PERFORMANCE OF HIGH STRENGTH LIGHTWEIGHT CONCRETE USING PALM WASTES

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ABSTRACT: The performance of high strength structural lightweight concrete (LWC) using palm wastes, oil palm shell (OPS) as well as palm oil clinker (POC) is of foremost concern. Existing literature used either OPS or POC individually for production of LWC. In this study, both OPS and POC have been put together as coarse aggregate on the way to see the improvement of mechanical properties of waste-based LWC. Regular coarse aggregate has been fully replaced by OPS and POC in the concrete. This structural-grade, lightweight concrete is called palm shell and clinker concrete (PSCC). A series of OPS and POC mixtures have been investigated aimed at identifying better performance. The quantity of OPS and POC mix has been varied as 30, 40, 50, 60 and 70%. Evaluated mechanical properties of PSCC include density, workability, compressive strength at different ages, flexural strength, splitting tensile strength as well as modulus of elasticity. It is revealed that the proposed PSCC has extensive potential in terms of high compressive strength and good material behavior to perform as a better LWC. The study could offer structural lightweight concrete of compressive strength up to 46.47 MPa that is 30.5% higher than the control mix (P100). The usage of 50% OPS to 50% POC coarse aggregate by vol. in the concrete mix is found to be the optimum mix. Furthermore, simple correlation equations have been developed that can be used to predict the compressive strength, splitting tensile strength, flexural strength, modulus of elasticity and ultrasonic pulse velocity of the lightweight concrete using POC.

ABSTRAK: Prestasi struktur konkrit ringan (LWC) berkekuatan tinggi menggunakan sisa sawit, iaitu daripada minyak kulit kelapa sawit (OPS) dan juga mendakan (klinker) minyak kelapa sawit (POC) adalah keprihatinan utama. Kajian sedia ada telah mengguna pakai sama ada OPS atau POC secara berasingan bagi menghasilkan LWC. Dalam kajian ini, kedua-dua OPS dan POC telah digabungkan sebagai agregat kasar bagi mengkaji pembaikan pada ciri-ciri mekanikal sisa LWC. Agregat kasar tetap telah digantikan sepenuhnya dengan menggunakan OPS dan POC dalam konkrit. Struktur gred konkrit ringan ini telah dinamakan sebagai kulit kelapa sawit dan konkrit mendakan klinker (PSCC). Satu siri campuran OPS dan POC telah dikaji bagi mengenal pasti prestasi terbaik. Kuantiti campuran OPS dan POC telah diubah kepada 30, 40, 50, 60 dan 70%. Ciri-ciri mekanikal yang dikaji pada PSCC ini adalah ketumpatan, kebolehkerjaan, kekuatan mampatan pada umur berlainan, kekuatan lenturan, kekuatan tegangan pecahan, serta keanjalan modulus. Hasil menunjukkan PSCC ini mempunyai potensi luas dari segi kekuatan mampatan yang tinggi dan struktur material yang baik sebagai LWC terbaik. Kajian ini menawarkan struktur konkrit ringan berkekuatan mampatan sehingga 46 MPa iaitu sebanyak 31% lebih baik daripada campuran kawalan. Penggunaan 50% OPS kepada 50% POC agregat kasar secara vol. dalam campuran konkrit adalah campuran optimum.

Tambahan pula, korelasi mudah telah dibangunkan bagi menjangkakan dengan mudah kekuatan mampatan, kekuatan tegangan pecahan, kekuatan lenturan, keanjalan modulus dan halaju signal ultrasonik konkrit ringan.

KEYWORDS: *palm waste; oil palm shell; palm shell clinker; structural concrete; lightweight aggregate concrete;high strength*

1. INTRODUCTION

The recent trend in the construction industry shows increasing usage of lightweight concrete, which is more advantageous than traditional concrete of the same grade. Structural lightweight concrete allows engineers to use smaller structural elements due to the reduction of self-weight. As the lightweight aggregate concrete (LWAC) reduces the structural weight and hence the construction cost noticeably, it has a significant advantage over normal weight concrete (NWC) [1,2]. For this reason, production of structural lightweight concrete is becoming more popular every day in the construction industry. On the other hand, it is presently a thoughtful issue to find a suitable way to manage the solid waste produced from the agricultural and manufacturing industries [3]. Therefore, researchers expect to use the waste materials from the manufacturing industry to produce LWAC [4-6].

Yielding more than 50% of the world's palm oil supply every year has made Malaysia into the second largest source of palm oil globally [7,8]. The OPS and POC are the residues of the industry during palm oil production. Recently these agricultural wastes are being used for landfilling and production of charcoal. This causes soil pollution and affects groundwater supply. Therefore, its usage as a building construction material effectively turns waste into resources; a very efficient waste management option as well as a very useful structural design option. Obviously, the ideology can control the depletion of natural resources as well as retain ecological balance.

