Sustainable Lightweight Self-compacting Concrete Using Oil Palm Shell and Fly Ash

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Abstract

This research investigated fresh and hardened properties of lightweight self-compacting concrete (LWSCC) incorporated with oil palm shell (OPS) and fly ash (FA). Fresh concrete properties including passing ability, filling ability and segregation resistance were assessed. The properties fulfilled EFNARC guidelines. Incorporation of FA improved fresh properties, particularly filling ability, with the slump flow value increased from 665mm to 730mm. As for hardened properties, OPS-aggregate based LWSCC mixes achieved compressive strength of range 18-38MPa at 28-day age while the splitting tensile strength was in the range of 1.6 to 2.8MPa. SEM analyses showed good bonding in the interfacial transition zones (ITZ). Micro-pores of OPS were filled by cement hydration products and thus ITZ was enhanced. LWSCC incorporated with OPS, a renewable resource from agricultural waste, and with partial FA replacement, is potentially a sustainable alternative construction material.

Keywords: Oil palm shell, Fly ash, Fresh properties, Compressive strength, Splitting tensile strength, Interfacial transition zone, Water absorption

1.0 Introduction

Concrete is a most viable engineering material being used for construction [1]. For it to achieve designed strength and durability, fresh concrete has to be compacted in a proper way so as to make it homogeneous and dense. Compaction is normally done with the aid of vibrator during concreting and it raises concreting cost. In earnest quest for innovation in construction industry, Okamura and Ouchi [2] developed self-compacting concrete (SCC) in late 1980s and is gradually gaining popularity [3, 4]. SCC possesses properties to flow under gravity and more compactly fill the complex space of formwork as well as the area congested with reinforcement. Thus, it is not necessary to apply external concrete compaction method during casting of concrete. In accordance with the standards [5-7], SCC must possess characteristics of good durability, restrained flowing ability and filling ability with satisfactory resistance to segregation. In view of light weight structure, it is essential to utilize lightweight aggregates (LWA) to manufacture lightweight self-compacting concrete (LWSCC).

Normal weight aggregates (NWA), such as limestone, granite and sandstone are common materials used as coarse aggregates in concrete [8]. NWA is one of the (large) major constituents in concrete, be it normal concrete or SCC. Aggregates make up about 60% by volume in SCC and hence they are the main contributor to concrete weight [9]. About 20 billion tons of raw materials have been used for concrete production annually [10]. Aprianti [11] estimates the consumption of concrete will increase to 18 billion tons annually by 2050. As concrete production rate increases, NWA is gradually used up and thus causes its dwindling supply. The depleting supply of NWA can lead to significant hike in its cost as well as that of concrete. As such, it is of paramount importance that extensive research is to be carried out to develop more sustainable construction materials. Attempt has been made to utilise recycled aggregate from demolition waste [12-14]. Several recycle methods used include stock piling, crushing, presizing, sorting, screening and contaminant elimination. However, sizeable amount of energy is entailed in processing recycled aggregates, leading to higher carbon dioxide emission. Moreover, it is difficult to produce concrete with desirable strength by using recycled aggregates as their mechanical properties are altered during recycling process.

Meanwhile, numerous contemporary research works [15-17] have dedicated to replacing NWA with lightweight aggregates (LWA). Generally, there are two categories of LWA, which are artificial type and natural type. Naturally sourced aggregates include pumice, diatomite, volcanic cinders, scoria and tuff [18, 19] while those in artificial category are classified into industrial by-products and modified natural arising materials [20, 21]. Industrial by-products such as sintered slate, sintered pulverized fuel ash, expanded or foamed blast furnace slag and colliery waste are commonly utilised as LWAs whilst naturally arising materials are shale, expanded clay, slate, vermiculite and perlite [22]. Undeniably, more benefits can be derived from utilising wastes to replace aggregates in concrete as it can reduce the environmental impacts with respect to waste reduction, pollution containment as well as less consumption of energy.

Mill processing of oil palm fruits will generate oil palm shell (OPS) as the main solid waste products [23, 24]. Palm nut yields two types of oil, which are palm oil and kernel oil and they are taken from outer and inner cores of the nut respectively. Palm kernel, which is produced from inner core of the nut after its oil has been extracted, is a potentially suitable coarse aggregate to be used in casting concrete. More common name for this palm kernel shell, which has an external hard endocarp, is oil palm shell [25]. Oil palm trees are abundantly cultivated in Malaysia. According to Tripathi et al. [26], Malaysia yields more than 52% of world's total palm oil. Land area of oil palm tree in Malaysia started with 54,000 hectares in 1960 and later increased to 5.90 million hectares in 2019 [27].Huge quantities of OPS are being produced in oil palm mills with annual production of over 4 million tonnes [8, 20, 28]. This type of oil palm solid wastes is projected to increase as the demand for palm oil is increasing which leads to increasing waste management issues. The present OPS disposal methods are incinerating and landfilling [29]. These two approaches not only are environmentally hazardous but also entail high capital outlay. As such, to mitigate environmental impacts with regard to the agricultural waste handling and disposing, much research has been conducted to utilise OPS [23, 24, 30, 31] and agricultural wastes [32] as alternative materials. One very important aspect of the research is to utilise OPS as concrete constituents. According to Teo et al. [33], OPS can be incorporated into concrete as coarse aggregates.

For more than 3 decades, many researchers in South East Asia have been carrying out experiments in producing lightweight concrete by utilizing OPS [8]. Possessing porosity of 37% [23], OPS not only substantially reduces concrete density but also improves its thermal insulation property. Generally, by comparing to normal concrete, a density reduction of OPS concrete of about 20-25% is observed [31]. However, a negative effect of poor fresh concrete workability (low slump value) has been reported [23, 24, 34] in spite of using high water to cement ratio. The main reason for this is that OPS is irregular and flaky in shape. Nevertheless, the problem can be solved by incorporating some small quantity of superplasticizer which helps fresh concrete achieve desirable workability [35]. Subsequently, researchers in the related field attempt to develop OPS concrete by using superplasticizer as a constituent [36-38]. Yew et al. [39] conducted a study of the effects of OPS's age and size on concrete workability. By using age ranging from 3 to 15 years, older OPS was found to improve concrete workability. Nevertheless, decreasing maximum aggregate size from 12.5mm to 9.5mm decreased the workability. Explanation given by the authors was that full concrete compaction cannot be achieved due to irregular shapes of OPS caused by crushing process. To obtain optimum concrete workability, it is crucial that OPS with appropriate shape and right size gradation is selected. Meanwhile, Zawawi et al. [40] investigated the influence of fly ash blended with river sand as fine aggregate in OPS concrete. The authors concluded that the finer particle size of fly ash as fine aggregate can result in degradation of workability of OPS concrete at high replacement level. As for OPS based self-compacting concrete, Prayuda et al. [41] studied the effect of granite replacement with OPS from 0% to 50% on V-funnel time. The results showed that the V-funnel time increased when OPS content increased, indicating degraded filling ability. Nevertheless, limited tests had been carried out by the authors to study the self-compacting ability of OPS based LWSCC. For hardened properties of OPS concrete, Okafor [24] reported that it was not possible to produce concrete with compressive strength higher than 30MPa if OPS was used as coarse aggregates. Meanwhile, other researchers also studied methods of treating OPS chemically [30, 42, 43] as well as using curing conditions [36, 44] to increase concrete compressive strength. Also, as shown by a few researchers, OPS concrete compressive strength above 30MPa can be attained through proper proportioning of constituents [45, 46]. OPS concrete with 28-day strength of 42-48MPa had been made by Shafigh et al. [47]. Shafigh et al. [36] were able to successfully achieve the compressive strength of 34-53MPa. Farahani et al. [48], in their more recent research, used binary and ternary blended cement to create OPS concrete with compressive strength 28-40MPa. Meanwhile, Alengaram et al. [49] found that OPS concrete specimens containing mineral admixtures possessed higher compressive strength than those without mineral admixtures. The authors argued that the mineral admixtures enhance the bond between the OPS and the matrix in the interfacial transition zone (ITZ) by filling the pores. The compressive strength of OPS-based concrete can be inferred to depend greatly on the bonding between (ITZ) of binder and aggregates phase. In all these studies, though, the higher strengths of the OPS concretes were made possible with the use of relatively large amount of cement or binder content. At this junction, it must be pointed out that, till now, no other researcher has attempted to use oil palm shell (OPS) to produce LWA in SCC.

With regard to the splitting tensile strength of OPS concrete, studies done by previous researchers [36, 48, 50] have shown that the value of splitting tensile strength possessed by OPS concrete is about 6-10% of its compressive strength. Alengaram et al. [51] argued that the weaker bonding between the aggregate matrix, when compared to normal aggregates concrete, has contributed to the low tensile strength of OPS concrete. By comparing the splitting tensile between normal concrete and OPS concrete, Shafigh et al. [36] found that the tensile splitting strength of OPS concrete is about 28% lower than that of normal aggregate concrete. Shafigh et al. [52] investigated the effect of high level fly ash replacement on splitting tensile strength of OPS concrete and found that, with 10% of fly ash replacement, the splitting tensile strength decreased by 19.7% though the compressive strength increased by 3.6%. The authors attributed poor tensile strength to poor material quality in interfacial transition zone (ITZ). With respect to water absorption, Teo et al. [33] reported that the water absorption of OPS based concrete was respectively 11.23% and 10.64% for concrete subjected to air-dry curing and full-water submerged curing. Shafigh et al. [47] reported that the water absorption of OPS concrete was in the range of 3-6%. Nevertheless, relatively high cement content was used to produce OPS concrete with low water absorption.

Comprehensive researches have been carried out in developing LWSCC by incorporating LWA from different sources [53]. In many cases, artificial LWA have been used. Also, many researchers have conducted extensive studies on incorporating LWA into SCC. Hwang and Hung [16] (utilized) incorporated reservoir fine sediment into SCC as coarse aggregates whilst Bogas et al. [54] and Hubertová and Hela [55] used expanded clay as concrete coarse aggregates. Using pumice as LWA in concrete had been studied under different temperature and with various mix proportions by a few researchers [56-61]. Also, Shi and Wu [62] and Lo et al. [63] have studied incorporation of expanded shale as coarse aggregates into SCC. However, limited research is being conducted with regard to incorporation of agricultural waste into SCC. To date, no literature in respect of utilizing OPS as coarse aggregates for developing SCC has been published. All the related OPS concrete research is concerned on producing optimum lightweight concrete. In the meantime, Kanadasan and Razak [64] have been successful in utilizing oil palm clinker, which is also a type of oil palm waste, to make SCC. The authors have established an algorithm of SCC mix design by using particle packing concept. The mix design developed met the criteria of EFNARC [5] in respect to fresh concrete performance. Kanadasan and Abdul Razak [65] extended their study on SCC by utilizing palm oil clinker power as supplementary filler materials. It has been established that incorporation of oil palm clinker in SCC is sustainable in the aspects of energy efficiency and greenhouse gas emission.

