

Feasibility study of high volume slag as cement replacement for sustainable structural lightweight oil palm shell concrete



Kim Hung Mo ^{a,*}, U. Johnson Alengaram ^{a,b,*}, Mohd Zamin Jumaat ^{a,b}, Soon Poh Yap ^a

^a Department of Civil Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

^b Centre for Innovative Construction Technology (CCT), Department of Civil Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

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ABSTRACT

This paper presents a study on the use of high volume slag as a cement replacement material, and waste oil palm shell (OPS) as a lightweight aggregate to produce a sustainable lightweight concrete (LWC). In order to establish the feasibility of such concrete for structural purposes, the first part of the paper deals with the investigation of the mechanical and bond properties of OPS concrete (OPSC) with varying slag content. The results showed that even though an increase in the slag content led to the reduction in the strength, the OPSC with slag as a 60% cement replacement material exhibited compressive and splitting tensile strengths of 25 and 2.3 MPa, respectively, which exceeded the minimum stipulated strength required for structural LWC. In addition, the use of 60% slag in OPSC showed significant benefits in terms of the reduced cement consumption with improvement in the strength efficiency by almost 2-fold compared to that without slag. On the other hand, it was found that the slag content, albeit as high as a 60% cement replacement level, did not show any significant adverse effects on the normalized bond strength, failure mode, bond strength-slip curve and slip at the ultimate bond strength of the OPSC. To further justify the suitability of the OPSC for structural application, the second part of the paper focuses on the experimental investigation of the flexural behaviour of the actual full-scale reinforced concrete beams. From the flexural tests, it was observed that there were no negative effects on the ultimate moment capacity, failure mode and moment-deflection behaviour of the reinforced concrete beams upon cement replacement with up to 60% slag. Therefore, the utilization of high volume slag-lightweight OPSC could be recommended for actual structural purposes.

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1. Introduction

Owing to the ever-present construction activities around the world, one of the most worrying environmental concerns pertains to the high amount of carbon dioxide (CO₂) emissions due to the use of cement. Approximately 1 t of CO₂ is released from the manufacture of 1 t of cement. The cement industry alone contributes to approximately 5–7% of the world's CO₂ emission. The increasing demand for cement due to the rapid growth in the construction industry could further increase this figure. It is expected that by 2020, the global demand for cement would increase

by about 115–180% compared to the 1990s, and this is likely to surge to 400% by 2050 (Damtoft et al., 2008). Therefore, there is a need to seek alternatives to partially replace the cement to reduce the adverse effects of the excessive usage of cement. One of the ways is through the use of mineral admixtures. Some of the more commonly available mineral admixtures include silica fume, fly ash and slag. The use of slag to partially replace cement is generally well accepted in the cement industry due to its low cost and reasonable strength even at high replacement levels. Furthermore, the use of slag provides additional environmental advantages, which include natural resource conservation and the recycling of industrial by-products (Yang et al., 2014), since slag occurs as a by-product from the iron industry. Based on a study in China in 2012, the output of pig iron of more than 650 mil t produced around 200 mil t of blast furnace slag (Sun et al., 2014). The durability of concrete, particularly its resistance to chloride penetration, could be significantly improved with the use of slag, as this permits a longer corrosion-free service life of reinforced concrete structures under the most extreme natural environments (Bijen, 1996). Concrete

Abbreviations: CO₂, Carbon dioxide; LVDT, linear voltage displacement transducer; LWC, lightweight concrete; ODD, oven dry density; OPC, Ordinary Portland cement; OPS, oil palm shell; OPSC, oil palm shell concrete; SP, superplasticiser.

* Corresponding authors. Department of Civil Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia. Tel.: +60 379677632.

E-mail addresses: khmo890815@gmail.com (K.H. Mo), johnson@um.edu.my (U. Johnson Alengaram).