The oil palm shells are light, flaky and have an irregular shape, as per the nut breaking pattern [9]. As the OPS are hard and from a stable organic source, such materials do not leach or contaminate the concrete mix with toxic constituents [10]. It is revealed in existing works of literature that construction industries have introduced lightweight concrete using OPS of around 40 MPa [11-14] and using palm kernel shell aggregate of about 25–30 MPa [10] of 28-day cube compressive strength. Besides, POC is obtained from the blast furnace where OPS and OPS fibers are burned at high temperature in a boiler to generate energy. The lumped clinkers are then crushed and sieved to obtain the preferred particle sizes. The fine aggregate has a particle size of less than 5 mm and coarse aggregate has a particle size in the range of 5 – 12 mm. The compressive strength of POC concrete can range in between 25.54 – 44.89 MPa [3,15] that is clearly larger than the minimum strength requirement of structural LWC of 17 MPa.

The limitation of OPS lightweight concrete is that it sustains less compressive strength but the failure is rather ductile [16]. Steel fiber may improve the flexural toughness and other mechanical properties [17]. Besides, POC in concrete largely improves the consistency and compressive strength but in failure mode, becomes considerably brittle [16]. However, all the studies have employed OPS or POC separately. It is also clear that both OPS concrete and POC concrete have their advantages and disadvantages. In this study, the feasibility of combining OPS and POC as coarse aggregate will be explored in depth in the search to produce an improved high strength structural LWAC. The workability and density, compressive strength, modulus of elasticity flexural strength, and splitting tensile

strength are evaluated for the present innovative structural grade lightweight aggregate concrete, palm shell and clinker concrete (PSCC).

2. MATERIALS AND METHODS

2.1 Concrete Constituents

2.1.1 Cement

Ordinary Portland cement was utilized in the lightweight concrete throughout the experiments. The physical properties viz. specific gravity and specific surface area of this Malaysian manufactured cement were 3.14 and 3510 cm^2/g, respectively. Such binder material produced concrete with 34.2 MPa (at 7 days) and 45.9 MPa (at 28 days) compressive strength, respectively.

2.1.2 Aggregate

As a fine aggregate, Malaysian local sand was used in the lightweight concrete mix with 2.68 specific gravity fineness modulus of 2.65 and the maximum nominal grain size was 4.75 mm.

Fig. 1: Local waste (a) OPS as coarse aggregate; (b) POC as coarse aggregate.

The waste materials from the Malaysian palm oil industry, namely OPS and POC, were chosen as coarse aggregates in this study (Fig. 1). While OPS is a direct agriculture waste product form oil palm production, POC is produced through the incineration process of POS. The OPS, as shown in Fig. 1(a), was washed after collection and then a stone-crushing machine was used to crush them in the laboratory [18]. Such crushing decreases the OPS flakiness in order to enhance the performance of the coarse aggregates and obtain higher compressive strength. Thereafter, the crushed OPS were sieved and the aggregates larger than 5 mm size were identified and used in the mixes. The POC aggregate has been illustrated in Fig. 1(b). For POC as with the OPS, the palm oil clinker was sieved after crushing and aggregates larger than 5 mm were selected, expecting a greater abrasion value. Table 1 describes the physical properties and mechanical properties of both lightweight coarse aggregates.

Table 1: Physical and mechanical properties of OPS and POC coarse aggregate [3,19]

Coarse Aggregate	Aggregate size (mm)	Specific gravity [saturated surface dry]	Water absorption for 24 h (%)	Aggregate abrasion value, Los Angeles (%)	Bulk density [compacted] (kg/m^3)	Fineness modulus, FM	Flakiness index (%)	Elongation index (%)	Aggregate impact value (%)
OPS	5-12.5	1.17	23.3	4.8	590	6.24	65.17	12.36	7.86
POC	5-12.5	1.82	4.35	27.09	781.08	6.75	-	-	25.36

2.1.3 Admixture

The concrete mixes comprise Sika Viscocrete 2199 as a super plasticizer (SP), which is chloride free. This admixture was produced by Sika Kimia according to EN 934-2. To enhance the workability of LWAC, the SP was added as 2.0% of cement weight.

2.1.4 Water

The LWC mixes used potable water available in the materials laboratory. Similar water was used for curing the LWAC.

2.2 Concrete Mixtures Composition

The LWAC was designed by trial mixes [20]. Several studies used 480-550 kg/m^3 cement maintaining 0.3-0.4 water-cement ratio expecting compressive strength 30-44 MPa [21]. This study exploited 450 kg/m^3 cement contents and 0.35 water-cement ratio aimed at getting optimum trial mixes. Seven trial mixes were conducted. Four of the trial mixes were able to achieve grade 45 concrete offering high workability. Another two mixes were taken from the previous study to compare the results. Identical water-cement ratio was ensured in each and every mix. The SP was given in all the mixes to get the required workability.