Nevertheless, as mentioned by Mo et al. [37], it is necessary to use more cement in producing OPS concrete of anticipated compressive strength. In this regard, it will only make economic sense to use cheaper OPS in producing SCC in order to compensate for higher cost of bigger amount of cement required to achieve concrete self-compacting ability. Also, eradicating concrete vibration cost in SCC can further compensate for the extra cement material cost incurred. Moreover, fly ash, as supplementary cementitious material, if incorporated in concrete can not only improve the fresh state properties but also reduce cost. Produced by burning coal in furnaces of power plant, fly ash is considered as an industrial waste. Partial substitution of cement by fly ash is gaining popularity due to its ability to improve the fresh and hardened concrete properties. Bouzoubaa and Lachemi [66] reported that the use of superplasticizer tended to decrease when higher level of class F fly ash replacement was made. According to Khatib [67], workability improved with fly ash replacement up to 80%, by keeping constant both water-binder ratio and superplasticizer content in SCC. It has been stated by Ramanathan et al. [68] that partial substitution of cement with fly ash can lead to higher paste volume owing to its lower density, resulting in increased paste volume. Thus, friction at the fine aggregate-paste interface is reduced. These can improve the cohesiveness and plasticity of concrete, resulting in improved workability. This trend has been similarly reported by Jalal et al. [69]. The hardened properties of concrete containing fly ash is highly depending on the level of fly ash replacement and class of fly ash. Generally, compressive strength of fly ash concrete at early age is generally lower than that of cement concrete. This has been demonstrated by numerous researchers [66-68] and is mainly due to slow-rate pozzolanic reaction of fly ash with calcium hydroxide in hydrated cement. Liu [70] also studied fly ash substitution up to 80% in SCC. The study was carried out up to 180 days. 20% fly ash replacement was found to be optimum in their study as the strength close to control concrete at the age of 90 days. Significant strength development was observed for high level fly ash replacement (above 60%) in the study. Atiş [71] also reported that 50% fly ash replacement in SCC can achieve comparable strength of control concrete.

Indeed, it is beneficial to utilize OPS and fly ash in concrete production, and as such, further research and development in the field will be continued with enthusiasm. To date, limited research has been carried out utilizing OPS as coarse aggregate in LWSCC. The utilization of OPS and fly ash in producing LWSCC could not only enhance its performance but also promote environmental sustainability in the aspect of waste utilization. The proposed LWSCC can effectively reuse biomass waste, reduce self-weight and avoid the need of external mechanical vibration of fresh concrete and hence is a more innovative construction material. Thus, the study in this paper is aimed at evaluating fresh and hardened properties of LWSCC incorporated with OPS as coarse aggregates. Control mix was determined based on particle packing method. Three levels of fly ash replacement (30%,40%,50%) was made to the control mixes. The resulting workability parameters including filling ability, passing ability and segregation resistance were evaluated. Compressive and splitting tensile strength of concrete were also determined.

2.0 Experimental Programme

2.1 Materials

The materials used for this experiment were supplied from the same source as Ting et al. [72].

2.1.1 Ordinary Portland cement (OPC)

Grade 45 Ordinary Portland Cement (OPC) which conforms to ASTM: C150/C150M-12, was used. Physical properties of OPC is presented in Table 1 while Table 2 shows the material chemical composition.

Table 1: Physical properties of OPC

Physical properties	OPC
Blaine fineness	3510 cm^3/g
Specific gravity	3.14
Particle density	2950kg/m^3

2.1.2 Fly Ash

The fly ash used in this study was acquired from a coal-fired power plant in Kuching, Sarawak, Malaysia and could be categorised as "Class F low calcium fly ash" in accordance to ASTM C618. The coal used in fly ash production was obtained from Merit Pila coal mine in Kapit, Sarawak, Malaysia. Table 2 shows chemical compositions of the cement and fly ash.

Table 2: Chemical properties of cement and fly ash

Chemicals	Cement (%)	Fly Ash (%)
Silicon dioxide (SiO_2)	20.0	57.8
Aluminium oxide (Al_2O_3)	5.2	20.0
Ferric oxide (Fe_2O_3)	3.3	11.7
Calcium oxide (CaO)	63.2	3.28
Magnesium oxide (MgO)	0.8	1.95
Sulfur trioxide (SiO_3)	2.4	0.08
K_2O	-	3.88
TiO_2	-	2.02
Na_2O	-	0.30
Loss on ignition	2.5	0.32

2.1.3 Coarse Aggregates

Coarse aggregates used for concreting was Oil Palm Shell (OPS) which had been acquired from an oil palm processing mill in Miri, Sarawak, Malaysia. Physical properties of OPS are presented in Table 3. Specific gravity and water absorption of the OPS aggregate were determined in accordance with ASTM C127 [74] and ASTM C330 [75] respectively. The particle size distribution curve of OPS aggregates is shown in Figure 1. As for particle size distribution, OPS had 60% in size range of 5-10mm. After being washed and sieved, OPS had to be water submerged for a period of 24 hours. To obtain saturated surface dry (SSD) condition, OPS had to be air dried subsequently before being used for concreting purpose.

2.1.4 Fine Aggregates

Two types of fine aggregates used for this experiment were river sand and crushed OPS. OPS was crushed to the size range of 600µm to 5mm. Nominal size of river sand was 600µm. Physical properties of these two fine aggregates are shown in Table 3. Specific gravity and water absorption of the river sand were determined in accordance with ASTM C128 [76]. The particle size distribution curve of river sand is shown in Figure 1.

Table 3: Physical properties of aggregates

Physical Property	River Sand	OPS
Specific gravity	2.64	1.19
Fineness modulus	1.32	5.31
Water absorption (24h) (%)	1.1	18.11

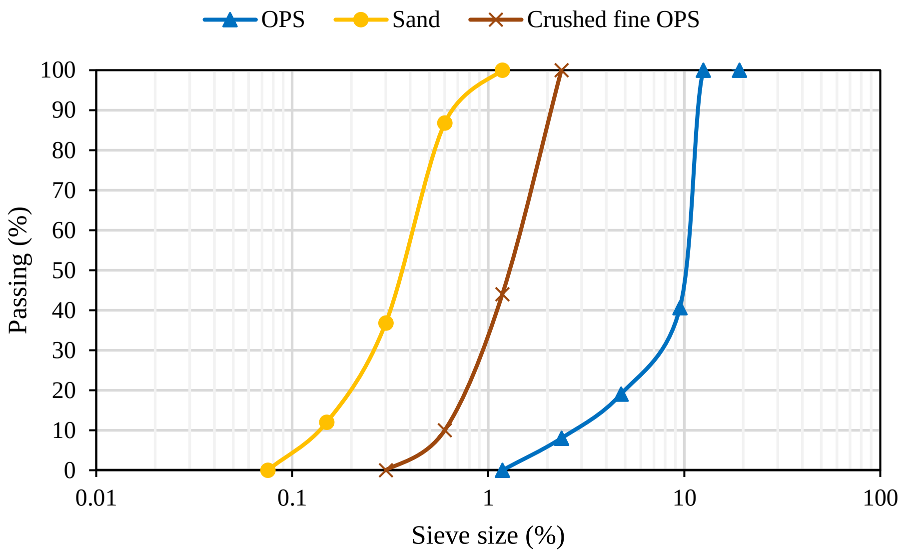

Figure 1: Particle size distribution of aggregates used

2.1.5 Superplasticizer

In the experiment, Glenium Ace 389, a high range water reducing admixture obtained from BASF Sdn. Bhd, was used. Categorized as Type F in ASTM C494 and BS En 934-2 European Standard, it is can reduce water requirement for concreting by 12% or more.

2.2 Mixing Method

For concrete mixing, small type forced action cylindrical pan mixer with vertical rotation axis had been used. Only about 0.07m^3 LWSCC was batched each time. First, both coarse and fine aggregates were poured into the pan and the mixer was kept running for 1 minute. Then, cement and fly ash were added and rotation of pan continued for another 2 minutes, until all the materials were well mixed. Next, about 50% of the required amount of water was poured into the pan slowly and the mixing continued for another 1 minute. Lastly, SP as well as the other half amount of water were gradually poured in and the mixer was left running for a further 1 minute.

2.3 Tests on Fresh Properties

Concrete fresh properties including filling ability, passing ability and segregation were evaluated against European Federation of National Associations Representing for Concrete (EFNARC) [5] standard procedures. The proposed tests to evaluate the filling ability in this research were slump flow and V-funnel tests. The passing ability was assessed by J-ring test while segregation resistance was assessed through Sieve Segregation Test and Visual Stability Index (VSI). The detailed methodology to carry out all these fresh properties test was depicted in the following section.

2.3.1 Slump Flow

Slump flow test was proposed to assess the filling ability. Abram's slump cone with base diameter of 200mm and 300mm in height was used for slump flow test. Standard procedure for carrying slump flow test was to fill fresh concrete into a slump cone and the cone was then lifted up, permitting concrete to flow freely. The maximum uninterrupted flow diameters in two orthogonal directions were then measured after the flow had stopped. T_{500} was recorded as time taken for LWSCC to achieve 500mm diameter circular spread. The slump flow diameter was then calculated by using Eq. (1).

$$S = \left(d_{max} + d_{perp}\right)/2 \tag{1}$$

where S is the slump value (mm), d_{max} is the maximum spread value (mm) and d_{perp} is the spread value perpendicular to the maximum spread.

2.3.2 V-funnel Test

V-funnel tests were also carried out to evaluate both the viscosity and filling ability of concrete. The shape of V-funnel restricts the flow of concrete and about 12 litres of concrete are required for the test to be carried out. The V-funnel was set on steel stand with bracing. Freshly prepared concrete was transferred to the V-funnel with trap door closed at bottom side. The trap door was kept closed for 10 seconds after filling and then opened. The test was repeated for 5 minutes after filling of V-funnel. The respective values of time taken after fresh LWSCC had flowed through V-funnel trap door were noted and recorded as T_{10s} and T_{5min}.

2.3.3 J-ring Test

Passing ability was evaluated through J-ring test. The purpose of this test was to assess blockage of LWSCC due to presence of steel bars. In carrying out the test, slump cone was placed at the centre of J-ring and fresh concrete was placed into the cone. Then, the cone was lifted up to let concrete to flow through steel bars. Maximum spread, $T_{500\,(\mathrm{J-Ring})}$, and difference in height between the centre (h_1) and outside of the ring (h_2) were noted. Block step value (S_H) can be calculated by using Eq. (2).

$$S_H = average(h_1 - h_2) \tag{2}$$

2.3.4 Sieve Segregation Test

Assessment of segregation resistance of fresh concrete was done through sieve segregation test. The test began by allowing the mass of fresh concrete to stand still in a container for 15 minutes. The mass of pan was then measured as $\mathrm{W_p}$ on weighing balance. The actual mass of LWSCC used was recorded as $\mathrm{W_c}$. It was then poured into sieve and permitted to flow through sieve with 4.75mm aperture within 2-minute duration. The weight of concrete which passed through the sieve was recorded as $\mathrm{W_{ps}}$. This value was computed as the percentage of total weight of LWSCC used by using Eq. (3).

$$\Pi = \left(W_{ps} - W_p\right)/W_c \times 100 \tag{3}$$

2.3.5 Visual Stability Index Test

Visual stability index (VSI) test was carried out by visual inspection of LWSCC before and after slump flow tests had been done. The index values varied from 0 to 3 [6]. However, accuracy of this method heavily rely on the knowledge and experience of the individual interpreting and evaluating segregation the results. The VSI criteria is adopted from PCI guideline [78] and shown in Table 4.

Table 4: VSI criteria [78]

VSI	Criteria
0	No sign of concrete segregation or bleeding.
1	No sign of concrete segregation but with inconsiderable bleeding noticed as a sheen on the surface.
2	A slight mortar halo ($\leqslant$ 10 mm) and/or aggregate heave in the middle of the concrete mass and some bleeding.
3	Clear evidence of segregation in the form of a large mortar halo ($\geqslant$ 10 mm) and/or a large aggregate pile in the centre of the concrete mass.

2.4 Test on Hardened Properties

2.4.1 Strength Test

Concrete cube specimens with size of 100x100x100mm were casted and prepared for compressive strength test. Meanwhile, splitting tensile test was done on 100mm diameter by 200mm height cylinders. When preparing the specimens, fresh concrete was mixed and poured into two respective types of mould immediately after it had been tested for slump flow. All the LWSCC specimens were allowed to self-compact without the aid of vibrator. 24 hours later, the concrete specimens were demoulded. The specimens were cured in water before being tested. All the cubes and cylinders were tested by using 600kN capacity GOTECH universal testing machine. The compressive strength test was conducted in accordance with the standard procedure described in ASTM C39-18 and BS 1181-116 for cylinder and cube respectively. The method prescribed by Norma [81] was used to carry out splitting tensile strength test.

