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Characteristics of lightweight foamed concrete with various contents of polypropylene fiber

Ngo Si Huy[1], Ho Si Lanh[2], and Huynh Trong Phuoc[3*]

[1]*Department of Engineering and Technology, Hong Duc University, Viet Nam*

[2]*Department of Geotechnical Engineering, University of Transport Technology, Viet Nam*

[3]*Department of Civil Engineering, College of Engineering Technology, Can Tho University, Viet Nam*

**Correspondence: Huynh Trong Phuoc (email: htphuoc@ctu.edu.vn)*

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ABSTRACT

This study investigates the influence of polypropylene (PP) fiber content on the mechanical properties of lightweight foamed concrete (LFC). Four LFC mixtures with a target dry density of 1000 kg/m^3 were designed with different PP fiber volumes of 0%, 0.25%, 0.5%, and 0.8%. The fresh unit weight (UW), dry density, compressive and flexural strengths, water absorption, thermal conductivity, ultrasonic pulse velocity (UPV), and scanning electron microscopy (SEM) of the LFC were examined. The results indicate that the fresh UW, dry density, UPV, and thermal conductivity decreased when the PP content varied from 0% to 0.8%. At 28 days, the compressive and flexural strengths of the LFC increased approximately 11.85% and 41.8% when the PP fiber amount varied from 0% to 0.8%, respectively. The result implies that the PP fiber content had a higher influence on the flexural strength content than the compressive strength. Furthermore, the results of SEM could explain well the obtained mechanical properties. The findings of this study indicate that PP fiber could be used up to 0.8% by volume to reduce the self-weight of the LFC and enhance the mechanical strength as well as thermal isolation characteristics of the LFC.

1. INTRODUCTION

The effective utilization of resources is an important and urgent issue in modern society. Recently, several innovative materials have been developed for the construction industry (i.e., reactive powder concrete (RPC), engineered cementitious composites (ECC), lightweight foamed concrete (LFC), etc.). While the RPC with super strength and excellent durability is used in the main structure subjecting to high loads (Ahmad et al., 2015; Hiremath & Yaragal, 2018), the LFC with relatively low density and thermal conductivity is suitable for use in thermal and acoustic insolated structures (Amran et al., 2015; Kozłowski & Kadela, 2018). However, similar to conventional heavy concrete, the major challenge of the RPC is the large material consumption and high density, resulting in high dead loads acting on the foundation and high construction costs. In addition, with high thermal conductivity, the use of conventional concrete in construction is a cause to raise the environmental temperature, especially in urban areas (Juraschek et al., 2018). To deal with this problem, the use of LFC instead of conventional concrete is an alternative solution; because the LFC consumes much lower materials and has significantly lower thermal conductivity than those of the conventional concrete (Amran et al., 2015; Kozłowski & Kadela, 2018). Besides, it was found that relatively low strength is a disadvantage issue, limiting the application of LFC (Abd & Jarullah, 2016). To enhance the LFC's strength, polypropylene (PP) fiber has been used in several studies (Falliano et al., 2019; Xu et al., 2021). However, the results from previous studies are not consistent. While the use of PP fiber has been stated to increase the flexural strength of LFC, its effect on compressive strength is not consistent among authors. For instance, Bing et al. (2012) have indicated that the use of PP fiber increased the compressive strength of LFC, while Falliano et al. (Falliano et al., 2019) reported that PP content had an insignificant influence on the LFC's compressive strength. Therefore, more studies are required to clarify this argument.