The mining sand fills the place of a fine aggregate. The OPS and POC were used as coarse aggregate in various proportions. In the mix P70, OPC to POC proportion in coarse aggregate was 70-30% by volume. This proportion was gradually varied in the successive mixtures as 60-40%, 50-50%, 40-60%, and 30-70% referred to as P60, P50, P40, and P30, respectively. P100 and C100 were incorporated with only OPS and POC, respectively. Table 2 shows the proportions of ingredients and specifications of the LWAC concrete mixes.

Table 2: Concrete mix proportions in kg/m^3

Mix ID	Cement	Water	W/C ratio	SP	Sand	OPS	POC
P70	450	158	0.35	2%	1013	248 (70%)	141 (30%)
P60	450	158	0.35	2%	1025	212 (60%)	187 (40%)
P50	450	158	0.35	2%	1158	148 (50%)	195 (50%)
P40	450	158	0.35	2%	1048	142 (40%)	281 (60%)
P30	450	158	0.35	2%	1060	106 (30%)	328 (70%)
P100	450	158	0.35	1%	978	354 (100%)	0
C100	450	158	0.35	2%	1095	0	469 (100%)

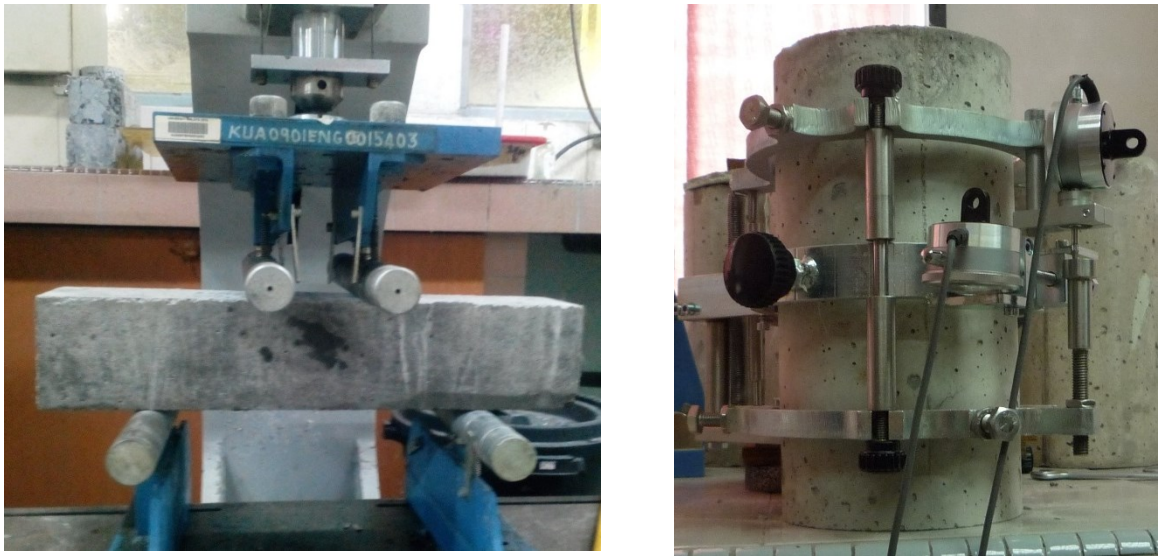
2.3 Specimen Preparation

The concrete ingredients, cement, sand, OPS, and POC, were blended with a pan mixer for 5 minutes to prepare the LWAC mixtures. Once thoroughly mixed, the SP mixture was

added with about 80% water. The remaining 80% SP was added after 5 minutes of mixing into the pan mixture while continuing the mixing process for 10 min. Afterward, the samples were cast in steel molds and vibration table to compact the specimens. The specimen casting follows the code BS 1881 [22]. The samples were demolded after 24 hours. Curing was continued until testing days in water at a temperature of 28 ± 2 °C. To obtain average values, three samples of each category were prepared.

2.4 Measurement Device and Experimental Testing

At the outset, the slump tests were performed for the LWAC mixes. The LWAC specimens' compressive strengths were measured for the 1st, 3rd, 7th and 28th day. Flexural tensile strength and splitting tensile strength were tested on the 3rd, 7th and 28th day as well. The modulus of elasticity was measured on the 28th day. All the tests followed BS 1881: Part 116 [22] employing a universal compression testing machine of 3000 KN capacity, which maintained a loading controller rate. The results of the tests were then averaged for the three randomly selected samples for every category. Figure 2 shows the equipment setup for (a) the flexural strength test and (b) the compressometer for modulus of elasticity (E_s).



