

## Research Article

# Comparative Study of Lightweight Cementitious Composite Reinforced with Different Fibre Types and the Effect of Silane-Based Admixture

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This study aims to develop a type of fine-grained lightweight concrete, also known as lightweight cementitious composite (LCC), containing perlite microsphere (PM) and fibres with enhanced impermeability. The effect of polypropylene (PP), polyvinyl alcohol (PVA), and basalt fibres on the fresh and hardened properties of LCC was investigated. Besides, silane-based water repellent admixture was incorporated to reduce the water absorption and enhance the hydrophobicity of LCC. The dry densities of LCC developed were in the range of 912–985 kg/m<sup>3</sup>. PP fibres have lesser influence on the strengths of LCC. However, PVA fibres enhanced the strength of LCC by up to 35.2% and 28% in the compressive strength and flexural strength, respectively, while the basalt fibres increased both strengths up to 30.1% and 43.5%, respectively. By considering the overall performance, LCC with 0.5% PVA fibres has achieved a good balance in workability and strength. Additionally, silane-based water repellent admixture had an excellent effect in reducing the water absorption and improving the hydrophobicity of LCC. By incorporating 1% of silane-based water repellent admixture, the LCC with 0.5% PVA fibres obtained water-resistant properties with the softening coefficient of 0.85 and water contact angle of 128.2°. In conclusion, a combination of PVA-LCC with 1% waterproofing admixture showed the best performance in terms of mechanical strength as well as hydrophobic properties and had the potential to be used in the fabrication of concrete façade.

## 1. Introduction

Concrete and cement-based materials are commonly used to fabricate façade panels because of their durability and versatility. With the use of lightweight concrete, the lifting efficiency of the panels can be improved, which shortens the installation process. According to BS EN 206, the oven-dry density of lightweight concrete is in the range of 800 kg/m<sup>3</sup> to 2000 kg/m<sup>3</sup>. The low density of lightweight concrete can be achieved by incorporating lightweight aggregates. Conventional lightweight aggregates such as expanded perlite also possess low thermal conductivity, thus providing thermal insulation to the building [1]. However, the incorporation of expanded perlite reduces the compressive strength and increases the water absorption of concrete due to its porous nature [2]. Although façade panels are

nonstructural elements that are only subjected to self-weight and wind load, the increase in water absorption of lightweight concrete will increase the self-weight of the panels during the wet season. This drawback can be minimised by utilising microsized expanded perlite, namely, perlite microsphere (PM).

PM has a closed pore structure which allows it to achieve lower water absorption than conventional expanded perlite. The typical water absorption of expanded perlite is between 30 and 71% [1, 3, 4]. On the other hand, the water repellence of PM is 10% higher than the conventional expanded perlite [5]. In addition, the reduction in particle size of expanded perlite can increase the strength of PM [6, 7]. So, PM is less vulnerable to shearing force. Previously, the authors have developed a lightweight cementitious composite (LCC) using PM. LCC is a type of fine-grained lightweight

aggregate concrete with a high specific strength. The developed LCC achieved a 28-day compressive strength of 23.7 MPa with the dry density of 979 kg/m<sup>3</sup> [8]. Considering the lower strength requirement for facade panel, the LCC mix could be altered to suit this application.

Lightweight cement-based material is usually more brittle than normal-weight concrete [2, 9]. The addition of fibres to the lightweight cementitious composite can be a promising solution to overcome the drawback of brittleness. The existence of fibres in cementitious composite delays and mitigates the propagation of microcracks and macrocracks [10]. Many researchers have manifested the effectiveness of using fibrous material to improve the hardened properties of the concrete [11–13]. The distribution, orientation, geometry, and volumetric proportion of fibres in the matrix are essential parameters in affecting the mechanical properties of composites. Therefore, it is crucial to determine the suitable type and optimal dosage of fibres for LCC made of PM while maintaining the low density of LCC.

Furthermore, enhancing the hydrophobic properties of LCC can be an added value since one of the main challenges encountered in façade wall application is surface staining due to weathering [14]. Hydrophobic properties can be achieved by using a hydrophobic agent during the mixing stage [15, 16] or water repellent coating [17]. However, the surface coating method can become more vulnerable under UV radiation [18]. Therefore, from the practical point of view, mixing the hydrophobic agent directly in LCC is preferable because if the surface of LCC is destroyed, the newly exposed part of the LCC can still exhibit hydrophobicity. Therefore, in this research, a silane-based water repellent admixture was added in LCC during mixing.

In short, this study aims to develop LCC containing PM and fibres with enhanced impermeability. The effect of polypropylene (PP), polyvinyl alcohol (PVA), and basalt fibres on the workability and mechanical strength of LCC was evaluated. Besides that, silane-based water repellent admixture was incorporated to reduce the water absorption and enhance the hydrophobicity of LCC. This study would be useful for the application of LCC as a façade panel.