In another aspect, the volume of solid waste is increasing due to rapid industrial development, while the natural resources are gradually depleting. Thus, both the generation of solid waste and the depletion of natural resources have recently been recognized as the primary problems in the world. In Viet Nam, approximately 16.4 million tons of thermal power plant ashes were discharged in 2019 and a large portion of such amount was buried in landfills (Ngo et al., 2020). There is only 47% of fly ash was recycled over the world (Kurama & Kaya, 2008). In addition, around 5 million tons of steel slag were released in 2021, in which 1.2 million tons is ground granulated blast furnace slag (GGBFS) that can be used as a binder material, partially substituting cement in concrete and mortar (Ngo & Huynh, 2022). The serious influence of these industrial by-products on human health and the environment has been stated in previous studies (Ahmaruzzaman, 2010; Mohapatra & Rao, 2001). In Viet Nam, the exceeding allowance capacity of storage yards and leaking of these ashes into the environment is alerted. On the other hand, 100 million tons of cement were produced for domestic consumption and export in 2020. A large amount of CO_2 is generated and a huge quantity of natural resources is consumed during cement production, leading to the greenhouse effect and depletion of natural resources (Chen et al., 2010). Thus, encouraging the use of GGBFS and fly ash to partially replace cement is an urgent issue, which is encouraged by the Vietnamese Government in some policies.

The GGBFS and fly ash have been used in producing LFC in several studies (Kearsley & Wainwright, 2001; Wee et al., 2006); however, incorporating both GGBFS and fly ash in LFC mixtures is still limited. Besides, the use of PP fiber in LFC has been studied (Falliano et al., 2019; Wan Ibrahim et al., 2014), but most of them are used in the mixtures with only cement as the binder. To fill the gap in the literature on the effect of PP fiber content on the LFC properties and enable the use of locally available fly ash and GGBFS sources, this study investigated the effect of PP fiber content on properties of LFC containing both fly ash and GGBFS. The effect of PP fiber content on the LFC properties is investigated through the tests of fresh unit weight (UW), dry density, water absorption, thermal conductivity, flexural and compressive strengths, ultrasonic pulse velocity (UPV), and scanning electron microscopy (SEM) observation.

2. MATERIALS AND EXPERIMENTAL METHODS

2.1. Materials

Table 1 shows the chemical compositions of cement, fly ash, and GGBFS. Fly ash with a specific gravity of 2.16 was taken from Nghi Son thermal power plant. With the proportion of SiO_2, Al_2O_3, and Fe_2O_3 higher than 70%, fly ash is classified as class F based on ASTM C618 (2019). Cement type PCB40 was acquired from the Nghi Son cement company, while GGBFS type S95 was obtained from the Hoa Phat steel factory. The specific gravities of cement and GGBFS were 3.12 and 2.84, respectively. The natural sand sourced from the Ma river in Thanh Hoa province (density of 2680 kg/m^3 and water absorption of 0.42%) was used as fine aggregate. To avoid segregation and volume instability of LFC mixtures after casting, the particle size of sand was controlled within the range of 0.15 – 0.63 mm (Krämer et al., 2015). The fine powder superplasticizer (SP) (commercially named THTSP-10) with a density of 1070 kg/m^3 and the liquid foaming agent (commercially named EABASSOC) with a density of 1020 kg/m^3 were acquired from the Thang Tien company. The SP was used to ensure the flowability and flexibility of fresh mixtures. It is noted that the foaming agent was diluted with water in a ratio of 1:40 to generate the foam with a density of approximately 40 kg/m^3. The PP fiber with characteristics as shown in Table 2 was used to enhance the strength of LFC.

Table 1. Chemical compositions of cementitious materials

Compositions (wt.%)	Cementitious materials		
	Cement	Fly ash	GGBFS
SiO_2	22.30	55.73	36.87
Al_2O_3	6.68	21.67	12.38
Fe_2O_3	4.73	6.58	0.00
CaO	55.45	1.06	30.73
MgO	2.40	2.17	14.80
SO_3	1.28	0.01	0.41
Na_2O	0.56	0.22	0.33
K_2O	0.74	2.07	0.92
TiO_2	0.65	0.68	0.39
P_2O_5	0.31	0.21	0.03
MnO	0.15	0.07	1.46
LOI	0.45	6.90	0.38
Others	4.30	2.63	1.30