(a) (b)

Fig. 2: Equipment setup for (a) the flexural strength test, (b) the compressometer for E_s.

3. RESULTS AND DISCUSSION

3.1 Workability

The workability results of PSCC are presented in Fig. 3. Each and every trial mix shows acceptable workability. As the water-cement ratio and the usage of SP were kept quite constant, identical slump values are expected with acceptable workability. P50 shows the lowest slump value of 50 mm. The slump of other trial mixes ranges from 55 mm to 70 mm. In the P50, about 13% more fine aggregate is used than other trial mixes. Hence, the total surface area in the P50 has increased. Therefore, P50 absorbs more water than others. The slump value of P50 has been found to be lower than other mixes as the W/C ratio and amount of SP are the same. The compaction of this mix is satisfactory among the trial mixes. All the coarse aggregates were taken as saturated surface dry condition (SSD). Therefore, in measuring the slump value, no influence of coarse aggregate has been observed. Mehta and

Monteiro [23] recommended a slump of 50–75 mm for structural LWC to obtain workability similar to 100–125 mm slump for regular concrete. In this experimental program, trial mixes having slump value within the suggested acceptable limits indicate the acceptable performance of the PSCC in the real application.

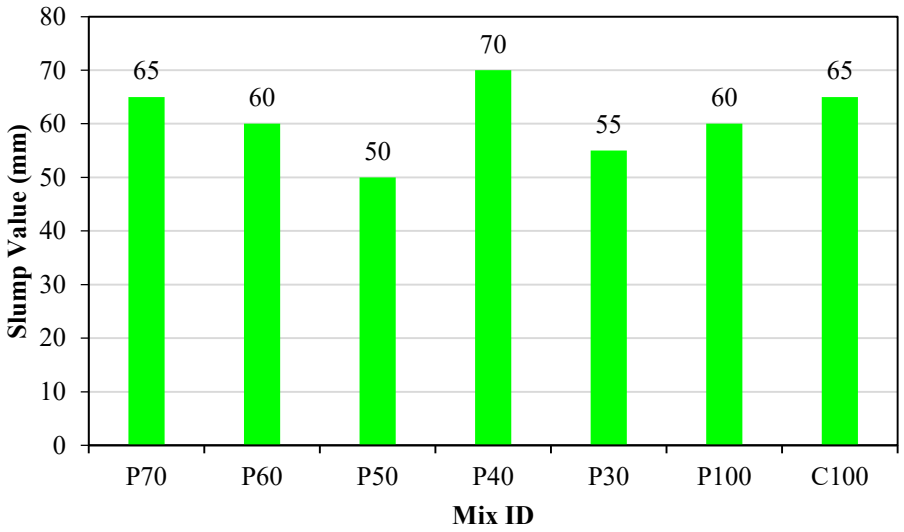


Fig. 3: Slump values for different trial mixes.

3.2 Density

The presented PSCC can be treated as structural lightweight concrete, which should have a density in oven dry condition of below 2000 kg/m^3 [24]. The densities of each and every mix are in the structural LWC range (Table 3). The 28-day oven dry density of PSCC range between 1951 to 2075 kg/m^3 and their air-dry densities are from 2190 to 2060 kg/m^3. Considering the density of NWC to be 2400 kg/m^3, the oven dry density and air-dry density of PSCC at 28-days are around 16–19% and 10–14% less than the corresponding densities of ordinary concrete.

Table 3: Densities at different condition

Mix ID	Density (kg/m^3)	
	Air dry density	Oven dry density
P70	2083	1951
P60	2115	1991
P50	2175	2020
P40	2130	1970
P30	2190	2069
P100	2060	1888
C100	2189	2075

3.3 Compressive Strength

The 28-day compressive strength of PSCC reduces with an increase in OPS percentage in coarse aggregate content (Table 4). The P50 mix, having 50% POC shows a maximum compressive strength of 46.47 MPa and it is 30.5% greater than the P100. The mix with the highest percentage of OPS content, P70, exhibits the lowest compressive strength. Again, 100% replacement of OPS content with POC aggregate increases the compressive strength

about 15%, whereas its 50% replacement upsurges compressive strength by about 30%. In P70, OPS content goes up to 70%, resulting in 18% lower compressive strength than P50. This may be due to the round and plain surface texture of OPS that is responsible for poor bondage to concrete if excessively present. The compressive strengthening value is a little bit lower than P50 but higher than for the P40 mix, though it has a high slump of 70 mm. It also shows a good combination. It is noteworthy that the OPS is of larger size than POC. The void of such 40% OPS is getting more POC to be filled as the mix has 60% POC and such interaction reflects good bonding among coarse aggregate. Therefore, the P40 mix shows its potential for contributing 42.35 MPa to the 28-day compressive results and may be the second choice of optimum mix. Definitely, the POC aggregate induces strong bonding with cementing paste due to its rough and porous texture. P100 and C100 show the 28-day compressive strength for OPS- and POC-based concrete, respectively. Concrete containing OPS only (P100) poses the lowest compressive strength. Besides, concrete containing POC only (C100) shows a compressive strength of 41 MPa, 12% lower than P50. Because of shortcoming of OPS and POC individually, an optimum mix should be designed that may ensure enhanced compressive strength as well as better bonding. The P50 mix refers to the desired optimum mix.

