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Research Article

Improvement of Mechanical Properties in Polypropylene- and Glass-Fibre-Reinforced Peach Shell Lightweight Concrete

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The use of the polypropylene fibre and glass fibre with different volume fractions to improve the mechanical properties of peach shell lightweight concrete was investigated in this study. The volume fractions of 0.25%, 0.50%, and 0.75% were used for each fibre. The results showed that, as the polypropylene fibre and glass fibre were added into peach shell concrete, the density was reduced by up to 6.1% and the compressive strength, splitting tensile strength, and flexural strength were increased by 19.1%, 54.3%, and 38.6%, respectively. The highest compressive strength, splitting tensile strength, and flexural strength of 29.3 MPa, 2.87 MPa, and 3.09 MPa, respectively, were produced by peach shell concrete with 0.75% glass fibre. The results indicated that the incorporation of fibres significantly enhanced the postfailure toughness of peach shell concrete. It was found that the glass fibre was more effective than the polypropylene fibre in improving the mechanical properties of peach shell concrete. Although the incorporation of fibres slightly increased the water absorption and porosity, the type and content of fibres had no significant effect on water absorption and porosity. Therefore, the mechanical properties of peach shell lightweight concrete can be improved by adding polypropylene fibres and glass fibres.

1. Introduction

The use of agricultural or industrial wastes in concrete to replace the conventional raw material has achieved environmentally friendly and sustainable development by reducing the production costs of the raw material and contributing to waste disposal. The expanding extraction of conventional aggregates such as granite aggregate and sand in concrete production has caused serious environmental pollution problems [1]. The use of lightweight aggregates such as expanded clay, foamed slag, and natural pumice instead of conventional coarse aggregates can produce lightweight aggregate concrete (LWAC) [2]. LWAC has a lot of advantages including better fire resistance, heat insulation, sound absorption, and frost resistance [3]. Recently, the utilization of agricultural wastes such as coconut shell, oil palm shell, and apricot shell as a substitute for normal weight aggregates (NWAs) is gradually rising. On the other hand, the additional advantages of using agricultural wastes instead of normal aggregates to produce LWAC are to reduce environmental pollution and to deal with wastes [4]. Agricultural waste is rapidly storing in developing countries, and peach shell (PS) is the seed of peach fruits, which causes environmental problem around their cultivated areas. More than thousand tons of PS wastes need to be discharged each year in China. The lightweight and regenerative characteristic of PS compared to the NWAs can make PS as one of the potential lightweight aggregates and sustainable building materials in the production of LWAC. This could reduce the environmental pollution caused by PS and contribute to the reutilization of PS.

The improvement in the mechanical properties of LWAC depends on the oven-dried density, water-to-cement ratio, addition of other binder materials, aggregate content, and particle size [5, 6]. Previous studies showed that LWAC with higher compressive strength can be produced, but this concrete was prone to brittle and poor tensile strength due to the fact that the lightweight aggregate is usually weaker under tension [7, 8]. The tensile strength of LWAC is about one-tenth of its compressive strength [9]. The use of PS instead of NWA has a positive impact on density, and a reduction in density up to 30% can be achieved in the peach shell concrete (PSC). However, the splitting tensile and flexural strengths and modulus of elasticity (MOE) of PSC are lower than those of LWAC made of other lightweight aggregates such as pumice and expanded clay. The low tensile strength tends to cause significant tensile cracking to occur under lower tensile loads [10]. Hence, the improvement of the mechanical properties of PSC requires more attention.

Incorporation of fibres is an effective way to improve the mechanical properties of concrete, such as splitting tensile and flexural strengths and other related characteristics [11]. In fibre-reinforced concrete, the role of fibres is to improve the performance of concrete through the crack bridge effect of fibres and the fibre-cement-aggregate interfacial bond [5]. Previous research showed that fibre-reinforced concrete with two types of different fibres had better ductility, crack growth resistance, and impact resistance. In the composite fibre material system, the harder fibres enhance the first crack stress and ultimate strength, and the softer fibres control the crack propagation and increase the ductility [12]. Yap et al. [13] reported that oil palm shell lightweight concrete with 0.9% steel and 0.1% polypropylene (PP) fibres had better improvement in flexural toughness characteristics.

Although a lot of study works are ongoing on the addition of fibres in LWAC, there is only little literature on the incorporation of fibres in PSC. In order to make PSC like other LWAC applied to practical building structure elements such as sidewalks, parking lots, roadblocks, and partition walls, the mechanical properties and durability of PSC need to be further improved. The addition of fibres into PSC can make it as a ductile and sustainable building material. Commonly used fibres are the steel fibre, PP fibre, and nylon fibre, and there are few literatures available on the use of glass (G) fibres in LWAC. The main disadvantages of adding steel fibres to LWAC are a significant increase in density and reduced workability. The PP fibre is mainly used in concrete to enhance the ductility, toughness, and impact resistance, but do not expect them to improve the strength [12]. Mastali et al. [14] reported that adding G fibres led to a significant improvement in compressive strength, tensile strength, and impact resistance of G fibre-reinforced concrete. Compared to steel fibres, the advantage of adding PP fibres and G fibres to PSC is that the density is less than 2000 kg/m^3 and lower than the upper limit of the density set for LWAC. However, there are few literatures on the comparison of PP fibre- and G fibre-reinforced peach shell lightweight concrete.

The purpose of the present study is to investigate the influence of two types of fibres (PP fibre and G fibre) and each fibre at a volume fraction of 0.25%, 0.50%, and 0.75% on the mechanical properties of peach shell lightweight concrete. A comparison of the performance of PP fibre- and G fibre-reinforced peach shell lightweight concrete is investigated and reported, including workability, density, compressive strength, splitting tensile strength, flexural strength, modulus of elasticity, residual compressive strength, water absorption, and porosity. This work helps to expand the knowledge on the effect of PP fibres and G fibres with different contents on the mechanical properties of peach shell fibre-reinforced concrete (PSFRC).