2.4.2 Density

The relevant values of concrete density were determined when it was demoulded, air-dried and finally oven-dried. The demoulded density of concrete samples was determined immediately after the removal of concrete mould. The air-dry density was determined after the demoulded sample had been air dried. Oven-dry density of LWSCC was determined through the test prescribed in ASTM C567-14. The apparent mass of cylinder (G) was measured when it was completely submerged in water. The cylinder was allowed to air dry for 1 minute and the surface water was using absorbent cloth. The mass was then recorded as saturated surface-dry cylinder (F). Concrete samples were then placed in an oven and continually weighted until there was minimal change in the weight. The final weight recorded under room temperature was mass of oven-dry cylinder (D). The Oven-dry density can be calculated by using Eq. (4).

$$O_m = (D \times 997)/(F - G) \tag{4}$$

2.4.3 Immersed Water Absorption

Immersed water absorption test was conducted according to the procedure prescribed in ASTM C642-13. In the experiment, the prepared sample was weighted and then allowed to oven dry at 110°C for 24 hours. The sample was weighted again at room temperature after oven drying process. If the difference between two successive measured weights was more than 1g, oven drying process had to be repeated until the difference was less than 1g. This value was noted as M_1. The sample was then immersed into water for 48 hours. After the immersion, concrete surface was dried using cloth. The mass was measured as M_2. The water absorption was computed by using Eq. (5).

$$Water\ absorption = (M_2 - M_1)/M_1 \times 100 \tag{5}$$

3.0 LWSCC Mix Design

Presently, there is no standard method which can be used for the mix design of LWSCC. Nevertheless, for this study, a method proposed by Kanadasan and Razak [64], which was known as particle packing method, was adopted. This method assumed that the voids between aggregates particles are filled by paste. Figure 3 shows the overall mix design procedure.

3.1 Particle Packing Method

Particle packing (PP) is defined as volume of packed aggregate particles in a unit volume [84]. The study is targeted at determining suitable LWSCC mix design method. The method recommends that PP test has to be carried out first. It is a prerequisite to pre-soak all the aggregates in water for 24 hours and air dry to saturated surface dry condition (SSD). Fixed amounts of fine and coarse aggregates are prepared and put into a container of known volume. The aggregates are mixed thoroughly so that they are well-blended. Known amount of water is added into the container until it is full, as illustrated in Figure 2. This volume of water represents total volume of voids in aggregates, which is equal to the required amount of paste to be used for proportioning LWSCC. The PP ratio is obtained by subtracting the void ratio from container volume.

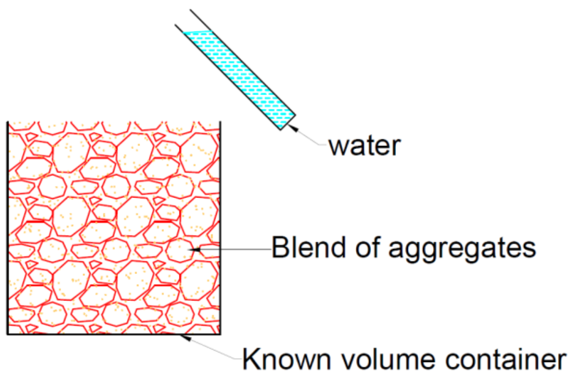

Figure 2: PP Test Illustration [64]

3.2 Mix Design Algorithm

The procedures to determinate the LWSCC mix design is presented in this section.

Step 1: Determination of particle packing factor

The first step in proportioning LWSCC mix, which incorporates OPS as full coarse aggregates replacement, is to determine the particle packing factor between the blended OPS as coarse aggregates and river sand as fine aggregates, by using Eq. (6). The minimum paste volume necessary for lubricating aggregates so as to produce the required characteristics of flowing and filling ability of LWSCC is represented by the voids [64]. Required amount of paste to fill OPS aggregate void is more with a lower value of PP ratio. On the other hand, a high PP ratio indicates that less paste is required as aggregates are tightly packed. The PP value is determined based on the procedure described in previous section.

$$PP = 1 - e \tag{6}$$

where PP is particle packing value and e is void ratio

Step 2: Calculation of aggregates content

The aggregate content of proposed LWSCC mix design can be determined from Eq. (7). The subscript of f/c agg in each term represents respective type of aggregate used and the ratio of each aggregate to total aggregates in a unit volume of LWSCC has been considered. The main concern of aggregates in this research is fine aggregate which is sand, and OPS as coarse aggregate. The optimum ratio of each aggregate to total aggregates was determined from the blended aggregates bulk density curve.

$$\mathrm{W_{f/c\ agg}} = \mathrm{PP} \times \mathrm{AR_{f/c\ agg}} \times \mathrm{SG_{f/c\ agg}} \times 1000 \tag{7}$$

where $\mathrm{W_{f/c\ agg}}$ is aggregate content (kg/m^3), $\mathrm{AR_{f/c\ agg}}$ is ratio of aggregate to total aggregates in volume and $\mathrm{SG_{f/c\ agg}}$ is specific gravity of aggregates.

Step 3: Calculation of cement content

Cement content must be chosen properly to ensure the concrete fresh properties as a SCC, including filling ability, passing ability and segregation resistance, fulfil the specified requirements while not to compromise the compressive strength. Good adjustment of cement content will ensure sufficient amount of cement paste is available to lubricate aggregates so as to attain self-compacting ability. The volume of cement can be determined using Eq. (8).

$$V_{cement} = W_{cement}/SG_{cement} \quad (8)$$

where V_{cement} is volume of cement, W_{cement} is cement content (kg/m^3) and SG_{cement} is specific gravity of cement.

Step 4: Calculation of paste volume

The voids that exist in particle packing of aggregates represent the amount of paste required to be filled to ensure good concrete self-compacting ability. This can be calculated by using Eq. (9).

$$V_{paste} = 1 - PP \quad (9)$$

where V_{paste} volume of paste

Step 5: Determination of water content

Water content can be calculated by water to binder (W/B) ratio using Eq. (10) and Eq. (11). The actual W/B needs to be validated and adjusted by trial mix.

$$V_{water}/V_{cement} = W/B \quad (10)$$

$$W_{water} = V_{water} \times SG_{water} \times 1000 \quad (11)$$

where W/B is water to binder ratio, V_{water} is volume of water content, W_{water} is water content (kg/m^3) and SG_{water} is specific gravity of water.

Step 6: Determination of superplasticizer dosage

SP is an essential constituent to allow SCC to achieve followability and passing ability. However, excessive dosage of SP can cause severe bleeding and segregation. Determination of optimum SP can help SCC achieve optimum performance. The SP content can be calculated by using Eq. (12). Adjustment of dosage has to be made if its fresh properties do not fulfil the criteria in the EFNARC [5].

$$W_{SP} = SP(\%) \times (W_{cement} + W_{SCM}) \quad (12)$$

where W_{SP} is superplasticizer content (kg/m^3), $SP(\%)$ is superplasticizer dosage and W_{SCM} is supplementary cementitious material content (kg/m^3).

The mix proportion computed by using PP test is the baseline for designing LWSCC mix. It is also necessary to conduct fresh and hardened concrete tests to ascertain compliance to EFNARC [5]. The mix design is checked and fine tuned to the requirements in Annex C of BIBM and ERMCO [85]. Flowchart for mix design is presented as Figure 3.

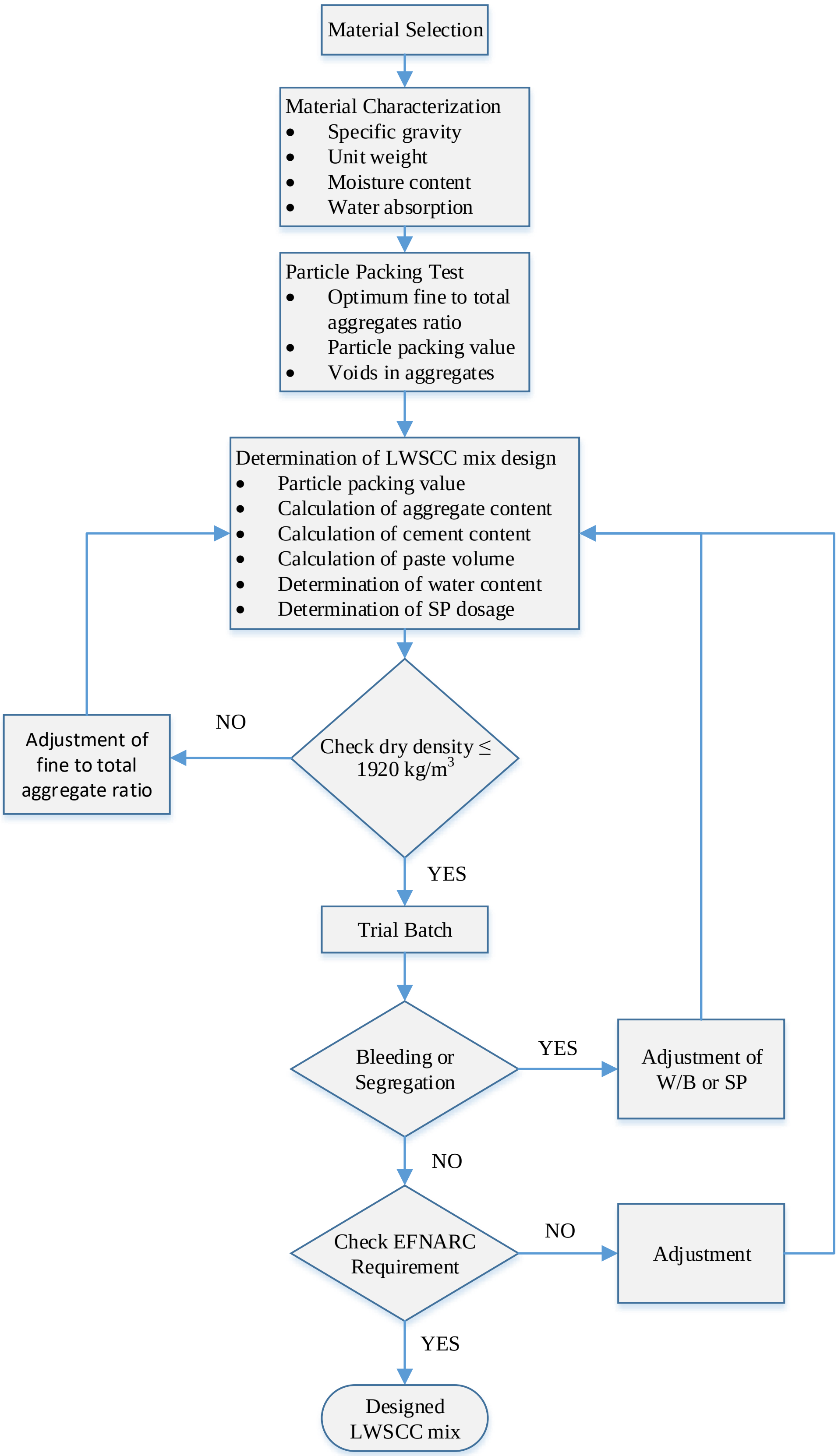

Figure 3: Flowchart for achieving LWSCC mix design

3.3 LWSCC Mix Proportion

Based on ASTMC29 , the relationships between bulk density as well as void ratio and aggregates ratio were established in Figure 4. For bulk density versus coarse to total aggregate ratio, it is noted that the bulk density decreased with increasing coarse aggregate content. It is because coarse aggregate (OPS) has lower specific gravity compared to fine aggregates (river sand). Lowest void ratio can be observed when the coarse to fine aggregates ratio is 1:1. This indicates that ratio of 50% of coarse aggregate and 50% fine aggregate is the optimum aggregate content for OPS and river sand combination. When coarse to total aggregate ratio is increased from 0.5 to 0.6, even though the density decreases, the void ratio exhibits a rising trend. This rising trend indicates more paste is necessary for filling voids. Several researchers have used coarse to total aggregate ratios of 0.5 [64, 87] and 0.6 [62, 64, 88] in proportioning LWSCC. Cement content of 520 kg/m^3 was chosen since OPS concrete requires more cement paste to facilitate self-compacting ability. Coarse to total aggregate ratio of 0.6 was chosen since it could reduce the density of proposed LWSCC and more economic mix is produced that can compensate the high cement content used.