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with longer service life require less demolition and renovation works, which could effectively reduce greenhouse gas emissions and global warming index (Valipour et al., 2014). Based on the benefits of using slag as a cement replacement material, researchers in the past (Shafigh et al., 2013b; Mo et al., 2014b) had experimented with the use of ground granulated blast furnace slag in lightweight oil palm shell concrete (OPSC) to develop a more sustainable concrete.

In Malaysia, large amounts of waste oil palm shell (OPS), which occurs as a by-product from the palm oil extraction process, is dumped and stockpiled in the vicinity of factories. In 2011, oil palm plantation in the country covered about 4.98 million ha, which is approximately 15% of the land area in the country. Furthermore, based on the past 25 years of statistics, an increase in the plantation area by about 0.14 million ha/y and coupled with the growing demand for palm oil (Hansen et al., 2014), the industrial waste of OPS is expected to be in abundance in the future. As time passes, this growing amount of OPS dumped causes land pollution and creates an unwelcoming sight. The utilization of such waste, OPS, as a lightweight aggregate for the production of lightweight concrete (LWC), may ease these environmental concerns, and, at the same time, reduce the dependency on natural coarse aggregate, such as granite. Furthermore, the sourcing of locally available OPS for concrete could also lower the embodied energy associated with construction materials due to the reduction of imported materials (Stephan and Stephan, 2014), particularly conventional manufactured lightweight aggregates, which are not readily available in the country. Therefore, the combined usage of OPS and slag to reduce granite extraction and CO₂ emission could therefore produce a desired sustainable 'green' lightweight concrete.

It was found that there was a reduction of about 50% in the overall CO₂ emission for the production of a unit compressive strength of the OPSC when the amount of slag, as a partial cement replacement, was increased up to 70% (Mo et al., 2014a). As reported by Shafigh et al. (2013b) and Mo et al. (2014a), although increasing the amount of slag in the OPSC could lead to a reduction in the compressive strength, the replacement level, as high as 70%, could still produce a structural grade LWC. Such findings encourage further investigations concerning the use of OPSC with a high volume slag for structural application. Past research works mainly focused on the investigation of the mechanical properties; however, this is not sufficient to ascertain the structural feasibility of such concrete as one of the most important properties is the bond characteristic.

Although the bond properties are essential for the performance of the structural members, the effect of the mineral admixture on the bond between the concrete and the reinforcing bar was not given much attention in the past. Studies that were conducted mainly focused on the effects of silica fume (Hwang et al., 1994; Karatas et al., 2010) and fly ash (Hossain and Lachemi, 2008; Arezoumandi et al., 2013) on the bond strength of concrete, whereas very limited information is available for the effects of slag on the bond properties of concrete. Furthermore, some of these reports present contrasting findings and uncertainty still exists over the effect of the mineral admixture on the bond properties. Also, although preliminary studies on the bond capacities of plain OPSC were carried out in the past (Teo et al., 2007; Alengaram et al., 2010), the full bond behaviour was not investigated and very little information is available on the effect of high volume cement replacement on the bond behaviour of OPSC. Therefore, the first part of the study is devoted to investigating the effects of slag as a partial cement replacement on the bond properties of lightweight OPSC. This investigation focuses on three different levels of cement replacement with slag, specifically, 0%, 20% and 60%. This is particularly important, especially in the case of the OPSC with 60%

slag since replacing the majority of the traditional cement could significantly affect the concrete properties. Proper knowledge on the effects of slag on the bond properties in OPSC could provide the necessary guidance for designers involved with such concrete, and further enhance the feasibility of sustainable 'green' concrete for actual structural applications.

