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EFFECTS OF COARSE PALM OIL CLINKER ON PROPERTIES OF SELF-COMPACTING LIGHTWEIGHT CONCRETE

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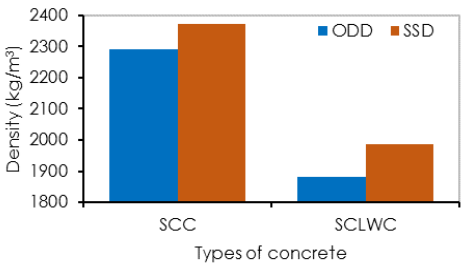
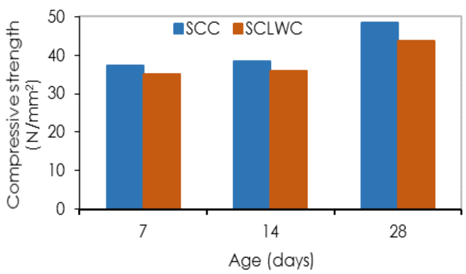
Graphical abstract





Abstract

Self-compacting lightweight concrete (SCLWC) is an innovative high performance concrete which uses palm oil clinker (POC), a waste by-product from the palm oil industry, as the lightweight aggregates. This paper presents a research on the effects of utilising only POC as coarse aggregates on the fresh and hardened properties of SCLWC. Properties of SCLWC were compared to self-compacting concrete (SCC) containing crushed granite aggregates. Tests of slump flow, V-funnel, J-ring, L box and sieve segregation were conducted to characterise the self-compactability in fresh state. The hardened concrete specimens were tested for density, water absorption, ultrasonic pulse velocity (UPV), compression, tensile splitting and flexural. Results revealed that both mixes had fulfilled the self-compactability requirements as per European Guidelines whereby the fresh SCLWC exhibited better filling ability and passing ability at low segregation resistance. The inclusion of coarse POC reduced the concrete density and strength, but the SCLWC exhibited good UPV values despite greater porosity in the concrete. It can be concluded that the POC can be potentially used as coarse aggregates for producing SCLWC to manage the waste and promote environmental sustainability.

Keywords: Self-compacting lightweight concrete, palm oil clinker, self-compacting concrete, fresh properties, hardened properties

Abstrak

Konkrit ringan mampat sendiri (SCLWC) adalah satu konkrit berprestasi tinggi yang berinovasi dengan menggunakan batu hangus kelapa sawit (POC), satu bahan sisa sampingan dari industri kelapa sawit, sebagai agregat ringan. Kertas ini membentangkan kajian mengenai kesan-kesan penggunaan POC sebagai agregat kasar ke atas ciri-ciri basah dan keras SCLWC. Ciri-ciri SCLWC telah dibandingkan dengan konkrit mampat sendiri (SCC) yang mengandungi agregat granit. Ujian-ujian runtuhan aliran, corong-V, cincin-J, kotak L, dan kestabilan ayakan telah dijalankan untuk mengetahui keupayaan mampat sendiri semasa keadaan basah. Spesimen konkrit keras telah diuji untuk ketumpatan, penyerapan air, halaju denyut ultrasonik (UPV), mampatan, tegangan dan lenturan. Hasil kajian menunjukkan bahawa kedua-dua konkrit telah memenuhi syarat-syarat keupayaan mampat sendiri seperti digariskan dalam garis panduan European di mana konkrit basah SCLWC telah mempamerkan keupayaan mengisi dan melepasi yang lebih baik pada rintangan pengasingan yang rendah. Agregat kasar POC telah merendahkan ketumpatan dan kekuatan konkrit, namun SCLWC mempamerkan nilai UPV yang baik walaupun keliangan yang lebih besar di dalam konkrit tersebut. Ia boleh disimpulkan bahawa POC berpotensi digunakan sebagai agregat kasar untuk menghasilkan SCLWC bagi menguruskan sisa tersebut dan menggalakkan kelestarian alam sekitar.

Kata kunci: Konkrit ringan mampat sendiri, batu hangus kelapa sawit, konkrit mampat sendiri, ciri-ciri basah, ciri-ciri keras

1.0 INTRODUCTION

Self-compacting concrete (SCC) is an innovative concrete and a remarkable achievement in modern concrete technology [1]. SCC is able to spread through dense reinforcement, fill every corner of the formwork and consolidate under its own weight [2]. Not only it possesses a high deformability that gives high filling capacity, it is also able to maintain its stable composition throughout transportation and placing [1, 2]. These fresh properties have made SCC a distinctively unique concrete type. When hardened, SCC continues to exhibit good strength and durability similar to or better than comparable conventional concrete [3]. Because of these, SCC has been an interesting research topic since the 1990s and being extensively used since the past two decades.

