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LIGHTWEIGHT FOAMED CONCRETE REINFORCED WITH DIFFERENT POLYPROPYLENE FIBER CONTENTS

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Abstract

The combined utilization of fly ash and ground granulated blast-furnace slag as a partial cement substitution in the production of lightweight foamed concrete (LFC) incorporating different polypropylene (PP) fiber was investigated in this study. The LFC was prepared with a target dry density of 1200 ± 50 kg/m^3 and the influence of PP fiber contents (e.g., 0, 0.3, 0.6, and 1.0% by volume) on the characteristics of LFC was examined in terms of fresh unit weight, dry density, water absorption, thermal conductivity, compressive strength, flexural strength, ultrasonic pulse velocity (UPV), and microstructural analysis using scanning electron microscopy (SEM) technique. Results show that the inclusion of PP fiber affected all of the studied characteristics of LFC. Increasing PP fiber percentages resulted in reducing dry density, thermal conductivity, and UPV. Whereas, both the mechanical strength and water absorption were found to be increased with PP fiber content. The result of the SEM analysis also supported these findings. At 28 days, all of the LFC obtained the target dry density of 1200 ± 50 kg/m^3, satisfying the requirements of TCVN 9029:2017. The water absorption, thermal conductivity, UPV, compressive strength, and flexural strength values of the LFC specimens were recorded at the respective ranges of below 10%, 0.394–0.461 W/mK, 2955–3019 m/s, 15.98–17.33 MPa, and 2.31–4.07 MPa. Furthermore, the results suggested that 1.0% PP fiber was the most suitable level for the production of LFC.

Keywords: lightweight foamed concrete; polypropylene fiber; mechanical strength; thermal conductivity; microstructure.

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1. Introduction

In recent years, the strong development of science and technology has led to the rapid urbanization process in the world. Consequently, the demand for concrete is also increasing rapidly, thus concrete has become the second most consumed material in the world [1]. It is fact that almost all constructed infrastructures are cement-based products that possess a high thermal conductivity of 1.3–2.9 W/mK [2]. In addition, concrete structures absorb solar radiation from the sun in the daytime and then emit heat at night, raising the temperature in the cities. Statistical data show that more than half of the world's population lives in urban areas [3]. Hence, the increased temperature in urban areas contributes to global warming, affecting the climate and the lives of urban residents. Therefore, finding

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an alternative material to conventional concrete with a lower thermal conductivity is an urgent issue. In that context, lightweight concrete is a potential consideration.

Lightweight concretes can be produced with dry density in the ranges of 300–2000 kg/m^3 using various principal techniques including (1) Creating air-filled voids by eliminating the finer fraction of normal aggregate (no-fines concrete), (2) Forming a cellular structure by adding bubbles of gas in a cement paste/ mortar matrix (lightweight aerated/ foamed concrete), and (3) Replacing normal weight aggregate in concrete mixture with lightweight aggregate (lightweight aggregate concrete) [4]. Lightweight foamed concrete (LFC) is well-known as a new material with a relatively low density, low material consumption, and excellent thermal and acoustic insulation [5–7]. The use of low-density LFC contributes to reduce the dead load of the structure and foundation, resulting in cost advantage. In addition, LFC demonstrates a high potential to be utilized for isolated thermal structures because of its low thermal conductivity. Besides, several industrial by-products such as fly ash (FA) [8], ground granulated blast furnace slag (GGBFS) [9], and silica fume [10] can be considered as the LFC's components. So far, low compressive strength has been found as one of the major challenges of LFC, limiting its application in non- or semi-structures (e.g., lightweight bricks [11], acoustic and thermal insulation architectural members [12]). Especially, the flexural strength of LFC is really low due to its low density, while the bending stress in building walls is in the range of moderate to high [13]. Thus, enhancing the flexural strength capacity of LFC is necessary, and incorporating polypropylene (PP) fiber into the LFC mixture is a potential approach [13–15]. PP fiber is a kind of linear polymer synthetic fiber obtained from propylene polymerization either by the technique of melt spinning and creating monofilaments or from a sheet of polypropylene film producing fibrillated fibers [16, 17]. PP fiber has some advantages such as light weight, high strength, high toughness, and corrosion resistance [17]. Nowadays, with a relatively cheap price and available in many sizes, PP fiber is easily acquired from the markets. It plays a role as reinforcement in concrete to enhance the tensile and flexural strengths [18–20], prevent micro-cracks [20, 21], and improve durability [21, 22]. Mazaheripour et al. [18] have indicated that using PP fiber in self-compacting concrete increased tensile strength and flexural strength by 14.4% and 10.7%, respectively. Similarly, Yao and Zhong [19] stated that the addition of 0.2% PP fibers by volume registered the increment in tensile strength of both normal and high strength concretes after 28 days. Çelik and Bingöl [20] reported that the presence of 0.15 – 0.3% PP fiber by volume not only increased the tensile and flexural strengths but also prevented the formation and development of microcracks in concrete. The positive effect of PP fiber on the resistance to post-crack propagation was also reported in Wang et al.'s study [21]. Furthermore, the durability indicators of concrete including drying shrinkage, rapid alkali-silica reaction expansion, frost resistance [21], and the impact loading resistance [22] were also enhanced due to the addition of PP fiber.