## 2. Materials and Methods

**2.1. Materials.** CEM I Ordinary Portland Cement (OPC) of class 42.5 N was used in this study. Silica fume (SF) and fly ash (FA), fulfilling EN 13263-1 and EN 450-1, were used as supplementary cementing materials to improve the properties of the composites. PM with a bulk density of 700 kg/m<sup>3</sup> and an average particle size of 200 µm was used as lightweight aggregate to produce LCC (Figure 1). PP, PVA, and basalt fibres used in this study are shown in Figure 2. The properties of fibres provided by manufacturer are presented in Table 1. To produce LCC with adequate consistency and improved cohesiveness of the mixture, polycarboxylate ether-based superplasticiser (SP) and styrene butadiene rubber (SBR) were used in all mixes. Additionally, silane-based water repellent admixture was incorporated in the selected mix, and the hydrophobic properties of LCC were investigated.

**2.2. Mix Proportioning and Sample Preparation.** Ten mixtures with a varying volume of PP, PVA, and basalt fibres were prepared. Besides the control mix (PM-0), the LCCs were categorised into 3 groups (LCC-PP, LCC-PVA, and LCC-basalt) based on the respective fibre type. The volume fraction of each type of fibre varied between 0%, 0.125%, 0.25%, and 0.50%. Additionally, two mixes of LCC with 0.50% PVA fibres were added with 1% and 2% of silane-based admixture. The mixture proportion of LCCs is tabulated in Table 2. All other parameters such as binder content (600 kg/m<sup>3</sup>) and the water/binder ratio, dosage of SP, and SBR were kept constant in all mixtures.

The mixing process of LCC started with dry mixing of binders and PM for one minute. It was then followed by adding water and chemical admixtures while continuing mixing for another two minutes. Next, the fibres were gradually dispersed in the mix, and the mixing process continued until a homogeneous mixture was obtained. A portion of the fresh LCC was used to conduct the flow table test, while the rest was cast into prelubricated moulds. After compaction, the specimens were covered by plastic sheets to avoid loss of moisture. From each batch, six 50 mm cubes (for compressive strength) and three prisms with a dimension of 40 mm × 40 mm × 160 mm (for flexural strength test) were cast. For LCC with silane-based admixture, additional 50 mm cubes (water absorption test and water saturated compressive strength test) and LCC tiles with a dimension of 70 mm × 75 mm × 16 mm (contact angle test) were prepared. All the specimens were demoulded 24 hours after casting, and the hardened LCC specimens were air-cured in laboratory condition until the age of testing.

**2.3. Test Methods.** The flow table test was carried out following ASTM C1437. The compressive strength test was carried out at the age of 7 days and 28 days and in accordance with ASTM C109. The flexural strength test was conducted via 3-point bending. The machine used in the bending test is INSTRON displacement-controlled testing machine with a load capacity of 100 kN. Besides that, the water absorption of specimens with silane-based water repellent admixture after immersion for 30 mins and 48 hours was determined. The contact angle test was carried out to determine the surface hydrophobicity of LCC which was incorporated with silane-based admixture. The contact angle was measured using an optical contact angle measuring system, OCA 15EC, with Spinocerebellar Ataxia Type 20 (SCA20) software (Figure 3) after placing a distilled water droplet on the specimen surface.

## 3. Results and Discussion

**3.1. Workability.** Figure 4 shows the workability of fresh LCC with varying types and dosages of fibres. Based on the results, an increase in fibre dosage decreased the workability of LCC regardless the type of fibre. Similar findings were reported by Jiang et al. [19] and Loh et al. [20]. With the inclusion of 0.50% of PP, PVA, and basalt fibre, the workability of the control mix decreased by 24.6%, 32.5%, and 56.9%, respectively. Under the condition of fixed binder content and dosage of chemical admixture, the surface area

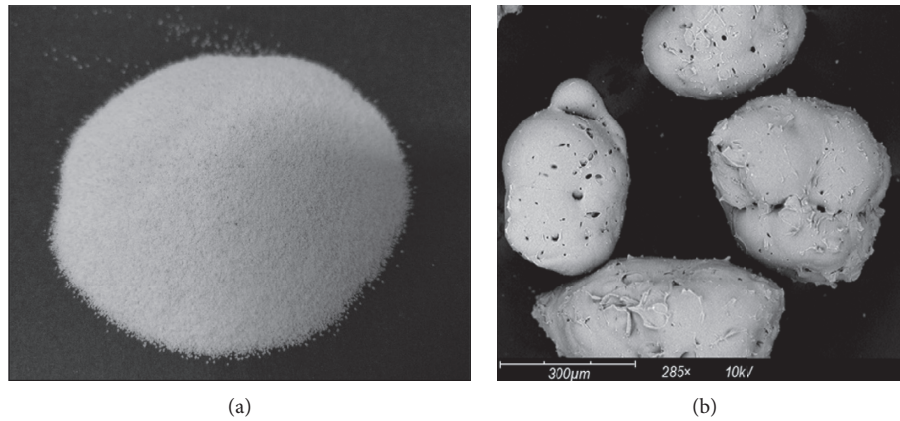


FIGURE 1: (a) Physical appearance of PM; (b) SEM image of PM.