However, the utilisation of SCC can be limited due to its high demand for natural aggregates such as crushed granite that may leave environment and construction impacts. This is translated to a need for rapid mining activity of the aggregates that depletes the non-renewable natural resource and triggers ecological imbalance. With increasing scarcity of the natural resource, it also leads to price hike on the construction material that significantly increases the overall project cost [4]. The large amount of crushed aggregates used also means that SCC has high self-weight added onto the structure's existing dead load. This has brought on a growing emphasis on the utilisation of lightweight aggregates to reduce the self-weight and also the adverse environmental impact, thus leading to the formulation of a new type of high performance concrete known as "self-compacting lightweight concrete" (SCLWC).

Similar to SCC, concrete placement using SCLWC is effortless. The added value of SCLWC as compared to SCC is the prospect of a simpler and more economical structural design due to a lighter self-weight imposed on the structure. In the past, research has been devoted to develop SCLWC by using natural lightweight aggregates such as pumice and artificial lightweight aggregates such as expanded shale, leca, lytag, perlite and expanded clay [5]. Most experiments have reached a conclusive finding of a SCLWC which met the desired performance requirements of SCC and LWC [6]. Nevertheless, the primary constraint is the availability of lightweight aggregates in some countries.

Malaysia has a type of lightweight aggregates that is abundantly available from the palm oil industry, which is the palm oil clinker (POC) - a waste by-product generated after the burning of palm oil shell and mesocarp fibre in the boiler of the palm oil mill. It is grey in colour, porous, irregularly shaped with rough and spiky broken edges and has low specific gravity due to the numerous inner pores [7]. In the current practice, the abundant POC has less commercial value in which it is either used as a road paving material [8] or disposed to the landfill. The latter has recently raised some concerns on possible environmental pollution and the consumption of large land area for dumping purpose [9]. Hence, the utilisation of POC as lightweight aggregates in concrete production has been seen as an innovative solution to effectively manage the vast amount of solid waste produced along with an effort to conserve the depleting natural resources and promote environmental sustainability [10].

The increasing rate of palm oil extraction due to the growing global demand for palm oil has resulted in a huge amount of POC being continuously produced in the palm oil mill. This directly implies that there is a consistent supply of freshly generated porous lumped POC which can potentially surpass the supply of non-renewable crushed granite. In addition, the POC is an ideal alternative lightweight aggregates since it can be crushed into desired sizes. A previous study conducted by Ahmmad *et al.* [11] demonstrated that high strength lightweight concrete containing coarse POC can be produced with a 28-day compressive strength of up to 62 N/mm^2 and oven-dry density of 1971 kg/m^3. Apart from that, contemporary studies reported that the pre-tensioned beams [12], reinforced beams [10] and slabs [13] made from POC aggregates exhibited satisfactory structural behaviour comparable to normal weight concrete structural members. Therefore, it is evident that the POC can be used as lightweight aggregates for producing lightweight concrete which is feasible for structural application. It is also worth noting that the POC can be directly used to replace natural aggregates in the concrete without the need of treatment because it does not contain any harmful substances which can potentially deteriorate the quality [14].

Due to its proven performance as lightweight aggregates in the vibrated lightweight concrete, the aim of this study is to give added value to the knowledge bank by further investigating the effects of coarse POC on the fresh and hardened properties of SCLWC as compared to SCC. The tested experimental parameters included filling ability, passing ability and segregation resistance for the fresh properties as well as density, water absorption, ultrasonic pulse velocity (UPV), compressive strength, tensile splitting strength and flexural strength for the hardened properties.

2.0 METHODOLOGY

2.1 Materials

The materials involved were cement, water, coarse aggregates, fine aggregates, and superplasticiser. Ordinary Portland cement (OPC) with a specific gravity of 3.15 was used for all concrete mixes. Ordinary tap water was used for mixing and curing the concrete along with soaking the coarse POC aggregates before mixing. The superplasticiser used was a polycarboxylic ether based high range water-reducing admixture. Local river sand that passed through 4.75 mm sieve was used as fine aggregates. The crushed granite and POC with a maximum nominal size of 10 mm were used as normal weight and lightweight coarse aggregates, respectively. The POC shown in Figure 1(a) was obtained from a palm oil mill located in the southern part of Johor. The large chunks of POC were crushed using a crusher machine and then sieved to obtain particle sizes of between 4.75 mm and 9.5 mm as shown in Figure 1(b). The physical and mechanical properties of coarse aggregates are summarised in Table 1. A point to note is that although the coarse POC was lighter than the crushed granite, it had higher water absorption. The crushing and impact values of coarse POC were also significantly greater than crushed granite, which indicated that coarse POC was weaker. These are mainly attributed to its natural open cellular structure; the palm oil shell and mesocarp fibre are natural compound originated from oil palm trees that have a cellulose feature [15]. Figure 2 depicts the particle distribution of coarse POC and crushed granite. The materials are well-graded since their sizes fell within the grading limit in BS EN 12620 [16]. Since the loose bulk density of the well-graded coarse POC was 793 kg/m^3, which was less than 1200 kg/m^3 as stipulated in BS EN 13055 [17], the coarse POC can be classified as lightweight aggregates.