2. Materials and Methods

2.1. Materials

2.1.1. Cement and Silica Fume. Type I 42.5 grade ordinary Portland cement was used in this study and obtained from a local cement company. The Blaine specific surface area and specific gravity are 3532 cm^2/g and 3.14 g/cm^3, respectively. In addition, silica fume (SF) was added in concrete as an additional mineral binder to improve the performance of concrete. SF content at 10% of the cement weight was used in all mixes.

2.1.2. Coarse and Fine Aggregates. Peach shell (PS) was used as an alternative coarse aggregate, and crushed pebble was used as a normal weight coarse aggregate. The density of PS is 63% lower than that of normal weight aggregates (NWAs), which is significant for reducing dead loads of building structures. River sand was used as a fine aggregate and obtained from a local sand company. The physical properties of the aggregates are shown in Table 1. PS was collected from a local peach plantation. Before using, they were washed to remove the residual dried peach pulp and the dust from the PS surface. Then, the dry PS was crushed by a crushing machine in the laboratory. Crushed PS was sieved with 4.75 mm and 9.5 mm sieves, respectively. Particles of size 4.75–9.5 mm were considered as coarse aggregates. Uncrushed and crushed PS and scanning electron microscopic (SEM) image at 5000 magnification times of crushed PS are shown in Figure 1. As can be seen from Figure 1, crushed PS has an irregular and rough surface, and the PS aggregate has a lot of circular porosity on the surface, and the diameter of the micropore is about 10–20 μm. Although a large number of porosity on the surface of PS reduces the density, it leads to the fact that PS has a higher water absorption compared to NWA. Therefore, PS was submerged in water for 24 h and kept in an internal saturated and surface dry condition before mixing.

2.1.3. Water and Superplasticizer. The water used in this study was normal tap water. A high-range naphthalene sulphonated superplasticizer (SP) was used in the study to increase the workability of fresh concrete. SP content at 1% of the cement weight was used in all mixes.

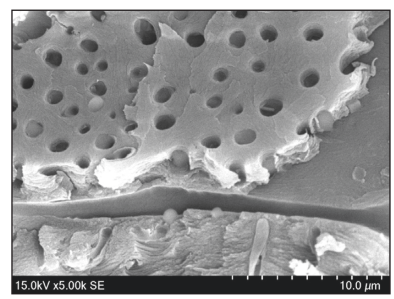
2.1.4. Fibres. Two different fibres used in this study are the (i) polypropylene (PP) fibre and (ii) glass (G) fibre. The properties of fibres are shown in Table 2.

Table 1: Physical properties of the aggregates.

Physical property	Coarse aggregate		Fine aggregate
	PS	NWA	River sand
Specific gravity (g/cm^3)	1.26	2.66	2.65
Fineness modulus	5	4.9	2.7
Bulk density (kg/m^3)	536	1449	1538
Water absorption (24 h) (%)	26.84	0.5	1.2
Aggregate impact value (%)	1.95	16.72	—
LA abrasion value (%)	6	25	—
Flakiness index (%)	48	24	—
Elongation index (%)	61	34	—
Grading			
Sieve size (mm)	Cumulative % by weight passing		
16	100		100
9.5	98.2		100
4.75	24.8		99
2.36	0		86
1.18	0		74.7
0.6	0		48.3
0.3	0		16.3
0.15	0		0

(a)

(b)



(c)

Figure 1: (a) Uncrushed PS, (b) crushed PS, and (c) SEM image of the crushed PS particle at 5000 magnification times.

2.2. Mix Proportioning. The mix proportion of concretes is presented in Table 3. A total of six concrete mixes were prepared with different fibre contents, and a control mix without the addition of fibres was also produced for comparison purpose. The total amount of materials for all mixes was the same except in the case of two different fibres and three fibre volumes. The volume fractions of fibres were 0.25%, 0.50%, and 0.75%, respectively.

2.3. Specimen Preparation and Test Methods. The procedure of specimen preparation of peach shell fibre-reinforced concrete (PSFRC) was detailed as follows: firstly, PS and river sand were poured into a blender and dry mixed for 2 min. Then, fibres and cement and SF were added to the mixture and dry mixed for 1 min. Before the fibres were mixed, fibres were manually distributed. Following this, 60% water mixed with SP was added to the mixture and mixed for 3 min. Finally, 40% water was added to the mixture and mixed for 5 min. After mixing was complete, the slump test was carried out immediately, and then, the specimens were cast in oiled plastic moulds. All specimens were compacted by the vibrating table. Immediately after compaction, all specimens along with the moulds were covered by a plastic sheathing to prevent moisture evaporation. Specimens were removed from the moulds after 24 h. Finally, specimens were stored in a controlled room with a relative humidity of 95% ± 5% and a temperature of 20°C ± 2°C until the test age.

The workability of all mixes was measured by the slump test according to ASTM C143/C143M-12 (Figure 2). The density of all specimens was measured in accordance with ASTM C138. 100 mm cube specimens were used for the compressive strength test (BS EN12390-2:200 9 and BS EN12390-3:200 9) at the age of 3, 7, 28, and 56 days (Figure 2). The splitting tensile and flexural strengths and modulus of elasticity of all mixes were measured at the age of 28 days according to ASTM C496/C496M-11, ASTM C78-10, and ASTM C469-10 (Figure 2), respectively. The average value of at least three specimens is taken for each test result.

The water absorption test was carried out according to the procedures prescribed in ASTM C642. All specimens were oven-dried at 110 ± 5°C for not less than 24 h to remove moisture and achieve constant before testing. The specimens were then submerged in water for 24 h. The water absorption values of the specimen were calculated using the following formula:

$$\text{Water absorption (\%)} = \frac{M_2 - M_1}{M_1} \times 100, \tag{1}$$

where M_1 is the mass of the oven-dried specimen in air (g) and M_2 is the mass of the surface-dried specimen in air after immersion (g).

The porosity of all specimens was determined in accordance with ASTM C642. Absolute density is necessary to determine the total porosity by the method prescribed in ASTM C642; hence, the pycnometry method was applied for

Table 2: Properties of the PP fibre and G fibre.