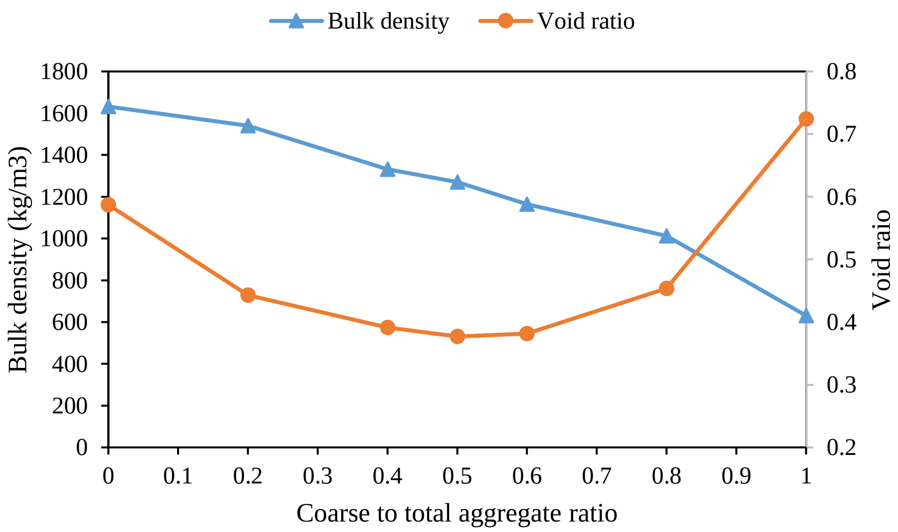

Figure 4: Influence of coarse to fine aggregate ratio on bulk density and void ratio

Table 5 presents the finalized mix design to be studied. In this research, 30% to 50% of fly ash replacements were made to the control mix. With the replacement of fly ash, water demand was decreased, so as W/B was decreased from 0.33 to 0.31. The presence of fly ash was able to improve the packing of LWSCC which in turn reduced the water demand although fly ash exhibited characteristic of high affinity to water. The capability of fly ash to improve the workability of LWSCC can be explained in terms of the spherical and smooth nature of fly ash particles which induce the ball bearing effect. Partial replacement of cement by fly ash can result in higher paste volume, which in turn reduces the friction at the fine aggregate-paste interface. Consequently, the cohesiveness and plasticity of concrete improve [68]. Hence, the improved concrete workability is achieved with lesser water demand. The comparison of these four mix designs was made in the following section.

Table 5: Summary of mix design

Mix	M0	M30	M40	M50
Cement (kg/m^3)	520	364	312	260
Fly Ash (kg/m^3)	0	156	208	260
Water (kg/m^3)	171.6	161.2	161.2	161.2
Sand (kg/m^3)	715	715	715	715
Coarse Aggregate (kg/m^3)	455	455	455	455
SP (kg/m^3)	8.58	8.58	8.58	8.58
Air content	1%	1%	1%	1%
Water to binder ratio	0.33	0.31	0.31	0.31
Coarse Aggregate to total aggregate ratio	0.39	0.39	0.39	0.39

4.0 LWSCC Mix Design

4.1 Fresh Properties

Guidelines for carrying out SCC workability tests have been formulated in several publications such as EFNARC [5] and ACI-237 [7]. In this study, all the workability tests have been conducted in accordance with the criteria spelled out in EFNARC [5]. Table 6 summaries the

SCC workability performance. As indicated, all the test results have been evaluated against the criteria in EFNARC [5]. In short, all the LWSCC mixes must pass fresh property assessment tests, including filling ability (J-ring), passing ability (V-funnel and Slump flow) and segregation resistance (visual segregation index and sieve stability).

Table 6: EFNARC requirement

Workability	Test	Class	Criteria
Filling ability	Slump Flow (mm)	SF1	550-650
		SF2	660-750
		SF3	760-850
	T500 (s)	VS1/VF1	≤ 2 V $-$ Funnel ≤ 8
		VS2/VF2	≥ 2 time(s) $9 - 25$
Passing ability	Step height in J-ring (mm)	PA1	Sj ≤ 15 (59 mm bar spacing)
		PA2	Sj ≤ 15 (40 mm bar spacing)
	L-Box		0.8 - 0.1
	U-Box		0 - 30
Segregation Resistance	Sieve segregation (%)	SR1	≤ 20
		SR2	≤ 15

As discussed in methodology section, fresh properties of LWSCC had to be assessed. The filling ability was assessed using J-ring test while passing ability was assessed through V-funnel and slump flow tests. Segregation resistance was assessed using visual segregation index and sieve stability tests. Table 7 shows the fresh property test results. Further evaluation and elaboration of these results will be done in the following section.

Table 7: Summary of fresh properties

Tests	Mixes	M0	M30	M40	M50
J-Ring	T_{500} (s)	10	9	8.4	7
	Dm (mm)	520	580	530	600
	Block Step (mm)	12.5	9.75	8.5	9.5
Slump flow	T_{500} (s)	5.04	4.38	4.35	1.82
	Dm (mm)	665	700	710	730
V-funnel	T_{10s} (s)	15	14	13	13
	T_{5min} (s)	24	18	18	17
Sieve segregation	Sieved Portion (%)	6.28	6.84	5.95	4.8
Visual Index	Index	1	1	1	1

4.1.1 Filling Ability

Filling ability is meant to measure the ability of fresh LWSCC to flow and fill formwork under self-weight without the need of external vibration. In this research, assessment of flow ability of LWSCC have been done by carrying out slump flow and V-funnel tests.

All the LWSCC mix designs in this research have achieved the slump flow spread of 660-730mm as shown in Figure 5. These values were within the range 550-850mm of European guidelines [6]. In particular, they fell within class SF2 of European Guideline with range of 650-750mm. SCC which fulfils Class SF2 requirement is meant for use in vertical structural components such as walls and columns. The maximum spread of LWSCC tends to increase with higher level fly ash replacement. It is a well-established fact that the use of FA in SCC can reduce the water demand required to achieve a given workability. Meanwhile, incorporation of fly ash can reduce the need of superplasticiser at constant w/b ratio to obtain a given slump flow. Similar outcomes were observed by Yahia et al. [89] and Ramanathan et al. [68].

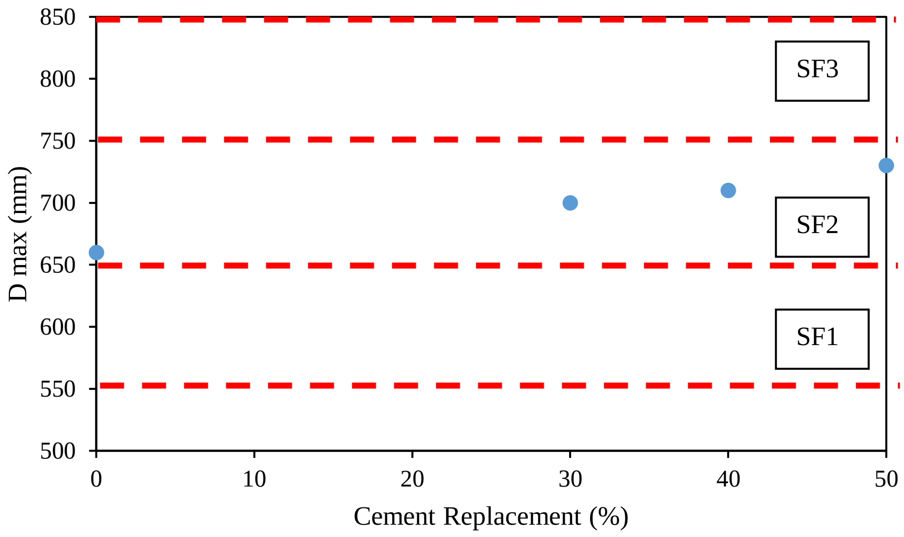

Figure 5: Comparison of maximum slump spread

T_{500} and V-funnel flow times are used to assess the viscosity and stability of SCC respectively. Figure 6 and Figure 7 present T_{500} and V-funnel flow times of all mixes respectively. A low values of T_{500} and V-funnel flow time indicate that the fresh concrete possesses low plastic viscosity and therefore it has faster filling rate. The time to spread 500mm for four mixes fell in the range of 1.82 – 5.04s. The control mix, 30% and 40% were classified as class VS2 as the flow time was more than 2s while mix 50% was classified as class VS1. T_{500} was found to decrease with the increasing content of fly ash. V-funnel test was carried out in two conditions, which were when funnel trap door was opened 10 seconds and 5 minutes after filling with LWSCC respectively. V-funnel time was in the range of 13 -15s for T_{10s} and 17-25s for T_{5min}. Since T_{10s} was more than 8s, all the LWSCC were classified as Class VF2 of European guidelines. The inverted cone shape of V-funnel restricts concrete flow and the prolonged flow time can give an indication of fresh concrete blocking tendency. The control mix was found to have the highest v-funnel flow time. T_{10s} tended to decrease with the increase of fly ash replacement. Similar trend was found for T_{5min}. This is depicted in Figure 7. The relationship between T_{500} and V-funnel flow time is presented in Figure 8. Two mixes fall in VS2/VF2 category. According to EGSCC [6], the mix that falls within VS2/VF2 region gives rise to good filling rate. The mixes which fall within this region can experience thixotropic effect that can help to reduce formwork pressure. However, the resultant hardened concrete may experience blow hole finishing surface. Slump flow and flow times depend highly on replacement level of fly ash. As such, fly ash is found to be able to improve filling ability of LWSCC. The capability of fly ash to improve workability of LWSCC is derived from the round shape and smooth nature of fly ash particles which induce ball bearing effect. Replacing cement partially with fly ash can result in higher volume of paste and this eases friction at the interface between fine aggregate and paste. Consequently, cohesiveness and plasticity of concrete improve. Hence, the improved concrete workability is achieved [68]. In short, incorporating fly ash as partial binder content in LWSCC with OPS as coarse aggregates has been proven, by good filling ability results, to have similar performance to conventional SCC.