Table 2. Characteristics of PP fibers

Properties	Values (provided by the suppliers)
Diameter	0.03 mm
Length	12 mm
Density	0.91 g/cm^3
Melting point	160 − 170^{o}C
Tensile strength	> 500 MPa

2.2. Mixture proportions

Table 3 shows the material proportions with a fixed water-to-binder ratio of 0.22 for all LFC mixtures. Based on a suggestion of a previous study (Abdollahnejad et al., 2018), the cement: fly ash: GGBFS ratio was 2.5: 1.5: 1 and the sand: binder (including cement, fly ash, GGBFS) ratio was 0.25. Four mixtures were designed with PP fiber volume of 0%, 0.25%, 0.5%, and 0.8%, referred to as PP00, PP25, PP50, and PP80, respectively. The mixture without PP fiber, named PP00, was used as a reference mixture for comparison. The target dry density of all mixtures was 1000 kg/m^3, thus any samples with dry density out of the range 1000 ± 50 kg/m^3 were eliminated from the investigation. Based on extensive experimental work, to achieve the density of 1000 kg/m^3, the fresh UW should be about 1.1 – 1.15 times the dry density. The foam contents presented in Table 3 are the suitable values from extensive trials.

Table 3. Mixture proportions for the preparation of LFC samples

Sample code	Material proportions (kg/m^3)							
	Cement	Fly ash	GGBFS	Sand	Water	Foam	PP	SP
PP00	375.8	225.5	150.3	187.9	165.3	19.4	0.0	1.194
PP25	375.0	225.0	150.0	187.5	165.0	19.4	2.3	1.198
PP50	374.3	224.6	149.7	187.1	164.7	19.3	4.5	1.204
PP80	373.2	223.9	149.3	186.6	164.2	19.2	7.5	1.211

2.3. Sample preparation and test methods

Similar to previous studies (Bing et al., 2012; Falliano et al., 2019), dry materials were mixed first, and the solution of SP and water was gradually put in, then PP fiber was added. The foam was added in the final step and mixed until a homogeneous mixture was obtained. The UW of fresh LFC mixture was checked to satisfy the target density, then prismatic specimens with a dimension of 40 × 40 × 160 mm were prepared for properties testing. The samples were de-molded after 24h casting and kept in the laboratory condition until the testing time. The flexural strength test was conducted on the prepared prismatic specimens, then the compressive strength test was done on the two half of the broken sample after flexure. This procedure is similar to the previous study (Falliano et al., 2019). The SEM observation was carried out on the broken fragment after the compression test at 28 days. The dry density, water absorption, and compressive strength of LFC specimens were tested complying with TCVN 9030:2017 (2017), while flexural strength was tested based on TCVN 3121:2003 (2003). Thermal conductivity and UPV were directly measured using ISOMET-2014 and MATEST-C369N devices, respectively. The procedures of the UPV test are conformed to ASTM C597 (2016). While strength properties of LFC were carried out at 7, 14, and 28 days, other properties of LFC were measured at only 28 days. The average value of three specimens at each testing age was reported in this study.

3. RESULTS AND DISCUSSION

3.1. Fresh UW and dry density

The fresh UW and dry density of different LFC mixtures are shown in Figure 1. The fresh UW ranged from 1081 to 1126 kg/m^3, while the dry density varied from 965 to 1029 kg/m^3. The values of fresh UW and dry density presented in Figure 1 indicate that the difference between fresh UW and dry density was smaller than 120 kg/m^3, which satisfies the recommended requirement for foam concrete as indicated in the previous work (Thanoon et al., 2004). It can be seen that the fresh UW and dry density decreased with increasing PP fiber content. The fresh UW reduced by approximately 1.28%, while the dry density decreased around 6.22% when the PP fiber content increased from 0% to 0.8%. The reduction of fresh UW and dry density can be explained by the lower density of PP fiber in comparison with other materials in this study. Furthermore, PP fiber can occupy the volume of cement paste, thus resulting in porous microstructure and more pores (as observed in the SEM section) that contribute to the reduction of fresh UW and dry density. This result is in agreement with the findings found in the previous studies of foam concrete with the inclusion of PP fiber or polyethylene powder (Dang et al., 2022; Ibrahim et al., 2014).