Table 4: Compressive Strength of PSCC concrete

Mix ID	**Compressive Strength (MPa)**			
	1 day	**3 day**	**7 day**	**28 day**
P70	22.87	31.39	35.43	38.28
P60	26.62	33.70	36.01	38.57
P50	32.34	39.95	44.64	46.47
P40	30.70	36.23	40.13	42.35
P30	27.88	34.86	38.56	40.64
P100	21.45	26.86	30.55	35.60
C100	30.10	38.47	39.79	41.08

The relationship of the development of compressive strength in 28-d with the concrete age is shown in Fig. 4. Usually, the logarithmic increment offers high coefficient values with increasing age of the concrete [25]. Lo, Cui [26] stated a correlation of 82-90% for 28-d LWAC compressive strength at 7-d age incorporating coarse aggregate, expanded clay that is comparable to this study (85-95%). The equations of correlations of compressive strengths are derived in Eq. (1) ~ (7) for the selected mixes. The scenario shows the maximum development of compressive strength in the case of P50. The strength expansion is deliberated sequentially by the gradual equations.

$$f'_{c28(P50)} = 4.2339\ \ln(day) + 34.10 \quad (1)$$

$$f'_{c28(P40)} = 3.5108\ \ln(day) + 31.76 \quad (2)$$

$$f'_{c28(C100)} = 3.0926\ \ln(day) + 32.43 \quad (3)$$

$$f'_{c28(P30)} = 3.7891\ \ln(day) + 29.45 \quad (4)$$

$$f'_{c28(P60)} = 3.4669\ \ln(day) + 28.20 \quad (5)$$

$$f'_{c28(P70)} = 4.5484\ \ln(day) + 24.74 \quad (6)$$

$$f'_{c28(P100)} = 4.2338\ \ln(day) + 21.87 \quad (7)$$

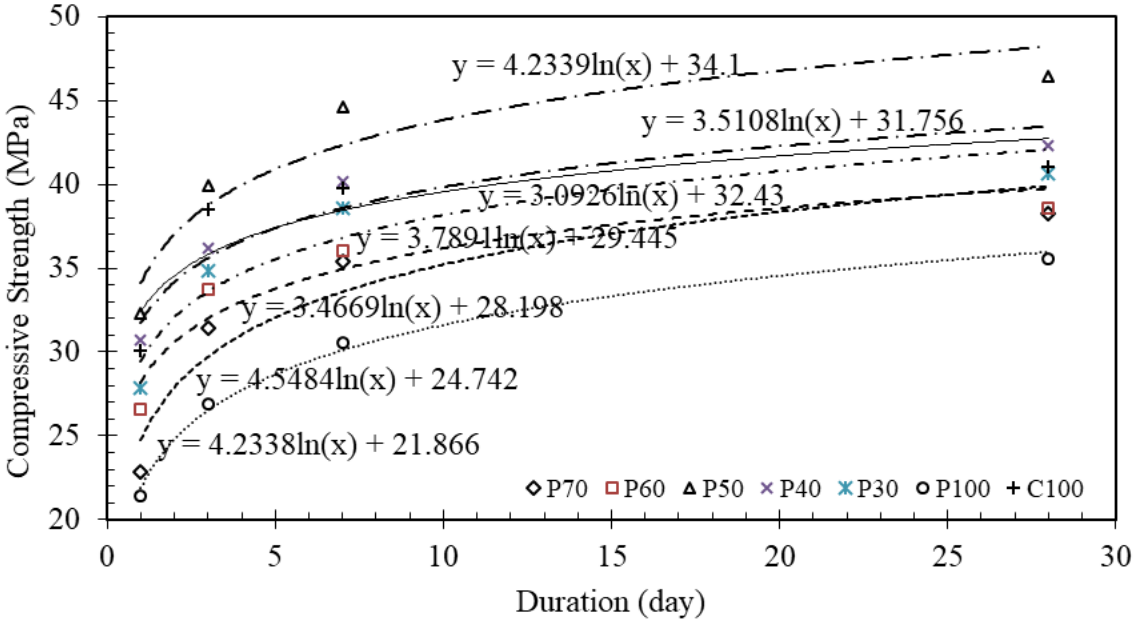


Fig. 4: Correlation of compressive strength with concrete age.