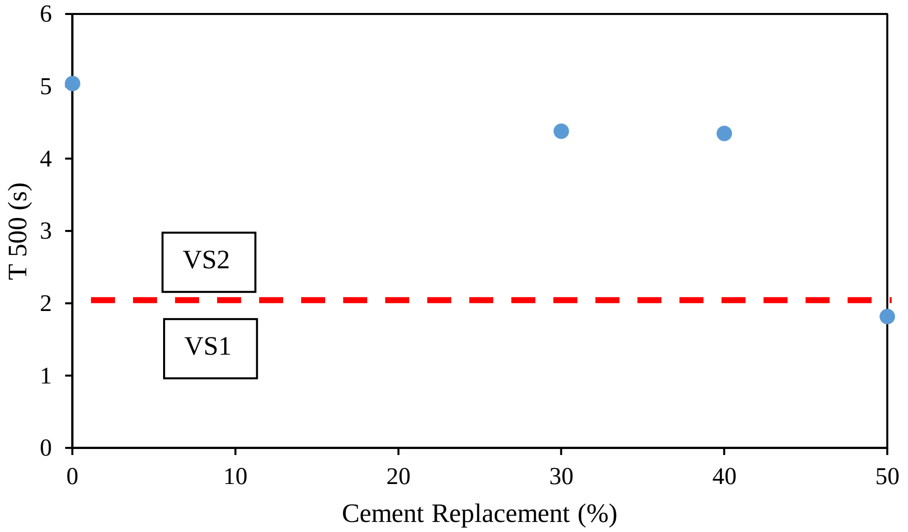

Figure 6: Comparison of slump flow time

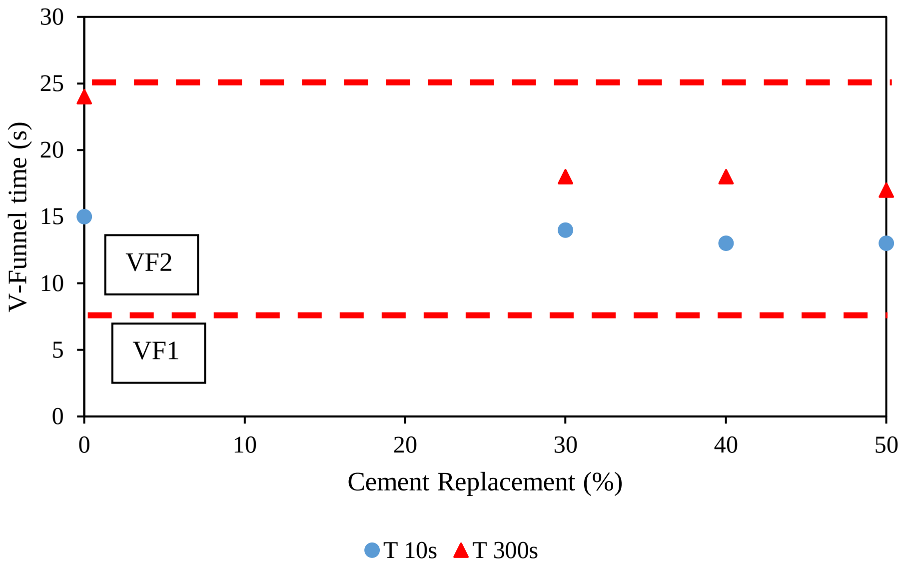

Figure 7: V-funnel time comparison

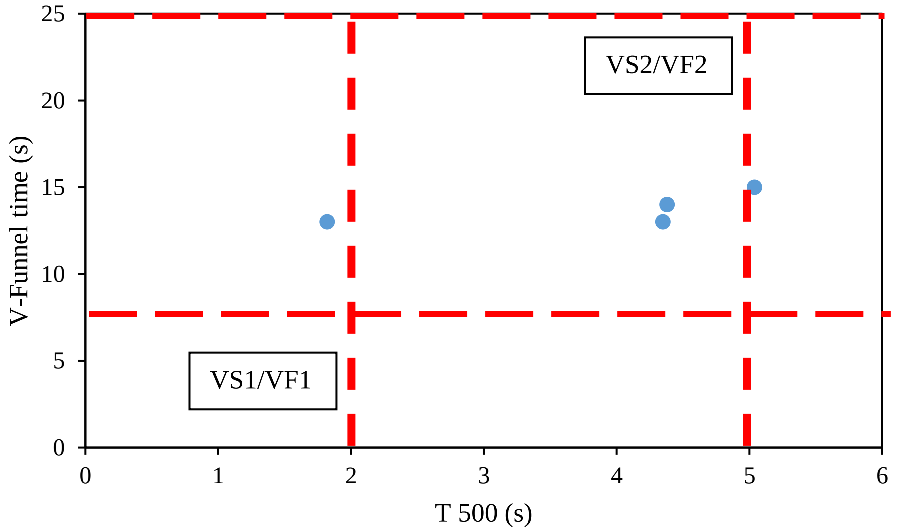

Figure 8: Viscosity class variation with T500 and V-funnel flow time

4.1.2 Passing Ability

Passing ability is assessed to determine the capability of a fresh LWSCC to pass through narrow openings in confined space such as heavily steel reinforced area, with no segregation and loss of its uniform consistency or without blockage in the confined space.

Passing ability of LWSCC was determined by conducting J-ring test. Three key parameters of J-ring test are indicated as T_{500} (time to spread 500mm diameter), D_m (maximum spread) and block step. The main concern is block step value which is the difference in concrete height between inside and outside of J-ring bars. Block step of 15mm is within acceptable range of EGSCC [6]. From Table 7, the time used to spread 500mm diameter is in the range of 7s to 10s while the maximum spread is ranging from 520mm to 600mm. These values are shown in Figure 9. The time taken to spread 500mm decreased with higher replacement of fly ash in j-ring test. The block step is in the range of 9.5mm to 12.5mm. Higher block step values indicate higher viscosity whereby there is higher blockage tendency of coarse aggregate when the fresh SCC flows through steel bars. Figure 10 shows block step height of three SCC samples. It is noted that block step height reduces when the fly ash replacement is increased from 0 to 40%. However, the block step height increases when fly ash replacement is increased from 40% to 50%. This signifies that passing ability of LWSCC improves with replacement of fly ash up to 40%. In short, replacement of fly ash in LWSCC offers better passing ability up to an optimum point.

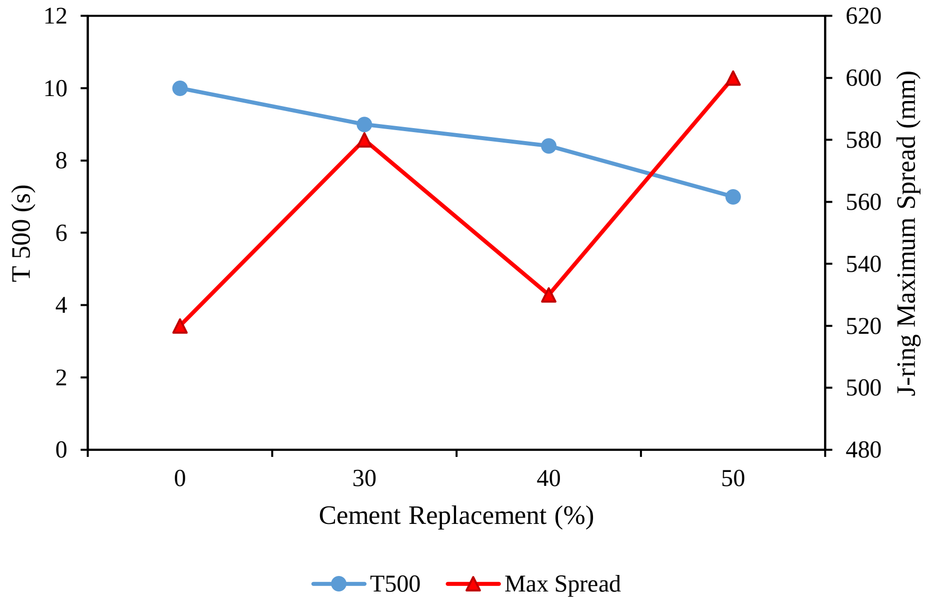

Figure 9: T 500 and max spread comparison

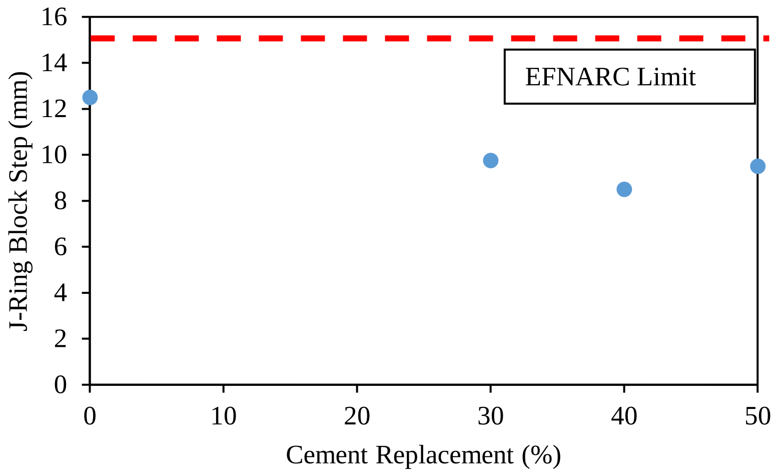

Figure 10: Comparison of j-ring block step height

4.1.3 Segregation Resistance

Segregation resistance is assessed to ensure LWSCC maintains its homogeneity which means it does not bleed and its aggregates do not segregate during concreting and transportation processes. Sieve segregation and visual indexing were used to assess LWSCC segregation resistance.

Percentage of concrete mix passing through 5mm sieve is expressed as segregation ratio. Figure 11 depicts the comparison of segregation of LWSCC at different levels of fly ash replacement. Smaller segregation ratio indicates that LWSCC has better segregation resistance. From the figure, all the four concrete mixes achieved segregation ratio of less than 15%, which meant that their segregation resistance fell within class SR2. Concrete mixes within Class SR2 can be utilized in tall vertical structures. All the LWSCC can be considered as quite consistent in eschewing segregation and bleeding. The binder content, w/b ratio, amount of SP and aggregates content were proportioned carefully to produce mixes with constant fresh concrete properties. By comparing the segregation ratio of 30% mix with the control, 30% mix resulted in slightly poorer sieve segregation. However, as fly ash content increased, the segregation resistance improved up to 50% of fly ash replacement.

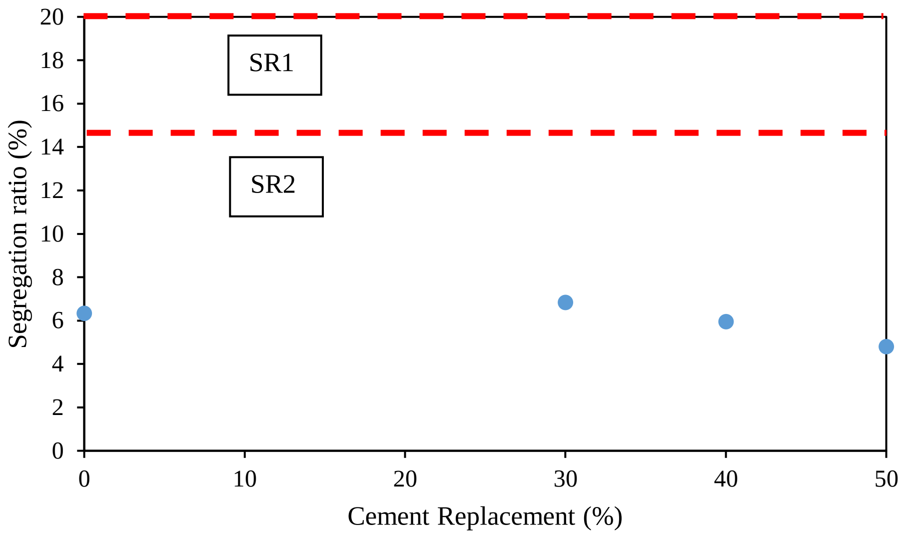

Figure 11: Comparison of segregation ratio

In this study, visual segregation indices were taken straight after the slump flow tests. These indices were recorded based on the presence of mortar halo and aggregates piling up at the centre of spread, as well as any separation of aggregates and mortar at the edge. Figure 12 shows the VSI indices of all four LWSCC mix designs. All the mix designs show the VSI index of 1.0, which indicated no mortar halo or aggregate piled up at the centre and also, minor evidence of air popping on the surface of LWSCC spread. Typical slump flow spread is shown in Figure 13. These VSI indices have agreed with the results of sieve segregation and thus demonstrated satisfactory segregation resistance of the mix.

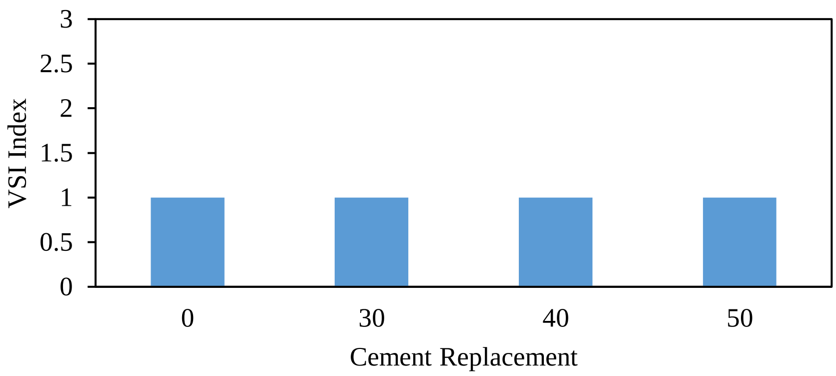

Figure 12: Comparison of VSI index

Figure 13: Typical slump flow appearance

These experiments have shown that the OPS based SCC satisfies the requirement of the fresh state properties of SCC such as filling ability, passing ability and segregation resistance. As such, OPS is considered a potential material which can be used to replace normal aggregate in manufacturing SCC.

