate fly ash) or class F Fly Ash, according to BSI standards [35] where the essential chemical components are silicates and aluminates. The Blaine fineness (specific surface area) of the FA was 35.48 m^2/N (3478 cm^2/g). GGBS in this research comprises mainly of CaO, SiO_2, Al_2O_3 and MgO. It has the same main chemical composition as ordinary Portland cement, but in different proportions. The metakaolin used in this research contained 25% silicon and 20% aluminate. MetaStar 501, obtained from IMERYS Performance Minerals Company, was utilised in this investigation. According to the data sheet provided by IMERYS [36], the specific gravity of the sample used with white colour was 2.5 g/cm^3. The limestone powder used as filler in this study was hydrated lime with 38% calcium and fine particles. Table 1 gives the chemical compositions of cement, MK, FA and GGBS and limestone powder.

The coarse aggregates used in this research were crushed limestone. These aggregates were in one grade size of 10mm, supplied by a local quarry in the UK in compliance with the requirements of BS EN 12620:2002 + A1: 2008 [37]. The sand used throughout this study was natural sea-dredged from the Bristol Channel in accordance with PD 6682-1:2009 [38] and BS EN 933-1:2012 [39]. ADVA Flow 340 from Grace Company was used as a High Range Water Reducer Admixture (HRWRA) or Superplasticiser (SP). ADVA Flow 340 conforms to BS EN 934-2:2009+A1:2012 [40].

Table 1 Chemical and physical properties of PC, MK, FA, GGBS and Limestone powder

Chemical elements %	**PC**	**MK**	**FA**	**GGBS**	**Limestone powder**
O	49.09	52.83	54.11	46.42	60.87
Ca	30.10	-	2.06	27.48	38.63
Si	9.82	25.45	24.78	14.80	-
Al	4.88	20.03	14.92	4.94	-
Mg	0.98	-	0.59	4.50	0.49
K	1.04	1.70	2.25	0.50	-
Fe	2.38	-	1.29	0.28	-
Physical properties					
Specific gravity (g/cm^3)	3.1	2.5	2.1	2.9	2.3

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2.2 Mix design

Mix design method employed in this research was based on the paste volume [34] with appropriate water/powder ratios, which were kept in the range of 0.85 to 1.1 recommended by The European Guidelines for Self-Compacting Concrete [34]. Figure 1 shows the flowchart of the mix design method used in this study.

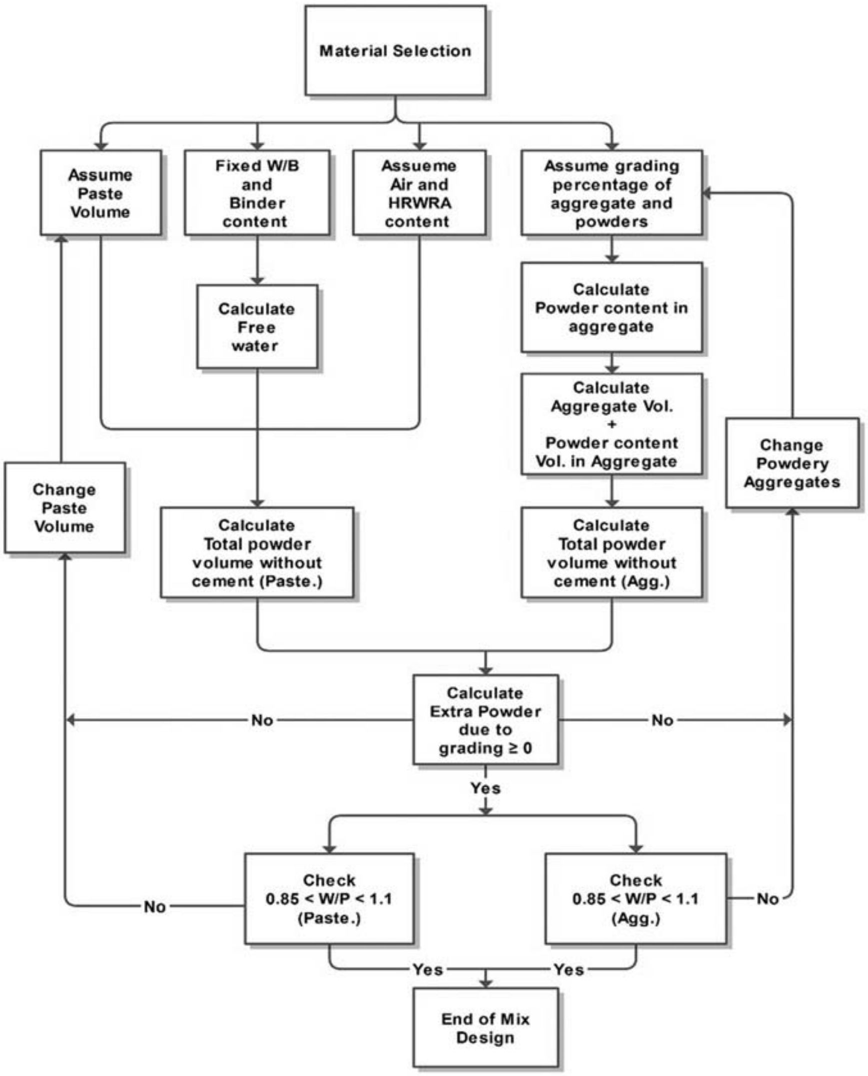

Figure 1 Mix design method

In total, 18 SCC mixtures with two water/binder ratios (0.4 and 0.45), including two PC only SCC mixes and two groups of 8 mixtures with different percentage of SCMs, were