3.4 Splitting Tensile and Flexural Strength

The splitting tensile and flexural strengths of the trial mixes are illustrated in Table 5. From the tabular sketch, it is seen that 2.86 MPa is the lowest 28-day splitting tensile strength that fulfills the minimum requirement (2.0 MPa) for lightweight concrete [27]. Besides, the minimum 28-day flexural strength has been found to be 3.93 MPa. P50 has the largest value of splitting tensile (3.67 MPa) and flexural strength (6.0 MPa) over the control mixes P100 and C100. About 80-90% of both types of strength are developed during the first 7 days. Therefore, the splitting tensile together with the flexural strength of structural member made from this LWAC may be exploited at an early age of 7 days. Usually, different equations are required for lightweight concrete made from different aggregates. Hence, the relationship among the compressive strength (f_c), splitting tensile strength (f_t) and flexural strengths (f_r) at 28 days of PSCC have been engendered and presented in Fig. 5. Accordingly, empirical equations have been suggested to predict splitting tensile (Eq. 8) and flexural strength (Eq. 9) of the PSCC concrete.

$$f_t = 0.0748 f_c^{1.0126} \quad (8)$$

$$f_r = 0.0011 f_c^{2.2401} \quad (9)$$

Table 5: Flexural and splitting tensile strength of OPS and POC concrete

Mix ID	Splitting tensile strength (MPa)			Flexural strength (MPa)		
	3 day	7 day	28 day	3 day	7 day	28 day
P70	2.41	2.76	2.90	3.71	3.75	3.93
P60	2.36	2.75	3.02	3.98	3.85	4.33
P50	3.38	3.53	3.67	5.18	5.83	6.00
P40	2.86	3.14	3.37	4.77	5.21	5.47
P30	2.32	2.52	3.11	4.04	4.15	4.27
P100	2.50	2.76	2.86	2.93	3.03	3.34
C100	2.79	3.00	3.25	4.00	4.44	4.69

From Table 5, the influence of OPS-POC aggregate combinations in the PSCC can be observed. It is perceived that if the percentage of OPS aggregate is greater, the splitting tensile and flexural strength is also lower. These strengths increase gradually with the upsurge of POC content. After the ratio of 50% of OPS and 50% of POC aggregate mix (P50), both the splitting tensile as well as flexural strength tend to reduce. This happens due to the round surface of OPS aggregates possessing a weaker bond in concrete and bonding strength reduction for allowing cementing material entering to the pores of POC aggregate [16]. Therefore, P50 is the optimum mix that obtains the maximum splitting tensile and flexural strength.

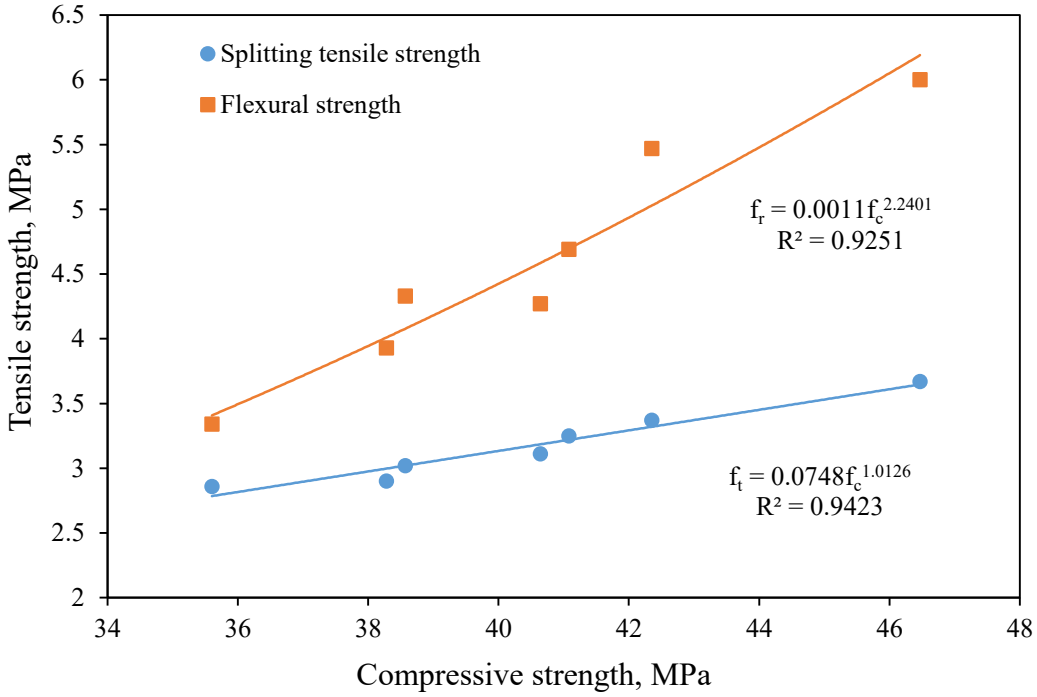


Fig. 5: Correlation among 28-day compressive, splitting tensile and flexural strength.