(a) Raw POC

(b) Coarse POC after crushing and sieving

Figure 1 Physical appearance of palm oil clinker (POC)

Table 1 Physical and mechanical properties of coarse aggregates

Properties	Coarse Aggregates	
	POC	**Crushed Granite**
Specific Gravity (Oven-dry)	1.76	2.61
Water Absorption (%)	4.67	1.6
Bulk Density (kg/m^3)	793	1611
Aggregate Crushing Value (%)	47.9	24.3
Aggregate Impact Value (%)	48.6	25.60

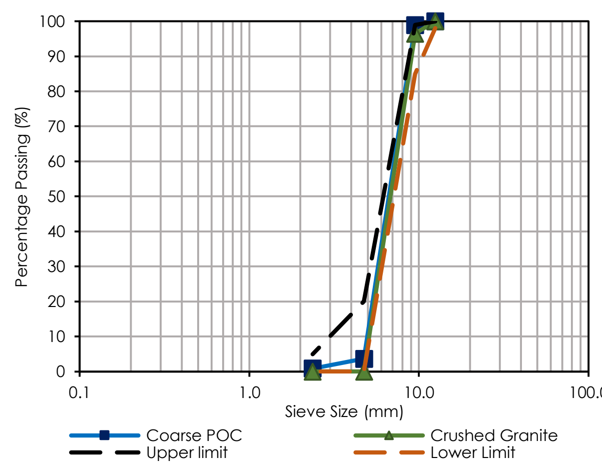


Figure 2 Particle size distribution of coarse aggregates

2.2 Mix Proportions and Mixing Procedure

Two concrete mixes were prepared in this study, namely SCC and SCLWC made of crushed granite and coarse POC aggregates, respectively. Both mix proportions were designed using an empirical design method and referred to the European guidelines for SCC [18]. The cement content and the water-cement ratio for both mixes were fixed at 485 kg/m^3 and 0.38, respectively. The proportion of fine aggregates was kept constant for both mixes to examine the effects of coarse POC on the concrete properties. Both mix proportions were obtained after extensive trial mixes to ensure that the designed mixes had an adequate self-compactability without segregation. Table 2 presents the mix proportions of the two mixes.

Table 2 Mix proportions of SCC and SCLWC

	SCC	SCLWC
Cement (kg/m³)	485	485
Water (kg/m³)	185	185
w/c	0.38	0.38
SP (kg/m³)	3.0	2.0
Sand (kg/m³)	814	814
Granite (kg/m³)	755	-
POC (kg/m³)	-	440

Note: w/c = water-cement ratio; SP = superplasticiser

The mixing procedure was the same for both mixes to obtain equivalent homogeneity and uniformity in all mixes. All aggregates were prepared in a saturated surface dry (SSD) condition before mixing. Considering the high water absorption of coarse POC, the lightweight aggregates were immersed in water for 24 hours at room temperature prior to concrete batching and mixing and was then allowed to surface dry to prevent it from absorbing mixing water and maintain the water-cement ratio. Each concrete batch was mixed using a drum mixer. The mixing process began by mixing the coarse and fine aggregates for a minute, followed by adding cement into the mixer. After another minute, three-quarters of mixing water was added and mixed for another minute. The remaining water containing superplasticiser was then added. The concrete was mixed again for an additional three minutes and set to rest for three minutes. The final step was mixing for two minutes. After that, tests were performed on the fresh concrete to assess the fresh concrete properties. The fresh concrete was then poured into the moulds measuring 100 mm x 100 mm x 100 mm (cubic), 100 mm in diameter x 200 mm in height (cylindrical), and 100 mm x 100 mm x 500 mm (prismatic). After casting, all specimens were demoulded and cured in water until the day of testing.