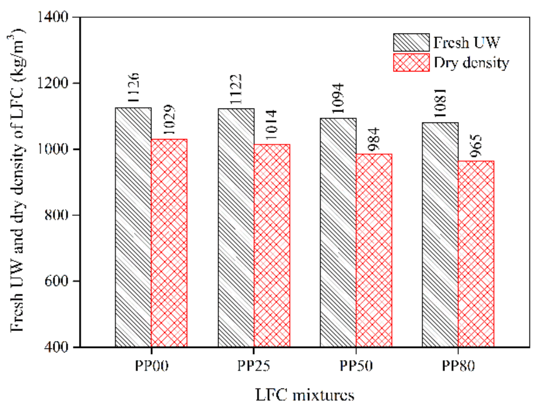


Figure 1. Fresh UW and dry density of LFC

3.2. Water absorption

Figure 2 shows the results of water absorption for four LFC mixtures at 28 days. The water absorption increased with an increase in PP fiber content, the PP fiber content raised from 0% to 0.8%, the water absorption increased by 3.5%. Although the dry density decreased, the water absorption increased with increasing the PP fiber content. This result is different from the results of foam concrete without PP fiber inclusion (Nambiar & Rammurthy, 2006; Ramamurthy et al., 2009). Previous studies of the foam concrete without PP fiber inclusion indicated that water absorption of foam concrete was mostly affected by the paste phase, thus reducing the paste volume phase (i.e., lower density) caused the reduction of water absorption in this case. In contrast, the result of this study was in agreement with the results obtained in previous studies of foam concrete with fiber or polyethylene powder inclusion (Dang et al., 2022; Raj et al., 2020). The increase in water absorption can be attributed to more voids (pores) with more inclusion of PP fiber, which can be observed in Figure 6 (in the SEM observation section). It is assumed that the surface of PP fiber can also absorb water (Huynh et al., 2020). Thus, a higher PP fiber inclusion resulted in higher water demand in the mixture. Then, the drying process led to the evaporation of water, which provided the main pore, consequently leading to a higher water absorption level. Furthermore, the inclusion of PP fiber may also damage the cell wall of foam in the fresh mixture, generating more micro-void in foam concrete, which causes a higher water absorption (Dang et al., 2022).