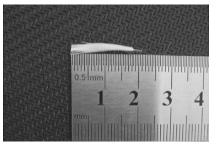
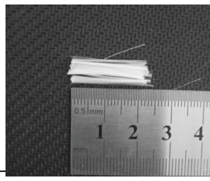
Fibre		Fibre type	Length (mm)	Diameter (μm)	Specific gravity (g/cm^3)	Tensile strength (MPa)
PP		Monofilament	19	40	0.91	500
G		Monofilament	22	10	2.65	1200

Table 3: Mix proportion of concretes.

Mix code	Cement (kg/m^3)	SF (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	SP (kg/m^3)	PS (kg/m^3)	PP fibre (%)	G fibre (%)
Control	550	55	180	780	5.5	360	0	0
PP25	550	55	180	780	5.5	360	0.25	0
PP50	550	55	180	780	5.5	360	0.50	0
PP75	550	55	180	780	5.5	360	0.75	0
G25	550	55	180	780	5.5	360	0	0.25
G50	550	55	180	780	5.5	360	0	0.50
G75	550	55	180	780	5.5	360	0	0.75

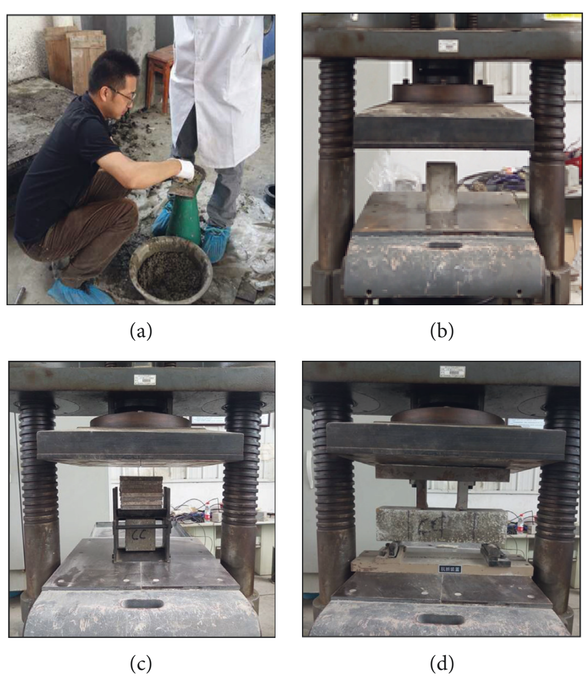


Figure 2: (a) Slump test, (b) compressive test, (c) splitting tensile test, and (d) flexural strength test.

the determination of absolute density. The total porosity and open porosity values of the specimen can be calculated by (2) and (3), respectively. The closed porosity volume can be obtained by subtracting the open porosity volume from the total porosity volume.

$$\text{Total porosity volume}\,(\%) = \frac{\rho_a - \rho_b}{\rho_a} \times 100, \qquad (2)$$

where ρ_a is the absolute density of the specimen (g/cm^3) and ρ_b is the bulk density of the specimen (g/cm^3).

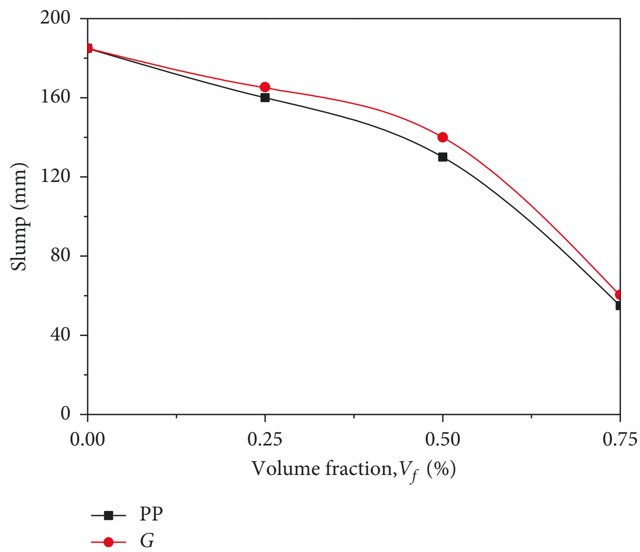


Figure 3: Relationship between the fibre content and slump value.

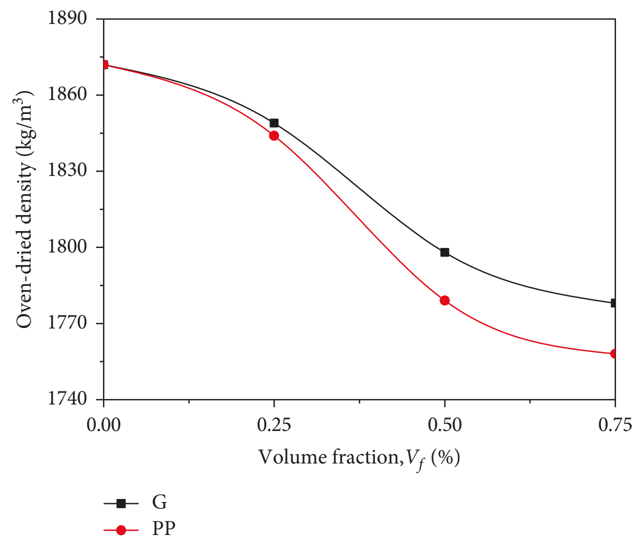


Figure 4: Relationship between the fibre content and oven-dried density.

$$\text{Open porosity volume (\%)} = \frac{M_3 - M_1}{M_3 - M_4} \times 100, \quad (3)$$

where M_1 is the mass of the oven-dried specimen in air (g); M_2 is the mass of the surface-dried specimen in air after immersion (g); M_3 is the mass of the surface-dried specimen in air after immersion and boiling (g); and M_4 is the apparent mass of the specimen in water after immersion and boiling (g).

3. Results and Discussion

3.1. Workability (Slump). Relationship between the fibre content and slump value is shown in Figure 3. Yew et al. [9] reported that the incorporation of different types of PP fibres in oil palm shell concrete caused a considerable decrease in the slump value. As expected, the results showed that the slump values of the fresh PSC with PP fibres and G fibres were reduced to 55 mm and 60 mm, respectively. The reason for this phenomenon can be explained by the fact that the fibre-cement paste interfacial bond in concrete restricts the dispersion and flow of the cement paste and improves the viscosity of the mixtures. With the increase in fibre volume fraction, the capability of the fibre-cement paste interfacial bond in concrete becomes stronger as more fibres absorb the cement paste to wrap around it. Therefore, the workability of concrete decreased as the fibre volume (V_f) increased from 0% to 0.75%. Mehta and Monteiro [15] reported that the LWAC with a slump value of 50–75 mm is similar to normal weight concrete with a 100–125 mm slump value. In the case of PSC, the slump value of PP fibre- and G fibre-reinforced PSC between 55 mm and 60 mm can easily be compacted.