2.3 Fresh Concrete Tests

The self-compactability properties included filling ability, passing ability and segregation resistance were determined through the tests of slump flow, V-funnel, J-ring, L box and sieve segregation. The filling ability of the fresh concrete was determined through slump flow test and V-funnel test. The former was conducted in accordance with BS EN 12350-8 [19] by assessing the horizontal free flow of the concrete in the absence of obstructions. The diameter of flow spread, *SF*, and time taken for the concrete to flow to a diameter of 500 mm, t_{500}, were measured. In the case of V-funnel test, V-funnel flow time, t_v, was measured by taking the time for the concrete to flow out of the funnel in accordance with BS EN 12350-9 [20]. Apart from determining filling ability, the t_{500} slump flow time and V-funnel flow time can also provide an indication of the viscosity of the fresh mixture. On the other hand, J-ring and L box tests were conducted to assess the passing ability of the fresh concrete. In the J-ring test, the diameter of flow spread, SF_J, and the differences in concrete height between outer and centre of the J-ring with 16 steel bars (known as blocking step, *PJ*) was measured according to BS EN 12350-12 [21]. Besides that, the L box test was conducted in accordance with BS EN 12350-10 [22] to determine the passing ability ratio, *PL*, of the fresh concrete using L box with three steel bars. Meanwhile, the segregation resistance was evaluated through the sieve segregation test by allowing concrete to pass through a 5 mm sieve for two minutes in accordance with BS EN 12350-11 [23]. Segregation portion, *SR*, was determined in the test through the calculation of the percentage of the mass of passed material based on initial mass of concrete on the sieve.

2.4 Hardened Concrete Tests

The hardened properties tested included density, water absorption, ultrasonic pulse velocity (UPV), compressive strength, tensile splitting strength and flexural strength.

2.4.1 Density and Water Absorption

The cubic specimens measuring 100 x 100 x 100 mm were tested after 28-day curing period for density and water absorption according to ASTM C462 [24]. An average value was taken from a total of three tested specimens for every concrete mix. The specimens were dried in an electric oven at a temperature of 105 °C ± 5°C for 72 hours to be fully dried before testing. After the specimens had cooled down to room temperature, the specimens were weighed and recorded as w_d before being immersed in water for another 72 hours. After that, the specimens were surface-dried using a towel. The specimens were weighed again and recorded as w_s. The water absorption of specimens was calculated using the following equation:

$$Absorption\ (\%) = \frac{w_s - w_d}{w_d} \times 100 \qquad (1)$$

where, w_d is the mass of oven-dried specimen in air and w_s is the mass of surface-dried specimen in air after immersion.

2.4.2 Ultrasonic Pulse Velocity

The non-destructive ultrasonic pulse velocity (UPV) was conducted on 18 cubic specimens aged 7, 14 and 28 days in accordance with BS EN 12504-4 [25] to examine the quality of the concrete. The pulse velocity of ultrasonic longitudinal waves travelling through the specimens was measured by placing transmitter transducer to the receiver transducer on two surfaces of the specimens opposite to each other.

2.4.3 Strength Tests

The 18 cubic specimens tested for ultrasonic pulse velocity were then subjected to compressive strength test in accordance with BS EN 12390-3 [26]. Meanwhile, the cylindrical specimens and prismatic specimens were tested for tensile splitting strength and flexural strength (two-point loading method) at the age of 28 days according to BS EN 12390-6 [27] and BS EN 12390-5 [28], respectively. For each concrete mix, three specimens were tested. All tests were carried out using a universal testing machine at the loading rate of 4 kN/s, 0.18 kN/s and 0.16 kN/s, for compression strength, tensile splitting strength and flexural strength, respectively. The mode of failure for all tested specimens was visually inspected.

3.0 RESULTS AND DISCUSSION

3.1 Fresh Concrete Properties

The recorded fresh properties of SCC and SCLWC are summarised in Table 3. In the case of slump flow, the obtained results demonstrated that both mixes exhibited satisfactory slump flow values, falling under class SF2 in accordance with BS EN 206 [29]. This indicates that both mixes had good filling ability, and thus were suitable for many normal applications such as columns and walls [18]. A point to note is that the SCLWC had higher slump flow with low dosage of superplasticiser than that of SCC at constant water-cement ratio. This was due to the lightweight of coarse POC that had reduced the self-weight of fresh SCLWC. Eventually, it reduced the internal friction between coarse POC and cement paste which consequently eased the flowability of the concrete. The result also implied that the coarse POC had been more actively-mobilised than crushed granite. These results are similar to the findings by Kim *et al.* [30] in which the authors concluded that coarse lightweight aggregates with lower density can enhance the flowability of SCLWC. On the contrary, the lower flowability of SCC was attributed to the heavier matrix and greater collision between aggregates in the mixture which then reduced the mobility of the fresh concrete.