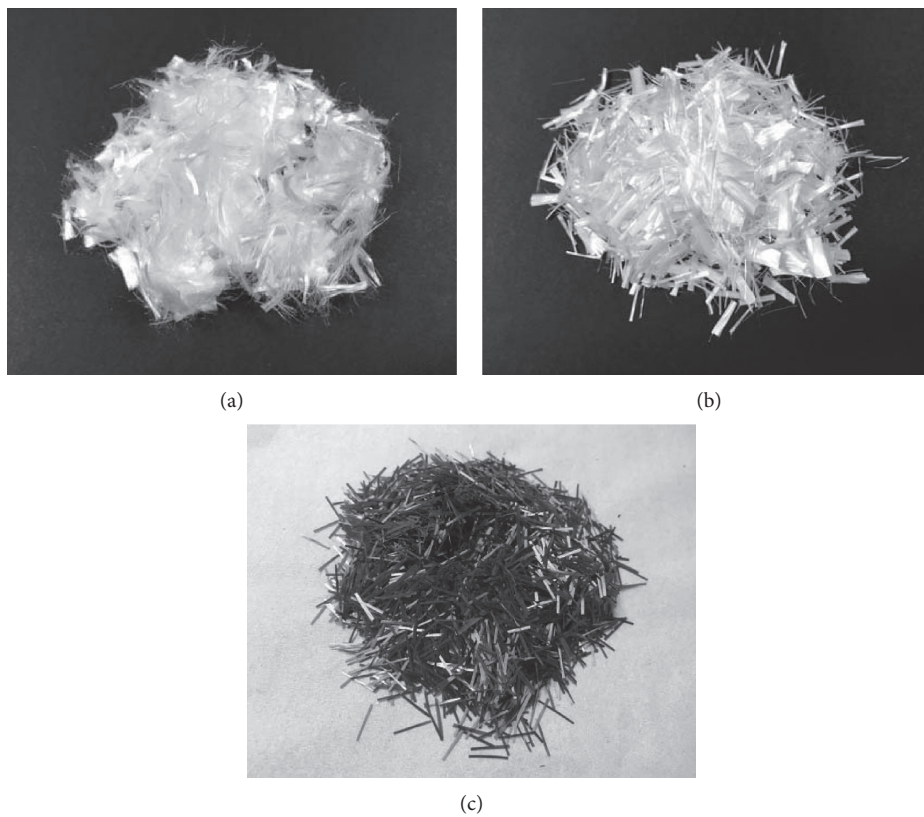


FIGURE 2: (a) PP fibres; (b) PVA fibres; (c) basalt fibres.

and stiffness of fibres are the factors affecting the workability of fibre-reinforced mortar. Since basalt fibre has the highest aspect ratio and modulus of elasticity among the fibres used, this led to the greatest reduction in workability of the LCC.

**3.2. Density.** The density of LCC developed in this study was in the range of 912 to 985 kg/m<sup>3</sup>. The effect of fibres on LCC density was less significant in this study due to the low incorporation level of fibres, which was less than 1%. The highest percentage difference was observed with 0.50% PVA fibres, where the density of the control mix increased by 8%. A similar trend was observed in both LCC-PP and LCC-

PVA. The density increased with a higher dosage of fibres. However, in the case of basalt fibres, the density of LCC with 0.50% basalt fibres (PM + 0.50 B) was lower than that of LCC with 0.25% basalt fibres (PM + 0.25B). In fact, this correlates with the low workability of PM + 0.50 B, which resulted in poor compaction and low density.

### 3.3. Compressive Strength

**3.3.1. Effects of Fibres on Compressive Strength.** The compressive strength of LCCs is tabulated in Table 3. Early strength development of LCC was observed by

TABLE 1: Properties of fibres.

Properties	Types of fibre		
	PP	PVA	Basalt
Length (mm)	12	12	12
Diameter ( $\mu\text{m}$ )	50	40	12
Density ( $\text{g}/\text{cm}^3$ )	0.90	1.29	2.67
Tensile strength (MPa)	350–500	1600	4150–4800
Modulus of elasticity (GPa)	3.5–3.9	41	100–110
Aspect ratio (length/diameter)	240	300	1083

TABLE 2: Mixture proportions of LCC (by weight of binder).