Figure 3 also shows that the two types of fibres have an impact on the workability of concrete. For all V_f, the G fibre produced slightly higher slump values than the PP fibre. The increase in slump values at a range of 5–10 mm and the biggest difference between the G fibre and PP fibre were observed at $V_f = 0.50\%$, and the slump value of G50 was 7.8%

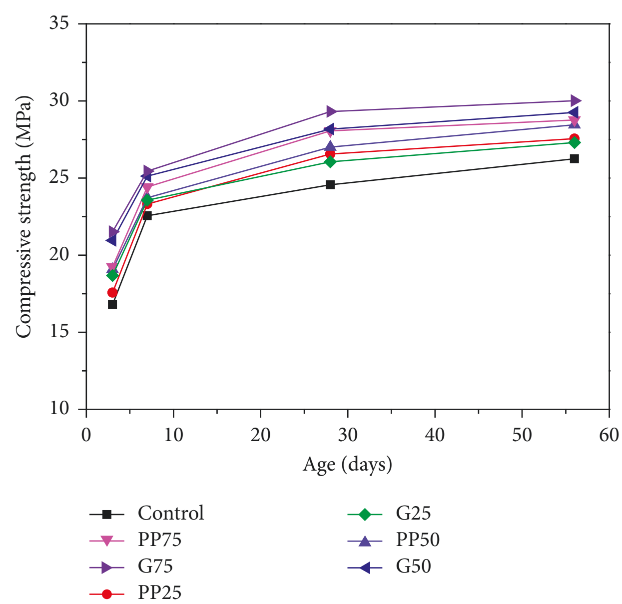


Figure 5: The development of the compressive strength of concretes.

higher than that of PP50. Song et al. [16] reported that the workability of fibres with a shorter length was lower than that of longer fibres. The shorter fibres have more surface area for the reinforcing fibre-cement paste bond [9]. Since the length of the G fibre is longer than that of the PP fibre and the surface of the G fibre is smoother, G fibres have lower effective surface area to develop a fibre-cement paste bond compared to PP fibres. Hence, the slump value of PSC incorporated with G fibres was slightly higher than that of PP fibres.

3.2. Density. Lightweight aggregate concrete (LWAC) is defined as concrete with a compressive strength of more than 15 MPa and an oven-dried density (ODD) in the range

Table 4: Compressive strength of concretes.

Mix	Compressive strength (MPa)				% increase in compressive strength (28 days)
	3 days	7 days	28 days	56 days	
Control	16.8 (68.3%)	22.6 (91.9%)	24.6	26.3 (106.9%)	—
PP25	17.6 (66.2%)	23.3 (87.6%)	26.6	27.6 (103.8%)	8.1
PP50	19.1 (70.7%)	23.7 (87.8%)	27.0	28.5 (105.6%)	9.8
PP75	19.2 (68.3%)	24.4 (86.8%)	28.1	28.8 (102.5%)	14.2
G25	18.7 (71.6%)	23.6 (90.4%)	26.1	27.3 (104.6%)	6.1
G50	21.0 (74.5%)	25.1 (89.0%)	28.2	29.3 (103.9%)	14.6
G75	21.5 (73.4%)	25.5 (87.0%)	29.3	30.2 (103.1%)	19.1

Note. Values in brackets denote the percentages of compressive strength to the corresponding 28-day compressive strength.

of 1600–2000 kg/m^3 [17]. Relationship between the fibre content and ODD is shown in Figure 4. The results showed that the ODD of all PSC ranged from 1758 kg/m^3 to 1872 kg/m^3 and fulfilled the requirement of LWAC because PS is about 63% lighter than NWA. The addition of PP fibres and G fibres in concrete reduced the ODD of PSC because fibres have a low specific gravity. When the volume fraction of PP fibres is added at percentages of 0.25%, 0.50%, and 0.75%, the ODD of these concretes decreased by 1.5%, 5.0%, and 6.1%, respectively, compared to the control mix.

Figure 4 also showed that the different types and volume fractions of fibres had an influence on the ODD of PSC. It was found that concrete with G fibres produced a slightly higher ODD than PP fibres, and the difference in the ODD of PSC is more significant as fibre volume fraction ranges from 0.25% to 0.75%. At $V_f = 0.75\%$, G75 had the lowest ODD of 1778 kg/m^3, and it was only 1.1% higher than PP75. It should be noted that although the specific gravity of PP fibres and G fibres is significantly different, its impact on the ODD of PSC is not obvious. However, compared to the density of approximately 2400 kg/m^3 for ordinary weight concrete, the ODD of PSC is reduced by about 26%, which is a significant reduction in the weight of concrete.

3.3. Compressive Strength. The development of the compressive strength of concretes up to 56 days is shown in Figure 5. The test results revealed that the compressive strength of all concretes increased as the curing age increased. As can be seen from Figure 5, there is a significant difference in the compressive strength between PSC containing different types and contents of fibres and control mix without any fibres. The enhancement of the ultimate compressive strength may be attributed to the fact that fibres arrest the growth of cracks due to the fibre-cement paste interfacial bond and the crack bridging effect of fibres [18].

The addition of PP fibres and G fibres had significantly increased the compressive strength of PSC at all ages, and the compressive strength increased as an increase in fibre content. The 28-day compressive strength of all mixes varied between 24.6 MPa and 29.3 MPa, which fulfilled the requirements for the strength and density of LWAC. It can be observed that compared to the control mix, the 28-day compressive strength of PP25, PP50, and PP75 increased by 8.1%, 9.8%, and 14.2%, respectively, and the 28-day compressive strength of G25, G50, and G75 increased by 6.1%, 14.6%, and 19.1%, respectively. Except for $V_f = 0.25\%$, the 28-day compressive strength of G fibre-reinforced PSC was slightly higher than that of PP fibre. This phenomenon indicated that the use of G fibre-reinforced PSC is a good choice.