The t_{500} slump flow time and V-funnel time were used to evaluate the viscosity and filling ability of the mixture. In general, a shorter flow time implies a higher filling ability, higher flow rate, and lower viscosity [2]. It can be seen that the t_{500} slump flow time and V-funnel time of SCLWC were shorter than those of SCC. This was primarily due to the lower viscosity of the fresh SCLWC with coarse POC that had made the concrete less viscous and enhanced the fluidity. A similar observation has been documented by Uygunoğlu and Topçu [31] whereby they reported that the SCLWC was less viscous and flowed easily because of the pumice aggregates incorporated. On the contrary, the heavier matrix reduced the fluidity of the paste and caused greater friction between aggregates particles and cement paste. Despite the variation in the flow time, it is interesting to note that the t_{500} slump flow time and V-funnel time for both mixes had satisfied the performance criteria as required by European Guidelines and can be classified in VS2 and VF1, respectively, in accordance with BS EN 206 [29].

The passing ability of SCC and SCLWC was measured through J-ring flow, blocking step and passing ability ratio. From the results obtained, it can be seen that the blocking step and passing ability ratio for both mixes had met the acceptance criteria prescribed in European Guidelines and falling into classes of PJ2 and PL2, respectively, according to BS EN 206 [29]. Generally, the typical classes of J-ring flow are identical to the classes of slump flow [2]. Hence, the J-ring flow falling into class SF2. Both mixes demonstrated excellent deformability without segregation and no visible blocking throughout the tests. Nevertheless, the findings strongly pointed out that the SCLWC had better passing ability with its higher J-ring flow, lower blocking step, and higher passing ability ratio. Similarly, this was attributed to the lightweight of POC and the low viscosity of SCLWC. In practice, this could mean a better flow through congested reinforcement.

The segregation portion serves as an indicator of the segregation resistance of the fresh concrete mixtures. From Table 3, it can be seen that both mixes were stable since the pertaining values were less than 15 % and can be classified under class SR2 according to BS EN 206 [29]. Hence, both mixes can be used in vertical applications [18]. In general, the lower segregation portion indicates a higher resistance to segregation and vice versa. It had been noticed that the SCLWC had relatively low segregation resistance, as indicated by its high segregation portion, compared to SCC. This was mainly credited to the variation in specific gravity between coarse POC and mortar in SCLWC as reported by Kobayashi [32]. Owing to the lower density of coarse POC than mortar, the resultant SCLWC had lower viscosity than SCC. Consequently, it promoted the separation of mortar in SCLWC and thus resulting in higher segregation portion. On the contrary, the SCC was less prone to segregation due to its higher viscosity that had restricted the separation of mortar.

From the overall results of fresh properties in this study, it was concluded that the SCLWC containing coarse POC had satisfied all the criteria of self-compactability. In fact, the coarse POC did not adversely affect the fresh properties of SCLWC when administered a proper mix proportion.

Table 3 Filling ability, passing ability and segregation resistance of fresh SCC and SCLWC

Properties	Test	SCC	SCLWC	Performance Criteria Stipulated in European Guidelines and BS EN 206	
				Class	**Range**
Filling Ability	Slump Flow, *SF* (mm)	675	730	SF1	550 – 650 mm
				SF2	660 – 750 mm
				SF3	760 – 850 mm
	t_{500} Slump Flow Time (s)	2.77	2.29	VS1	< 2.0 s
				VS2	≥ 2.0 s
	V-Funnel Time, t_v (s)	7.35	5.58	VF1	≤ 8.0 s
				VF2	9.0 - 25.0 s
Passing Ability	J-Ring Flow, SF_J (mm)	667.5	725	SF1	550 – 650 mm
				SF2	660 – 750 mm
				SF3	760 – 850 mm
	J-Ring Blocking Step, *PJ* (mm)	9.75	9.0	PJ1	≤ 10 mm with 12 rebars
				PJ2	≤ 10 mm with 16 rebars
	Passing Ability Ratio, *PL*	0.82	0.85	PL1	≥ 0.80 with 2 rebars
				PL2	≥ 0.80 with 3 rebars
Segregation Resistance	Segregation Portion, *SR* (%)	2.15	8.5	SR1	≤ 20
				SR2	≤ 15

Note: SF = slump flow class; VS = viscosity class for the t_{500} slump flow test; VF = viscosity class for the V-funnel test; PJ = passing ability class for the J-ring test; PL = passing ability class for the L-box test; SR = segregation resistance class

3.2 Hardened Concrete Properties

3.2.1 *Density*

Density is an important parameter that must be taken into account to measure the concrete denseness. The oven-dry density (ODD) and saturated surface-dried density (SSD) results of the selected cubic specimens are shown in Figure 3. From the results, it can be clearly seen that SCLWC had the lowest densities, which were approximately 16 % (based on SSD) and 18 % (based on ODD) lower than SCC. Duggal [33] reported that the specific gravity of aggregates would profoundly alter the density of concrete. The reduction in the density of SCLWC was obviously caused by the replacement of crushed aggregates with coarse POC; the specific gravity of POC was 33 % lower than crushed granite's (see Table 1). In addition, when oven-dried, the variation in density became more obvious. The inference drawn was that POC had more moisture dried up from its greater number of voids than crushed granites. In general, lightweight concrete is a concrete with density does not exceed 2000 kg/m^3 [34]. Since the densities of SCLWC were less than 2000 kg/m^3, the SCLWC using coarse POC can be considered as lightweight concrete.