3.5 Modulus of Elasticity

For calculating the deflection and the stiffness of any structural element, modulus of elasticity (E_s) appears to be an important parameter. Therefore, it is necessary to find a suitable correlation depending on the compressive strength for predicting this modulus of elasticity that relies on the elastic modulus of its components and their volumetric proportions [28]. For addition of POC aggregate contents in the LWC mix, the modulus of elasticity increases as shown in Fig. 6. This increase results from the higher specific gravity of POC content. In this study, the mixture with P50, gives the maximum value of modulus of elasticity. P40 shows 6% lower value of elastic modulus. When the mixes (P60 and P70) contain POC lower than 50% by vol., the modulus of elasticity dips down about 20%.

Figure 6 shows a correlation of E_s and cube compressive strength of PSCC which have been compared with the previously used equation (Eq. 10) for predicting E_s of LWC in CEP/FIP manual [29]. Figure 6 also compares empirical equations (Eq. 11 and Eq. 12) suggested by existing research to predict the E_s for OPS concrete, but none of them are universally accepted [16,30].

$$E_{s(pre)} = [\rho/2400]^2 \; x \; f_c^{1/3} \; x \; 9.1 \quad (10)$$

$$E_{s(pre)} = [\rho/2400]^2 \; x \; f_c^{1/3} \; x \; 5.0 \quad (11)$$

$$E_{s(pre)} = 0.0005 \; x \; f_c^{2.69} \quad (12)$$

where, $E_{s(pre)}$ (GPa) is the predicted elastic modulus, f_c (MPa) is cube compressive strength and ρ (kg/m^3) is the concrete's air-dry density.

Figure 6 shows that the CEB/FIP manual highly overestimates the E_s. The equation derived by the Alengaram, Mahmud [30] also overestimates the E_s for the PSCC that contains lower amounts of POC content. The equation proposed by Ahmmad, Jumaat [16] also approaches the higher E_s value for the PSCC that contains a higher amount of POC content. From the above experimental findings, a simplified equation (Eq. 13) has been suggested for predicting the E_s as per the experimental compressive strength data.

$$E_s = 0.0257 \; x \; f_c^{1.6205} \quad (13)$$

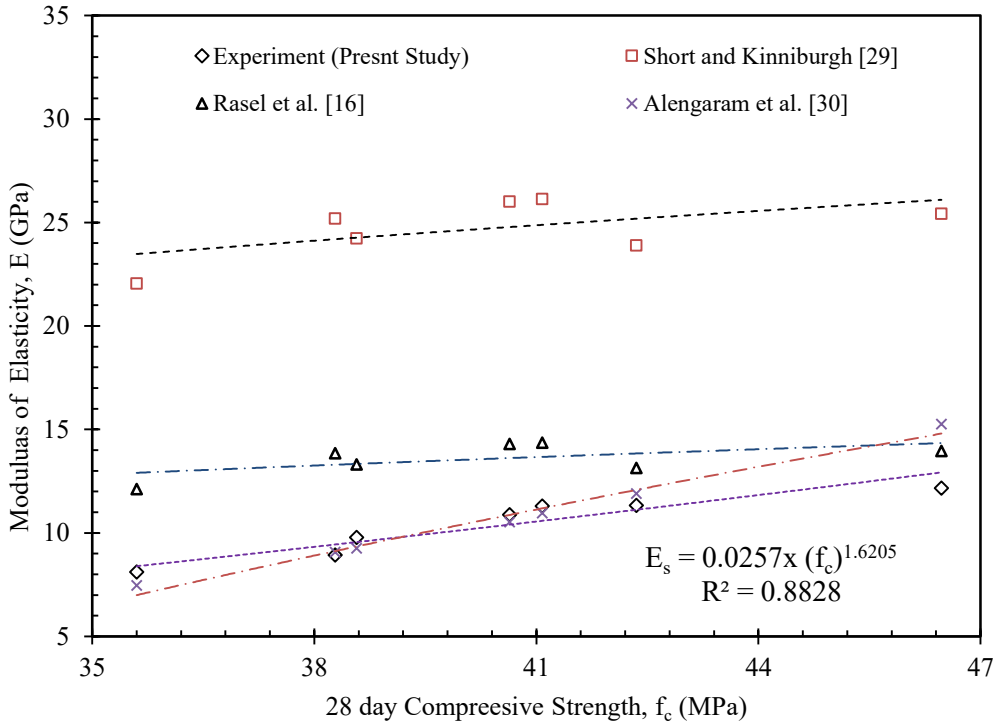


Fig. 6: Compressive strength vs. modulus of elasticity curve.