Table 4 shows the compressive strength of concretes. All concretes attained approximately 66%–75% of compressive strength at 3 days and 87%–92% of compressive strength at 7 days. This indicated that all PSC developed high early compressive strength because the incorporation of SF increased the cohesiveness of cement paste and reduced the advance of microcracks, and eventually, the early compressive strength of PSC is increased. The addition of PP fibres and G fibres in concrete increased the 28-day compressive strength by about 6%–19%. At $V_f = 0.75\%$, G75 produced the highest 28-day compressive strength of 29.3 MPa, which is 19.1% higher than the control mix of 24.6 MPa. Although not every kind of lightweight aggregate is suitable for the production of LWAC, the results based on this study indicate that it is feasible to produce LWAC using PS as a lightweight aggregate.

Generally, the initiation and advance of cracks in concrete are due to the continuous increase in compressive loading. Since the tensile stress generated by the fibre is perpendicular to the crack propagation path, the debonding begins at the interface between the fibre and cement paste. Once the advancing cracks reach the fibre-cement paste interface, the stress concentration at the crack tip is released, and as a result, the development of the advancing crack is blunted and blocked. The fibre is like a bridge in this process that arrests the advancing cracks and consequently improves the strength of concretes [19, 20]. Therefore, the addition of PP fibres and G fibres enhanced the bonding of the fibre-cement paste interface and improved the compressive strength [16]. The compressive strength of G fibre-reinforced PSC is higher than that of PP fibre-reinforced PSC. This reason can be explained by the following: firstly, the tensile strength of G fibres in this study is 2.4 times that of PP fibres, and thus, compared to the PP fibre, the G fibre is easier to transfer higher tensile stress from a cracked fibre-cement interface to fibre. Secondly, under the same fibre volume fraction, the density of G fibre-reinforced PSC in this study is higher than that of PP fibre-reinforced PSC. Although the addition of fibres in this study reduced the density of PSC,

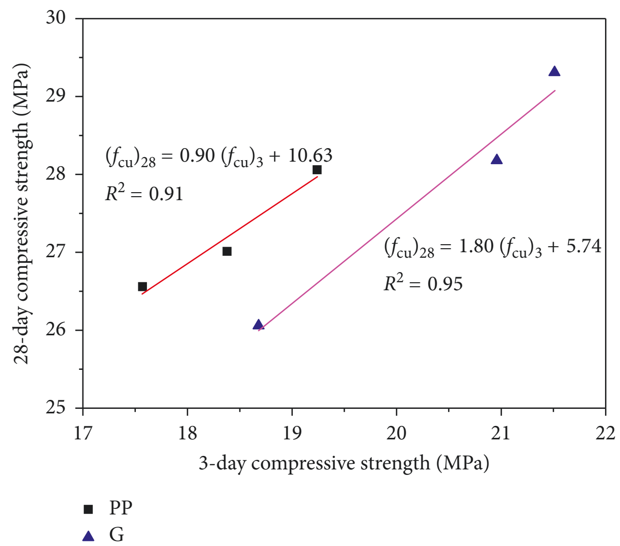


Figure 6: Relationship between 3-day and 28-day compressive strengths.

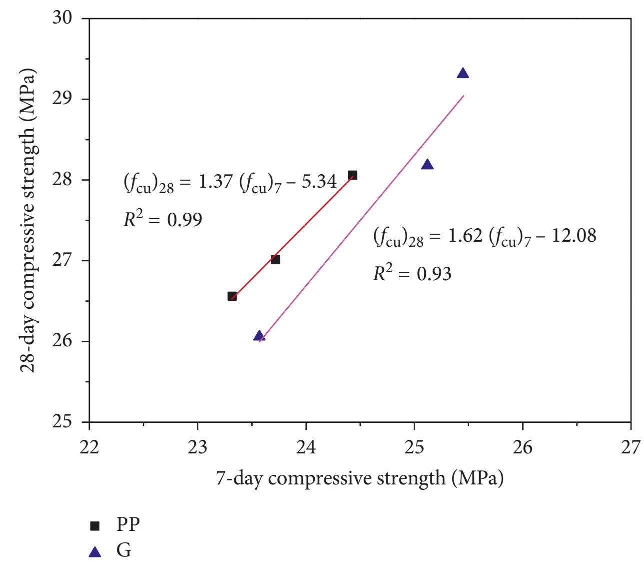


Figure 7: Relationship between 7-day and 28-day compressive strengths.

for normal weight concrete, the higher the density the higher the compressive strength. Thus, the compressive strength of higher density of G fibre-reinforced PSC is higher than that of PP fibre-reinforced PSC.

Due to the importance of knowing the 28-day compressive strength from the early age compressive strength, Figures 6 and 7 show the relationship between the 28-day compressive strength and compressive strength at early ages of 3 days and 7 days, respectively. As can be seen from Figures 6 and 7, there is a linear relationship with the high correlation coefficient between the 28-day compressive strength and the early compressive strength, and the 28-day compressive strength of PSC can be predicted by the early compressive strength.

Table 5: Splitting tensile and flexural strengths and modulus of elasticity of concretes (28 days).