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investigated. In each group, metakaolin replaced at 10 and 20 percent of the normal SCC mixture’s cement content by weight. GGBS and FA also replaced at 10, 20 and 30 percent of cement content. Binder content 400 kg/m^3 was kept the same for all mixtures. The mixture proportions are given in Table 2. The amount of superplasticiser was added until satisfying the fixed slump flow target 750±20 mm. The mix codes, shown in Table 2, are based on: a) water to binder ratio, b) first letter of SCMs and c) the SCMs replacement percentage. For example:

- 45M10: w/b=0.45, 10% Metakaolin as cement replacement
- 40G30: w/b=0.4, 30% GGBS as cement replacement

Table 2 Mix proportions (kg/m^3)

Mix code	PC	MK	GGBS	FA	Sand	Gravel	Lime	Water	SP
Group 1, w/b=0.4									
40C	400	-	-	-	802.9	877.2	89.4	160	4.5
40M10	360	40	-	-	802.9	877.2	89.4	160	8.6
40M20	320	80	-	-	802.9	877.2	89.4	160	10.4
40G10	360	-	40	-	802.9	877.2	89.4	160	5.3
40G20	320	-	80	-	802.9	877.2	89.4	160	6.1
40G30	280	-	120	-	802.9	877.2	89.4	160	6.5
40F10	360	-	-	40	802.9	877.2	89.4	160	3.9
40F20	320	-	-	80	802.9	877.2	89.4	160	3.3
40F30	280	-	-	120	802.9	877.2	89.4	160	2.6
Group 2, w/b=0.45									
45C	400	-	-	-	732.5	851.7	121.6	180	4.3
45M10	360	40	-	-	732.5	851.7	121.6	180	7.9
45M20	320	80	-	-	732.5	851.7	121.6	180	9.6
45G10	360	-	40	-	732.5	851.7	121.6	180	4.9
45G20	320	-	80	-	732.5	851.7	121.6	180	5.3
45G30	280	-	120	-	732.5	851.7	121.6	180	5.8
45F10	360	-	-	40	732.5	851.7	121.6	180	3.6
45F20	320	-	-	80	732.5	851.7	121.6	180	3.1
45F30	280	-	-	120	732.5	851.7	121.6	180	2.3

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2.3 Fresh properties

The main fresh properties of SCC mixes such as deformability, passing ability and segregation resistance were analysed by slump flow spreading diameter, J-ring step height, L-box passing ratio, U-box step height and V-funnel flow times according to the procedure recommended by The European Guidelines for Self-Compacting Concrete [34] and EFNARC [41].

2.4 Mechanical properties

The compressive strength tests were performed according to BS EN 12390-3:2009 [42] requirements and it was carried out on the three water cured cubes of 100×100×100 mm for each mix at 7, 28 and 56 days. Modulus of elasticity was measured in accordance with BS EN 12390-13:2013 [43] at 28 days with water curing on the cylindrical specimens of diameter 150mm and height 300mm.

2.5 Microstructural properties

The microstructural properties were established only on the water cured samples with highest volume of SCMs at 28 days. The Scanning Electron Microscope (SEM) was used to observe the transition zone between paste and aggregate. The Energy-dispersive X-ray spectroscopy (EDS) analysis was also utilised to determine the chemical components of the paste in the transition zone.

3 Results and Discussion

3.1 Fresh state results

The slump flow values for all SCC mixes were fixed and achieved in the range of 750±20 mm. The demand of SP changed based on the target slump flow value on each SCC mix.

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The amount of SP increased dramatically with the increase of MK and GGBS. However FA made the SCC more flow-able and decreased the amount of SP as given in Table 2.

Moreover, the J-ring, L-box, U-box and V-funnel tests were carried out to ensure the satisfactory fresh properties of SCC mixes. Table 3 gives the fresh properties results and all SCC mixes were found to satisfy The European Guidelines for Self-Compacting Concrete [34] and EFNARC [41] benchmarks.