In Vietnam, the industrialization process is happening rapidly, so the demand for energy and steel is also increasing. Many thermal power plants and steel factories have been built to meet the above needs. A large amount of FA and bottom ash has been released by the thermal power plants [23], while around 1.2 million tons of GGBFS were released by the steel factories in 2019 [24]. Several critical problems related to the generation of these industrial by-products have been indicated as exceeding the capacity of storage yards, environmental pollution, and human health [23–25]. Thus, turning FA and GGBFS into useful construction materials instead of burying them in landfills is a crucial concern. On the other hand, cement has been widely used as a primary binder in LFC production [11, 26, 27]. However, the production of cement depletes the natural resources and emits a large quantity of CO_2, seriously impacting the natural environment [28, 29]. Therefore, some studies had been done to investigate the use of either FA or GGBFS as a partial cement substitution in producing LFC [8, 9].

There still has a gap in the literature regarding the combined use of both FA and GGBFS in LFC. Moreover, most previous studies put the major concern on compressive strength only, thus the flexural strength of LFC needs to be studied more. To fill this gap, this study aims to use FA and GGBFS to replace 50% cement in the production of LFC. Various PP fiber contents were also incorporated to enhance the mechanical strength of LFC. Then, the influence of PP fiber content on the engineering properties of LFC was investigated in terms of fresh unit weight (UW), dry density, water absorption, thermal conductivity, flexural strength, compressive strength, and ultrasonic pulse velocity (UPV). The microstructure of the LFC was also examined using the scanning electron microscopy (SEM) technique. Furthermore, the results of the present study encourage the reuse of industrial by-products in the production of sustainable construction materials and thus can be considered as a potential solution for industrial solid wastes treatment.

2. Materials and experimental methods

2.1. Materials

A mixture of grade-40 Portland cement blended (PCB), FA, GGBFS, natural river sand, water, superplasticizer (SP), PP fiber, and foam was used for the preparation of LFC specimens. It is noted that the PCB, FA, and GGBFS used were supplied by Nghi Son cement company, Nghi Son coal thermal power plant, and Hoa Phat steel corporation with their specific gravities of 3.12, 2.16, and 2.84, respectively. The major chemical compositions of these binder materials are shown in Table 1. In addition, this investigation used locally available raw FA with its loss on ignition (LOI) of 6.9%, which is slightly higher than the suggested value in ASTM C618 [30]. The natural river sand with a density of 2.68 T/m^3, water absorption of 0.42%, and particle size in the ranges of 0.15–0.63 mm was used as fine aggregate. The particle size of sand was selected following the recommendation of Krämer

Table 1. Chemical compositions of cementitious materials

Materials	Compositions (% by weight)								
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	Others	LOI
PCB	22.3	6.7	4.7	55.5	2.4	1.3	0.6	6.0	0.5
FA	55.7	21.7	6.6	1.1	2.2	-	0.2	5.6	6.9
GGBFS	36.9	12.4	-	30.7	14.8	0.4	0.3	4.1	0.4

