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EVALUATION OF LONG-TERM STRENGTH AND DURABILITY PERFORMANCE OF CEMENTITIOUS COMPOSITES WITH LOW POLYPROPYLENE FIBER CONTENT AND LOCAL RIVER SAND

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Abstract

This study aims to investigate the long-term mechanical properties and durability of cementitious composites (CC) with low polypropylene (PP) fiber content and local river sand. The CC samples were prepared with different water-to-binder (w/b) ratios (0.20, 0.25, and 0.3), low PP fiber content (0.6% by mass of binder), locally available river sand, and fly ash (FA) sourced in the Mekong Delta region, corresponding to the mixture name WB20, WB25, and WB30, respectively. Then, the mechanical properties were investigated through compressive and flexural strengths and ultrasonic pulse velocity tests, while durability was assessed via chloride ion penetration and sulfate resistance. The results revealed that the mixture with the w/b of 0.25 achieved the best performance in terms of both mechanical and durability performance due to the optimal conditions of compaction, mixing water content, and also the latent pozzolanic reaction of FA in the hydrated cementitious composites. Besides, the CC samples with 0.6% PP fiber exhibited ductility behavior under compression and flexure, characterizing that CC samples do not completely separate from each other when damaged due to the fiber bridging effect. Moreover, the CC samples obtained excellent long-term durability (up to 120 days old) in terms of sulfate attack and chloride resistance in the following order WB25 > WB20 > WB30. The results of this study confirm the applicability of the local materials for producing good quality and low-cost cementitious composites.

Keywords: cementitious composites; polypropylene fiber; long-term strength; durability.

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1. Introduction

Concrete is known a common material that used in the construction industry. It has many merits such as high compressive strength and elastic modulus, cost-effectiveness, and availability of local materials, however, it contains some disadvantages such as brittle properties and low tensile strength.

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In general, short fibers are employed to enhance the durability and brittleness of concrete. There are two types of high-performance fiber-reinforced concrete/composite including engineered cementitious composites (ECC) and ultra-high-performance concrete (UHPC). ECC was a class of ultra ductile fiber-reinforced cementitious composites invented in the early 1990s [1], which has been applied in many aspects of civil engineering works such as maintenance and repairing of construction works. ECC has a tensile strain higher than 3%, which is much larger than that of conventional concrete [1–3]. Due to the excellent performance such as small crack width properties (smaller than 100 µm), high ductility, and high strain characteristics, ECC can be applied for many structures, which have some special and specific requirements for repairing bridges. Besides, UHPC, developed in France in the 1990s, was a new class of concrete with superior characteristics including high flowing ability, high mechanical strength and ductility, and high resistance to environmental attacks. Generally, UHPC is characterized by compressive strength of greater than 150 MPa [4].

Generally, there are several research approaches to ECC, including the design of mixture proportion and evaluation of mechanical properties and durability [5, 6]. ECC commonly consists of cement, micro silica sand, fly ash (FA), and fiber content of 2% by volume [7, 8]. Polypropylene (PP) and polyvinyl alcohol (PVA) are generally supplied to cementitious material to generate ECC [7]. Although the fiber content in ECC is limited by 2%, the cost to produce the ECC is still much higher than conventional concrete due to the high cost of fiber [9]. Indeed, not all concrete structures require a high tensile strength ability (higher than 3%). Thus, it is necessary to consider the balance of fiber content as well as the mechanical characteristic of ECC. A study investigated the effect of PVA fiber content varying from 0 to 2% with an interval of 0.5% on the mechanical properties, density, and workability of ECC. It was found that the mechanical properties of ECC improved with the increase of PVA content, while the density and workability reduced. Pakravan et al. [10] indicated that excessive amounts of fiber caused a reduction in toughness and ductility of ECC due to low workability and rheology. Due to the high cost of materials, the reduction in workability, low abrasion resistance (due to usage of very fine sand), and an appropriate requirement of the mechanical properties, it is necessary to find other suitable solutions. Many attempts have been done to partially replace cement with by-product materials such as FA and ground granulated blast-furnace slag, they revealed that this solution could reduce drying shrinkage, enhance workability, and reduce material cost, but affected the early strength of ECC [11–16]. A previous study indicated that a ratio between FA to cement (FA/C) ranging from 0.11 to 2.8 is appropriate to produce ECC [17] and to obtain high and fast strength at an early age, a lower ratio of FA/C is used. Currently, due to the fast development in the economy, a huge amount of FA has been discharged every day from the thermal power plant in Southern Vietnam. However, FA has not been treated effectively, which causes many problems related to environmental issues. Therefore, using FA as a binder or construction material in the concrete industry is a good solution to utilize FA.