Table 3 Fresh properties results

Mix code	**Slump flow spread diameter (mm)**	**J-ring step height (mm)**	**L-box passing ratio**	**U-box step height (mm)**	**V-funnel**	
					1min	5mins
Group 1, w/b=0.4						
40C	740	3	0.94	5	7	10
40M10	730	10	0.89	10	10	15
40M20	730	20	0.85	20	12	18
40G10	750	5	0.92	5	6	11
40G20	750	10	0.95	8	8	12
40G30	750	15	0.96	10	9	13
40F10	730	3	0.95	5	6	8
40F20	750	0	0.95	3	5	8
40F30	760	0	0.98	2	4	8
Group 2, w/b=0.45						
45C	750	2	0.92	2	5	9
45M10	770	5	0.89	5	9	14
45M20	740	10	0.89	15	10	18
45G10	750	5	0.91	3	6	10
45G20	760	10	0.95	6	8	11
45G30	750	10	0.98	10	9	11
45F10	760	0	0.94	4	4	6
45F20	740	0	0.96	3	6	8
45F30	750	0	0.98	1	7	7

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3.2 Mechanical results

3.2.1 Compressive strength

The compressive strengths of all SCC mixtures at 7, 28 and 56 days for two w/b ratios are plotted in Figures 2, 3 and 4. It can be seen that mixtures having higher metakaolin replacement levels with both w/b ratios gained high strengths. SCC with 20% MK showed an extraordinary high strength at all ages, particularly 77.7 MPa at 7 days with at w/b ratio 0.4. The enhanced early strength of MK blended SCC is mainly due to quick pozzolanic reaction of metakaolin [44]. This pozzolanic reactivity is related to the higher amount of silicon in MK with about 25% which can improve the C-S-H gel in fresh concrete and also affect the hardened properties at early and later ages. The large total surface area of MK particles leads to an increase in reactivity as well.

GGBS blended SCC with w/b ratio 0.4 showed a significant growth in strength at all ages with the increase of GGBS replacement level. All GGBS mixes obtained lower strength at 7 days compared with control mix. However, 30% GGBS replacement of PC exhibited better performance after 28 days. All GGBS mixes with w/b ratio 0.45 achieved higher strength than control mix at all ages.

The SCC mixes containing FA unveiled lower strength at all ages than control mix, though the strength of all FA SCC mixtures was enhanced with the increase of FA replacement level.

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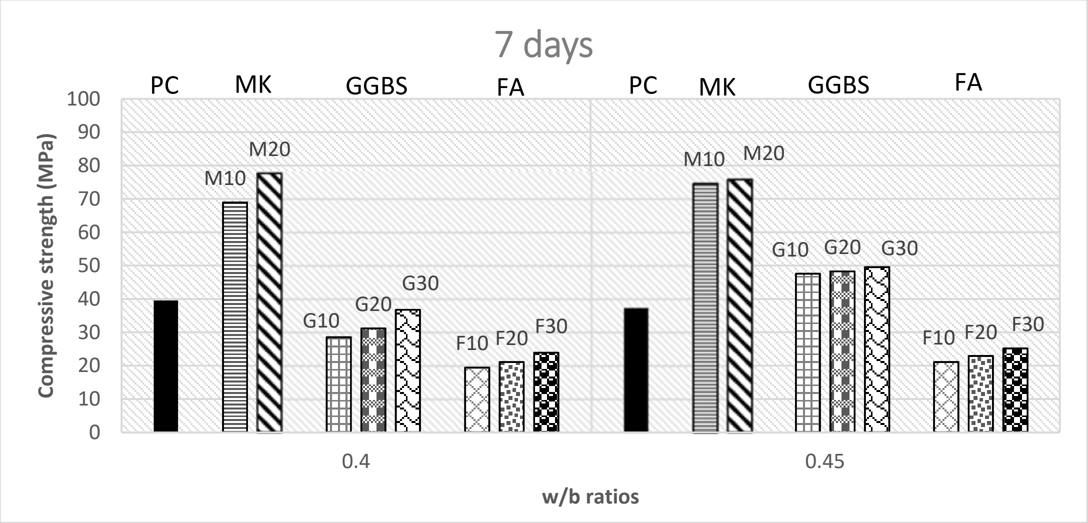

