

FRESH AND HARDENED PROPERTIES OF SELF-COMPACTING LIGHTWEIGHT CONCRETE USING COARSE PALM OIL CLINKER

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Abstract: The utilisation of industrial waste from the palm oil industry offers benefit to the construction industry and environment. This paper presents the experimental investigation of the fresh and hardened properties of self-compacting lightweight concrete (SCLWC) using coarse palm oil clinker (POC). In this study, POC, a waste by-product of palm oil mill, was utilised at 100 % full replacement of coarse aggregates in the production of self-compacting concrete (SCC). Fresh properties of the concrete mix were determined through tests of slump flow, V-funnel, J-ring, L box and sieve segregation. Meanwhile, the hardened concrete properties were evaluated by means of density, ultrasonic pulse velocity (UPV), compression, tensile splitting and flexural tests. The fresh and hardened properties of SCLWC were compared to normal SCC using normal weight coarse aggregates. Test results indicated that the SCLWC exhibited accepted self-compacting characteristics as recommended by European Guidelines. The SCLWC can be classified as lightweight concrete since its hardened density at 28 days was 1985 kg/m^3 and good in quality according to its UPV values. In addition, the substitution of POC reduced the compressive and tensile strengths of the concrete due to its lightweight and porous nature. Based on the performance of SCLWC utilising coarse POC aggregates, the POC is potentially viable to replace natural aggregates and suitable to be used in SCLWC.

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

1.0 Introduction

Concrete is the most extensively used construction material in the construction industry which has outstanding versatility feature (Gesoğlu *et al.*, 2014). Today, the concrete industry is continuing to consume an enormous amount of limited natural resources (Shafiq *et al.*, 2013) such as crushed granite which is commonly used as coarse aggregates in the concrete production (Mo *et al.*, 2016). The growing infrastructure development throughout the world has caused high demand for natural aggregates utilised in the construction (Brito and Saikia, 2013). However, the situation is causing rapid mining activity of aggregates and consequently leads to the depletion of natural

resources as well as an ecological imbalance. Due to the environmental concern, one of the best options is to introduce waste materials in the concrete (Mohammed *et al.*, 2014).

Palm oil industry is one of the prominent agricultural industries in Malaysia which produce large quantities of palm oil. Nevertheless, the extraction of palm oil also generates high volume of waste by-product known as palm oil clinker (POC). POC is obtained from the boiler of the palm oil mill through the incineration of palm oil shell and mesocarp fibre. The abundant POC has less commercial value and is commonly utilised as a paving material on the roads leading to the mills (Vijaya *et al.*, 2008). Otherwise, the POC is disposed to the landfill which leads to the environment problems. The disposal of abundant POC is currently escalating the environmental issue since it is able to pollute the surroundings and requires more landfill areas for its dumping purpose (Kamaruddin *et al.*, 2016). Hence, deploying POC as an alternative construction material could effectively manage the solid waste. The utilisation of the waste by-product will not only mitigates the waste disposal problem but also conserve the depleting natural resources and promote the environmental sustainability (Mohammed *et al.*, 2014). As the porous lumped POC is lightweight in nature and can be crushed into required sizes, it is possible to be utilised as an alternative lightweight aggregates in the concrete (Kanadasan *et al.*, 2015). In the past, researchers investigated the structural behaviour of reinforced lightweight concrete beams (Mohammed *et al.*, 2014) and slabs (Mohammed *et al.*, 2011) made from POC aggregates. They reported that the POC can be used as lightweight aggregates in structural lightweight concrete based on their promising structural performance which comparable to the normal weight concrete structural members. It is also worth noting that the POC can be directly used to replace natural aggregates in the concrete without the need of treatment as it does not contain any harmful contents which potential to deteriorate the concrete (Kanadasan *et al.*, 2015).