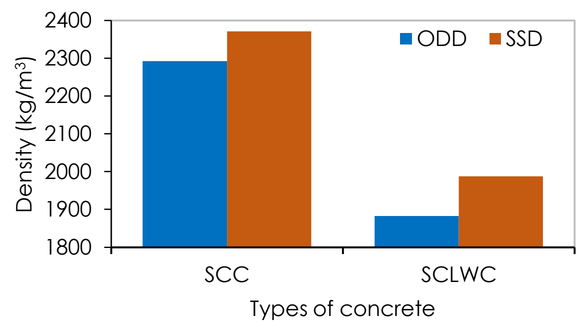


Figure 3 Oven-dry density (ODD) and saturated surface-dried density (SSD) of SCC and SCLWC specimens

3.2.2 *Water Absorption*

The results of water absorption of all concrete mixes measured after 24 and 72 hours are presented in Figure 4. SCLWC containing coarse POC exhibited higher water absorption compared to SCC containing crushed granite at about 1.6 times. This was attributed to the higher water absorptive tendency of the coarse POC. Topçu and Uygunoğlu [35] also reported that the high absorption capability of lightweight aggregates (diatomite, pumice and tuff) had led to an increment in the absorption of SCLWC when compared with crushed limestone. In addition, the open cellular structure in coarse POC had given SCLWC great allowance in absorbing water. On the contrary, the denser concrete structure of SCC would inhibit ingress of water into the concrete matrixes. Neville [36] reported that the water absorption of good concretes does not exceed 10 % by weight. Therefore, it can be deduced that the measured water absorption values for SCLWC as well as SCC remain within the range of good concrete.

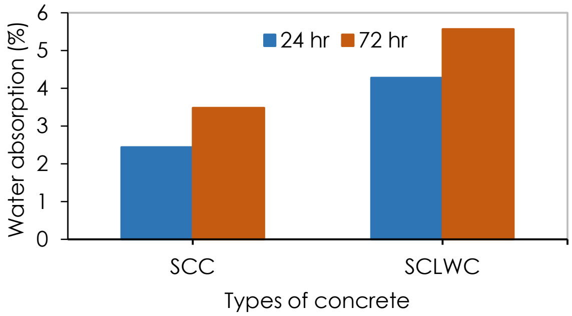


Figure 4 Water absorption of SCC and SCLWC specimens after 24 and 72 hours

3.2.3 *Ultrasonic Pulse Velocity (UPV)*

The UPV values give an indication on the denseness of the concrete specimens, which is related to the characteristics of internal particles of the concrete [37]. Figure 5 shows the UPV values of all concrete mixes at the age of 7, 14 and 28 days. Generally, the UPV values for all mixes had gradually increased with age due to the hydration process during continuous curing. Apart from that, it can be observed that the SCLWC had consistently given the lowest UPV values. This was primarily due to the presence of porous cellular structure and irregular shape of coarse POC [38]; the numerous pores in the POC reduced the packing level of the concrete matrix and consequently decreased the rate of pulse velocity. Meanwhile, a denser SCC structure implied that the void content was relatively lower and this had enhanced the velocity of the pulse. A concrete is in good condition if its UPV values lie in the range of 3.66-4.58 km/s [39]. Based on the results, even though the highly porous POC has decelerated the pulse velocity, it is still considered a good quality concrete. This indicates that the structural integrity of SCLWC will not be compromised.