Mix	Splitting tensile strength (MPa)	Flexural strength (MPa)	Modulus of elasticity (GPa)
Control	1.86	2.23	8.71
PP25	2.05	2.38	9.63
PP50	2.15	2.50	10.15
PP75	2.54	2.63	10.85
G25	2.00	2.35	9.79
G50	2.52	2.69	10.75
G75	2.87	3.09	11.32

3.4. Splitting Tensile and Flexural Strengths. Splitting tensile strength and flexural strength of all mixes are shown in Table 5. Comiloli et al. [21] reported that the incorporation of PP fibres in concrete can slightly enhance the flexural toughness of concrete. The fibre enhances the strength of concretes by the crack bridging effect and carrying part of load [12]. The results showed that the incorporation of PP fibres and G fibres in concrete increased both splitting tensile strength and flexural strength of PSC, and the more the fibre content, the higher the splitting tensile strength and flexural strength. The addition of PP fibres from 0.25% to 0.75% and glass fibres from 0.25% to 0.75% increased the splitting tensile strength up to 10.2%–36.6% and 7.5%–54.3%, respectively. Furthermore, the flexural strength of PP fibre- and G fibre-reinforced PSC was also improved. The flexural strength of PSC increased as an increase in fibre volume fraction. When the fibre volume fraction varies from 0.25% to 0.75%, the flexural strength for PP fibre and G fibre reinforced PSC increased by 6.7%–17.9% and 5.4%–38.6%, respectively. The advantage of PSC could be further explained based on Figure 8. From Figure 8, it was evident that the control concrete without any fibres failed once the ultimate splitting tensile strength was reached due to low ductility. Furthermore, the fibre-reinforced PSC showed excellent crack arresting performance as the specimen was not broken into two pieces even after the failure load. This phenomenon attributed to the crack bridging effect of fibres, and fibres in concrete provide additional strength to the fibre-cement interfacial bond which carries a partial load.

Although the ODDs of PP75 and G75 were lower in this study, the splitting tensile strength and flexural strength of PP75 and G75 were higher than those of the control mix. Since the tensile stress of G fibres is greater than that of PP fibres, glass-fibre reinforced PSC produced a higher splitting tensile strength and flexural strength. At $V_f = 0.50\%$ and 0.75%, splitting tensile strength and flexural strength of PSC containing G fibres were found to be about 12.5%–13.0% and 7.6%–17.5%, respectively, and higher than those of PP fibres. Splitting tensile strength and flexural strength of G75 were 2.87 MPa and 3.09 MPa, respectively, which increased by 54.3% and 38.6%, respectively, compared to the control mix. Compared to the PP fibre, the higher tensile stress of the G fibre is more effective in transferring the tensile stress. At the

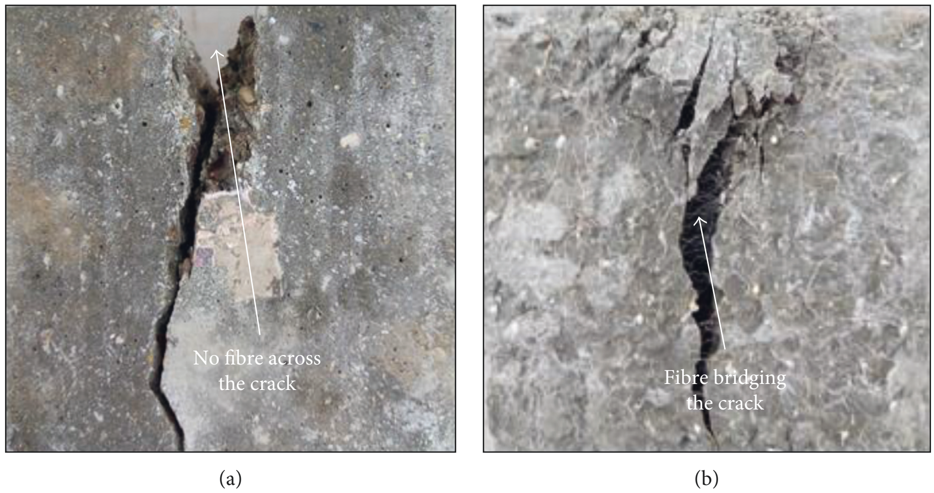


Figure 8: Specimen after the splitting tensile test: (a) control concrete without fibres and (b) concrete containing fibres.

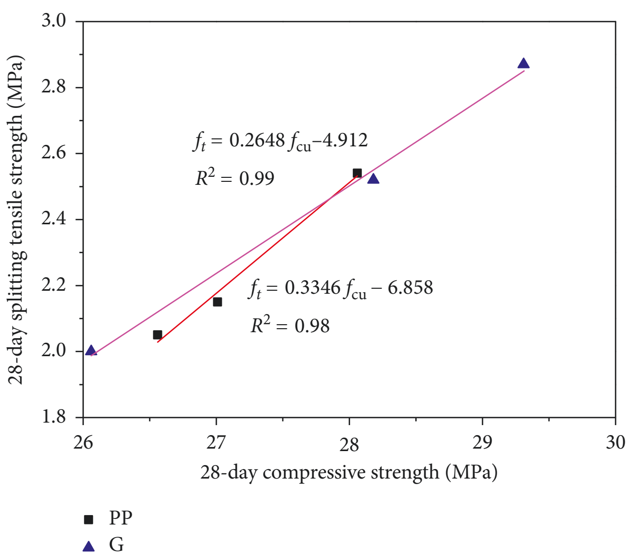


Figure 9: Relationship between the compressive strength and splitting tensile strength.

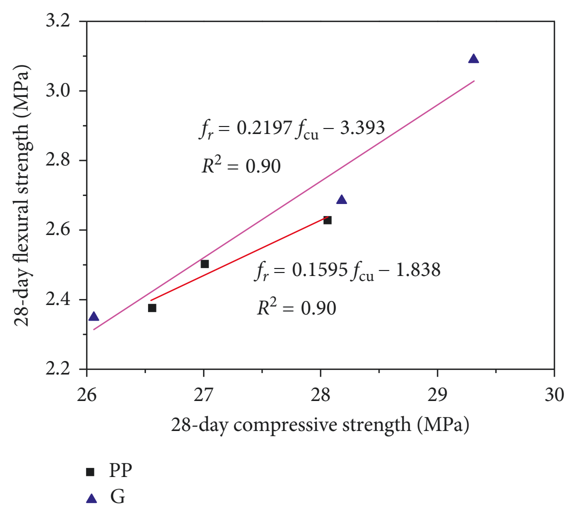


Figure 10: Relationship between the compressive strength and flexural strength.

same fibre volume fraction, the G fibre has a smaller diameter, leading to more fibres to join the cracks [22]. Due to the bridging effect of fibres, the stress concentration around cracks is reduced and the development of cracks is hindered. Eventually, the tensile strength of PSC is improved.