Self-compacting lightweight concrete (SCLWC) is a new kind of high performance concrete that combines the features of self-compacting concrete (SCC) and lightweight concrete (LWC). Self-compacting concrete (SCC) is an innovative concrete that can easily flow and consolidated under its own weight in a formwork without compaction, while LWC can reduce the self-weight of the structure due to its low density. Hence, SCLWC not only has self-compacting characteristics that ease the concrete placement and produce high quality of the final product, but it is also lighter than ordinary SCC which is beneficial in decreasing the dead load of the structure and the size of structural members by incorporating lightweight aggregates. Over the years, the SCLWC has been developed by replacing aggregates with natural lightweight aggregates such as pumice, and artificial lightweight aggregates such as expanded shale, leca, lytag, perlite and expanded clay (Papanicolaou and Kaffetzakis, 2011; Vakhshouri and Nejadi, 2016). It was proved that the high quality of SCLWC can be produced with respect to their satisfactory mechanical behaviour and meet the desired performance requirements as SCC and LWC (Kaffetzakis and Papanicolaou, 2012).

Despite the use of POC in replacing natural aggregates in many research works, research works have only focussed on the production of vibrated lightweight concrete using the crushed POC aggregates. Because of this, the SCLWC containing coarse POC is still a relatively new concrete production and there is a lack of knowledge on its performance. This indicates that there is a need to examine the effects of coarse POC on the fresh and hardened properties of SCLWC as well as determine the suitability of using the waste by-product in the concrete. Hence, the aim of this study is to investigate the fresh and hardened properties of SCLWC by utilising POC as coarse lightweight aggregates and compare to that of SCC. The experimental parameters include the filling ability, passing ability and segregation resistance for the fresh properties along with the density, ultrasonic pulse velocity (UPV), compressive strength and tensile strength for the hardened properties are discussed.

2.0 Experimental Program

2.1 Materials

2.1.1 Cement

Ordinary Portland cement (OPC) with a specific gravity of 3.15 was used as a cementitious material for all the concrete mixes in this study. It is suitable for all general purpose usage and conformed to CEM I of BS EN 197-1 (2011).

2.1.2 Aggregates

Local river sand that passed through 4.75 mm sieve was used as fine aggregates. The crushed granite and POC were used as normal weight and lightweight coarse aggregates respectively with the nominal size of 10 mm. The POC as shown in Figure 1(a) was collected from a palm oil mill located in southern part of Johor. The large chunks of POC were crushed using hammer and 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 properties of crushed granite aggregates and coarse POC are presented in Table 1. Based on the aggregates properties, it can be seen that the coarse POC has low specific gravity and bulk density while high in water absorption, void content and aggregate crushing value compared to the crushed granite. These are mainly attributed to its open cellular structure with the presence of numerous pores. Figure 2 shows the results of sieve analysis for coarse POC, crushed granite and river sand. The materials are well-graded as their sizes are within the grading limit according to BS EN 12620 (2008) for coarse aggregates and ASTM C33/C33M (2013) for fine aggregates. Since the loose bulk density of coarse POC is 793 kg/m^3 which is less than 1200 kg/m^3 as stipulated in BS EN 13055 (2016) and its size falls within the specified grading, the coarse POC is

qualified to be classified as lightweight aggregates and can be utilised in the production of SCLWC.



Figure 1: POC (a) Raw POC collected from palm oil mill and (b) Coarse POC aggregates after crushing and sieving

Table 1: Physical properties of aggregates

Properties	Coarse aggregates		
	Crushed granite	POC	Standard Method
Specific gravity (OD)	2.61	1.76	ASTM C127 (2012)
Specific gravity (SSD)	2.65	1.84	ASTM C127(2012)
Water absorption (%)	1.6	4.67	ASTM C127 (2012)
Bulk density (kg/m ³)	1611	793	ASTM C29/C29M (2009)
Void content (%)	38.2	54.8	ASTM C29/C29M (2009)
Aggregate crushing value (%)	24.3	47.9	BS 812-110 (1990)