Mix ID	Binder			Water/binder ratio	PM	*Fibre (%)			**Chemical admixture (%)		
	OPC	FA	SF			PP	PVA	Basalt	SBR	SP	Water repellent
PM-0 (control mix)						—	—	—			—
PM + 0.125PP						0.125	—	—			—
PM + 0.25PP						0.250	—	—			—
PM + 0.50PP						0.500	—	—			—
PM + 0.125PVA						—	0.125	—			—
PM + 0.25PVA						—	0.250	—			—
PM + 0.50PVA	0.78	0.17	0.05	0.35	0.42	—	0.500	—	10.0	1.2	—
PM + 0.125B						—	—	0.125			—
PM + 0.25B						—	—	0.250			—
PM + 0.50B						—	—	0.500			—
W1PM + 0.50PVA						—	0.500	—			1.0
W2PM + 0.50PVA						—	0.500	—			2.0

Notes: \*means by volume of aggregate; \*\*means by weight of binder.

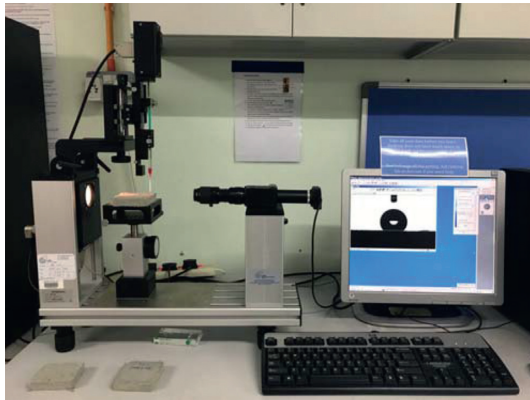


FIGURE 3: OCA 15EC with software SCA 20 module.

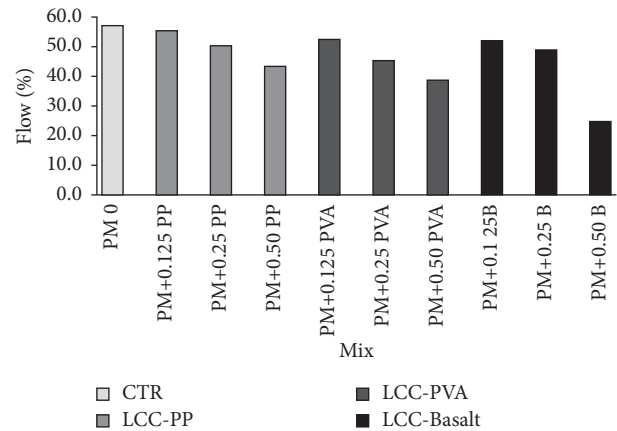


FIGURE 4: Flow value of LCC.

attaining 75.2% to 98.8% of its 28-day compressive strength at 7 days. This could be attributed to the use of SF [20] and SBR [21], which increased the cohesiveness of the matrix. Besides that, the inclusion of 0.125–0.25% of PP fibres and 0.125% of basalt fibres had a negligible effect on the compressive strength of LCC at the early age of 7 days. Nevertheless, the maximum compressive strength of these mixes at 28 days was 15.9% higher than that of the control mix. This finding is in line with results reported by Wu et al. [22], where the bonding strength between matrix and fibres increased with the curing age of concrete. Moreover, the ultimate compressive strength of LCC increased by adding fibres with high modulus of elasticity. At the same fibre dosage of 0.25%, LCC-basalt achieved the highest

compressive strength, 15.9 MPa, followed by LCC-PVA, 13.9 MPa, and LCC-PP, 13.5 MPa.

Furthermore, the failure mechanism of LCC was improved with the use of fibres. Figure 5 shows the typical failure of LCC specimens after the compression test. For the LCC with fibres, no obvious spalling was observed. This observation indicates the effectiveness of fibres in constraining lateral deformation and reducing the brittleness of the LCC. Both LCC-PP and LCC-PVA achieved the highest compressive strength among their groups with 0.50% fibre volume. On the other hand, the addition of basalt fibres increased the compressive strength of LCC until a fibre dosage of 0.25%. The compressive strength of PM + 0.50B



TABLE 3: Density and compressive strength of LCC.

Mix ID	Density (kg/m <sup>3</sup> )	Compressive strength (MPa)	
		7 days	28 days
PM-0 (control mix)	912	12.0	12.2
PM + 0.125PP	923	10.9	13.1
PM + 0.25PP	935	10.0	13.5
PM + 0.50PP	959	13.9	14.2
PM + 0.125PVA	931	13.5	14.3
PM + 0.25PVA	939	13.3	13.9
PM + 0.50PVA	985	15.3	16.5
PM + 0.125B	940	10.8	14.1
PM + 0.25B	957	14.0	15.9
PM + 0.50B	932	11.6	14.4