Table 2. Characteristics of PP fiber

Properties	Values (provided by the suppliers)
Diameter	0.03 mm
Length	12 mm
Density	0.91 g/cm^3
Melting point	160–170°C
Elongation at break	15–20%
Tensile strength	> 500 MPa

et al. [27] in order to avoid the segregation and instability of foam in LFC. The SP of commercial named THTSP-10 in fine powder form with a density of 1.07 T/m^3, pH of 6-8, and chloride content of around 0.02% was used in the LFC mixture. The liquid foaming agent of EABASSOC with a density of 1.02 T/m^3 and pH of 6.7 was used to prepare foam. The foaming agent was mixed with water at a ratio of 1:40 (by volume). The foam with a density of about 40 g/l was generated by using a foam generator with a pressure of 6 bar. The properties of PP fiber are given as shown in Table 2. The images of foam and PP fiber are shown in Figs. 1(a) and 1(b), respectively.

(a) Foam product

(b) PP fiber

Figure 1. Foam product and PP fiber

2.2. *Mixture proportions*

Four LFC mixtures with different PP fiber contents were designed with a constant water-to-binder ratio of 0.22. Due to the lower specific gravity of FA and GGBFS in comparison to that of PCB, these materials were used to minimize the density of LFC with a respective quantity of 20% and 30%. To determine the fine aggregate content, a suggestion from a previous study [31] was carefully considered as the sand content should not be exceeded 50% binder amount. Thus, a sand content of 25% (by weight of total binder) was selected. The SP was used to reduce water content and adjust the workability of the LFC mixtures within the range of 18 ± 2 cm. The proportions of all materials are shown in Table 3. The control mixture (F00) was designed without PP fiber, while the other three mixtures were designed with PP fiber contents of 0.3, 0.6, and 1.0% (by volume), referred to as F03, F06, and F10, respectively. Notably, all of the LFC mixtures were designed with a target dry

Table 3. Mixture proportions of LFC

Sample name	Material proportions (unit: kg/m^3)							
	PCB	FA	GGBFS	Sand	Water	Foam	PP fiber	SP
F00	443.1	177.2	265.8	221.5	194.9	16.1	0.0	1.403
F03	442.2	176.9	265.3	221.1	194.5	16.1	2.7	1.412
F06	441.3	176.5	264.8	220.6	194.2	16.0	5.3	1.418
F10	440.1	176.0	264.0	220.0	193.6	15.9	8.8	1.431

density of 1200 ± 50 kg/m^3. Extensive trials were conducted to determine the suitable foam content for obtaining the above target dry density.

2.3. Sample preparation

Prior to mixing, all of the LFC ingredients were prepared as given in Table 3. Then, the dry materials (e.g., PCB, FA, GGBFS, and sand) were mixed for 3 minutes using a mechanical laboratory mixer. A solution of water and SP was gradually added to the dry mixture and mixed for another 3 minutes. After that, PP fiber was embedded and continuously mixed to obtain a homogenous fresh mixture. The foam was generated and immediately added to the fresh mixture; mixing was continued until the foam was uniform distribution in the fresh mixture. These mixing steps conform to the mixing method from previous studies [10, 13].

(a) Samples in casting (b) Samples after de-molding

Figure 2. The preparation of LFC samples

After mixing, the fresh unit weight (UW) of all LFC mixtures was measured. As the previous experience of the author, to achieve the dry density of 1200 ± 50 kg/m^3, the fresh UW of the LFC mixtures should be 5–7% higher than the target LFC's dry density. The LFC mixtures with appropriate fresh UW values were used to cast the LFC specimens for testing. Remarkably, TCVN 9030:2017 [32] suggested using the cubic specimen of 100×100×100 mm for the compressive strength test. However, this standard does not present the method for the bending test. Therefore, similar to the previous study [13], prismatic beams of 40×40×160 mm (see Fig. 2) were prepared for all test methods, which will be detailly described in the next section. It is noted that the bending test was conducted first and the compression test was then performed using the two halves of the broken prismatic beam. In the compression test, the square bearing steel plate with a dimension of 40 mm was used, thus the compressive strength was calculated based on the cross-section of 40×40 mm^2. The LFC specimens were fabricated using steel molds as shown in Fig. 2(a). After casting 24h, the specimens were de-molded and stored in the laboratory at open-air and room conditions (see Fig. 2(b)) until the testing time.