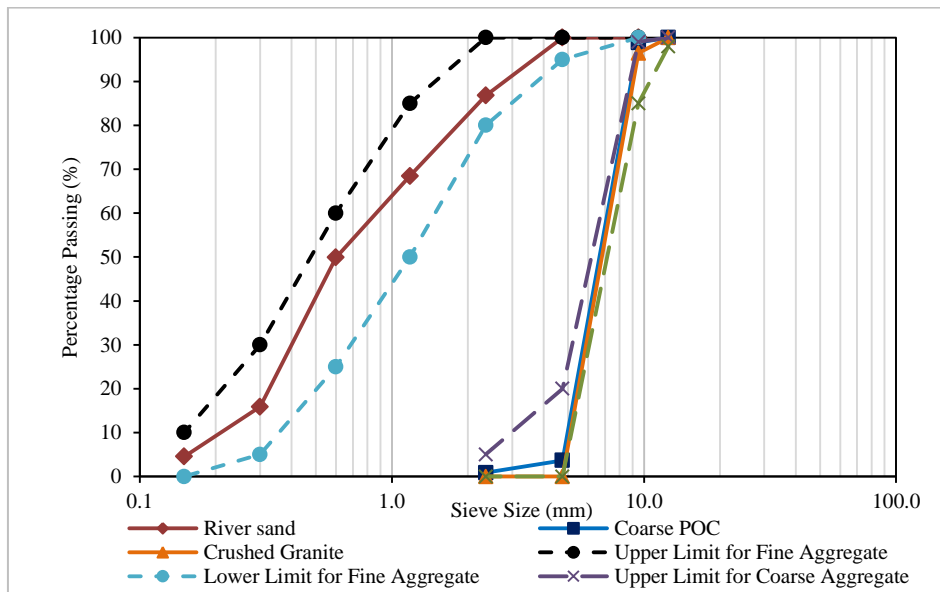


Figure 2: Sieve analysis grading curve

2.1.3 Superplasticiser (SP)

A polycarboxylic ether based high range water-reducing admixture was used in this study with an adequate dosage to acquire the fresh concrete of SCC and SCLWC with required flowability without any segregation. It is categorised as Type F admixture in accordance with ASTM C494/C494M (2015) and BS EN 934-2 (2012).

2.2 Mix Proportions

Two concrete mixes were prepared to investigate the fresh and hardened properties of SCC containing crushed granite and POC as coarse aggregates. The mix proportions of SCC and SCLWC were designed using an empirical design method and in comply with the European guidelines for SCC (European Project Group, 2005). The cement content and water-cement ratio for both mixes were kept constant at 485 kg/m³ and 0.38 respectively. The proportion of fine aggregates was also kept the same for both mixes to examine the effects of coarse POC on the properties of the concrete. For the production of SCLWC, the POC was utilised at 100 % replacement as coarse aggregates. The mix proportion of SCLWC was obtained after adjusting the proportion of coarse POC and dosage of superplasticiser to ensure that SCLWC with low density can flow without segregation. The details of the concrete mix proportions are presented in Table 2.

Table 2: Concrete mix proportions in kg/m³

Mix	Cement	Water	w/c	SP	Fine aggregates		
					Normal sand	Granite	POC
SCC	485	185	0.38	3.0	814	755	-
SCLWC	485	185	0.38	2.0	814	-	440

2.3 Mixing Method

To ensure the equivalent homogeneity and uniformity in all mixes, the same mixing operation was followed. All aggregates were prepared in a saturated surface dry (SSD) condition before mixing. Prior to mixing, the coarse POC was soaked in water for 24 hours at room temperature due to its high water absorption and was then allowed to surface dry. The soaking of coarse POC in water before mixing was to prevent it from absorbing mixing water and maintain the water-cement ratio. The mixing process began by mixing the coarse and fine aggregates for one minute in the mixer. Subsequently, cement was added to the mixer and the mixture was allowed to mix for another one minute. Then, three-quarters of mixing water was added and mixed for another one minute. The remaining water containing superplasticiser was then added and the concrete was mixed for an additional three minutes and then rest for three minutes. The mixing operation was continued for another two minutes to produce fresh concretes.