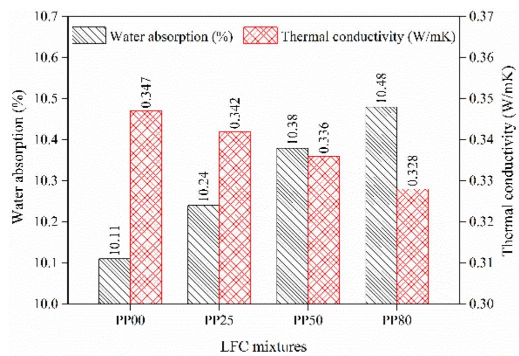


Figure 2. Water absorption and thermal conductivity of LFC

3.3. Thermal conductivity

The thermal conductivity of concrete is a crucial factor when the amount of heat transfer via conduction is considered (Asadi et al., 2018). In this study, thermal conductivity reduced from 0.347 W/mK to 0.328 W/mK when PP fiber content growing from 0% (PP00 mixture) to 0.8% (PP80 mixture) (Figure 2). This range of thermal conductivity in this study is located in the range (0.23 – 0.42 W/mW) of the LFC with dry densities from 1000 to 1200 kg/m^3 (Jones & McCarthy, 2006). The thermal conductivity of PP00 mixture (0.347 W/mK) and PP80 mixture (0.328 W/mK were 78.3% and 79.5% lower than that of conventional concrete (1.6 W/mK) with a dry density of 2200 kg/m^3 (Zahari et al., 2009). The reduction of thermal conductivity caused by the increment of PP fiber content can be explained as follows. First, it was stated that the lower dry density of LFC resulted in lower thermal conductivity (Mydin, 2011). As the above discussion on the dry density observed in Figure 1, the dry density decreased with increasing in the PP fiber content, resulting from the reduction of the thermal conductivity. Besides, another study revealed that the inclusion of PP fiber content caused a reduction in thermal conductivity (Raj et al., 2020). Because the increment of the PP fiber amount resulted in a higher porosity, resulting in the lower thermal conductivity (Raj et al., 2019).

3.4. Compressive strength

Figure 3 presents the compressive strength development of LFC with different PP fiber contents. It can be observed that the longer curing period exhibited higher compressive strength, this is explained by the cement hydration process. For all curing ages in this study, the compressive strength slightly increased with the increase of PP fiber amount. At 28 days, although the dry density decreased approximately around 6.22% when the amount of PP fiber increased from 0% to 0.8% as above discussion, the compressive increased by approximately 11.85%. This is dissimilar to the results found in previous studies of foamed concrete without PP inclusion, which indicated that the compressive strength decreased with the reduction of dry density (Falliano et al., 2019; Ramamurthy et al., 2009). The increased compressive strength found in this study is consistent with the result found in the previous studies up to 0.9% PP fiber (Bing et al., 2012; Huynh et al., 2020) but is not in agreement with other previous studies of foam concrete with fiber inclusion (Chorzepa & Masud, 2017; Mahdi et al., 2019). The increased strength can be explained by a good cohesion between PP fibers and other constituents, which can be also observed in the SEM observation result (Figure 6) (Huynh et al., 2020).

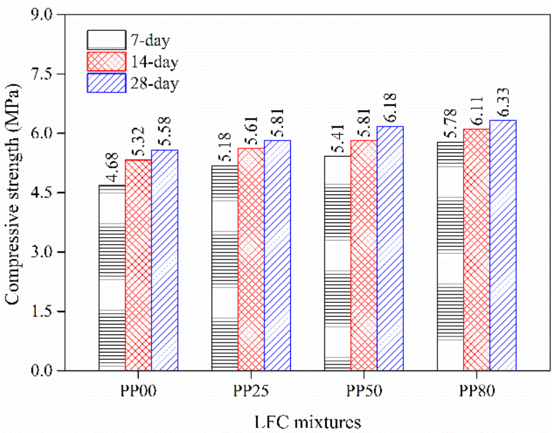


Figure 3. Compressive strength of LFC

3.5. Flexural strength

The flexural strength of different LFC mixtures is shown in Figure 4. Similar to the compressive strength, for all mixtures the flexural strength increased by 41.1% and 41.8% from 7 to 28 days when the PP fiber content increased from 0% to 0.8%, respectively. It is found that the increment of flexural strength was much higher than that in the compressive strength. The increased flexural strength obtained in this study agreed well with the results found in the previous studies (Amin & Tayeh, 2020; Leong et al., 2020). Mahdil et al. (2019) revealed that the flexural strength improved by 1.15 and 1.34 times when 0.5 and 1.0% PP fiber content were added, respectively. The enhancement of flexural strength with an increment of PP fiber content can be attributed to the fracture process of the PP fiber (Leong et al., 2020; Ibrahim et al., 2014). Because, it was stated that fiber can link the matrix and have a role as internal reinforcement as can be observed in Figure 6 (in the SEM observation section), which can resist crack propagation as well as preserve load transfer during flexure (Leong et al., 2020).