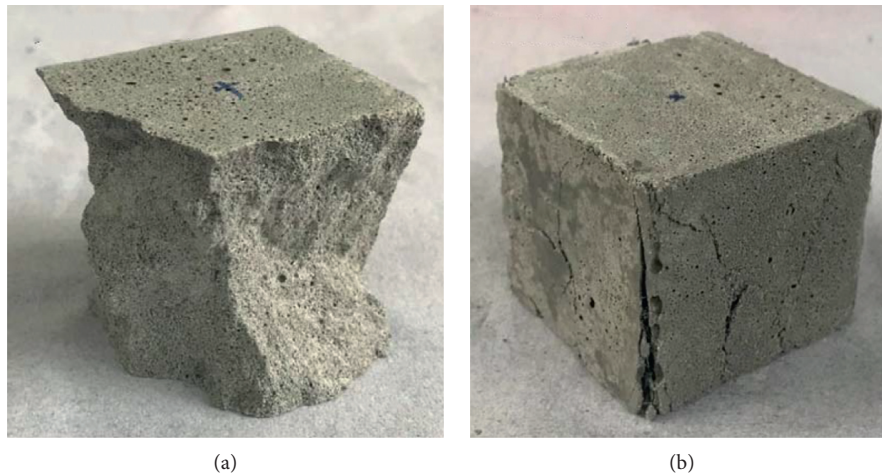


FIGURE 5: Failure pattern of LCC (a) without fibre; (b) with fibres.

was about 9.4% lower than PM + 0.25B. This could be related to the increased formation of pores and voids within the composite due to the poor workability of PM + 0.25B [23]. However, the composite containing 0.50% basalt fibres still had higher strength than the composite without fibres. Thus, for PM-0, the optimum incorporation level of each fibre type was 0.50% for both PP and PVA fibres, while it was 0.25% for basalt fibres. Beyond the optimum levels, a higher SP dosage is required to achieve adequate workability.

Among all the LCC developed, PM + 0.50PVA achieved the highest compressive strength of 16.9 MPa, and this mix also fulfilled the minimum compressive strength of structural lightweight concrete recommended by CEB/RILEM [24], which is more than 15 MPa. Moreover, based on the research done by Hanif et al. [25] and Blanco et al. [26], the 28-day compressive strength of LCC produced using fly ash cenospheres was between 5 and 18 MPa with a dry density of 885–1138 kg/m<sup>3</sup>. Therefore, PM + 0.50PVA was selected for further investigation on the effect of silane-based admixture since the 28-day compressive strength was within the reported range.

**3.3.2. Effects of Silane-Based Admixture on Compressive Strength.** The compressive strength and softening coefficient of PM + 0.50PVA mix with and without silane-based water repellent admixture are tabulated in Table 4. The use

of 1% and 2% water repellent admixture reduced the compressive strength of LCC by 34.0% and 26.4%, respectively. This result is in line with the findings reported by Li et al. [27] and Tittarelli and Moriconi [28]. Li et al. [27] reported that the maximum reduction in compressive strength was 13.3%, with the inclusion of 0.3% powder silane-based water repellent additive. Similarly, Tittarelli and Moriconi [28] found out that 2% of silane admixture used in the form of aqueous emulsion also caused a 10–20% reduction in compressive strength of concrete. The hydrophobic admixture may be associated with minor air-entraining effect, which increased the porosity in the hardened cement mortar [16].

Softening coefficient is the ratio between the water-saturated compressive strength and dry compressive strength of a material. The purpose of determining the ability of a material to maintain its original properties when exposed to water is because the moisture content of concrete has a significant effect on the compressive strength of concrete [29], especially for low strength material. The water-saturated specimens were prepared by immersing the oven-dried specimens in water for 48 hours. The softening coefficient of PM + 0.50PVA was 0.50. With 1% and 2% of water repellent admixture, the softening coefficients of PM + 0.50PVA were increased by 70% and 62%, respectively.

TABLE 4: Compressive strength, softening coefficient, and water absorption of LCC with water repellent admixture.

Mix ID	Compressive strength (MPa)		Softening coefficient	Water absorption (%)	
	Dry strength	Water-saturated strength		30 mins	48 hours
PM + 0.50 PVA	16.5	8.3	0.50	4.1	15.2
W1 PM + 0.50 PVA	10.9	9.2	0.85	0.7	3.6
W2 PM + 0.50 PVA	12.1	9.8	0.81	0.5	3.8

The PVA fibre-reinforced LCC with 1% admixture (W1PM + 0.50PVA) can be considered as a water-resistant material since the softening coefficient exceeds 0.85 [30]. The increment in softening coefficient is attributed to the lower water absorption of LCC specimens in the presence of the silane-based water repellent admixture. Compared with PM + 0.50PVA, the 48-hour water absorption of W1PM + 0.50PVA and W2PM + 0.50 PVA was reduced by 76.3% and 74.8%, respectively. Moreover, there is no significant difference between LCC performance with 1% and 2% water repellent admixture. Thus, the ideal dosage of silane-based water repellent admixture for the LCC in this research is 1%.