2.4 Fresh Concrete Tests

The fresh concrete mixes were tested for filling ability, passing ability and segregation resistance. The filling ability of the fresh concrete was determined through slump flow test and V-funnel test. The slump flow test was conducted in accordance with BS EN 12350-8 (2010d) 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 fresh concrete to flow to a diameter of 500 mm, t_{500} were measured. The V-funnel test was conducted in accordance with BS EN 12350-9 (2010e) whereby the time taken for the fresh concrete to flow out of the funnel was measured and recorded as V-funnel flow time, t_v . The t_{500} slump flow time and V-funnel flow time can also determine the viscosity of the fresh concrete. The passing ability of the fresh concrete was determined through J-ring test and L box test. The J-ring test was conducted according to BS EN 12350-12 (2010c) by measuring the diameter of flow spread, SF_j and the differences in concrete height between outside and centre of the J-ring with 16 steel bars or known as blocking step, PJ . Besides that, the L box test was conducted in accordance with BS EN 12350-10 (2010a) to determine the passing ability ratio, PL of the fresh concrete using L box with three steel bars. Meanwhile, the sieve segregation test was conducted in accordance with BS EN 12350-11 (2010b) to determine the resistance of the concrete to segregation by allowing concrete to pass through a 5 mm sieve for two minutes. Percentage of the mass of passed material by initial mass of concrete placed on the sieve was calculated and recorded as segregation portion, SR . All results for fresh concrete tests of fresh SCC and SCLWC were checked to ensure that the results are within the limit range as required by European Guidelines and the classes for properties of fresh SCC in accordance with BS EN 206 (2013) are given in Table 3.

2.5 Hardened Concrete Tests

The hardened concrete specimens were tested after reaching the required maturity. The hardened properties include density, ultrasonic pulse velocity (UPV), compressive strength, tensile splitting strength and flexural strength were determined in this study. The tests of density, UPV and compressive strength was conducted on cubic specimens with the size of 100 mm × 100 mm × 100 mm at the age of 7, 14 and 28 days in accordance with BS EN 12390-7 (2009d), BS EN 12504-4 (2004) and BS EN 12390-3 (2009a) respectively. The cylindrical specimens with the dimension of 100 mm diameter x 200 mm height were tested to determine the tensile splitting strength of concrete at the age of 28 days according to BS EN 12390-6 (2009c). Meanwhile, flexural strength test was performed on 100 mm x 100 mm x 500 mm of prismatic specimens at the age of 28 days in accordance with BS EN 12390-5 (2009b) to determine the flexural strength or known as modulus of rupture of concrete. The tests of compression, tensile splitting and flexural 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, respectively. The mode of failure of tested specimens was visually inspected.

Table 3: Performance criteria for fresh properties of SCC with respect to BS EN 206 (2013)

Classes		
Slump flow	Slump flow (mm)	
SF1	550 - 650	
SF2	660 - 750	
SF3	760 - 850	
Viscosity	t_{500} (s)	t_v (s)
VS1	< 2.0	
VS2	≥ 2.0	
VF1		< 9.0
VF2		9.0 - 25.0
Passing ability	J-ring	L box
PJ1	≤ 10 with 12 rebars	
PJ2	≤ 10 with 16 rebars	
PL1		≥ 0.80 with 2 rebars
PL2		≥ 0.80 with 3 rebars
Sieve segregation	Segregation portion (%)	
SR1	≤ 20	
SR2	≤ 15	

3.0 Results and Discussion

3.1 Fresh Concrete Properties

The results of fresh properties of SCC and SCLWC are presented in Table 4. Generally, it can be seen that the fresh SCC and SCLWC had satisfied the performance criteria as stipulated in European Guidelines and BS EN 206.

Table 4: Fresh properties of SCC and SCLWC

Properties	Test	SCC	SCLWC
Filling ability	Slump flow, SF (mm)	675	730
	t_{500} slump flow time (s)	2.77	2.29
	V-funnel time, t_v (s)	7.35	5.58
Passing ability	J-ring flow, SF_J (mm)	667.5	725
	J-ring blocking step, PJ (mm)	9.75	9.0
	Passing ability ratio, PL	0.82	0.85
Segregation resistance	Segregation portion, SR (%)	2.15	8.5

3.1.1 Filling Ability

From Table 4, it was found that the slump flow for both mixes was within the range of between 660 mm and 750 mm and thus can be categorised in class SF2. This indicates that both mixes had good filling ability, and thus suitable to be used in many normal applications such as columns and walls (European Project Group, 2005). The SCLWC had higher slump flow with low dosage of superplasticiser than that of SCC at the constant water-cement ratio. This is attributed to the lightweight structure of coarse POC that reduces the self-weight of fresh SCLWC. This eventually minimises the internal friction that occurs between coarse POC and cement paste, and consequently ease the flowability of the concrete. These results are in agreement with the findings from an experimental study by Kim *et al.* (2010) which indicated that the coarse lightweight aggregates with lower density can enhance the flowability of SCLWC. In contrast, the flowability of SCC is less than that of SCLWC due to the constraint of the heavier matrix and greater collision between aggregates in the mixture.