4.2 Hardened Properties under Room Temperature

4.2.1 Density

The density for all LWSCC mixes under fresh, air dry and oven dry conditions is shown in Table 8. Overall, all the mixes have achieved density in the range of 1800 kg/m^3 to 2000kg/m^3 for fresh density. The air dry density is about 40-70 kg/m^3 lower than fresh density while oven dry density is 125-175 kg/m^3 lower than fresh density. The comparison of density between mixes under different conditions is illustrated in **Error! Reference source not found. Error! Reference source not found.**. The density of control mix does not fall within the range of 1120-1920 kg/m^3 which is specified by ASTM C330 as light weight concrete. Nevertheless, the control mix has achieved weight some 17% lighter compared to normal granite based concrete. It is noted that the density of concrete reduces with increasing replacement level of fly ash in the binder content of concrete. This reduction of density is due to the lower specific gravity of fly ash compared to cement. Similar trend of results was reported by Shafigh et al. [50] with fly ash substitution up to 70% for normally vibrated OPS based concrete. Reduced density of concrete can lead to better economic design of structure as dead load of structure is decreased significantly.

Table 8: Concrete density

Mix	Density (kg/m^3)		
	Demoulded	**Air dry**	**Oven dry**
M0	1918	1887	1832
M30	1900	1864	1771
M40	1881	1825	1731
M50	1843	1776	1668

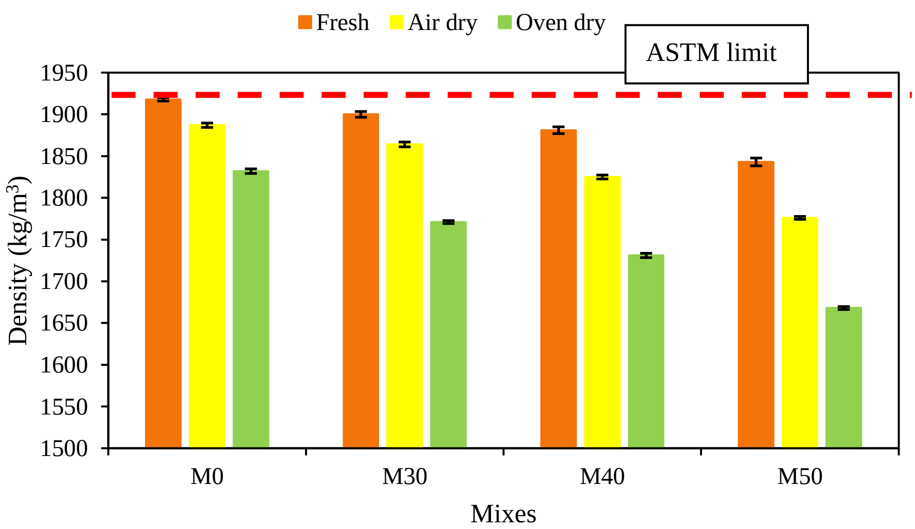

Figure 14: Comparison of mixes density

4.2.2 Compressive Strength

Concrete compressive strength is regarded as the most important property which determines structural performance of the material. The compressive strength of LWSCC mixes at 7, 28 and 90 day age is summarized in Table 9. The compressive strengths for all mixes fall within the range of 13-27MPa at 7 day, 18-39MPa at 28 day and 24-41MPa at 90 day. Development of compressive strength for all LWSCC mixes is illustrated in Figure 15**Error! Reference source not found.**. The compressive strength improved with increasing age from 7 days to 90 days. Test results show that control mix attained the highest compressive strength among all four mixes. When fly ash substitution level was raised from 30% to 50%, the compressive strength decreased drastically. From Figure 15**Error! Reference source not found.**, it is observed that the mixes that contain fly ash experienced slower rate of strength gain compared to control mix at early age. At latter age, mixes that contained fly ash still experienced significant strength gain while control mix did not. Mix M30 achieved comparable strength to control mix M0 at 90-day age. Similar trends were also observed in the studies of normally vibrated OPS based concrete done by Kupaei et al. [91] and Shafigh et al. [50]. These can be explained that the pozzolanic reactions in concrete have slowed down due to low calcium content in Class F fly ash, leading to significant delay in early strength gain. This effect is more significant when there is higher level of fly ash replacement.

For failure mode of LWSCC samples, it is observed that fracture occurred through the LWA particles. This observation indicates that aggregates are feeble within LWSCC concrete matrix. In the study of normally vibrated OPS concrete, Okpala [23] claimed that failure of OPS concrete was governed by the breakdown of bond between aggregates and cement mortar. Mannan et al. [30] also attributed OPS concrete failure to lack of adhesion between OPS aggregate and cement paste. Floyd et al. [87] reported similar observation in the study of expanded clay as LWA in LWSCC. Lotfy et al. [92] also reported that aggregate fracture was observed in failed sample after compression test for LWSCC. Thus, stiffness of LWA plays a critical role in contributing to strength of LWSCC. In other words, cement mortar in LWSCC is typically stronger than LWA and contributes the most strength [15]. It is thus concluded that the individual strength of LWA is important in contributing to the compressive strength of LWSCC.

Table 9: Concrete compressive strength at different age

Mix	Compressive Strength (MPa)		
	7 days	28 days	90 days
M0	27.30	38.88	40.59
M30	24.67	32.17	36.01
M40	18.44	23.96	28.72
M50	13.34	18.72	24.43

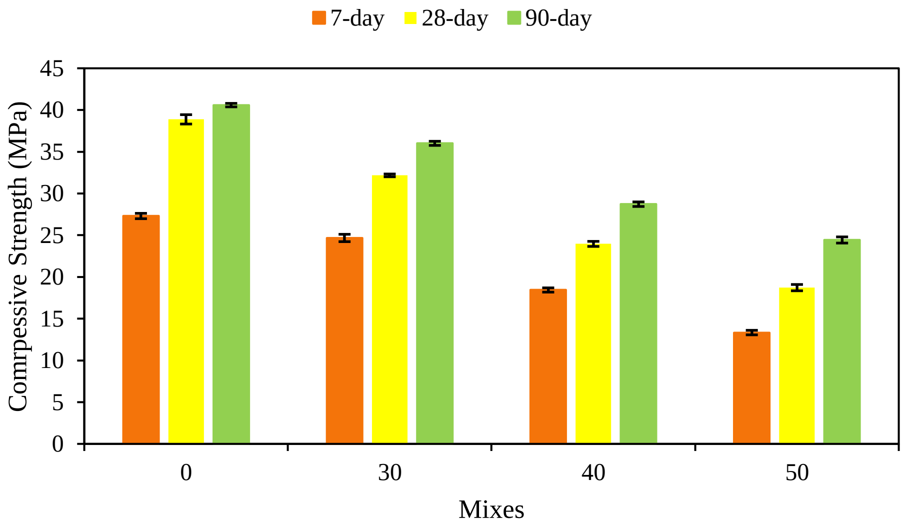

Figure 15: LWSCC compressive strength development with time

4.2.3 Splitting Tensile Strength

Splitting tensile strength is a material property which can be utilized to assess the diagonal tension resistance of LWSCC structure. The splitting tensile strength for OPS based SCC mixes at 7, 28 and 90 day is summarized in Table 10. The splitting tensile strength varies from 1.2-2.2MPa at 7 day, 1.6-2.8MPa at 28 day and 2-2.8MPa at 90 day. ASTM C330 has specified a minimum value of 2MPa splitting tensile strength for LWA concrete. All the mixes except M50 have achieved 2MPa and above strengths at 28 day. Development of LWSCC splitting tensile strength is shown in Figure 16**Error! Reference source not found.**. Splitting tensile strength is observed to increase as concrete ages. Similar to compressive strength, slower rate gain in splitting tensile strength is noted on concrete that contains fly ash. This effect is more significant at higher level of fly ash substitution. In short, increase in fly ash content decreases concrete splitting tensile strength.

Table 10: Concrete splitting tensile strength at different age

Mix	Splitting Tensile Strength (MPa)		
	7 days	28 days	90 days
M0	2.19	2.82	2.84
M30	2.09	2.54	2.75
M40	1.62	2.05	2.33
M50	1.20	1.62	2.07

Similar to granite based concrete, splitting tensile strength of OPS based SCC can also be correlated to its compressive strength. Relationship between compressive strength and splitting tensile strength is shown in Figure 17. The splitting tensile strength is noted to increase with increasing value of compressive strength. As shown in the experimental results, splitting tensile strength is about 7.2- 8.6% of compressive strength which is within the range of normally vibrated OPS based concrete reported by several researchers. Mahmud et al. [93] reported values of 6-10% of their OPS based concrete compressive strength. Values of 6.7-8.1% were also reported by Shafigh et al. [36] based on their extensive research on splitting tensile strength. A recent study on normally vibrated OPS based concrete with fly ash replacement by Shafigh et al. [50] shows the values of 5-7%.

As illustrated in Figure 18, the ratio of splitting tensile strength to compressive strength decreases when the compressive strength of LWSCC increases. The trends agree with the findings of Shafigh et al. [36] for normally vibrated OPS based concrete. This trend shows that

OPS based SCC exhibits similar properties to normally vibrated OPS based concrete. The correlation between splitting tensile strength and compressive strength of concrete from various researchers are shown in Table 11. These equations are used to predict the splitting tensile strength and plotted in Figure 19 for comparison purpose. The vertical axis is expressed as ratio of calculated value to experimental value. It is noted that the predicted values from equation of Farahani et al. [48] are closest to the experimental results. The proposed equation by Felekoğlu et al. [94] overestimates the splitting tensile strength as the equation is meant for granite based SCC. Contradictory to Felekoğlu et al. [94], the equation proposed by Lotfy et al. [92] underestimates the splitting tensile strength as this equation is actually proposed for furnace slag, expanded clay and expanded shale based SCC. These findings demonstrated that the splitting tensile strength of concrete is highly dependent on the type of aggregates used. An equation for correlation of compressive strength with tensile splitting strength for OPS based SCC, which has been proposed in the present study is shown as Eq. (13) below:

$$\mathrm{f_t} = 0.1803\mathrm{f_{cu}^{0.7573}} \quad (\mathrm{R^2} = 0.9896) \tag{13}$$

where f_t is splitting tensile strength and f_{cu} is ultimate cube strength of concrete.