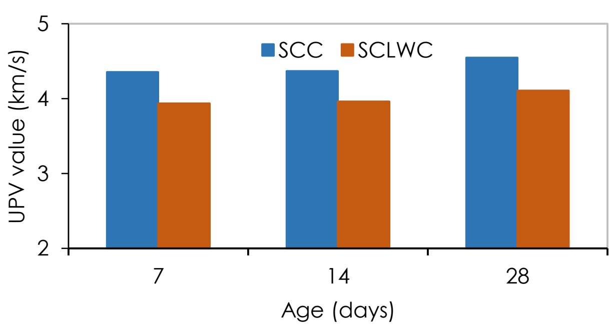


Figure 5 UPV values of SCC and SCLWC specimens

3.2.4 *Compressive Strength*

The compressive strength of all mixes at the age of 7, 14 and 28 days is presented in Figure 6. The test results revealed that the utilisation of coarse POC in SCLWC had significantly affected the compressive strength compared to that of SCC with crushed granite. The compressive strength of SCLWC was lower than that of SCC in the range of 5.8-10.3 % at all ages. The compressive strength of lightweight aggregate concrete depends primarily on the strength of the lightweight aggregates [40]. The ACV of coarse POC, which was two times higher than crushed granite as shown in Table 1, decreased the load bearing capacity of the aggregates and consequently reduced the compressive strength. The numerous pores in POC had also weakened the SCLWC matrix. The combined effect had caused cracks to propagate once formed as compared to SCC. Similar observation was also reported by Abutaha *et al.* [38] and Ahmmad *et al.* [11]. Observation on the mode of failure of specimens for SCLWC and SCC as shown in Figure 7 (a) and (b), respectively, confirmed these in which most SCLWC specimens had failed due to crack propagation and crushing of aggregates. On the contrary, the primary failure mode of SCC was mainly due to loss of aggregates-cement paste bonding in the interfacial zone. Nevertheless, the compressive strength of SCLWC after 28 days curing period was still higher than 40 N/mm^2, qualifying it as a high strength lightweight concrete and satisfied the minimum 28-day compressive strength of structural lightweight aggregate concrete of 17 N/mm^2 as stipulated in ASTM C330/C330M [41].

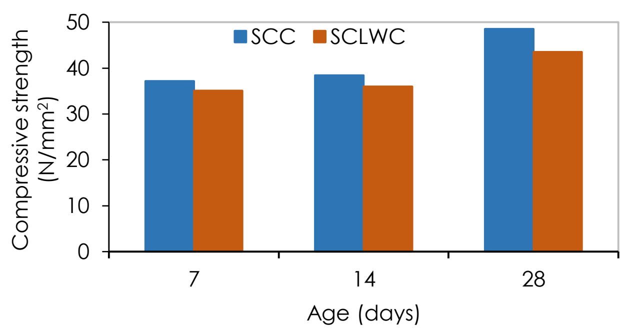
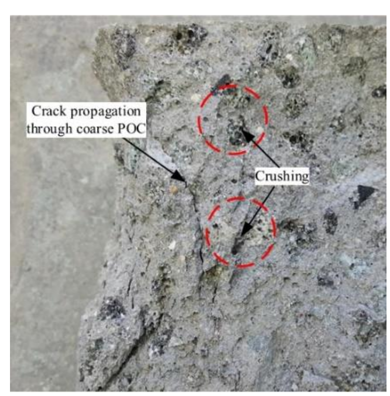


Figure 6 Compressive strength of SCC and SCLWC specimens



(a)

(b)

Figure 7 Failure mode of cubic specimens (a) SCLWC (b) SCC

3.2.5 Tensile Splitting Strength

The 28-day tensile splitting strength of all mixes is illustrated in Figure 8. Generally, the trending followed that of compressive strength in which the SCLWC had lower tensile splitting strength than SCC. The dominant cause was aggregates failure in SCLWC. When visually observed, it was found that the failure began from the coarse POC aggregates and propagated along the aggregates and mortar interface as shown in Figure 9 (a). The deduction was that the strength of the lightweight aggregates was lower than mortar's. Lo and Cui [42] also observed similar failure mode in the lightweight concrete containing expanded clay. On the contrary, since the strength of crushed granite was higher than the bond strength, the fracture path in the SCC specimens began around the normal weight aggregates and failure took place at the weak interface zone between the aggregates and mortar as shown in Figure 9 (b).

In general, a minimum 28-day tensile splitting strength of 2.1 N/mm^2 is required for structural lightweight concrete in accordance with ASTM C330/C330M [41]. The tensile splitting strength of SCLWC had exceeded the minimum requirement, deeming it fit for structural application. Tensile splitting strength is closely related to compressive strength and normally increases with increased compressive strength, but at a decreasing rate [36]. The ratio of tensile splitting strength to compressive strength for SCLWC and SCC were about 8.3 % and 8.8 %, respectively. Ahmad *et al.* [43] also found that the tensile splitting strength of lightweight aggregate concrete containing coarse POC aggregates was about 8 % of its compressive strength. It can be seen that the ratio for SCLWC is lower than that of SCC of the same grade, similar to the findings reported by Zhang and Gjorv [44] when comparison was made between lightweight aggregate concrete and normal weight concrete of equivalent grade. The ratio of tensile splitting strength to compressive strength for high strength lightweight aggregate concrete is commonly in the range of 6-7 % [45]. In this study, the ratio for SCLWC was slightly higher than the specified range.