Besides that, the t_{500} slump flow time and V-funnel time for both mixes were satisfied the performance criteria as required by European Guidelines and can be classified in VS2 and VF1 respectively. It can be seen that the t_{500} slump flow time and V-funnel time of SCLWC were shorter than those of SCC which is probably caused by the lower viscosity of the fresh SCLWC. This is due to the presence of the coarse POC in SCLWC which is lighter than the crushed granite in SCC and hence, produces a lighter matrix of concrete which enhances the rate of concrete flow. Uygunoğlu and Topçu (2009) made a similar observation in their study in which they found that the SCLWC was less viscous and can easily flow due to the incorporation of lightweight aggregates. On the contrary, the heavier matrix of SCC reduces the fluidity of the paste and greater friction between aggregates and paste occurs in the fresh concrete matrix which causes the fresh concrete more viscous and less likely to flow.

3.1.2 Passing Ability

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 corresponding results were within the limit range prescribed in European Guidelines and fall under PJ2 and PL2 for both mixes. Both mixes also showed excellent deformability without segregation throughout the tests. The results indicate that the SCLWC exhibited better passing ability as it had higher J-ring flow with low blocking as well as higher passing ability ratio than those of SCC. Such findings are caused by the reduction in self-weight and low viscosity of SCLWC that facilitates the fresh concrete to pass through obstacles. Hence, it has fewer tendencies to block when passing through congested reinforcement. Meanwhile, the low passing ability of SCC is attributed to the greater viscosity which reduces the degree of separation of coarse aggregates in the mixture and consequently increases its blocking tendency.

3.1.3 Segregation Resistance

The segregation portion serves as an indicator of the segregation resistance of the fresh concrete mixtures. From the results in Table 4, the segregation portion of both mixes was less than 15 % which was within the permissible limit in class SR2, and thus satisfied the requirements of European Guidelines. In general, the lower segregation portion indicates a higher resistance to segregation and vice versa. It was noticed that the SCLWC had relatively low segregation resistance as indicated by its high segregation portion compared to SCC. This is credited to the variation in specific gravity between coarse POC and mortar in SCLWC as reported by Kobayashi (2001). 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 is less prone to segregation due to higher viscosity that restricts the separation of mortar.

3.2 Hardened Concrete Properties

3.2.1 Density

Figure 3 shows the air-dry density of cubic specimens of SCC and SCLWC at the age of 7, 14 and 28 days. Generally, lightweight concrete is a concrete with density does not exceed 2000 kg/m^3 (Newman, 1993). Based on the results obtained, the density of SCLWC was found in the ranges of 1975 to 1985 kg/m^3 , which was less than 2000 kg/m^3 . Hence, SCLWC using coarse POC can be considered as lightweight concrete. This is mainly attributed to the low specific gravity of coarse POC in SCLWC compared to that of crushed granite in SCC. It is worth noting that SCLWC is approximately 16 % lighter than SCC which proved that the concrete weight can be reduced by replacing the crushed granite with coarse POC. Hence, this indicates that the inclusion of coarse POC in SCC is beneficial in reducing the dead load of the concrete structures.