2.4. Test methods

The properties of LFC specimens were evaluated in terms of dry density, water absorption, thermal conductivity, flexural strength, compressive strength, and UPV. Microstructural characteristic of the hardened LFC was also observed using the SEM technique. As above mentioned, all tests were conducted on prismatic samples with the dimension of 40×40×160 mm. In detail, dry density, water absorption, and compressive strength were tested following TCVN 9030:2017 [32]. The flexural strength was tested based on TCVN 3121:2003 [33], which is similar to the method stated in the previous study [13]. Thermal conductivity was directly measured using an ISOMET-2014 portable device, while UPV was also directly measured using a MATEST-C369N device complying with ASTM C597 [34]. A fractured LFC specimen in the compression test was selected for SEM observation under the EVO18 equipment. The compressive strength, flexural strength, and UPV tests were performed at 7, 14, and 28 days, while other tests were conducted at 28 days and the average value of three repeated measurements at each testing age was reported as the final value of each LFC mixture.

3. Results and discussion

3.1. Fresh unit weight and dry density

The prepared LFC mixtures had fresh UW and dry density values within the respective ranges of 1217–1304 kg/m^{3}and 1161–1239 kg/m^3 (Table 4). Averagely, the fresh UW values of the LFC mixtures were about 5–7% higher than their dry density values. In real practice, dry density can be considered as one of the indicators of the lightweight characteristics of LFC. Test results found that adding more PP fiber to the LFC mixtures resulted in lower fresh UW and then reduced the LFC's dry density. In detail, the LFC specimens with 0, 0.3, 0.6, and 1.0% PP fiber registered the dry density values of 1239, 1190, 1168, and 1161 kg/m^3, respectively. Thus, the incorporation of 0.3, 0.6, and 1.0% of PP fiber resulted in about 4.1, 6.1, and 6.7% dry density reduction compared to the no fiber LFC, respectively. In other words, the higher the PP fiber volume, the lower the dry density of the LFC specimens. This reduction is mainly attributable to the relatively low density of the PP fiber (see Table 2), which was also confirmed by the previous study [35]. As a result, all of the prepared specimens obtained the target dry density of 1200 ± 50 kg/m^3, satisfying the requirement stipulated in TCVN 9029:2017 standard [36].

Table 4. Fresh unit weight and dry density of LFC

Sample name	PP fiber content (% by volume)	Fresh unit weight (kg/m^3)	Dry density (kg/m^3)
F00	0.0	1304	1239
F03	0.3	1275	1190
F06	0.6	1252	1168
F10	1.0	1217	1161

3.2. Water absorption

Water absorption is one of the indicators of the durability characteristics of LFC concrete [37]. The water absorption results of the LFC specimens are shown in Table 5. It is found that water absorption increased proportionally with PP fiber content in the LFC mixtures. For instance, the LFC specimens with 0.3, 0.6, and 1.0% PP fiber contents absorbed 8.69, 8.97, and 9.11% water, respectively, which was about 0.3, 3.6, and 5.2% higher than the water absorption rate of the fiber-free specimen (8.66%). PP fiber is well-known as hydrophobic fiber, which retains water in the matrix. During the hardening process, such water will be released, forming air pores/voids within the LFC structure [38]. Therefore, when higher PP fiber was added to the LFC mixture, an increased void volume led to a higher water absorption rate of LFC. This finding is confirmed by the SEM observation, which will be discussed later in Section 3.7. In addition, similar findings were previously reported by

Wu et al. [35] and Jhatial et al. [38]. Moreover, the increasing void/ pore volume due to the addition of higher PP fiber percentage can also be used to explain the reduced dry density of LFC as already mentioned in Section 3.1. As stated by a previous study [39], although water absorption is rarely used to determine the concrete quality, most of the good concrete registered a water absorption rate of below 10% by weight. Based on this level, the LFC produced in this study can be considered as good-quality concrete.