Figure 2 Compressive strength of SCC for both w/b ratios at 7 days

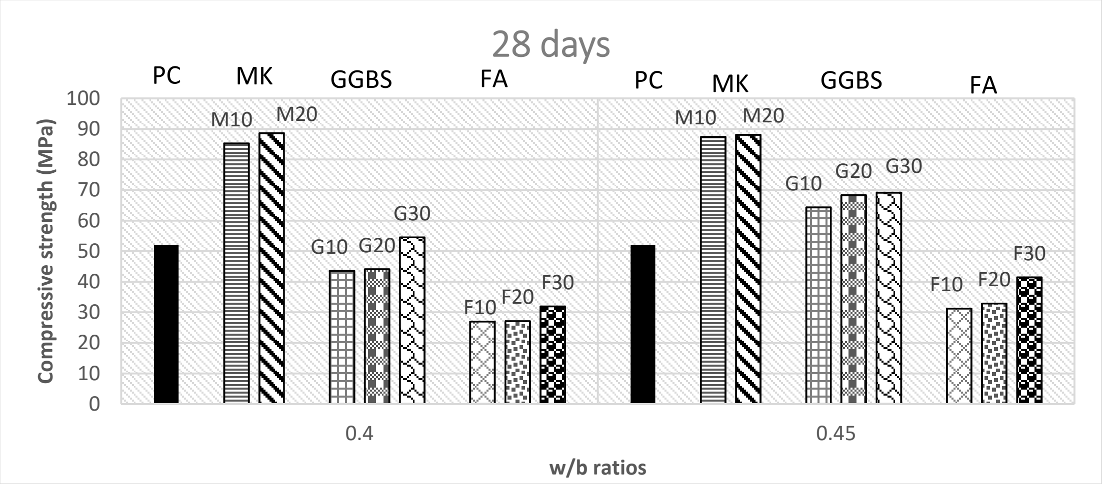

Figure 3 Compressive strength of SCC for both w/b ratios at 28 days

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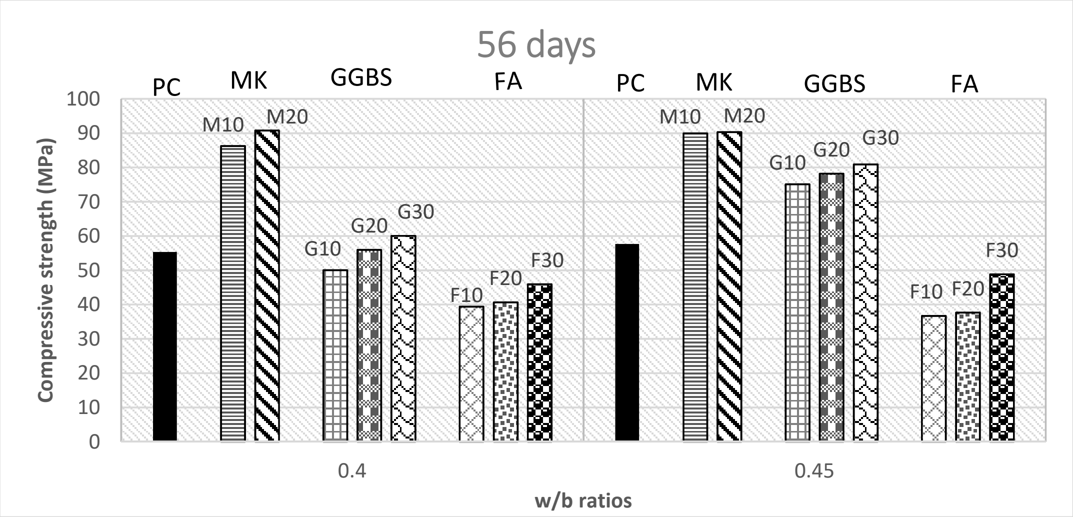

Figure 4 Compressive strength of SCC for both w/b ratios at 56 days

3.2.2 Modulus of elasticity

With the better performance of MK and GGBS in terms of compressive strength the modulus of elasticity has been examined on the mixes containing MK and GGBS. The correlation between the modulus of elasticity and replacement of MK in the SCC mixtures is presented in Figure 5 with appropriate polynomial relations between elasticity modulus and replacement level of MK for two w/b ratios.

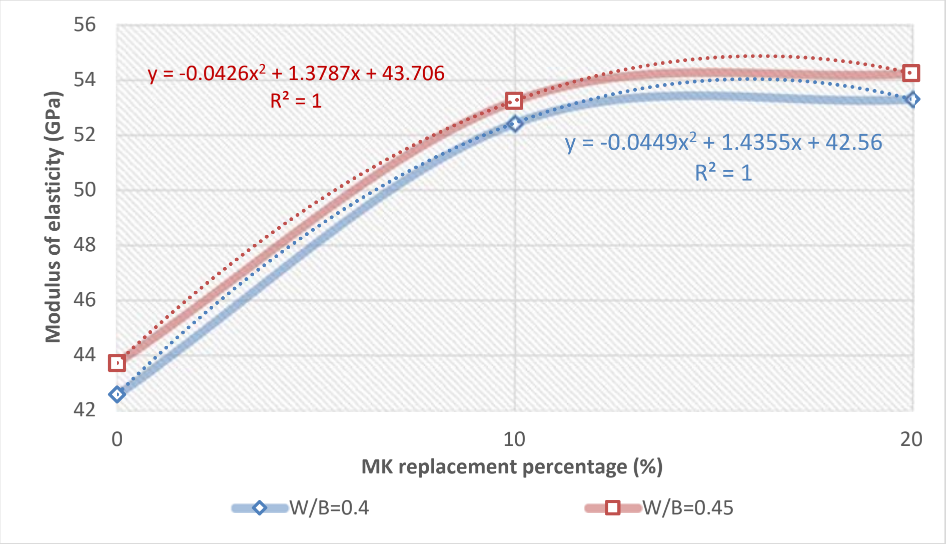

Figure 5 Modulus of elasticity per MK replacement in SCC

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For w/b ratios 0.4 and 0.45, the modulus of elasticity increases with the increase of the replacement of MK in the SCC mixtures. Two functions have been proposed in the equations 1 and 2. It is important to note that the equations were extracted for both w/b ratios used, respectively. For other w/b ratios a preliminary study should be carried out to conclude suitable equations.

$$E = -0.042\left(\frac{MK}{PC}\right)^2 + 1.38\left(\frac{MK}{PC}\right) + 43.7,\ R^2 = 1 \quad (1) \quad \text{for mixes with w/b=0.4 and,}$$

$$E = -0.045\left(\frac{MK}{PC}\right)^2 + 1.44\left(\frac{MK}{PC}\right) + 42.5,\ R^2 = 1 \quad (2) \quad \text{for mixes with w/b=0.45.}$$

Where E is modulus of elasticity (GPa); and MK/PC is the percentage of MK in SCC mix as a replacement of PC (%, by weight).