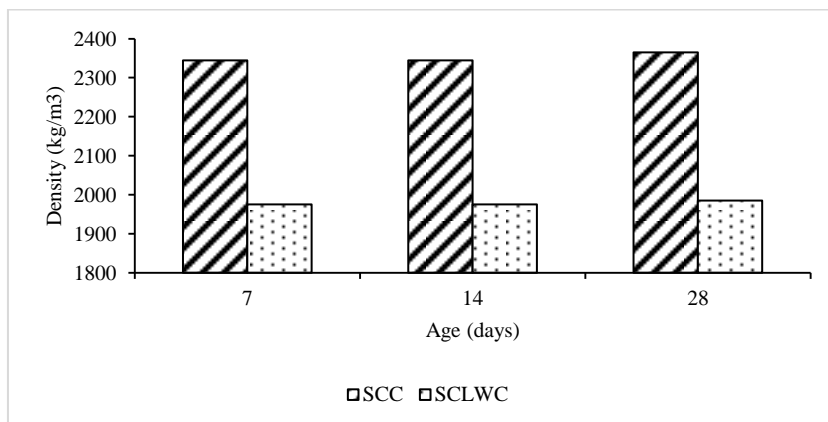


Figure 3: Density of SCC and SCLWC

3.2.2 Ultrasonic Pulse Velocity (UPV)

UPV which is a non-destructive test was conducted to determine the quality of the concrete. The UPV values of SCC and SCLWC at the age of 7, 14 and 28 days are presented in Figure 4. It should be noted that a good quality of concrete has the UPV values in the range of between 3.66 km/s and 4.58 km/s (Malhotra, 1976). From Figure 4, the UPV values of SCC were within 4.35 km/s and 4.55 km/s while for SCLWC, the UPV values were within 3.94 km/s and 4.10 km/s at the age of 7 days to 28 days. Therefore, SCC and SCLWC can be categorised as good quality of concrete. The UPV values of SCLWC were lower than that of SCC due to the presence of voids within the concrete matrix. The presence of voids is associated with the porous and irregular shape of coarse POC in SCLWC that reduces the packing level of the concrete matrix and thus decreases the rate of pulse velocity (Abutaha *et al.*, 2016). On the other hand, SCC had denser structure than SCLWC that accountable for the reduction in void content within the concrete matrix and thus enhanced the velocity of the pulse. Despite lower in UPV values, the SCLWC is still considered a good quality concrete.

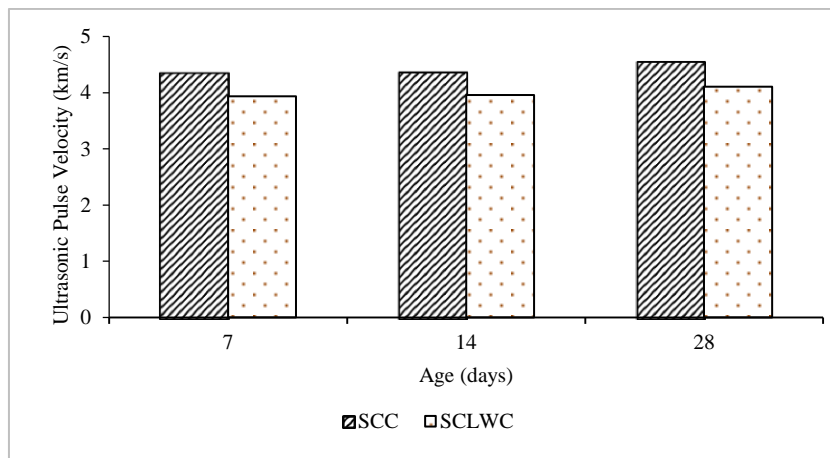


Figure 4: UPV values of SCC and SCLWC

3.2.3 Compressive Strength

The results of compressive strength of SCC and SCLWC at the age of 7, 14 and 28 days are presented in Figure 5. The test results revealed that the utilisation of coarse POC in SCLWC significantly affects the compressive strength compare to that of SCC with crushed granite. A reduction in compressive strength was observed whereby the compressive strength of SCLWC was lower than that of SCC in the range of between 5.8 % and 10.3 % at all ages. This is attributed to the ACV of coarse POC which became predominant in reducing the compressive strength. The ACV of coarse POC which is two times higher than crushed granite decreases the load bearing capacity of the aggregates and consequently reduce the compressive strength. Besides that, the

existence of numerous pores within the coarse POC also weakens the SCLWC matrix. Similar observation also has been made by Abutaha *et al.* (2016) and Ahmmad *et al.* (2016). The mode of failure of specimens for SCLWC and SCC is shown in Figure 6(a) and (b), respectively. It can be seen that the failure took place due to the crushing of coarse POC and crack propagated through the aggregates in the SCLWC specimens whereas the SCC specimens failed through the bonding of the aggregates and paste in the interfacial zone. Despite the weaknesses of coarse POC, the compressive strength of SCLWC can still surpass 40 N/mm^2 at the age of 28 days and satisfied the minimum 28-day compressive strength of structural lightweight aggregate concrete of 17 N/mm^2 as stipulated in ASTM C330/C330M (2014).