Table 5. Water absorption and thermal conductivity of LFC

Sample name	PP fiber content (% by volume)	Water absorption (%)	Thermal conductivity (W/mK)
F00	0.0	8.66	0.461
F03	0.3	8.69	0.428
F06	0.6	8.97	0.408
F10	1.0	9.11	0.394

3.3. *Thermal conductivity*

Thermal conductivity is one of the attractive characteristics of LFC [40] making this material type more advantageous in comparison with other normal materials. The thermal conductivity values of the tested LFC with different PP fiber contents are provided in Table 5. The LFC's thermal conductivity reduced as increasing the percentage of PP fiber. For example, the LFC specimens containing 0.3, 0.6, and 1.0% PP fiber had thermal conductivity values of 0.428, 0.408, and 0.394 W/mK, which were about 7.7, 13.0, and 17.0% lower than the no fiber specimen (0.461 W/mK), respectively. These results are in line with the above discussion as the inclusion of more PP fiber leads to the presence of more air pores/ voids, leading to the lower heat transferring through the LFC and thus resulting in lower thermal conductivity [38, 41].

3.4. *Compressive strength*

Compressive strength is a crucial mechanical property of LFC that is mostly considered in quality control. The compressive strength values of the LFC specimens at 7, 14, and 28 days are presented in Fig. 3, finding that all LFC specimens displayed a continuous increase with curing age. This is attributable to the combined effect of both cement hydration and pozzolanic reaction FA and GGBFS in the system [42]. In addition, compressive strength values were found to be increased slightly with the increase in PP fiber percentage. For example, the LFC specimens with 0.3, 0.6, and 1.0% PP fiber earned the 28-day compressive strength values of 16.08, 16.32, and 17.33 MPa, which were about 0.6, 2.1, and 8.4% higher than the strength value of the no fiber specimen at the same age, respectively. The observed strength enhancement may be attributed to the bridging effect of PP fiber, resisting the propagation of cracks and enhancing the bonding mechanism between fiber and foamed concrete [35, 43].

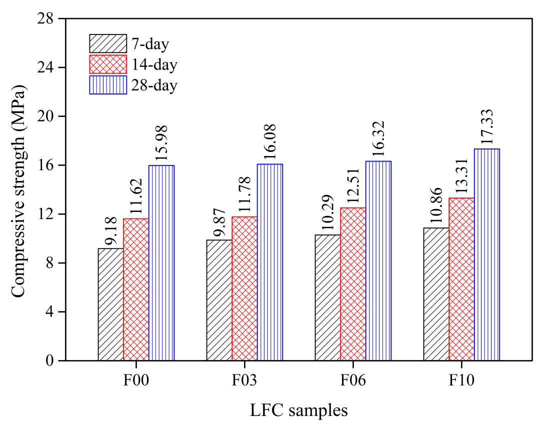


Figure 3. Compressive strength of LFC

3.5. Flexural strength

A similar trend to compressive strength development was observed for the results of flexural strength development of the LFC specimens (Fig. 4). As expected, the flexural strength of all LFC specimens increased with curing age. Also, the inclusion of higher PP fiber percentages enhanced the flexural strength of the LFC more significantly than the compressive strength. This finding is due to the super tensile strength of PP fiber (higher than 500 MPa) as seen in Table 2. For instance, the 0.3, 0.6, and 1.0% PP fiber specimens earned the respective flexural strength values at 28 days of 2.91, 3.42, and 4.07 MPa. These values were approximate 26.0, 48.1, and 76.2% higher than the flexural strength of the no fiber specimen. Therefore, the incorporation of PP fiber contributed to the flexural toughness enhancement and better resistance to bending stress [35, 44]. As a result, the concentration of stress around the cracks could be reduced, hindering the crack development and consequently improving the flexural strength of the LFC. From the obtained results, it can be said that the bridging effect was much more dominant than the pore-related issue indicated in the previous sections.