Figure 6 shows the relationship between modulus of elasticity and replacement level of GGBS in the SCC mixtures. For mixtures of both w/b ratios, suitable correlations ($R^2 = 0.98$) between modulus of elasticity and GGBS replacement level in SCC were obtained and the equations are proposed below:

$$E = 0.0099\left(\frac{GGBS}{PC}\right)^2 - 0.18\left(\frac{GGBS}{PC}\right) + 42.6, R^2 = 0.98 \ (3) \ \text{for mixes with w/b=0.4 and,}$$

$$E = -0.0044\left(\frac{GGBS}{PC}\right)^2 + 0.26\left(\frac{GGBS}{PC}\right) + 43.6, R^2 = 0.98 \ (4) \ \text{for mixes with w/b=0.45.}$$

Where E is modulus of elasticity (GPa); and GGBS/PC is the percentage of GGBS in SCC mix as a replacement of PC (%, by weight).

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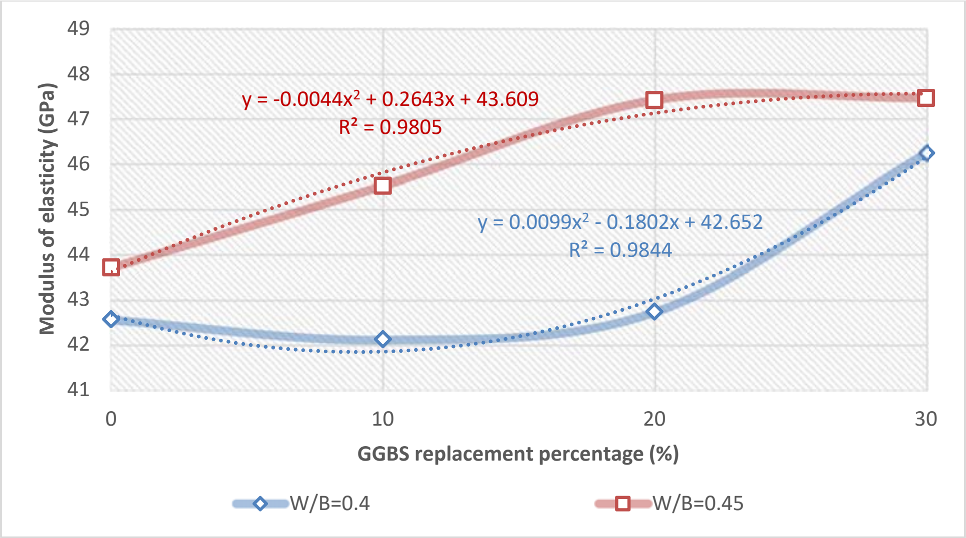

Figure 6 Modulus of elasticity per GGBS replacement in SCC

As known the modulus of elasticity is the function of compressive strength as well as the characteristics of the interfacial transition zone (ITZ) and moduli of elasticity of the principle constituents (paste and aggregates) [45]. MK increased compressive strength at all replacement levels as shown in Figure 4, so the modulus of elasticity increases. GGBS shows the same behaviour as MK, except at 10% replacement level for w/b=0.4. Both compressive strength and modulus of elasticity decreased at 10% replacement level which can be referred to the characteristics of the ITZ. This should be noted that GGBS provides less amount of silicon in comparison with MK, which can be affected the strength of transition zone. Moreover, by comparing the results shown in Figures 2, 3 and 4, and also Table 1, it is important to consider the amount of calcium and silicon elements in the suspension containing SCM as well as the ratio of Ca/Si which could lead to different behaviour of ITZ. This will be discussed further in the section of microstructural analysis.

Furthermore, the relationships between modulus of elasticity and compressive strength at 28 days for both SCC mixes containing MK and GGBS are shown in Figure 7, from which it can be seen that there are very good coefficients of determination (R^2 = 0.99 for MK and 0.82 for

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GGBS) between compressive strength and modulus of elasticity. Equations 5 and 6 present the relationships, respectively:

$E = 0.288f_c + 28, R^2 = 0.99$ (5) for mixes contains MK and,

$E = 0.161f_C + 36, R^2 = 0.82$ (6) for mixes contains GGBS.

Where E is the modulus of elasticity (GPa) and f_c is the compressive strength (MPa).