3.6 Correlation of Ultrasonic Pulse Velocity with Compressive Strength

In the existing literature, a distinctive correlation of concrete compressive strength and its ultrasonic pulse velocity (UPV) is rarely found [31]. However, it is obvious that the water/cement ratio affects the hardened mortar and consequently the UPV values are influenced. If water fills the voids, the travelling of UPV comes quicker compared to that for air filling. This phenomenon indicates that the UPV of the concrete is also affected by the moisture. The concrete containing the UPV values ranging from 3.66 to 4.58 km/s is labeled as 'good' [32]. Such concrete doesn't have large voids or cracks leading to reduced structural integrity. On the other hand, the concrete strength might be evaluated using this UPV test outcome. In the experimental investigation, all the mixes execute the UPV values

higher than 3.66 km/s. In addition, for the variation of coarse aggregate content, the LWAC strength also changes. Here, an empirical relation of compressive strength and UPV of the presented lightweight aggregate concrete, PSCC varying the percentages of coarse aggregates has been established (Fig. 7). Accordingly, succeeding equation (Eq. 14) has been derived for prediction of UPV.

$$f_c = 5.0658\, x\, (UPV)^{1.4502} \quad (14)$$

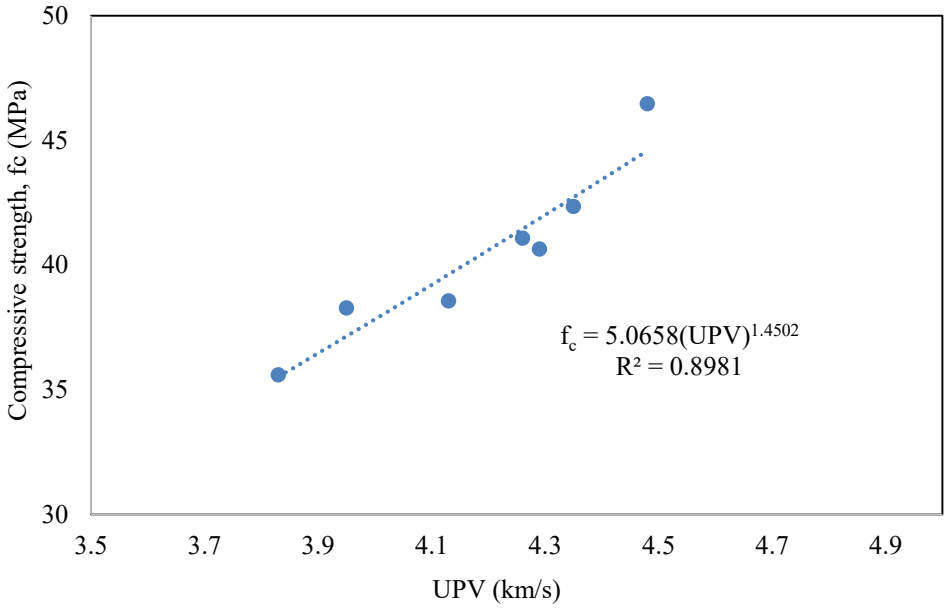


Fig. 7: Compressive strength vs. ultrasonic pulse velocity.

4. CONCLUDING REMARKS

The following findings can be summarized from the study:

- This research produces high strength structural lightweight concrete, PSCC of 28-day compressive strength of 46 MPa that can be used for structural purposes.
- The usage of 50% OPS to 50% POC coarse aggregate by vol. in the concrete mix is the optimum mix to produce grade 45 concrete. It requires 450 kg/m^3 cement, which is lowest among the recent studies for manufacturing grade 45 concrete.
- The average oven-dry density of PSCC having 28-day compressive strength in between 38–46 MPa is 18.7% lower compared to the case of normal weight concrete.
- PSCC has structural grade splitting tensile strength and flexural strength. However, POC content helps to gain these strengths up to a certain limit (50% POC content and 50% OPS content). After this limit, it tends to yield lower strength values.
- The modulus of elasticity increases with the increase of POC content in PSCC. However, if the POC content is greater than 50%, the modulus of elasticity is greater than 10 GPa, which conforms to the lightweight concrete requirement.
- The developed simplified equation easily determines the modulus of elasticity from compressive strength.
- The regression analysis of relating compressive strength of PSCC with UPV shows good correlation. The value for the R^2 is 0.8981.

- In order to enable the universal equation for predicting the splitting tensile strength, flexural strength, and modulus of elasticity, the regression model can be done by incorporating a vast amount of experimental data for future study.

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