Past investigations have shown that despite the reduction in the strength of the OPSC or other types of LWC upon a high volume of cement replacement, the concrete could attain sufficient strength for structural purposes. However, in the past, there was no actual test or investigation carried out to evaluate the flexural performance of reinforced OPSC beams containing high amount of cement replacement for structural application. Intuitively, it would be expected that the cement replacement would not affect the flexural behaviour or the reinforced concrete beam significantly; however, it is important to bear in mind that when a higher reinforcement ratio is used, concrete with a significantly low strength could result in a reduced ultimate moment capacity as well as brittle failure due to the over-reinforced section of structural members. The brittle failure mode of over-reinforced concrete structures will undeniably be catastrophic. Therefore, in order to establish the feasibility of OPSC with high volume slag for structural purposes, using controlled strength grade 30 OPSC with varying slag content of 0%, 20% and 60%, the second part of this study deals with the experimental investigation of the flexural behaviours of these full-scale reinforced lightweight OPSC beams with a fixed tensile reinforcement ratio of 1.0%.

2. Experimental programme

2.1. Materials

The slag used in the current study is ground granulated blast furnace slag, which is obtained from the steel-making process when molten iron slag is quenched from a blast furnace in water to form granules and ground to a specified fineness by using a grinding mill. The specific gravity of the ground granulated blast furnace slag used in this study was 2.90 compared to the specific gravity of 3.10 for Ordinary Portland cement (OPC). The chemical compositions of OPC and slag are listed in Table 1.

The coarse aggregate used was crushed OPS (specific gravity: 1.35) ranging in size between 2.36 and 9 mm (medium coarse gradation), and conforming to the specification of structural lightweight aggregates according to ACI 213R. The OPS was collected from a local palm oil factory and washed with detergent to remove the oil coating on the surfaces. Prior to casting, the OPS was soaked in water for 24 h before being air-dried to achieve a saturated surface dry condition. The OPS had bulk density of 658 kg/m³ and 24-h water absorption value of 25%.

Manufactured sand, which is obtained from the processing of crushed granite aggregate, is chosen to be used as the fine aggregate in this study instead of the conventional river sand. The manufactured sand provides a better environmentally friendly alternative since the excavation of natural sand can be avoided. The excessive excavation and use of natural river sand could lead to numerous environmental issues such as soil erosion, poor water

Table 1
Chemical composition of cement and slag.

Chemical composition (%)	SiO ₂	Fe ₂ O ₃	CaO	Na ₂ O	Al ₂ O ₃	SO ₃	K ₂ O	MgO	LOI
Cement	19.80	3.10	63.40	0.19	5.10	2.40	1.00	2.50	1.80
Slag	33.80	0.52	43.90	0.20	13.40	0.10	0.31	5.40	1.00

quality, loss of natural habitats, flooding etc. On the other hand, the manufactured sand is a by-product obtained from crushing of granite for coarse aggregates. Although the process of crushing granite to produce manufactured sand requires more energy compared to excavation of sand (Flower and Sanjayan, 2007), the use of manufactured sand would be beneficial in the long run considering that virgin aggregate deposits are fast depleting in many areas; further, procurement of natural river sand in undeveloped rural areas would therefore result in higher emission of carbon dioxide to the environment due to the transportation of machineries and river sand over longer distances. Furthermore, the use of manufactured sand also guarantees higher quality control compared to natural river sand, which might contain a varying amount of impurities depending on the source. In addition, previous research (Nanthagopalam and Santhanam, 2011) reported that the use of manufactured sand is a viable alternative to fully replace conventional river sand for the production of concrete as no significant adverse effects on the strength of the concrete were observed with the use of manufactured sand. In this study, manufactured sand with a specific gravity of 2.56 and size between 0.3 and 5 mm was used.

Potable water that was free from contaminants and impurities was used as mixing water in the casting. A polycarboxylate-ether based superplasticiser (SP) was added to facilitate workability. A grade 500 MPa high yield ribbed steel reinforcing bar with a diameter of 12 mm was used for the bond test.