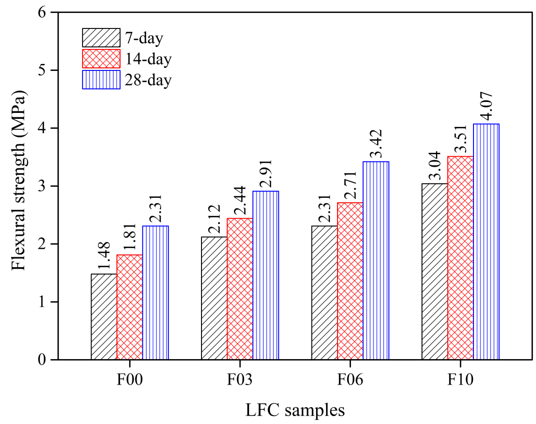


Figure 4. Flexural strength of LFC

3.6. Ultrasonic pulse velocity

UPV is a non-destructive test used commonly to estimate the quality of concrete such as detecting internal cracks and defects, predicting compressive strength and porosity, etc. [45]. Fig. 5 presents the UPV values at 7, 14, and 28 days of the LFC with different PP fiber percentages. It was consistent with the development in compressive strength that the UPV values of all LFC specimens increased with curing age due to the combined effect of both cement hydration and pozzolanic reaction FA and GGBFS in the system [42]. Besides, this study found that the inclusion of PP fiber slightly reduced the UPV values of the LFC. In other words, lower UPV values were recorded in the LFC specimens containing more PP fiber. For instance, the 28-day LFC specimens with 0.3, 0.6, and 1.0% PP fiber had UPV values of about 0.4, 1.0, and 2.2% lower than that of the no fiber specimen, respectively. As aforementioned, the addition of PP fiber was associated with the formation of voids/ pores, increasing the travel time of ultrasonic pulse through the test specimens and thus resulting in lower UPV values. A similar finding was also reported by Dawood et al. [46].

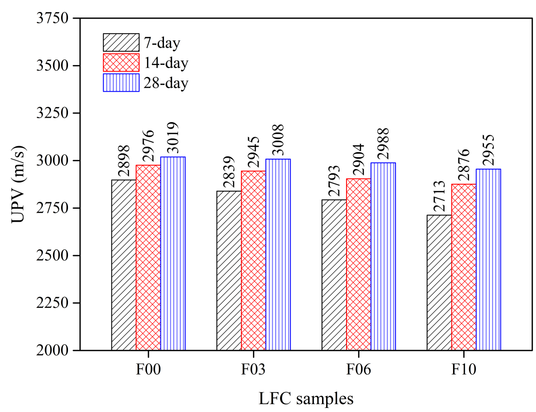


Figure 5. UPV of LFC samples

The relationship between dry density and UPV and thermal conductivity of the LFC at 28 days is displayed in Fig. 6. As shown, the approximate linear lines were validated using high coefficients of determination ($R^2 > 0.783$), indicating the close correlation among the three properties of all LFC mixtures. The fact that lower dry density was associated with lower thermal conductivity and lower UPV values of the LFC. This result suggests that one of the three characteristics (e.g., dry density, UPV, and thermal conductivity) may be used to determine the value of the others.

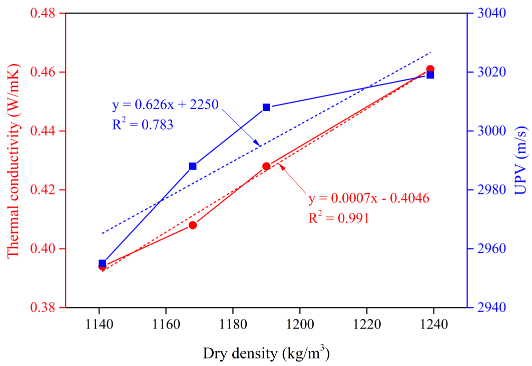
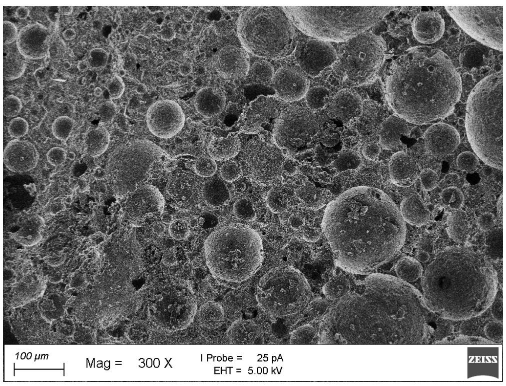


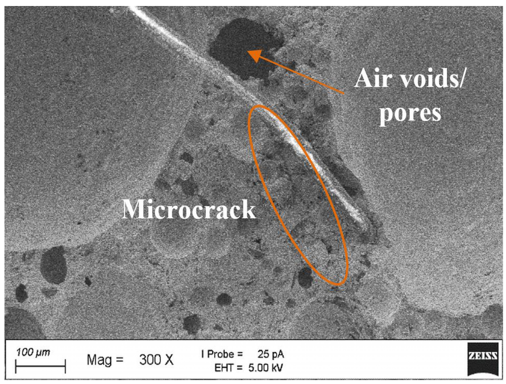
Figure 6. Correlation among dry density, thermal conductivity, and UPV of LFC