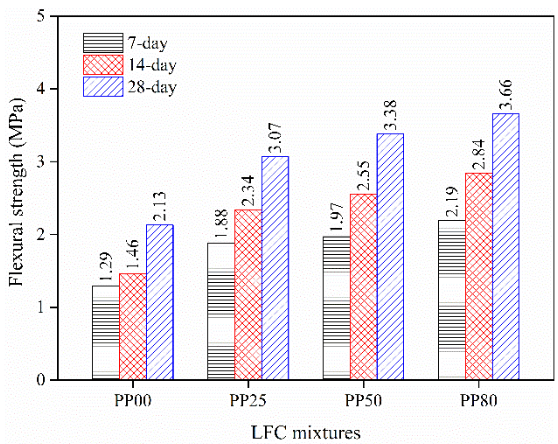


Figure 4. Flexural strength of LFC

3.6. Ultrasonic pulse velocity

Similar to compressive and flexural strengths, the UPV values increased with the curing period (from 7 to 28 days) for all mixtures. This increase is attributed to the further cement hydration process, which generates more cement hydrated products such as $Ca(OH)_2$ and calcium-silicate-hydrate (C–S–H) gel. However, when the PP fiber content increased from 0% to 0.8% (i.e., from PP00 to PP80 mixture), the UPV values decreased for all curing ages. The decrease rates were approximately 7% for three curing ages when the PP fiber content raising from 0% to 0.8%. The lower values of UPV imply the porous structure, which can be also confirmed by the lower density found and discussed in the previous section. The reduced UPV values were attributed to more pores, which can be observed clearly in SEM images (Figure 6 in the SEM observation section).

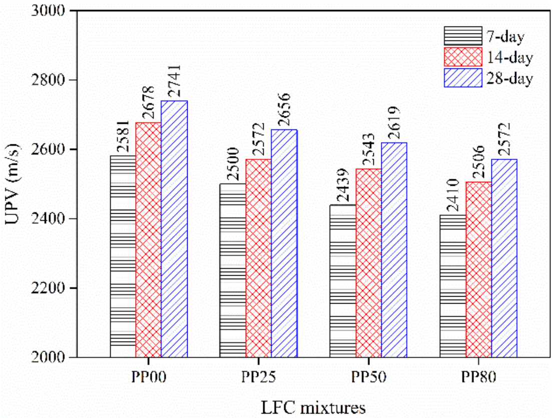
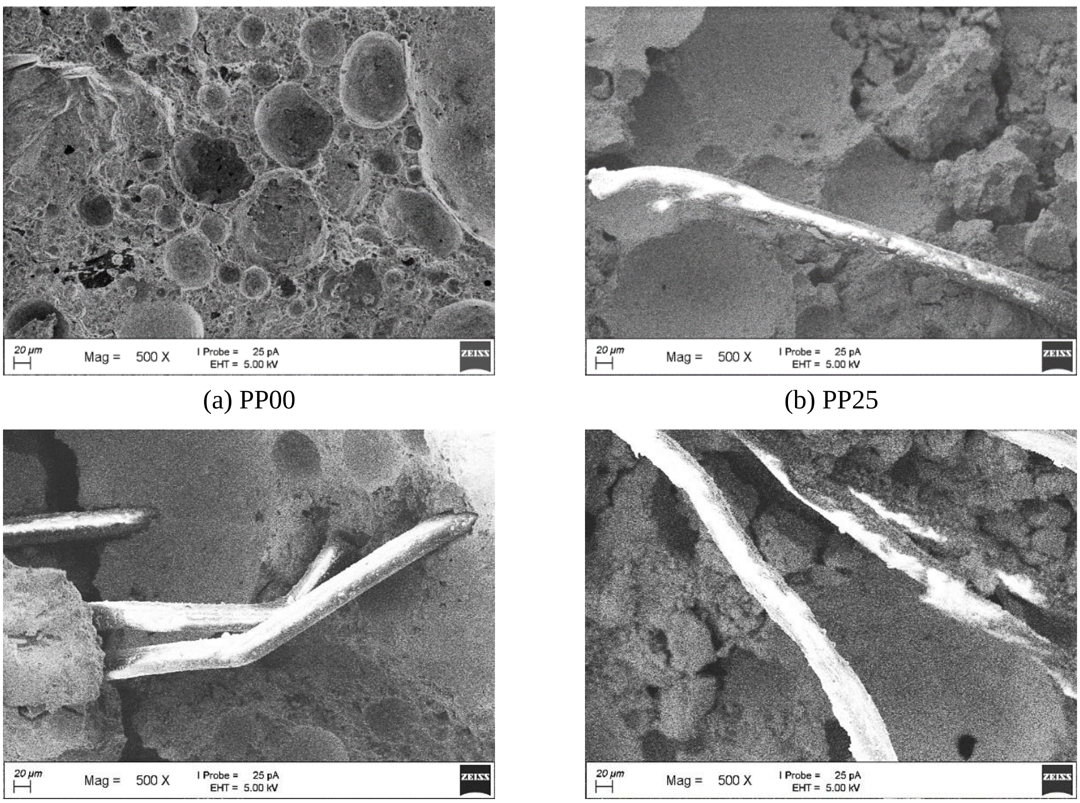