2.2. Mix proportion and procedure

As shown in Table 2, a total of three concrete mixes with constant binder, sand, OPS and water content were prepared for this study while the variable investigated was the varying levels of cement replacement with slag, specifically, 0%, 20% and 60%. The SP content was fixed at 1.0% by the mass of the binder for all mixes. Based on the mix design used in this study where the OPS content is 400 kg/m³ and assuming 65 m² of concrete is required for a unit of double storey terrace house, the amount of waste OPS available annually, which is about 4 million t in 2006 (Teo et al., 2007), could produce OPSC that would be sufficient for the construction of almost 150,000 units of double storey terrace houses in the country.

In the mixing process, the OPS and manufactured sand were dry mixed for 3 min, followed by the addition of OPC and slag, and mixed for a further 6 min. Thereafter, half of the required water was added and mixed for 3 min before the remainder of the water and SP were added. The entire wet mixing lasted for 10 min before being poured into oiled moulds and vibrated. All the specimens except for the beams were de-moulded after 24 h and then water cured for 28 d. The beams were kept in the mould and water cured for 7 d before being de-moulded. The beams were continuously cured with water until the age of 28 d, after which, all specimens were air-cured until age of testing.

2.3. Test method

2.3.1. Mechanical properties test

The 100 mm cube specimens were tested for compressive strength (BS EN 12390-3: 2002) whereas cylindrical specimens

with dimension of 100 mm Ø × 200 mm height were tested for splitting tensile strength (BS EN 12390-6: 2000). A total of three specimens were tested for each mix and the average of the three values was reported. All specimens were tested at the age of 180 d.

2.3.2. Bond test

For the bond test, a concrete prism specimen measuring 200 × 200 × 350 mm³ with an embedded reinforcing steel bar was used. As shown in Fig. 1, the bonded length was fixed at 4 times the diameter of the reinforcing bar (48 mm) at the centre of the embedded steel bar. A PVC tube sleeve was used in the un-bonded length to ensure smooth contact between the steel bar and the concrete. The protruding steel reinforcing bar was gripped and concentric pull-out force was applied via a displacement-controlled Universal Testing Machine. The slip of the steel reinforcing bar relative to the concrete was measured through the use of four linear voltage displacement transducers (LVDT). The average readings from the four LVDTs were taken as the value of the slip. During testing, the pull-out load from the Universal Testing Machine and the displacement measurements from the LVDTs were recorded continuously at intervals of 1 s using a data logger. A total of two specimens were tested for each mix at the age of 180 d.

2.3.3. Flexural test

The cross section of the beam is shown in Fig. 2. The dimensions of the beam were 150 mm (width) and 300 mm (height), with a clear cover of 25 mm. All beams were designed as under-reinforced to ensure flexural failure with 4 × 12 mm diameter steel reinforcing bars as tension reinforcement and 2 × 10 mm diameter steel reinforcing bars as compression reinforcement. Mild steel links of 6 mm diameters were provided at 75 mm c/c as shear reinforcement at the shear span. The beams cast were 3300 mm in length and had a clear span of 3000 mm. All the reinforced concrete beams were tested under two point loads; the load was transferred from the actuator of an INSTRON machine with 250 kN capacity via a spreader beam. The distance between the two point loads was fixed at 1000 mm for all the beams (Fig. 3). The flexural testing was conducted under load-controlled rate at 10 kN/min followed by a

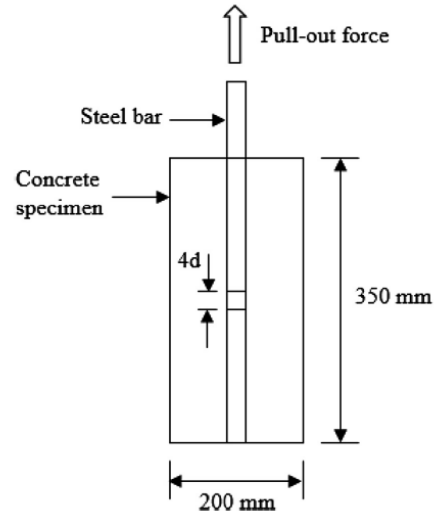


Fig. 1. Bond test set-up.