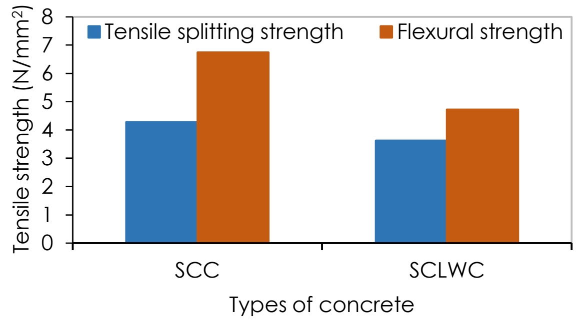
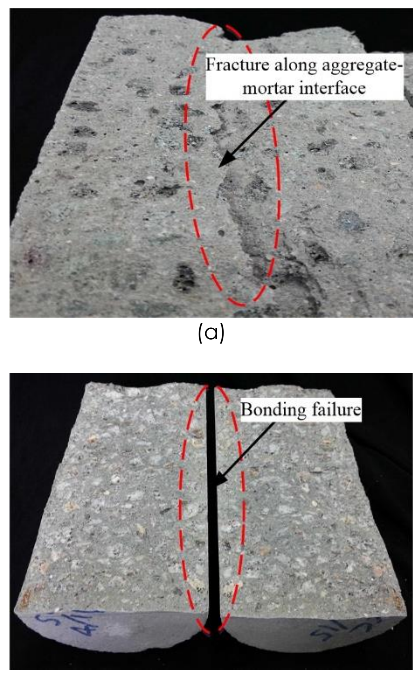


Figure 8 Tensile splitting strength and flexural strength of SCC and SCLWC specimens



(a)

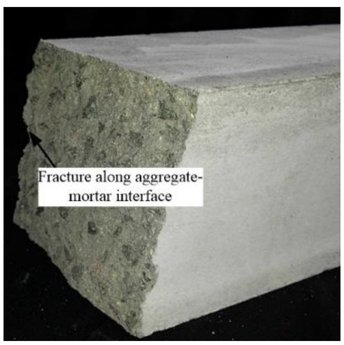
(b)

Figure 9 Failure mode of cylindrical specimens (a) SCLWC (b) SCC

3.2.6 Flexural Strength

The test results for the 28-day flexural strength of both mixes are presented in Figure 8, in which the flexural strength of SCLWC was approximately 30 % lower than that of SCC. Since the coarse POC was weaker than the mortar, the specimens had ruptured starting from the lightweight aggregates instead of the interfacial zone as shown in Figure 10 (a). The strong interfacial bond between the coarse POC aggregates and the mortar was attributed to the rough surface of the highly porous lightweight aggregates that had given a better interlock with the concrete matrix [46]. In addition, the fracture surface of SCLWC prismatic specimen was much flatter than that of SCC as the crack propagated along the aggregates and mortar interface. Meanwhile, in the case of SCC, the rupture occurred around the stronger crushed granite and propagated through the weaker mortar as shown in Figure 10 (b).

Similar to tensile splitting strength, the ratio of flexural strength to compressive strength for SCLWC was lower than that for SCC which was about 10.8 % and 13.9 %, respectively. These results are in agreement with Domagała [47]. Holm and Bremner [45] reported that the ratio of flexural strength to compressive strength for high strength lightweight aggregate concrete is in the range of 9-11 %. The ratio reported in this study fell within this range.



(a)

(b)

Figure 10 Failure mode of prismatic specimens (a) SCLWC (b) SCC

4.0 CONCLUSION

From the experimental results on the effects of utilising POC as coarse lightweight aggregates on the fresh and hardened properties of SCLWC, the following conclusions are drawn:

1. The self-compactability in terms of filling ability, passing ability and segregation resistance were satisfactory for all the mixes. The inclusion of coarse POC enhanced the filling ability and passing ability of SCC due to its function as an actively-mobilised material. The SCLWC exhibited less segregation resistance which was attributed to the low density of coarse POC compared to the density of mortar that promotes the separation of mortar.
2. The replacement of normal weight coarse aggregates with coarse POC in SCLWC reduced density by 16 % and 18 % in oven-dry condition and saturated surface-dry condition, respectively. The density values were in the acceptable range for the classification of lightweight concrete, thus implies that the SCLWC can be categorised as lightweight concrete.
3. Higher water absorption value was obtained for the SCLWC. However, it was still in the range of good concrete.
4. The SCLWC had lower UPV values than SCC due to greater void content within the concrete matrix. However, it can still be termed as a good quality concrete since its UPV values fell in the "good" category.
5. The utilisation of POC as coarse aggregates in SCLWC reduced the compressive, tensile splitting and flexural strengths. Nevertheless, the SCLWC can be considered as high strength lightweight concrete since its 28-day compressive strength exceeded 40 N/mm^2. Besides that, its compressive strength and tensile splitting strength fulfilled the strength requirement for structural lightweight concrete. In addition, its ratio of flexural strength to compressive strength corresponded well to that of high strength lightweight aggregate concrete.

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