**3.4. Flexural Strength.** The flexural strengths of LCCs are presented in Figure 6, while Figure 7 shows the fractured specimens after the 3-point bending test. Compared with the control specimen, all fibre-reinforced composites showed an appreciable increase in flexural strength. Theoretically, higher fibre dosage helps to sustain more load before failure, which can be observed in specimens with PVA fibres. When PVA fibres were added at 0.125%, 0.25%, and 0.50% dosage, the flexural strength was consistently enhanced by 14.3%, 25.7%, and 28.6%, respectively. Toutanji et al. [31] similarly reported that 0.6% PVA fibres increased the flexural strength of LCC by 25%. However, PP and basalt fibres showed otherwise.

For the specimen with PP fibres, fibre dosage at 0.125% minimally decreased the flexural strength (−3.9%). The possible reason is that 0.125% of PP fibre dosage was insufficient to have a significant fibre bridging effect, and the low modulus of elasticity of PP fibres makes the specimen less stiff. At 0.50% dosage of PP fibres, the flexural strength of PM-0 was improved by about 10%. A similar finding has been reported by Wu et al. [32], where incorporating 0.50% PP fibres in peach shell lightweight concrete increased the flexural strength by about 12%. On the other hand, for LCC-basalt, the flexural strength decreased from 5.0 MPa to 4.1 MPa at fibre dosage 0.25% and 0.50%. This was most likely due to the high aspect ratio and high modulus of basalt fibres having a detrimental effect on workability, hindering the basalt fibres from distributing homogeneously [23]. Hence, this can affect the compaction of the specimen.

Among the three types of fibre, namely, the PP, PVA, and basalt fibres, the basalt fibres gave the highest improvement in flexural strength (PM + 0.25B) followed by PVA fibres (PM + 0.50PVA) and PP fibres (PM + 0.50PP). This could be related to the stiffness of fibre. Basalt fibre has the highest modulus of elasticity, about 100–110 GPa; thus, it has better resistance to deformation of specimens [20]. However, the prismatic specimen of LCC-basalt broke into

half after testing, as shown in Figure 7(b). This could be due to the rupture of basalt fibres since it possesses high stiffness [20]. Nevertheless, the fibres could still bridge the specimens from breaking into half in the case of LCC-PP and LCC-PVA (Figures 7(c) and 7(d)). Additionally, from Figures 8(c) and 8(d), fibres pull-out failure was observed. This shows that PP and PVA fibres could resist tensile stresses effectively. Besides that, LCC-PVA had wider crack width compared with LCC-PP. The reason is that the PVA fibres have higher tensile strength than PP fibres, thus allowing LCC-PVA to undergo greater deflection.

Furthermore, the effect of waterproofing admixture on the flexural strength of LCC was studied. The result shows that with 1% and 2% silane-based water repellent agent, the flexural strength of PM + 0.50PVA was decreased by 13.3% and 17.8%, correspondingly. This further justifies the finding in the earlier section where the porosity of LCC was increased after incorporating the hydrophobic agent.

**3.5. Static Water Contact Angle.** The contact angles of water droplets on LCC tiles with different dosages of silane-based water repellent are presented in Figure 9. These results were used to determine the hydrophobicity of a material. When the water droplet remains on the surface in the form of a sphere, as shown in Figure 10 (hydrophobic surface), this indicates that there is no molecular attraction between water and the composite. In general, a solid surface with a water contact angle,  $\theta \geq 90^\circ$ , is considered as hydrophobic, while a solid surface with  $\theta \geq 120^\circ$  and  $\theta \leq 150^\circ$  is considered as over hydrophobic. On the other hand, a solid surface with  $\theta$  less than or equal to  $90^\circ$  is considered hydrophilic [33–35]. The hydrophobic properties of LCC were improved with the use of silane-based water repellent admixture. The water contact angle of W1PM + 0.50PVA and W2PM + 0.50PVA was  $128.2^\circ$  and  $109.2^\circ$ , respectively. It was 33% and 13% higher than the corresponding mix without water repellent admixture, PM + 0.50PVA. Therefore, the surface of W1PM + 0.50PVA is considered as over hydrophobic, while W2PM + 0.50PVA is considered as hydrophobic. The hydrophobic properties of LCC will be advantageous for industrial applications such as façade panels since surface staining can be avoided.

From the water contact angle results, 1% of silane-based water repellent is recommended, similar as described in the earlier section. It is interesting to note that even without the inclusion of silane-based water repellent admixture, the water contact angle of PM + 0.50PVA tile was still larger than  $90^\circ$ , which is considered hydrophobic. This result agrees well with the findings of Flores et al. [36] where the water contact angle of mortar tile was enhanced by about 26% using 1% PVA fibres. The incorporation of PVA fibres increased the

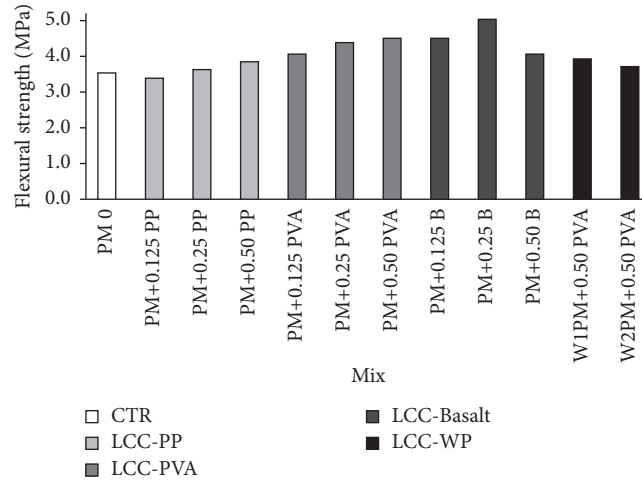


FIGURE 6: Flexural strength of LCC at 28 days.