Table 11: Splitting tensile strength equations from various researchers

Researchers	Equation	Description	
Shafigh et al. [31]	$0.2\sqrt[3]{f_c^2}$	Normally vibrated OPS concrete containing uncrushed OPS with compressive strength ranging from 17MPa to 37MPa	(14)
Shafigh et al. [36]	$0.4887\sqrt{f_c}$	Normally vibrated OPS concrete containing crushed OPS	(15)
Shafigh et al. [52]	$0.23f_c^{0.64}$	Normally vibrated OPS concrete containing crushed OPS and 10-50% fly ash	(16)
Farahani et al. [48]	$0.146f_c^{0.835}$	Normally vibrated OPS concrete containing crushed and blended binder of OPC, RHA and FA	(17)

Lotfy et al. [92]	$0.177f_c^{1.33}$	Lightweight self-compacting concrete containing furnace slag, expanded clay and expanded shale as LWA	(18)
Felekoğlu et al. [94]	$0.43f_c^{0.6}$	Self-compacting concrete with granite as aggregates	(19)

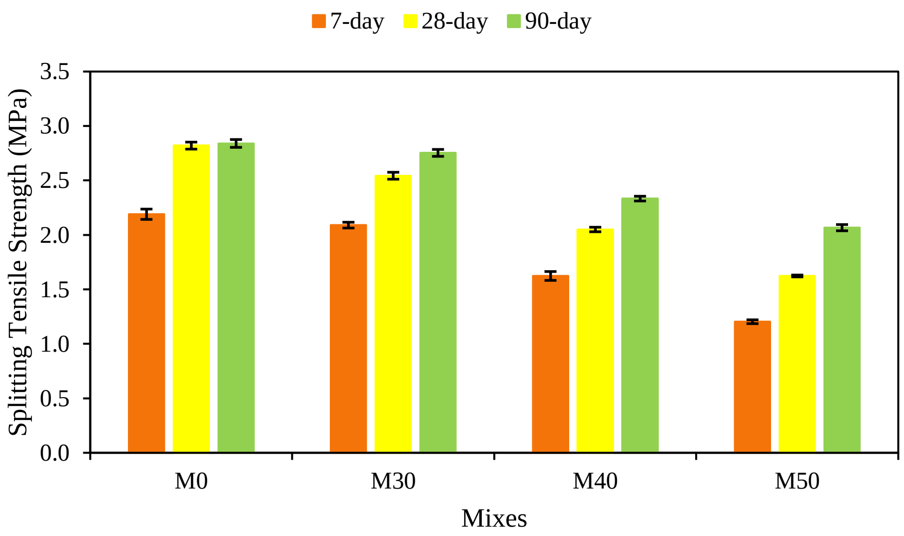

Figure 16: LWSCC splitting tensile strength development with time

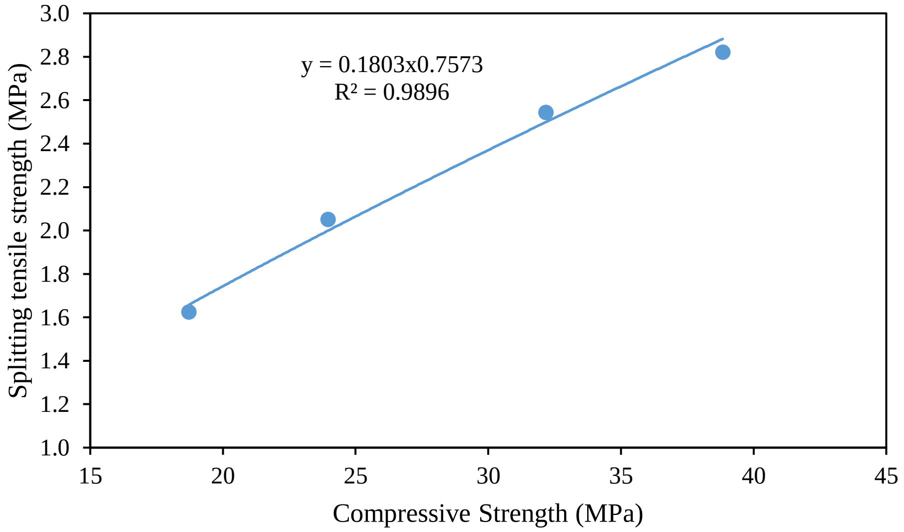

Figure 17: Correlation of LWSCC compressive strength to splitting tensile strength

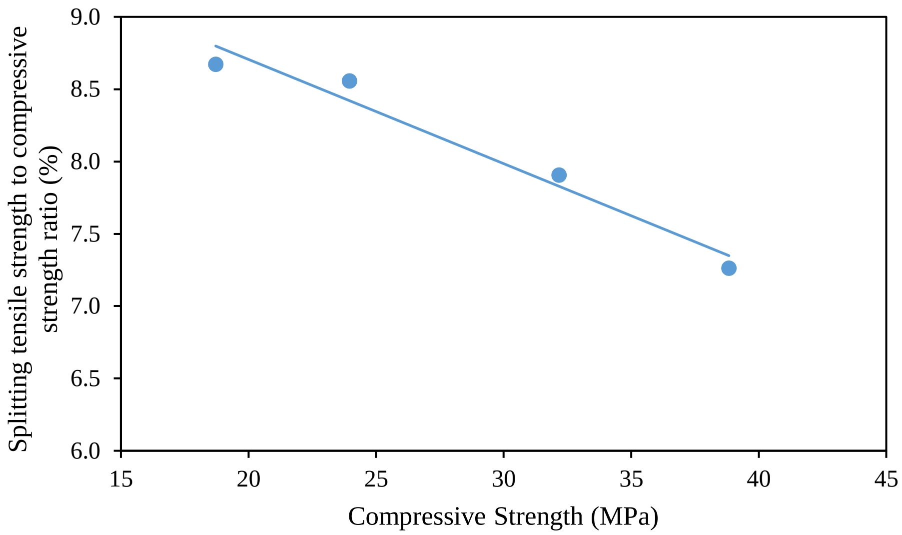

Figure 18: Correlation of compressive strength to ratio of splitting tensile to compressive strength

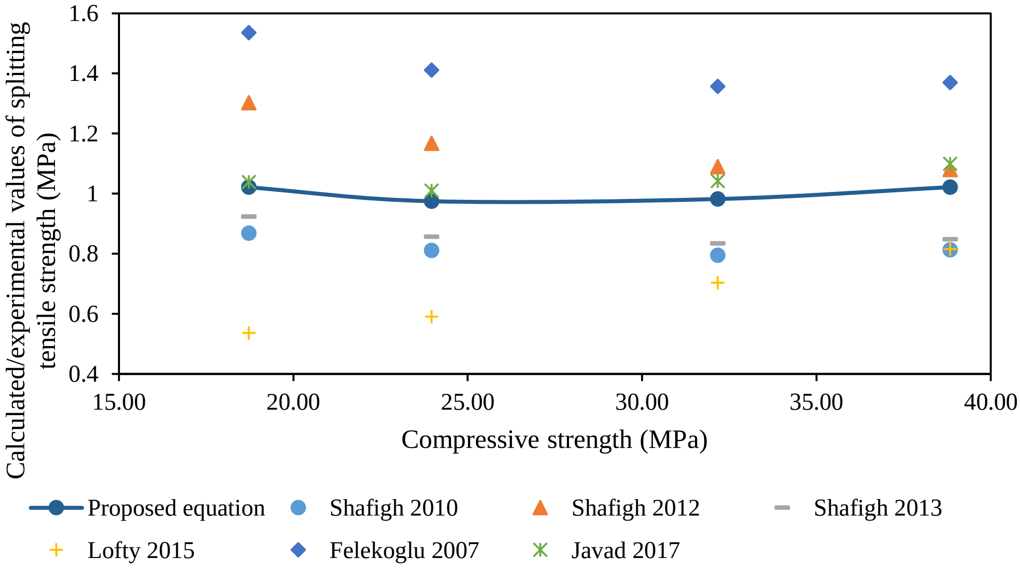

Figure 19: Relationship between 28-day compressive strength and calculated splitting tensile strength

4.2.4 SEM Analysis

The interfacial transition zones (ITZ) between binder and aggregates have been investigated by using SEM technique. This is to study the bonding characteristics between cement paste and aggregates of chosen LWSCC samples. The SEM images for Mix M0 at 28 day and 90 day are shown in Figure 20 and Figure 21 respectively. As shown in these two images, cement paste has considerably seeped into the surface pores of OPS aggregate in the interfacial transition zone (ITZ) to form interlocking structure. The rough surfaces and micro-pores of OPS provide bigger surface area to receive cement paste. Moreover, high workability of LWSCC has ensured homogeneity of hardened concrete. This can enhance the interlocking bond between cement paste and aggregates.

The SEM images for Mix M50 at 28 day and 90 day are shown in Figure 22 and Figure 23. It can be noticed in Figure 22 that smooth spherical fly ash particles are still present, which shows that fly ash is still in the early stage of hydration as its initial shape is spherical. As such, the pozzolanic reactions of fly ash and cement are not complete in the initial phase of hydration [95]. As concrete ages, decomposition of the spherical shape of fly ash gradually takes. Figure 23 indicates that the round-shaped fly ash particles are not as easily noticeable as the material is at the age of 90 days. These observations prove that the rate of hydration in concrete is reduced by fly ash. It is also noted that the aggregate surface is full of binder particles. The results accorded well with the works of Alengaram et al. [49] that finer supplementary cementitious material could enhance the ITZ to improve mechanical bonding.