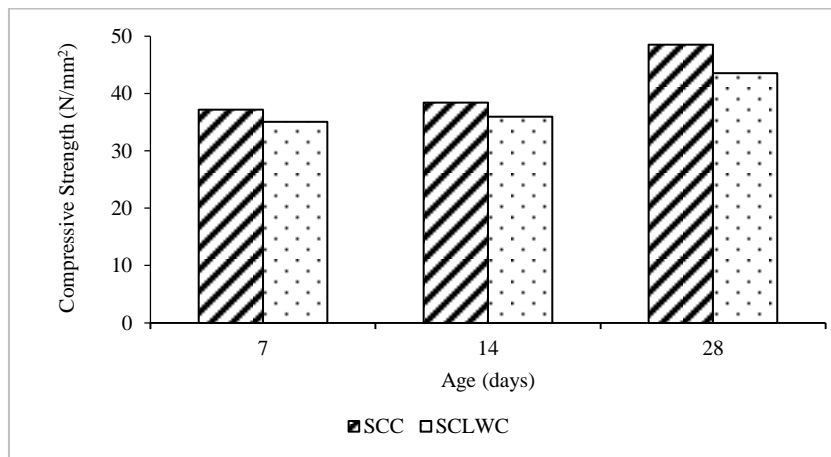


Figure 5: Compressive strength of SCC and SCLWC

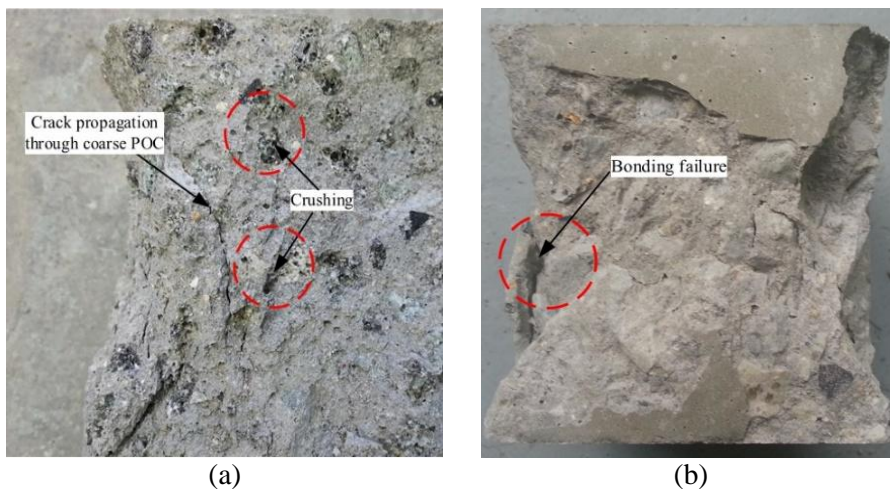


Figure 6: Failure mode of cubic specimens (a) SCLWC and (b) SCC

3.2.4 Tensile Splitting Strength and Flexural Strength

The determination of tensile strength of concrete through tests of tensile splitting strength and flexural strength can estimate the load at which the cracking may initiate in the concrete. The results of tensile splitting strength and flexural strength of SCC and SCLWC at the age of 28 days are shown in Figure 7. It can be noted that the findings showed the similar trend as that of compressive strength whereby the tensile splitting strength and flexural strength of SCLWC were 15.2 % and 30 % lower than that of SCC, respectively. This is caused by the occurrence of aggregates failure in SCLWC. The failure occurs through the coarse POC aggregates due to its lower strength than that of the mortar and crack propagated along the aggregates and mortar interface as shown in Figure 8. This observation is similar to the results reported by Topçu and Uygunoğlu (2010) for SCLWC containing diatomite, pumice and tuff. On the contrary, the failure of SCC specimens tends to take place through the mortar since the strength of crushed granite is higher than the bond strength, as shown in Figure 9.