FIGURE 7: Fractured LCC after 3-point bending test: (a) control mix; (b) LCC-basalt; (c) LCC-PVA; (d) LCC-PP.

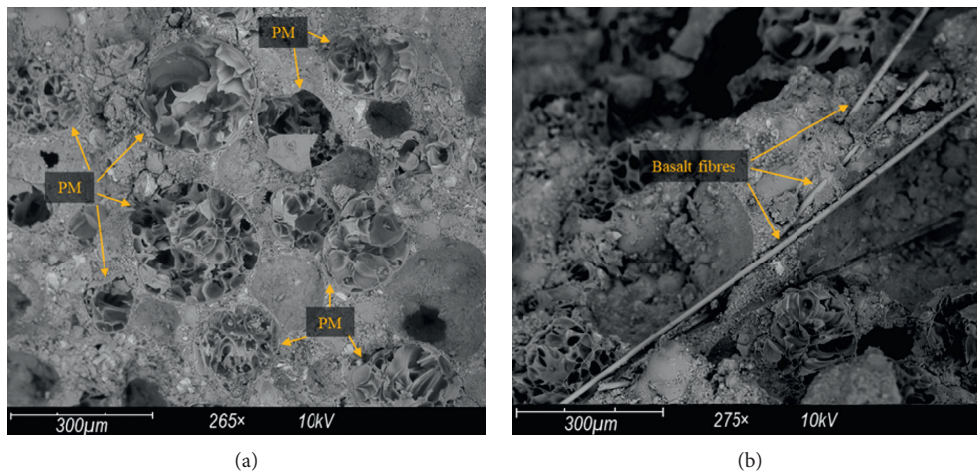


FIGURE 8: Continued.



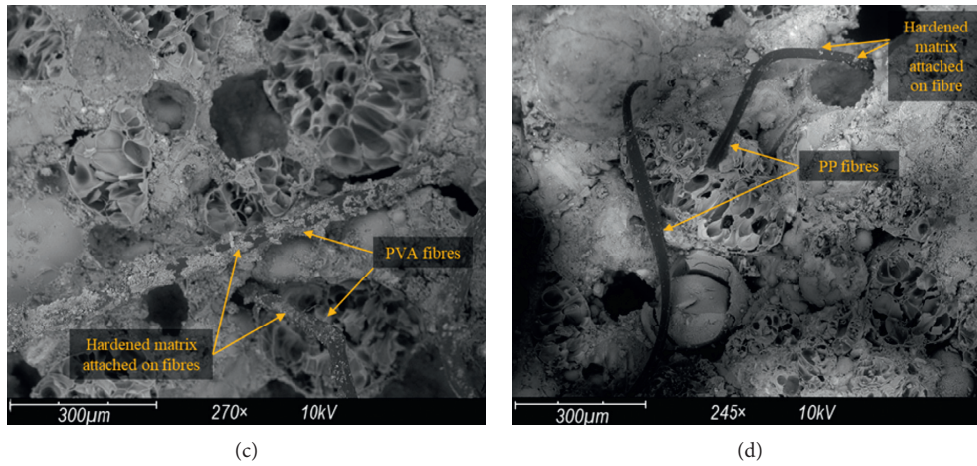


FIGURE 8: SEM images of (a) control mix; (b) LCC-basalt; (c) LCC-PVA; (d) LCC-PP.