3.7. SEM observation

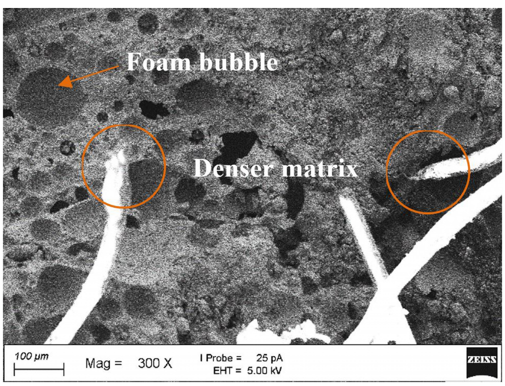
The microstructural characteristics of LFC specimens with different PP fiber content were examined through their SEM micrographs as shown in Fig. 7. As a result, the number of air voids/ pores was found to be gradually increased within the matrix containing more PP fiber. The interfacial bonding between the PP fiber and concrete matrix could also be observed. Due to the fibrillated process and interfacial adhesion, the denser matrix surrounding PP fibers was observed. The fiber networks created air bubbles, forming microporous and decreasing interfacial bonding in the system [47]. Hence, PP fiber played an important role in bridging force crossing the cracks formed within the system and



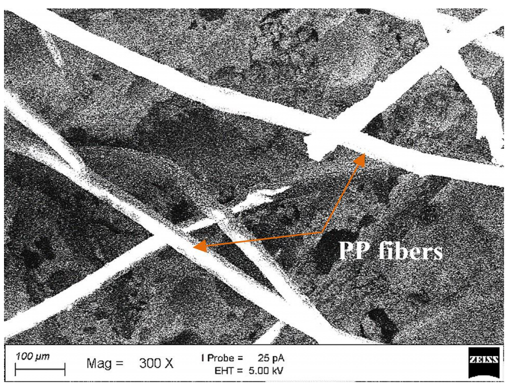
(a) F00



(b) F03



(c) F06



(d) F10

Figure 7. SEM images of LFC

thus reducing the microcracks [48]. The SEM observation provides strong evidence for the results of reduced dry density, thermal conductivity, and UPV; and increased water absorption and mechanical strength of the LFC as discussed in the previous sections.

4. Conclusions

This study evaluated the effect of different PP fiber additions on the characteristics of LFC incorporating FA and GGBFS as cement substitution. The influence of PP fiber percentages on the fresh UW, dry density, water absorption, thermal conductivity, flexural strength, compressive strength, UPV, and microstructure of the LFC was examined. Based on the experimental results, the following conclusions can be drawn:

- Although the fresh UW and dry density of the LFC were reduced with increasing PP fiber content, the reduction was insignificant. All of the prepared specimens obtained the target dry density of 1200 ± 50 kg/m^3, satisfying the requirements of TCVN 9029:2017.

- The addition of PP fiber reduced the 28-day thermal conductivity and UPV and increased the 28-day water absorption of LFC. At 28 days, all LFC mixtures registered water absorption, thermal conductivity, and UPV values of below 10%, in the ranges of 0.394–0.461 W/mK, and 2955–3019 m/s, respectively.

- Both the flexural and compressive strengths increased with increasing PP fiber content. The flexural strength was improved more significantly than the compressive strength. As a result, the LFC specimens earned the compressive strength and flexural strength values in the respective ranges of 15.98–17.33 MPa and 2.31–4.07 MPa.

- Both the number of air voids/ pores and the interfacial bonding between the PP fiber and concrete matrix could be observed in the SEM micrographs of the LFC, providing strong evidence for the results of reduced dry density, thermal conductivity, and UPV; and increased water absorption and mechanical strength of the LFC.

- As the experimental results, the F10 mixture could be considered the most suitable mixture because this mixture exhibited the highest strength and lowest dry density and thermal conductivity while water absorption was less than 10% and UPV was comparable to other mixtures.

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