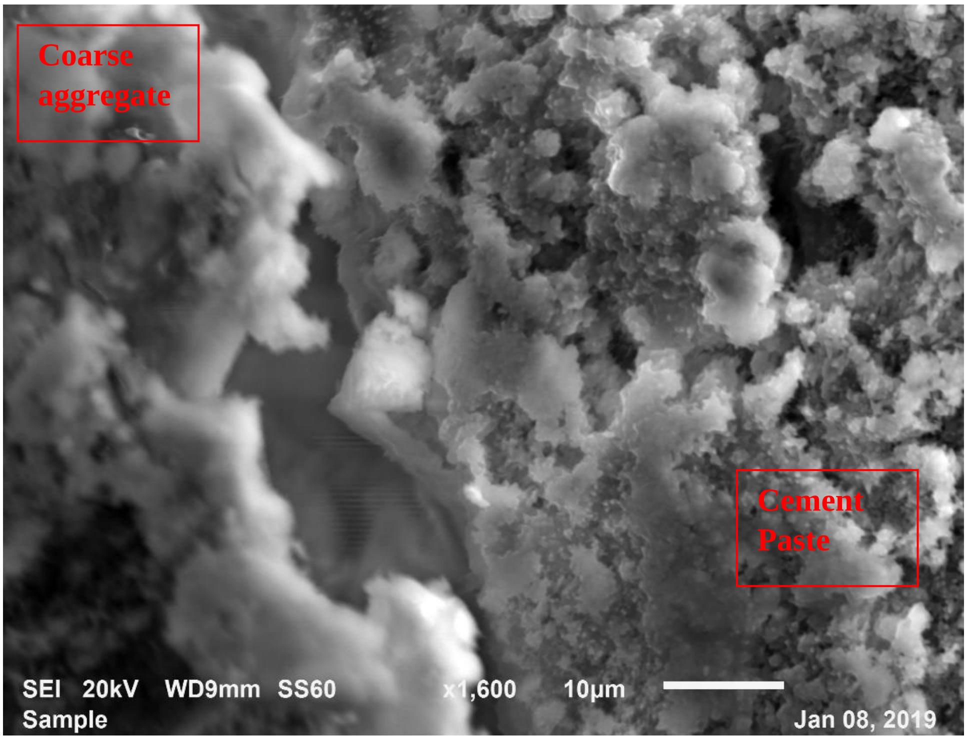

Figure 20: SEM image of ITZ of M0 at 28 day

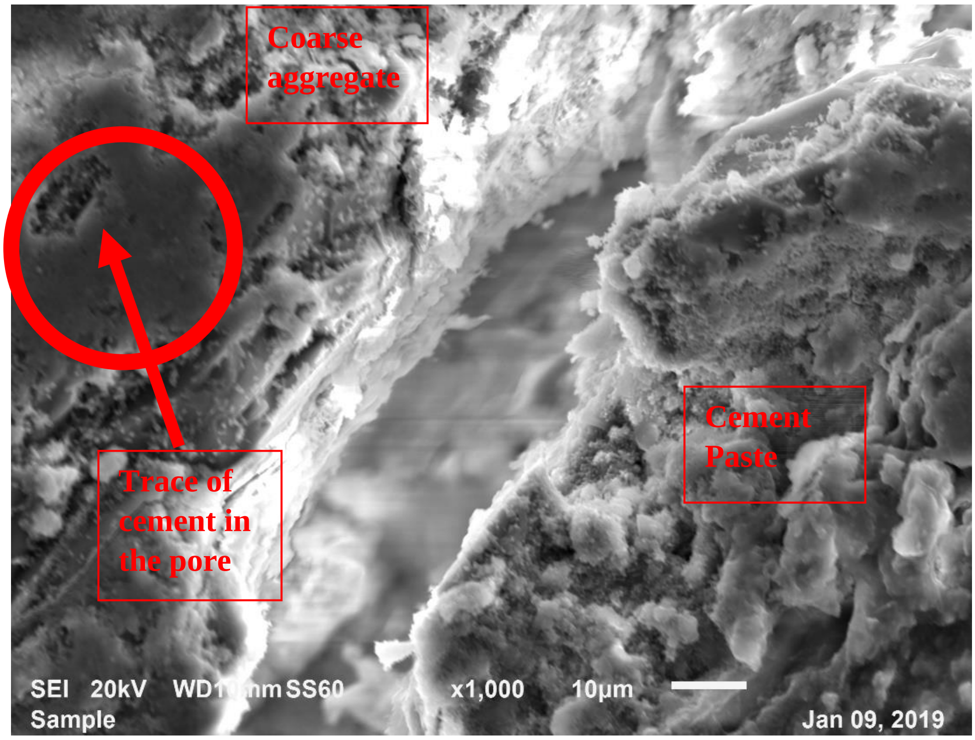

Figure 21: SEM image of ITZ of M0 at 90 day

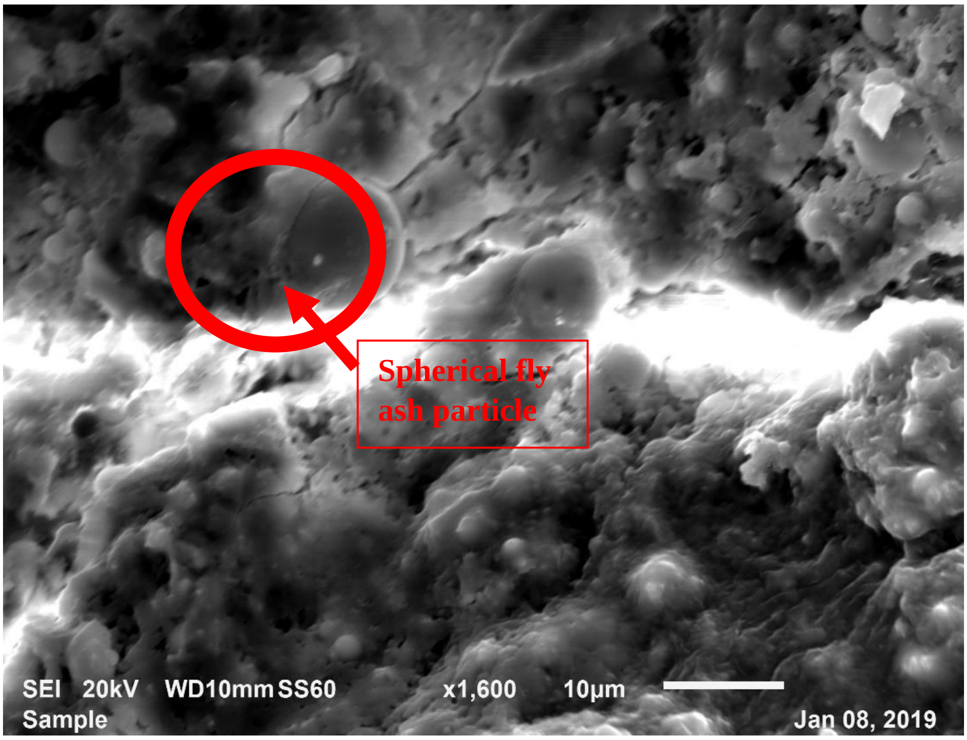

Figure 22: SEM image of ITZ of M50 at 28 day

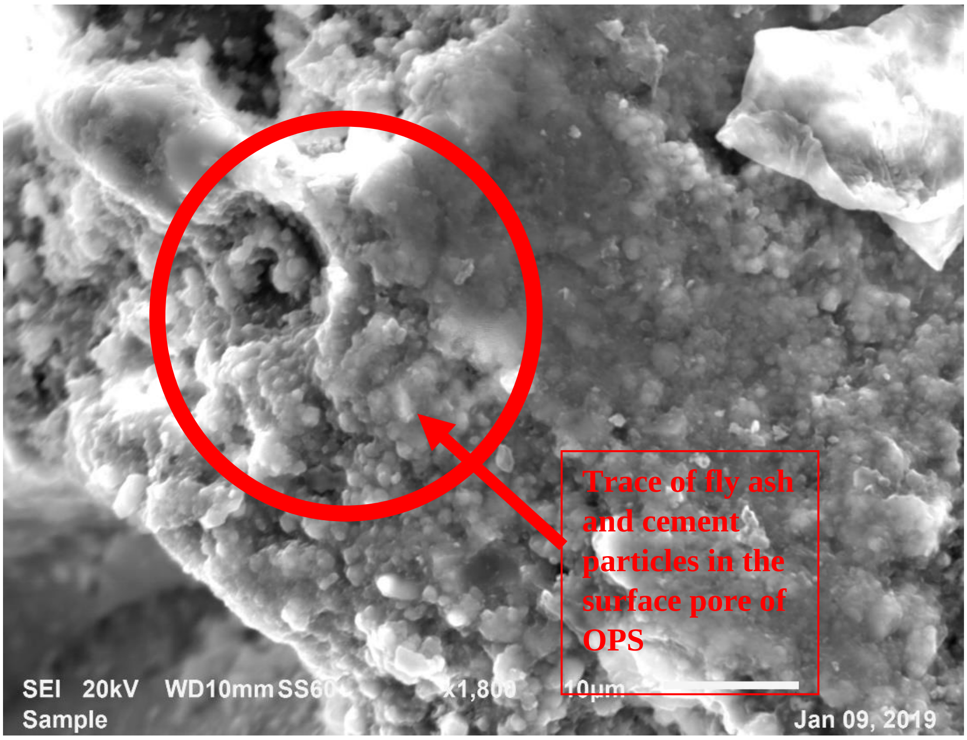

Figure 23: SEM image of aggregate part at ITZ of M50 at 90 day

4.2.5 Water Absorption

Concrete water absorption values of all four mix designs are presented in Table 12 and illustrated in Figure 24**Error! Reference source not found.**. The water absorption values for all mixes were 6.1-7.33% at 28 day and 4.47- 5.07% at 90 day. At 28-day age, control LWSCC mix had the lowest water absorption value among the four mixes. It is noticed that increasing the substitution of fly ash in OPS based LWSCC increases water absorption at earlier age. This is because increasing of class F fly ash content in concrete reduces the hydration process at earlier age. At earlier age, the hydration process in high fly ash content concrete is not complete and capillary pores still exist which are permeable, resulting in higher water absorption [96]. Several researchers [50, 52] have demonstrated that the water absorption of normally vibrated OPS increases with increasing of fly ash content. The study of Shafigh et al. [52] shows that the water absorption of normally vibrated OPS concrete increases from 5.5% to 6.6%, 7% and 9.8% when fly ash content is increased from 0% to 10%, 30% and 50% respectively.

At 90-day age, concrete of all the four mixes shows reduction in water absorption. It is observed that the water absorption at 90 day reduced by 17%, 27%, 34% and 39% for M0, M30, M40 and M50 respectively when compared to 28 day. At 90-day age, for concrete incorporated with fly ash, the voids between particles of materials were filled with fly ash at higher percentage and thus the porosity of concrete was reduced. The texture and size of the fly ash particles are able to minimize the voids in between particles [97]. The results show that water absorption of LWSCC decreases with age especially those with higher fly ash content. This is because the interconnectivity of the pores in concrete structure is reduced by fly ash as it uses $Ca(OH)_2$ from the cement and induces secondary calcium silicate to hydrate at later age [98]. However, the total porosity of concrete is increased with the incorporation of fly ash. Nevertheless, the ratio pore refinement to “pore size” is reduced [99].

Generally, all the concrete mixes exhibited water absorption of less than 8% at all ages. Neville [18] stated good concrete must possess the water absorption value of less than 10%, the result of which can be determined from immersed water absorption test.

Table 12: Water absorption value of OPS based LWSCC

LWSCC Mix	Water Absorption (%)	
	28-day	90-day
M0	6.10	5.07
M30	6.40	4.66
M40	6.85	4.54
M50	7.33	4.47

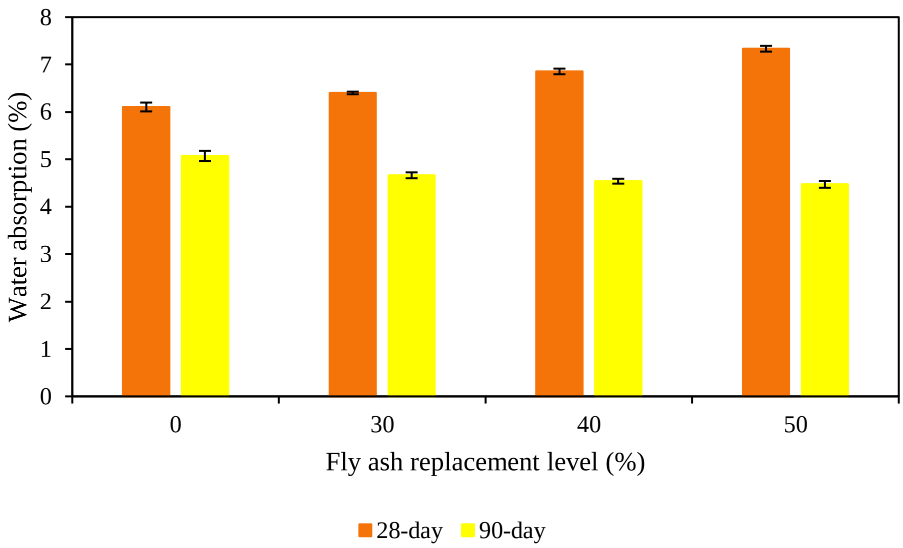

Figure 24: Water absorption of OPS based LWSCC

5.0 Conclusion

LWSCC control mix design has been successfully derived in this experimental research. Together with thorough investigation conducted on fresh and hardened properties of control LWSCC mix as well as the concrete mixes incorporated with various proportions of fly ash replacement to the control, the conclusions can be drawn as below:

1. LWSCC can be produced by using OPS as full replacement to normal weight aggregates (NWA), as well as with partial fly ash replacement, and the resultant concretes have satisfactorily achieved fresh state properties in respect of passing ability, filling ability and segregation resistance.
2. OPS-aggregate based LWSCC achieves satisfactory slump flow spread in the range of 665-730mm.
3. Satisfactory V-funnel flow time of less than 25s which meets specification in the European Guidelines has been achieved.
4. OPS based LWSCC has achieved good passing ability with the block step in the range of 8-15mm.
5. Excellent segregation resistance with value in the range of 4-7% has been achieved.
6. All the fresh concrete properties of SCC using OPS as aggregates improve with partial replacement of fly ash.
7. The density of OPS based SCC is found to be 15%-23% lower than normal concrete. Substitution of Ordinary Portland Cement with fly ash also reduces the concrete density.
8. The compressive strength of LWSCC is in the range of 18 to 38MPa at 28-day age. The compressive strength of LWSCC mix with fly ash replacement increases with curing age.
9. The splitting tensile strength of LWSCC is found to be in the range of 1.6-2.8MPa at 28-day-age. Splitting tensile strength falls in the range 7.2- 8.6% of its compressive strength. Its strength also improves with curing age.
10. As evidenced in SEM tests, cement paste has seeped into the pores of OPS aggregates giving rise to good bonding in the ITZ.
11. All the OPS based LWSCC exhibits water absorption of less than 8% at all ages. Water absorption of LWSCC decreases with age and, the decrease is more conspicuous for concrete with higher content of fly ash.

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Competing of Interests

The authors declare no competing interests.

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