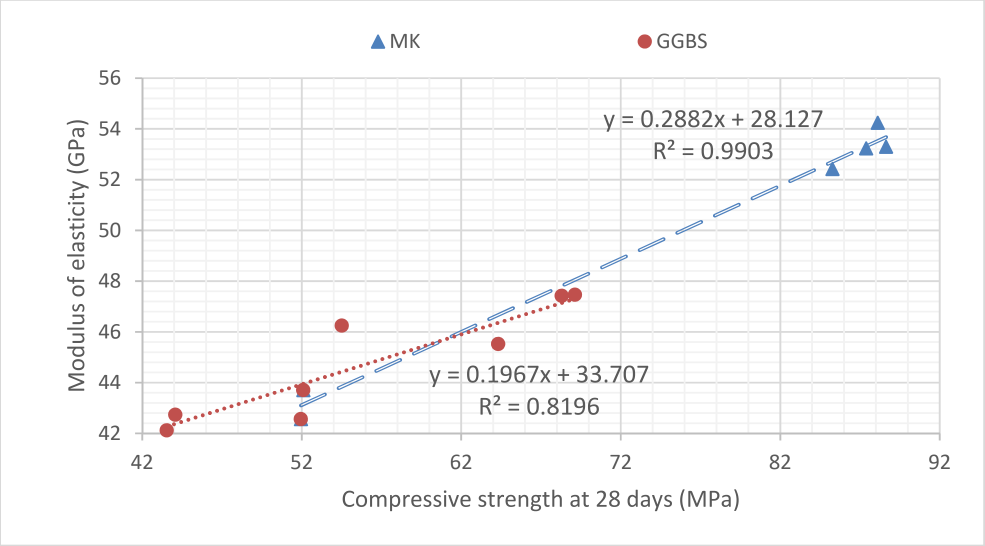

Figure 7 Compressive strength (MPa) vs modulus of elasticity of SCC with MK and GGBS

Figure 8 shows the ratio of modulus of elasticity (GPa) to compressive strength (MPa) at 28 days. Turcry, Loukili, and Haidar [46] found that the ratio of modulus of elasticity (GPa) to compressive strength (MPa) was approximately 0.6 for SCC. However, the ratio for all SCC mixes with two w/b ratios in this study is higher than 0.6 shown by the dash line in Figure 8. SCC mixes with PC only had approximately 0.8 and SCC mixes containing MK were in the same range of the value proposed by Turcry, Loukili, and Haidar [46]. SCC mixes with GGBS at w/b ratio 0.4 had slightly higher value than the same mixes with w/b ratio 0.45, but still higher than the value proposed by Turcry et al. [46].

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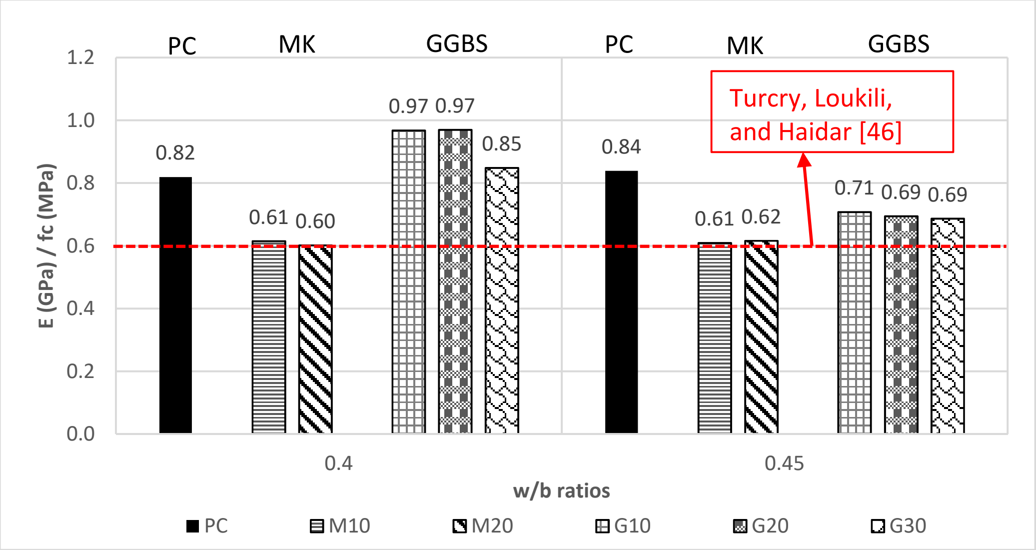

Figure 8 Ratio of modulus of elasticity (GPa) to compressive strength (MPa)

3.3 Microstructural properties

3.3.1 SEM observations

SEM images were taken on the SCC mixtures with highest amount of SCM to examine the microstructure properties in transition zone and paste around aggregates. SEM images for the 20% MK and 30% GGBS SCC mixes with both w/b ratios are shown in Figures 9 and 10.