Table 2
Mix proportion.

Mix	Cement (kg/m ³)	Slag (kg/m ³)	Sand (kg/m ³)	OPS (kg/m ³)	Water (kg/m ³)
S0	520	0	940	400	170
S20	416	104	940	400	170
S60	208	312	940	400	170

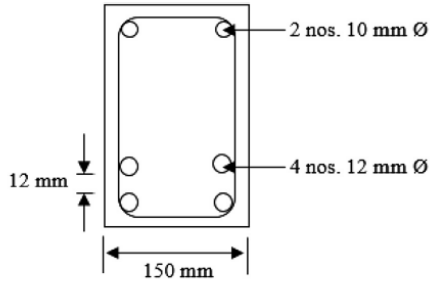


Fig. 2. Beam details.

displacement-controlled rate of 2 mm/min. The mid-span deflection of the beam was measured through the use of a LVDT connected to a data logger.

3. Results and discussion

3.1. Oven dry density

The oven dry density (ODD) of OPSC was obtained by drying the concrete specimens in an oven with a temperature of 105 ± 5 °C for 48 h. The ODD obtained in this study are presented in Table 3. It was found that all mixes had an ODD of below 2000 kg/m^3 and, thus, the OPSC produced in this study could be categorized as LWC according to EN206-1. The ODD of all mixes obtained had a standard deviation of less than 20 kg/m^3 , which gave a good confidence limit in the results obtained. The ODD of the OPSC obtained was generally about 20–30% lower compared to conventional concrete. The significant reduction in the density of the concrete reduces the dead load of the structural members, and, thus, this allows for flexibility in the structural design, such as increased span length, reduced depth of members and amount of reinforcement. The trend of decreasing the ODD with the increased amount of slag used in the OPSC observed in this study also confirmed the reported findings in previous research (Shafigh et al., 2013b), which was due to the lower specific gravity of the slag (Akcaozoglu and Atis, 2011).

3.2. Compressive strength

The compressive strength was found to decrease with the increased replacement of cement by slag; as shown in Table 3, the compressive strength reduced from 33.3 MPa to 30.8 MPa when the slag replacement level was 20% and this was further reduced to 25.4 MPa when the slag replacement level was increased to 60%. This observation agrees well with previous research in that the increased slag content led to a reduction in the compressive

Table 3

Oven dry density, compressive strength and splitting tensile strength.

Mix	Oven dry density (kg/m^3)		Compressive strength (MPa)		Splitting tensile strength (MPa)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
S0	1937	13	33.30	1.36	2.690	0.016
S20	1903	12	30.77	1.13	2.529	0.071
S60	1851	17	25.40	1.24	2.328	0.101

strength in the OPSC (Mo et al., 2014a). Nevertheless, all of the mixes exceeded the minimum requirement of compressive strength for structural grade lightweight concrete as per ACI 213R. Furthermore, the reduction in compressive strength of about 23% upon 60% cement replacement with slag was lower compared to the use of 50% fly ash, which caused a decrease in the compressive strength of about 30% in the OPSC (Shafigh et al., 2013a). This implies that the use of slag is preferable compared to fly ash with regard to the high level of cement replacement in the concrete.