Moreover, to reduce the material cost for producing ECC, micro standard sand should be replaced with another kind of local fine sand (including river sand), which has a particle size larger than micro standard sand. It was reported that medium-size river sand with a maximum particle size of 625 µm and average grain size of 300 µm could be used successfully to produce ECC [18]. Another study used river sand with a size smaller than 600 µm to produce a modified ECC, and they reported that it was feasible to use locally available ingredients in producing a new version of ECC that can perform well in compression and flexural [19]. Besides, a previous study employed a mixture of local river fine and coarse to make a low-cost ECC, it was indicated that this mixture of fine and coarse had an insignificant influence on the mechanical properties [20]. Based on the results of the previous studies, it could be concluded that ECC with a larger size of sand particle could have a comparable mechanical property. As a result, this study employed a large amount of local river sand, which is available in the Mekong Delta (in the South of Vietnam) to produce a modified ECC.

Regarding the literature review, the water-to-binder (w/b) ratio strongly affects the properties of conventional concrete [21–23]. Similar to traditional concrete, the w/b ratio also significantly influences the mechanical properties, and it was revealed that an optimum w/b ratio was 0.25 ± 0.05 [17]. A study on ECC reported that a decrease in w/b (from 0.42 to 0.2) led to an enhancement of the compressive strength [18]. Another study revealed that when the w/b ratio ranges from 0.13 to 0.24, the increase of the sand/binder ratio from 0.3 to 0.8 resulted in an improvement of compressive and tensile strength but caused a reduction of ductility [24]. The effects of the w/b ratio (from 0.25 to 0.37) on the mechanical properties of ECC found that at the ages of 7 and 28 days, the compressive and flexural strength reduced with an increment of the w/b ratio [25]. Thus, it can be said that the influences of the w/b ratio have been well investigated, however, these previous studies only conducted for ECC contain a high volume of fiber (normally 2% by volume). Thus, there is limited research regarding the effect of w/b ratios on the mechanical properties and durability of cementitious composites with low fiber content, which is considered a kind of modified ECC, intending to reduce the cost.

Based on above the literature, this study is aimed to assess the applicability of a modified ECC called cementitious composites (CC) using local river sand and FA incorporated with low PP fiber content. This study can contribute knowledge to practice and literature by following directions. First, this is the first study utilizing local river sand and FA for producing CC for a case study in Vietnam. Second, the long-term mechanical properties and durability were firstly evaluated using different tests. Furthermore, this study also investigated the influence of w/b ratios on the long-term mechanical properties, and the durability of CC with low fiber content.