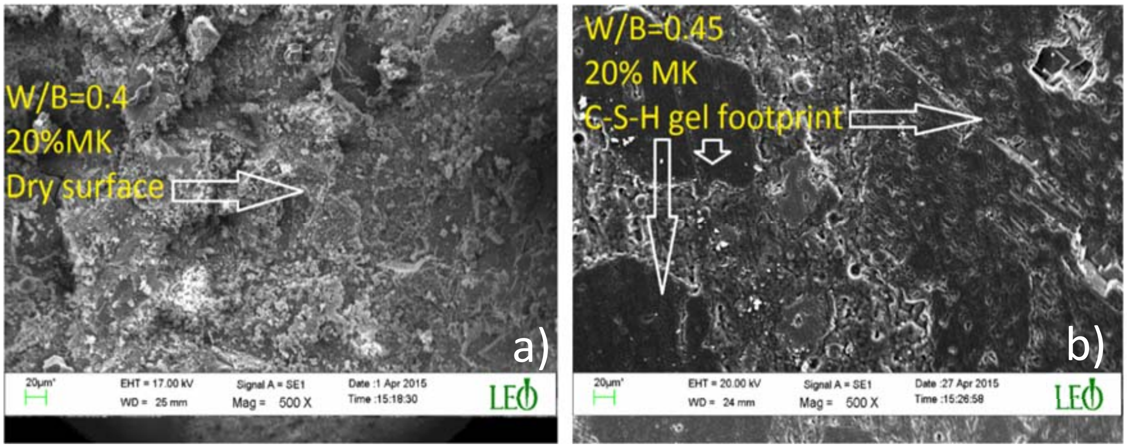

Figure 9 SEM pictures of 40M20 (a) and 45M20 (b)

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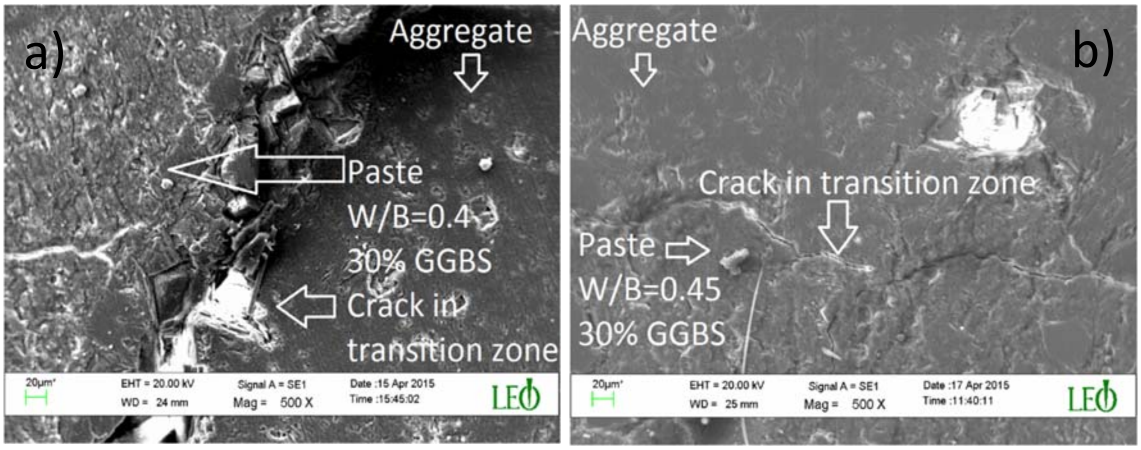

Figure 10 SEM pictures of 40G30 (a) and 45G30 (b)

Figure 9 presents the SEM images of SCC mixes containing 20 wt.% MK with two w/b ratios. Figure 9-a shows a dryer surface structure compared to the same mix with w/b ratio 0.45 (Figure 9-b). This confirms that MK is able to create higher volume of C-S-H gel in presence of more water which means MK is more active with extra water. However, according to the compressive strength results shown in Figures 2, 3 and 4 these two mixes showed almost the same strength in compression. This indicates in higher volume of MK, it is possible by increasing the water content to improve rheology without negative effect on strength.

Figure 10 shows the SEM images of SCC mixes containing 30% wt.% GGBS with two w/b ratios. It can be observed that there is a notable difference between the pastes in two SCC mixes. SCC mix with 30% GGBS with w/b ratio 0.45 (Figure 10-b) has more homogenous paste in comparison with same mix with w/b ratio 0.4 (Figure 10-a). Improved homogeneity is related to the higher volume of water, however no difference of the C-S-H gel in these two mixtures can be observed. This confirms that water would not affect GGBS to create more C-S-H gel. Moreover the type of crack in the mix 40G30 (Figure 10-a) is more crucial than the crack in 45G30 (Figure 10-b). This is also another evidence to demonstrate the importance of paste homogeneity, which has direct effect on the transition zone. Generally,

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based on the SEM images shown in Figure 9 and 10, it can be verified that MK has a greater effect on the microstructural strength of the transition zone than GGBS. This conclusion is in agreement with previous study carried out by Asbridge and Page [47].