The relationship between the compressive strength and splitting tensile strength and flexural strength for PSC at 28 days is shown in Figures 9 and 10, respectively. As can be seen from Figures 9 and 10, the splitting tensile strength and flexural strength of PSFRC increase as an increase in compressive strength.

3.5. Modulus of Elasticity. Table 5 shows the modulus of elasticity (MOE) of all concretes, which ranges between 8.71 and 11.32 GPa. The control concrete in this study produced a minimum MOE of 8.71 GPa. The results showed that the types of G fibres and PP fibres had a significant effect on MOE. At $V_f = 0.25\%$, 0.50%, and 0.75%, the MOE of PP fibre- and G fibre-reinforced PSC increased by 10.6% and 12.4%, 16.5% and 23.4%, and 24.6% and 30.0%, respectively. The incorporation of fibres enhances the MOE of PSC because fibres arrest the initial cracks caused by shrinkage, and the crack bridging effect reduces the strain caused by the compression loading and consequently improves the MOE.

The MOE of PSFRC was found to depend on the fibre volume fraction, while the type of fibres had an insignificant influence on it. The volume fraction of G fibres increased from 0.25% to 0.75%, the MOE of G fibre-reinforced PSC increased by 15.6% from 9.79 GPa to 11.32 GPa, and the MOE of G fibre-reinforced PSC was 1.7%, 5.9%, and 4.3%, respectively, slightly higher than that of PP fibre.

Figure 11 shows the relationship between the compressive strength and MOE. As can be seen from Figure 11, there is a good relationship between the MOE and 28-day

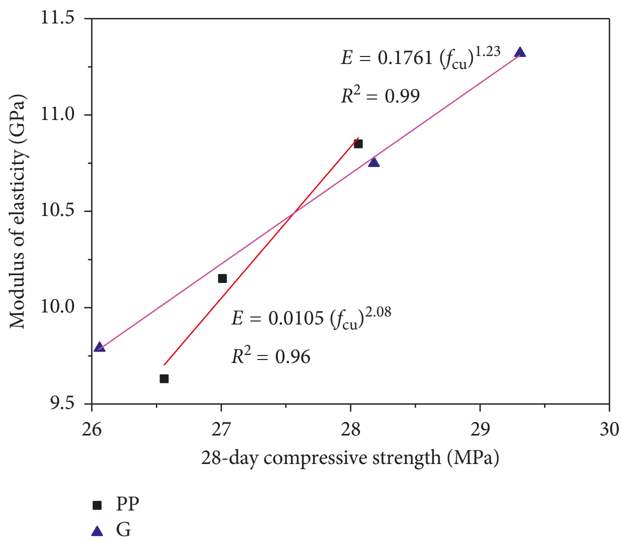


Figure 11: Relationship between the compressive strength and MOE.

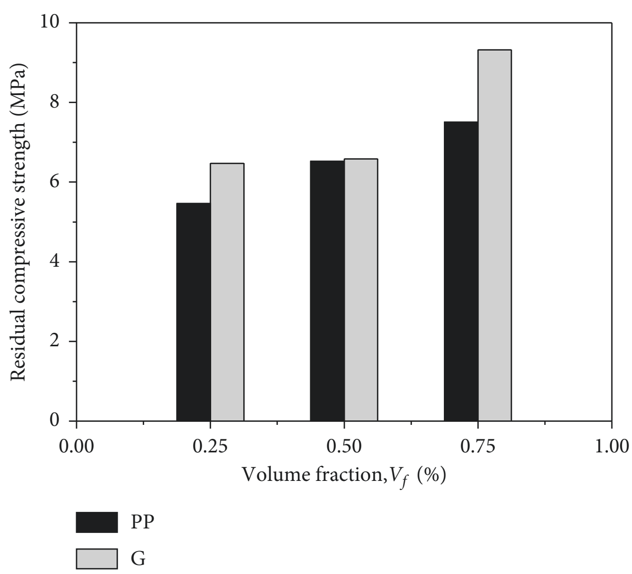


Figure 12: Residual compressive strength of concretes.

compressive strength of PSFRC, and the MOE of PP fibre-reinforced PSC and glass fibre-reinforced PSC can be predicted by the 28-day compressive strength, respectively.

3.6. Residual Compressive Strength. Residual compressive strength (RCS) can be used to evaluate the residual strength toughness of concretes. Figure 12 shows residual compressive strength of concretes. Because the crack bridging effect of fibres existed at two crack surfaces, in the fibre-reinforced concrete, additional loading forces are required for further growth of the crack. As expected, the incorporation of PP fibres and G fibres enhanced the residual strength toughness of PSC. The control concrete without any fibres had no RCS as the control concrete was immediately failed when the ultimate loading strength is reached. In

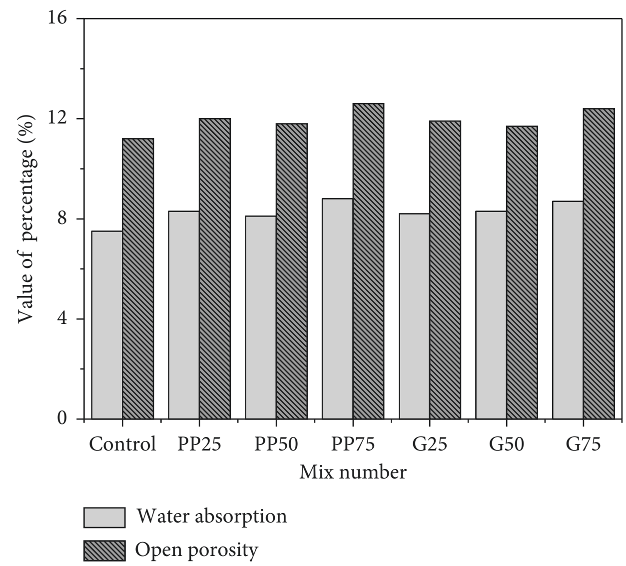


Figure 13: Percentage value of water absorption and open porosity of concretes.

addition, the more the fibre content, the higher the RCS value. At $V_f = 0.75\%$, PP fibre- and G fibre-reinforced PSC had the highest RCS value. It might be attributed to the crack bridging effect of fibres that existed at two crack surfaces, which can hinder further propagation of cracks, even after microcrack cracking. The results indicated that the influence of adding fibres on the improvement of postfailure toughness of PSC was very significant.