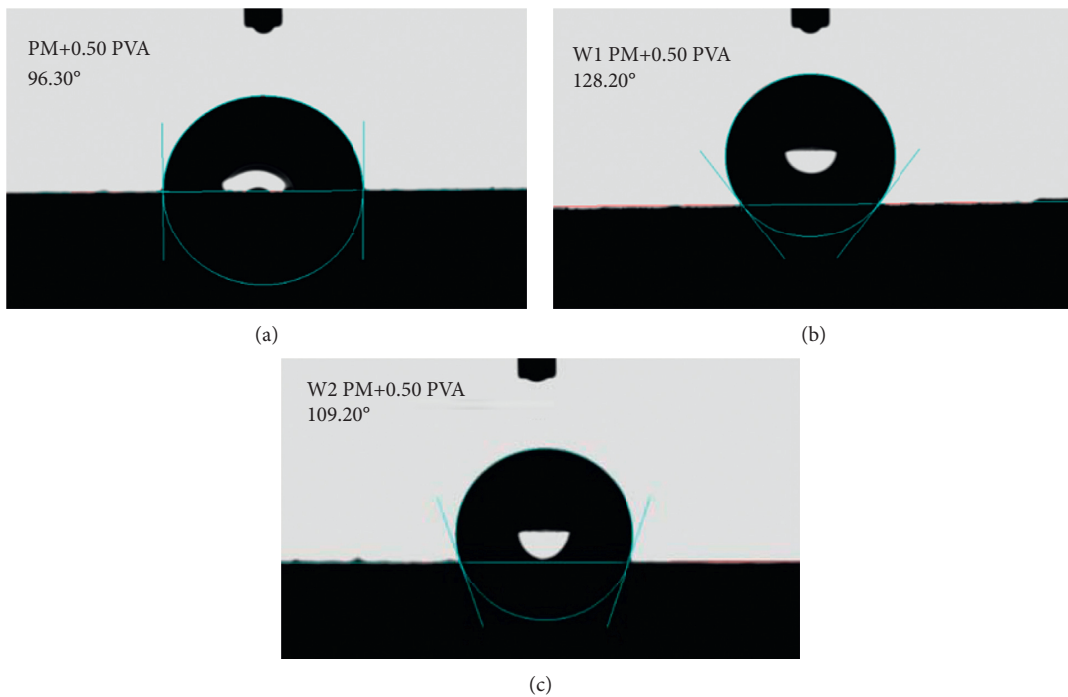


FIGURE 9: Water contact angle of LCC. (a) PM + 0.50PVA, (b) W1 PM + 0.50PVA, and (c) W2 PM + 0.50PVA.

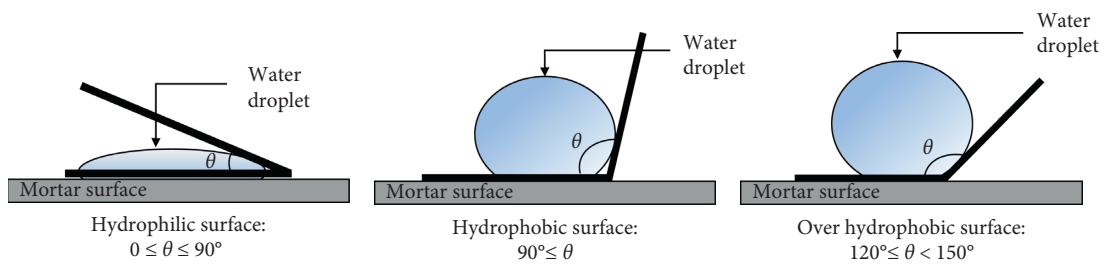


FIGURE 10: Range of water contact angle for hydrophilic, hydrophobic, and over hydrophobic surfaces [36].



surface roughness of the PM+0.50 PVA tile and consequently lowered the surface energy and enhanced the hydrophobic properties of the material.

#### 4. Conclusion

In this study, the effects of fibres and silane-based water repellent admixture on fresh and hardened properties of LCC were investigated. Based on the experimental results, the following conclusions can be drawn:

- (i) The workability of LCC decreased with the increasing fibre dosage. LCC with 0.5% basalt fibre experienced the highest reduction in workability as basalt fibre has a higher modulus of elasticity and aspect ratio than the PP and PVA fibres.
- (ii) The dry density of LCC developed was in the range of 912–985 kg/m<sup>3</sup>.
- (iii) The failure mechanism of LCC was improved with the use of fibres. The PP, PVA, and basalt fibres are effective in constraining lateral deformation and reducing the brittleness of LCC.
- (iv) An optimised amount of fibre is crucial in improving the mechanical strength of LCC. The ideal PP, PVA, and basalt fibre dosage in this study is 0.5%, 0.5%, and 0.25%, respectively. Among all the mixes, LCC with 0.5% PVA fibre achieved the highest compressive strength of 16.5 MPa.
- (v) The addition of fibre into LCC increased the flexural strength by 3.9% to 43.5%. The highest flexural strength achieved was 5.0 MPa when 0.25% basalt fibre was incorporated.
- (vi) Although silane-based water repellent admixture reduced the compressive and flexural strengths of LCC, it has an excellent effect in reducing the water absorption of LCC. The ideal dosage of silane-based water repellent admixture for the LCC is 1%.
- (vii) With 1% silane-based water repellent admixture and 0.5% PVA fibre, W1PM+0.50PVA exhibited a softening coefficient of 0.85 and a water contact angle of 128.20°. Hence, W1PM+0.50 PVA has the potential to be used in the fabrication of façade panels due to its adequate strength and hydrophobic properties.

#### Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

#### Conflicts of Interest

The authors declare that they have no conflicts of interest.

#### Acknowledgments

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