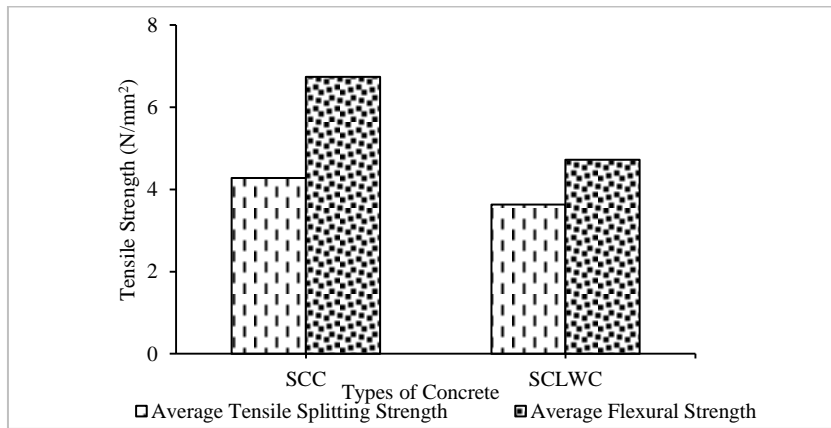


Figure 7: Tensile splitting strength and flexural strength of SCC and SCLWC

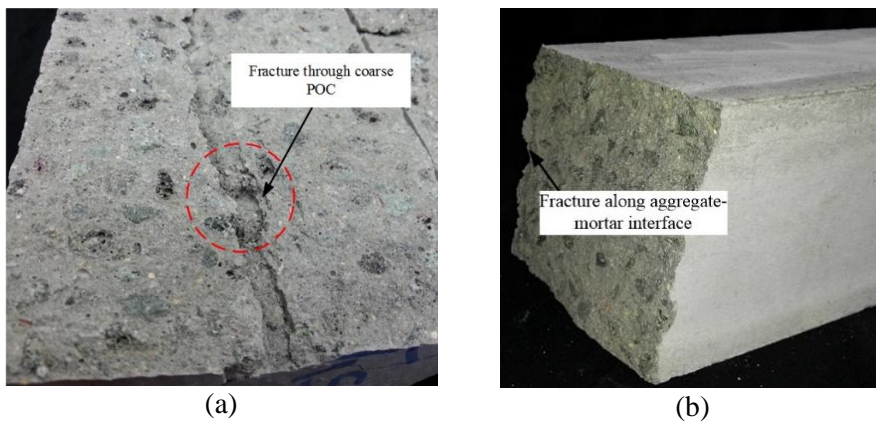


Figure 8: Failure pattern of SCLWC (a) Cylindrical specimen and (b) Prismatic specimen

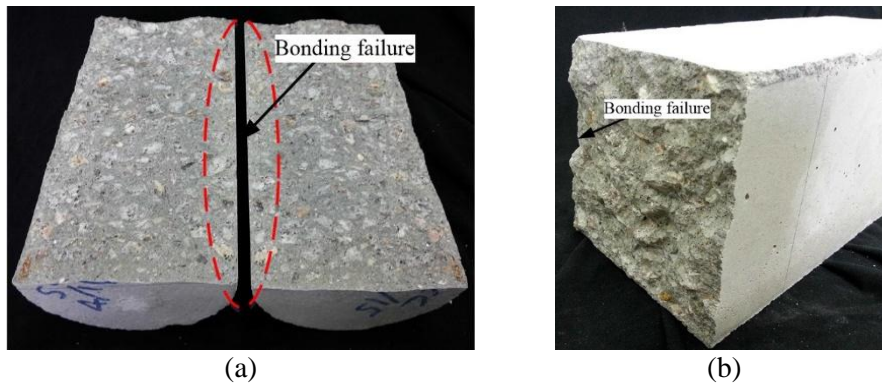


Figure 9: Failure pattern of SCC (a) Cylindrical specimen and (b) Prismatic specimen

4.0 Conclusions

From the findings revealed in this study, the following conclusions can be drawn:

- i. The fresh properties of SCC and SCLWC exhibited good self-compactability and fulfilled the requirements of European Guidelines and thus can be categorised as SCC.
- ii. The SCLWC with a 28-day density of 1985 kg/m^3 can be classified as lightweight concrete as its density was less than 2000 kg/m^3 . It saves about 16 % of concrete weight compared to normal weight SCC.
- iii. The SCLWC is in good quality despite greater void content within the concrete matrix.
- iv. The utilisation of POC as coarse aggregates in SCLWC reduced the compressive and tensile strengths. However, the good strength can still be attained in the concrete which comparable with normal weight SCC.

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