3.7. Water Absorption and Porosity. Twenty-four-hour water absorption and open porosity for all mixes are shown in Figure 13. Lo et al. [23] studied that the water absorption of the lightweight aggregate affected the internal microstructure of the hardened mortar and the interfacial zone of concrete, and an increase in the water absorption of the lightweight aggregate resulted in an increase in the number of pores in the interfacial zone of concrete. Figure 13 clearly showed that the incorporation of fibres slightly increased the water absorption and open porosity of PSC, and the water absorption values of all concretes varied from 7.5% to 8.8%. However, the type and content of fibres had an insignificant effect on water absorption and open porosity, and the more the number of open pores, the higher the water absorption for all concretes. The addition of fibres might affect the number and area of micropores in PSC, which resulted in a small increase in water absorption and open porosity. Neville and Brooks [24] reported that although the water absorption cannot be used to determine the quality of concrete, the water absorption of most of the good-quality concretes usually is much lower than 10% by mass. It can be seen from Figure 13 that all concretes have less than 10% water absorption and meet the requirements of good concrete.

Total porosity and open porosity of concretes are shown in Figure 14. The result showed that the total porosity of PSC was between 15.1% and 16.5%, and the open porosity

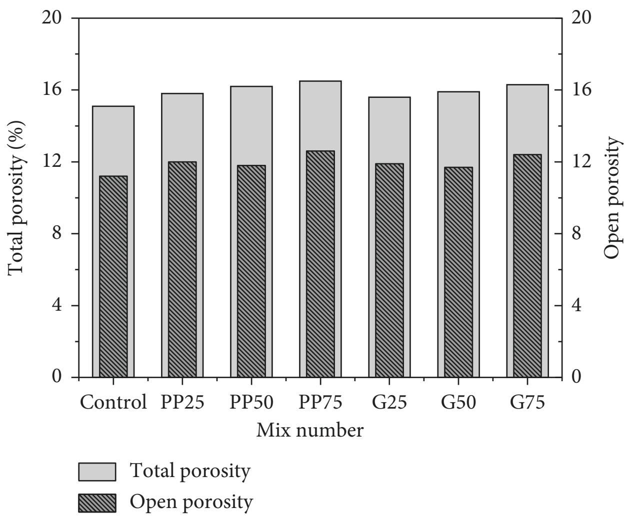


FIGURE 14: Total and open porosity of concretes.

varied from 11.2% to 12.6%. Furthermore, most of the total porosity in PSC was open porosity, and closed porosity accounted for a small portion of the total porosity because the surface of PS aggregates contains a lot of microscopic and connective pore structures. Results also showed that the type and content of fibres had an insignificant influence on the porosity of PSC, and the addition of fibres slightly increased the porosity of PSC. In addition, a slight increase in the total porosity was another reason that adding fibres reduced the density of PSC.

4. Conclusions

The influences of incorporating two types of fibres (polypropylene fibre and glass fibre) and different fibre volume fractions (0.25%, 0.5%, and 0.75%) on the mechanical properties of peach shell lightweight concrete have been investigated in this study. The following conclusions can be drawn based on the present study:

(1) The polypropylene fibre and glass fibre decrease the slump value of peach shell concrete. The slump values of the fresh peach shell concrete with polypropylene fibres and glass fibres are reduced to 55 mm and 60 mm, respectively. However, the concrete containing glass fibres produced slightly higher slump values than polypropylene fibres.

(2) The addition of polypropylene fibres and glass fibres reduces the oven-dried density of peach shell concrete. The oven-dried density of all concretes ranges from 1758 kg/m^3 to 1872 kg/m^3 and fulfills the requirement of lightweight aggregate concrete. In addition, the oven-dried density of peach shell concrete reduces with an increase in fibre content.

(3) All concretes have high early compressive strength. Polypropylene fibres and glass fibres significantly increase the compressive strength of peach shell concrete, and the compressive strength of peach shell concrete increases as an increase in fibre content. In addition, an increase in the 28-day compressive strength of peach shell concrete is about 6%–19%.

(4) The addition of polypropylene fibres and glass fibres in concrete increases the splitting tensile strength of peach shell concrete. Furthermore, the more the fibre content, the higher the splitting tensile strength. The addition of polypropylene fibres and glass fibres from 0.25% to 0.75% increases the splitting tensile strength up to 10.2%–36.6% and 7.5%–54.3%, respectively.

(5) The flexural strength of peach shell concrete increases as an increase in fibre volume fraction. The flexural strength for polypropylene fibres and glass fibres from 0.25% to 0.75% reinforced the peach shell concrete increase by 6.7%–17.9% and 5.4%–38.6%, respectively.

(6) The glass fibre-reinforced peach shell concrete produces a higher splitting tensile strength and flexural strength. At $V_f = 0.50\%$ and 0.75%, the splitting tensile strength and flexural strength of peach shell concrete containing glass fibres are found to be about 12.5%–13.0% and 7.6%–17.5%, respectively, and higher than those of polypropylene fibres.

(7) The effect of incorporating polypropylene fibres and glass fibres enhances the modulus of elasticity of peach shell concrete. Modulus of elasticity of all concretes ranges between 8.71 and 11.32 GPa. At $V_f = 0.25\%$, 0.50%, and 0.75%, the modulus of elasticity of polypropylene fibre- and glass fibre-reinforced peach shell concrete increases by 10.6% and 12.4%, 16.5% and 23.4%, and 24.6% and 30.0%, respectively.

(8) The control peach shell concrete produced no residual compressive strength. However, the addition of polypropylene fibres and glass fibres enhances the residual strength toughness of peach shell concrete. In addition, the higher the fibre volume content, the higher the residual compressive strength. At $V_f = 0.75\%$, the polypropylene fibre- and glass fibre-reinforced peach shell concrete have the highest residual compressive strength values and increase by 46% and 82%, respectively.

(9) The incorporation of fibres slightly increases the water absorption and porosity of peach shell concrete. However, the type and content of fibres have an insignificant effect on water absorption and porosity.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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