Although the use of slag as a cement replacement in OPSC led to a reduction in compressive strength, in terms of environmental consideration, it is appropriate to analyse the effect of cement consumption along with the resultant strength of concrete. Therefore, the compressive strength efficiency is used as a performance index for the purpose of this investigation. The compressive strength efficiency is defined as a unit compressive strength per kilogram cubic metre of cement used and denoted as MPa/kgm^{-3} (Chao-Lung et al., 2011). Pelisser et al. (2012) also utilized a similar performance index of kg/MPa , albeit in an inverse relationship, to evaluate the performance of LWC in this aspect. OPSC without any slag was previously reported (Shafigh et al., 2014) to have higher efficiency compared to conventional concrete and lightweight concrete made with expanded clay. In the present study, it was observed that the use of higher slag content in OPSC further increased the compressive strength efficiency. The compressive strength efficiency of 0.064, 0.074 and $0.122 \text{ MPa/kg m}^{-3}$ was found for the mixes S0, S20 and S60. It should be noted that from the present investigation, lightweight OPSC with a compressive strength of about 25 MPa was achievable with the aid of a high volume slag content and significantly reduced the cement consumption to approximately 200 kg/m^3 . The savings from the cement consumption through the use of slag as a partial cement replacement not only reduced the CO_2 being emanated from the production of cement, the re-use of industrial by-products, such as slag, could significantly scale down the environmental problems caused by the disposal of these materials, such as water and air pollution. This is highlighted in a life cycle assessment carried out by Blankendaal et al. (2014) where it was reported that the use of slag could reduce the environmental impact to a maximum of 39%. Similar savings in the embodied carbon emission of about 43% was also revealed by Rai et al. (2011) when slag was used at a 50% cement replacement level.

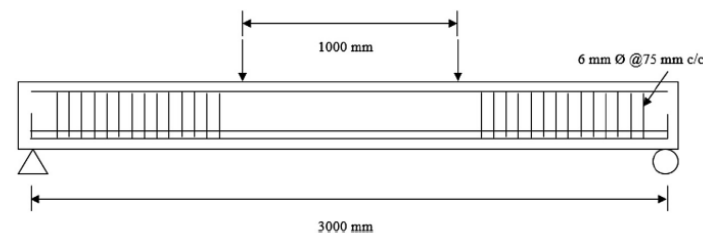


Fig. 3. Beam set-up.

3.3. Splitting tensile strength

The splitting tensile strength for mixes S0, S20 and S60 obtained was 2.69, 2.53 and 2.33 MPa, respectively. The splitting tensile strengths were about 8% of the corresponding cube compressive strengths in this study and corresponded well to the previous findings for OPSC (Alengaram et al., 2013). As a function of the compressive strength, the splitting tensile strength also reduced with the increased replacement of cement with slag. Shafigh et al. (2010) reported that there is a direct relationship between the cube compressive strength to the power of two-thirds and the splitting tensile strength for OPSC, as shown in equation (1), while Gesoglu et al. (2004) also proposed a similar relationship but with a larger coefficient (equation (2)) for LWC made from cold-bonded fly ash aggregates. In this study, it was found that the splitting tensile strength of OPSC could be predicted using Equation (2) since only 3–5% of the difference was observed between the experimental and predicted values of the splitting tensile strength.

$$f_t = 0.203 \sqrt{f_{cu}^2} \quad (1)$$

$$f_t = 0.273 \sqrt{f_{cu}^2} \quad (2)$$

where f_t is the splitting tensile strength (MPa) and f_{cu} is the corresponding cube compressive strength (MPa).

Although the increase in the slag replacement led to a reduced splitting tensile strength, the OPSC with a 60% slag replacement level still exhibited a splitting tensile strength exceeding 2.0 MPa; this is sufficient for the use of LWC in structural applications based on ASTM C330.

3.4. Bond properties

The knowledge of the bond is of significant importance since the bond between the steel reinforcing bar and the neighbouring concrete basically allows the reinforced concrete to function as a structural material. The transfer of forces from the reinforcing bar to the surrounding concrete occurs through three mechanisms, namely i) adhesion force between the reinforcing bar and the concrete, ii) frictional force, and iii) mechanical anchorage or bearing of reinforcing bar ribs against the concrete surface. An insufficient bond between the steel reinforcing bar and the concrete could lead to an excessive slip, which would result in a permanent deformation and the possibility of internal cracks (Mor, 1992), leading to a reduced load bearing capacity of structural members.