Figure 5. UPV of LFC

3.7. SEM observation

The SEM images of different LFC specimens at 28 days are presented in Figure 6. It can be seen that a uniform and dense microstructure of the PP00 mixture was observed (Figure 6a). However, with increasing PP fiber content, the microstructure of the foam concrete mixtures was more porous in order PP00, PP25, PP50, and PP80. The main reason was fiber's network created bubbles, which produced microporous (Hazlin et al., 2017). The porous structure of the mixture with the PP fiber addition could explain the reduction of density, thermal conductivity, and UPV values as well as the increase of water absorption. Furthermore, from the figure, it can be observed that the fiber that appeared on the cement paste matrix can contribute to increasing the flexural strength. Besides, the binding material on the surface of the PP fiber in the SEM images, which can help to improve the bonding between the PP fiber and cement matrix, resulted in the increased compressive strength found in the previous section. The results of SEM images could support and provide direct evidence to explain clearly the results found in previous sections.



(a) PP00 (b) PP25

(c) PP50 (d) PP80

Figure 6. SEM micrographs of LFC

4. CONCLUSIONS

This paper investigated the influence of different PP fiber contents on the mechanical properties of LFC. The SEM observation was conducted to explain the results of the obtained mechanical properties. Based on the achieved experimental results, some main conclusions can be derived as follows:

(i) The fresh UW and dry density decreased with increasing PP fiber content. The fresh UW reduced by approximately 1.28%, while the dry density decreased around 6.22% when the PP fiber content increased from 0% to 0.8%.

(ii) The water absorption increased with an increase in PP fiber content, when the PP fiber content was raised from 0% to 0.8%, the water absorption increased by 3.5%. On the other hand, thermal conductivity reduced from 0.347 W/mK to 0.328 W/mK and the UPV values also decreased by 7% when PP fiber content grew from 0% to 0.8%.

(iii) The addition of PP fiber led to a slight increase in compressive strength. At 28 days, the compressive increased approximately 11.85% when the PP fiber amount varied from 0% to 0.8%. The inclusion of PP fiber resulted in the improvement of flexural strength. The flexural strength increased by 41.8% at the age of 28 days when the PP fiber content increased from 0% to 0.8%. Thus, the PP fiber content had a more significant influence on the flexural strength than the compressive strength.

(iv) The findings of this study indicate that PP fiber could be used up to 0.8% (7.5 kg/m^3) to reduce the self-weight of the LFC and enhance the mechanical strength as well as thermal isolation characteristics of the LFC.

Because this study was only conducted for the specimens until 28 days, long-term mechanical properties and durability such as chloride penetration test should be carried out in future studies to understand clearly the effect of PP inclusion on the performance of lightweight foamed concrete.

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