3.3.2 Energy-dispersive X-ray spectroscopy (EDS) analysis

The EDS results on the SCC mixes containing higher replacement level of GGBS and MK with two w/b ratios are given in Figures 11, Figure 12 and Table 4. According to the obtained data from EDS analysis for SCC mixes containing MK, the atomic Ca/Si ratio is about 1.3 (1.308 for w/b ratio 0.4 and 1.299 for w/b ratio 0.45). The compressive strengths of these mixes at 28 days shown in Figure 3 are in the same range of 88 MPa, indicating there is significant relationship between the compressive strength and the Ca/Si ratio. For SCC mix containing GGBS, the Ca/Si ratio is 1.728 for w/b ratio 0.4 and 2.289 for w/b ratio 0.45, whereas the compressive strength at 28 days were 54.52 MPa and 69.14 MPa for w/b ratio 0.4 and 0.45, respectively. Generally, by comparing SCC mixes containing GGBS and MK with two w/b ratios, it can be confirmed that lower Ca/Si ratio reflects the compressive strength enhancement. This is in agreement with the previous study about MK in SCC by Kavitha et al. in 2015 [48].

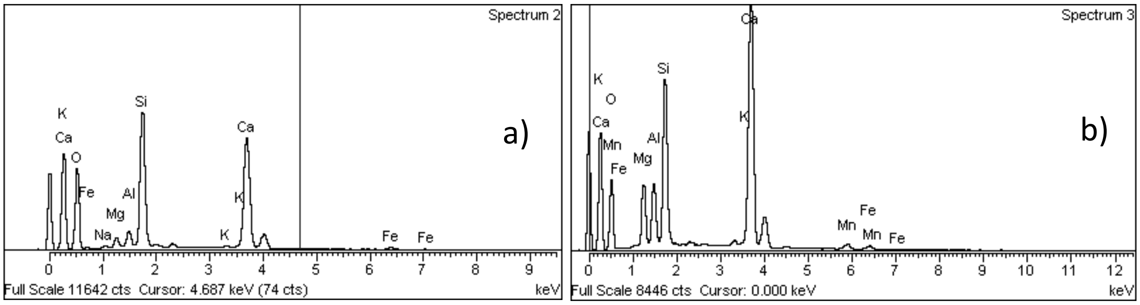

Figure 11 EDS (X-ray) analysis for 40M20 (a) and 45M20 (b) at 28 days

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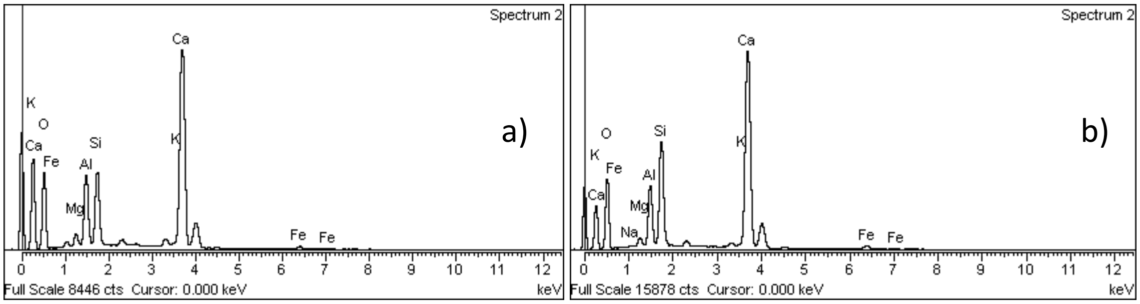

Figure 12 EDS (X-ray) analysis of 40G30 (a) and 45G30 (b) at 28 days

Table 4 Chemical elements (Atomic %) in the SCC containing MK and GGBS

Chemical elements (Atomic %)	**40M20**	**45M20**	**40G30**	**45G30**
O	54.81	56.19	63.93	67.54
Ca	22.59	18.17	18.54	16.90
Si	17.27	13.98	10.73	8.69
Al	1.75	4.36	3.28	3.75
Mg	1.50	5.89	1.22	1.30
Na	0.47	-	-	0.63
K	0.43	0.35	0.61	0.52
Fe	1.19	0.43	0.76	0.68

4 Conclusion

The main conclusions from the study can be summarized as follows:

- All SCC mixes satisfied fresh property criteria mentioned in The European Guidelines for Self-Compacting Concrete [34] and EFNARC [41].
- Based on the compressive strength results, MK had enhanced effect on compressive strength at all ages. Blends with GGBS also performed well in SCC at all ages except with lower w/b ratio (0.4) at 7 days. The SCC mixes containing FA unveiled lower strength at all ages.
- MK and GGBS were able to enhance modulus of elasticity at all replacement levels of PC except 10% GGBS. Moreover, two equations with appropriate coefficients of determination were obtained between modulus of elasticity and compressive strength for SCC mixes with MK and GGBS

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- SEM examinations were conducted to observe the effect of MK and GGBS with two w/b ratios on the microstructural properties and also to determine the chemical components especially Ca/Si ratio. The SEM observations approved that MK lead higher amount of C-S-H gel in presence of higher w/b ratio without affecting the mechanical properties. Furthermore, GGBS in higher w/b ratio improved homogeneousness of paste which has direct effect on the transition zone. MK has a greater effect on the microstructural strength of the transition zone than GGBS.
- The results of EDS analysis demonstrated that lower Ca/Si ratios indicate the improvement of compressive strength.

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