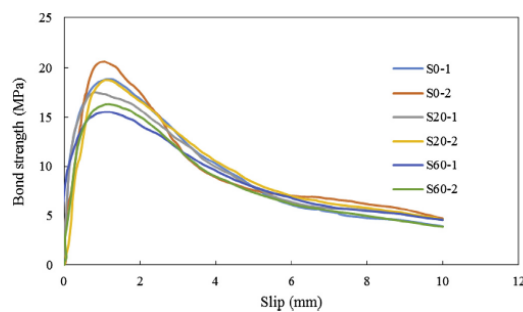


Fig. 4. Bond strength-slip relationship.

All specimens exhibited a pull-out mode failure in this study; this could also be reflected from the shape of the bond strength-slip graphs shown in Fig. 4. No significant difference was found from the shape of the bond strength-slip curve due to the amount of cement replacement with the slag. The bond strength is determined as follows:

$$f_{be} = P / (\pi \times \emptyset \times L) \quad (3)$$

where f_{be} is the experimental bond strength (MPa), P is the maximum pull-out load (N), \emptyset is the diameter of the steel reinforcing bar (mm) and L is the bond length (mm).

The results obtained for the bond strength and corresponding slip for all OPSC mixes are presented in Table 4. The bond strengths ranged between 15 and 19 MPa for the OPSC; these values were significantly higher than those previously obtained by Teo et al. (2007) and Alengaram et al. (2010). This could be attributed to the different failure modes observed in that splitting failure instead of pull-out failure was observed in the case of the bond test carried out by Alengaram et al. (2010).

The highest ultimate bond strength was found for the mix S0 and the bond strength reduced with the increase of cement replacement with slag. Nevertheless, as shown in Table 4, the bond strengths obtained were about 5–7 times higher compared to the theoretical bond strength proposed in BS 8110 (equation (4)) and 3 times compared to that proposed in EN 1992 (equation (5)). Thus, it can be said that the theoretical bond strength proposed in BS 8110 is conservative in the case of OPSC. Although the increased cement replacement with slag reduced the ultimate bond strength, the mix, S60, with high volume slag content could still achieve sufficient bond strength for structural applications.

$$f_{bt} = \beta \sqrt{f_{cu}} \quad (4)$$

where f_{bt} is the theoretical bond strength (MPa) and β is the bond coefficient (0.50 is used for this study).

$$f_{bt} = 2.25 \eta_1 \eta_2 f_t \quad (5)$$

where η_1 is the coefficient for the quality of the bond condition and position of the bar during concreting (1.0 is used for this study), and η_2 is the coefficient for the bar diameter (1.0 is used for this study).

A reduction of about 20% in the bond strength of OPSC was observed when 60% of slag content was used. As reported in Section 3.2, the increased amount of slag reduced the strength of the OPSC. This could be due to the limited hydration of the slag caused by the use of the low water-to-binder ratio in the OPSC (Mo et al., 2014a). Hence, the resulting concrete could have a weaker bonding with the steel reinforcing bar, which could lead to poorer adhesion and reduced bond strength when the slag content was increased (Xia et al., 2006). Hwang et al. (1994) and Hamad and Itani (1998) also reasoned that the use of silica fume as a cement replacement caused a loss in the friction between the concrete and steel reinforcing bar, which subsequently, led to a lower bond strength. In addition, Turk et al. (2010) reported a bond strength decrease when fly ash was used at a replacement level of 30% in self-compacting concrete. However, when mineral admixtures were added (Corinaldesi and Moriconi, 2009), the bond strength was increased due to the improved pore structure of the concrete, which could facilitate improved bonding.

Therefore, to fully ascertain the effects of the mineral admixture on the bond strength of concrete, the effect of the compressive strength needs to be taken into account, and, thus, the values of the bond strength were normalized with the square root of the compressive strength to eliminate the variations in the

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