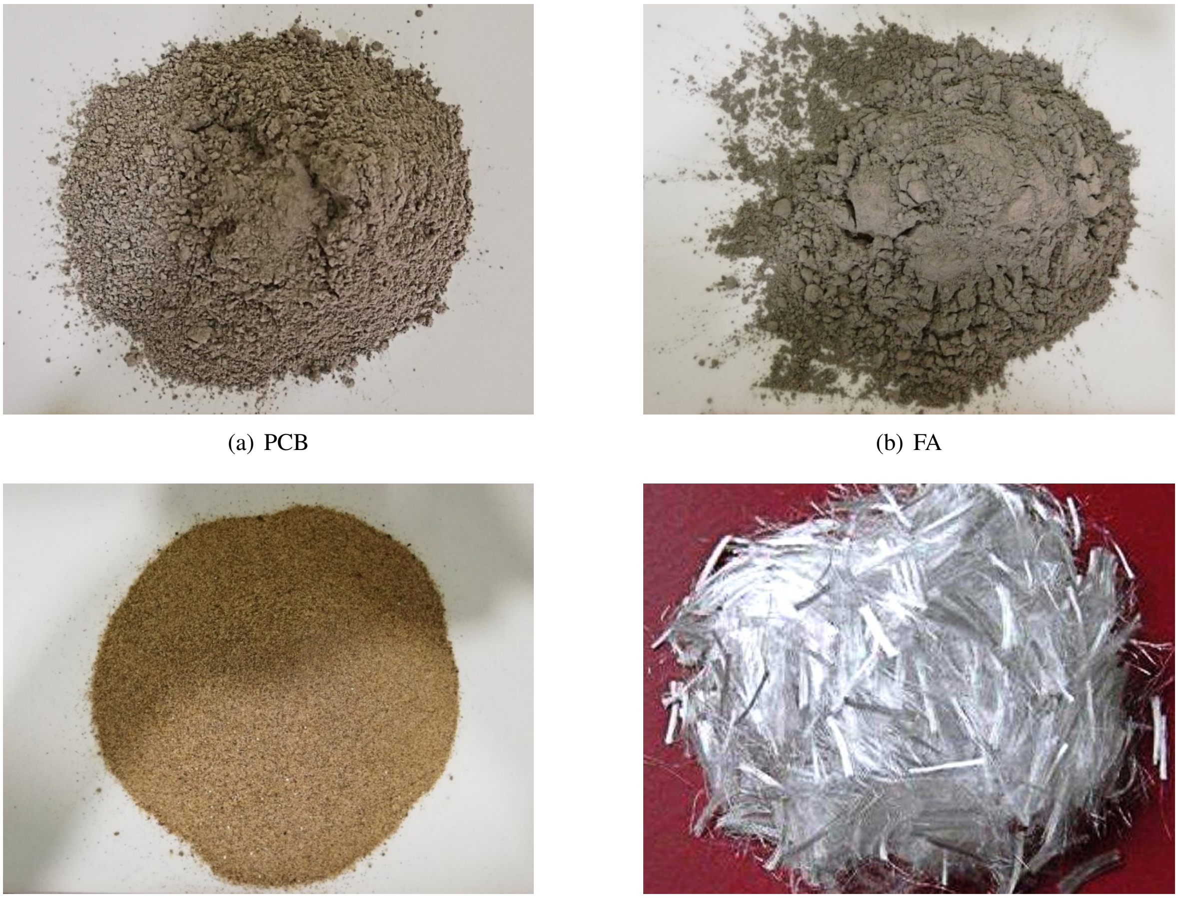
2. Materials and experimental methods

2.1. Materials

The materials used for preparing cementitious composites include Portland cement blended (PCB), FA class F, river sand (RS), and PP fiber (see Fig. 1). PCB was taken from Ha Tien Cement Joint Stock company and FA was taken from Duyen Hai thermal power plant (Tra Vinh province, Vietnam). The specific gravities and chemical compositions of PCB and FA are shown in Table 1. The density, water absorption, and fineness modulus of RS were 2.69 g/cm^3, 1.12%, and 1.45, respectively. The PP fiber satisfying ASTM C1116 standard was employed in this study. The diameter and length of PP fiber are 30 μm and 12 mm, respectively. Typical properties of PP fiber provided by the manufacturer are presented in Table 2. To adjust the workability of cementitious composite mixtures, a local sourcing polycarboxylate-based superplasticizer (SP) with a density of 1.15 g/cm^3 was used.

Table 1. Specific gravities and chemical compositions of PCB and FA

Materials	Specific gravities	Chemical compositions (% by mass)						
		SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	SO_3	Others
PCB	3.09	23.5	6.0	3.7	2.0	59.9	-	4.9
FA	2.13	59.2	26.7	6.1	0.9	1.1	0.1	5.9



(a) PCB (b) FA (c) RS (d) PP fiber

Figure 1. Images of raw materials

Table 2. Characteristics of PP fiber

Properties	Value
Diameter	0.03 mm
Length	12 mm
Melting point	160–170 °C
Elongation at break	15–20%
Tensile strength	> 500 MPa
Acid and alkali resistance	High
Density	0.91 g/cm^3

2.2. Mixture proportions

Table 3 lists the designed CC mix proportions for laboratory assessment based on the literature review. In this study, three different w/b ratios of 0.20, 0.25, and 0.30 were chosen for preparing the CC mixtures to have a better understanding of the effects of w/b ratios on the properties of CC with available local materials, FA, RS, and low PP fiber content. In Table 3, the abbreviation of the mixture (ID) is represented by the letter (WB indicating the water-to binder) and number (meaning the percentage of w/b). For example, the WB25 mixture implies the CC mixture with a w/b of 0.25. In this study, FA content is fixed at 15% by weight compared to the total weight of the binder (sum of PCB and FA) and the ratio of RS/binder is also fixed by 1:1. To control the slump flow in a range of 250–270 mm, the SP was adjusted and the amount of SP is shown in Table 3. The PP fiber content was designed to be 0.6% by mass of the binder for all mixtures based on the result of the earlier work [26]. Indeed, the PP fiber with a small percentage was added to the CC mixture to have a small reduction in workability but have an appropriate enhancement of mechanical properties as well reducing drying-shrinkage influence.

Table 3. Mixture proportions of the CC samples

Mixture ID	w/b	PCB (kg/m^3)	FA (kg/m^3)	RS (kg/m^3)	Water (kg/m^3)	SP (kg/m^3)	PP fiber (kg/m^3)
WB20	0.20	906	160	1066	213	21.3	6.4
WB25	0.25	862	153	1019	255	12.2	6.1
WB30	0.30	827	146	973	292	7.8	5.8

2.3. Sample preparation

The CC samples were made in the laboratory using a mechanical mixer. The mixing procedure can be briefly described as follows: (i) First, SP and water were mixed in a split container; (ii) Cement and FA were mixed in a dry state using the mixture for approximately 1 minute to achieve a uniform dry blended powder; (iii) the first part of the water-SP solution was added to the blended of FA and cement during the mixer was running, then continuing mixing for two minutes to ensure the homogeneity paste; (iv) Sand and the second part of water-SP solution were added and the mixture was mixed for two minutes; (v) all PP fibers and remaining solution of water-SP were added slowly and mixed for two more minutes until the fibers were well distributed in a uniform mixture. After mixing, the fresh CC mixtures were cast into the mold to prepare the specimens for other tests. After casting, the specimens were stored in the laboratory for 24 hours, after that, the CC specimens were de-molded and cured in water until the designated age.

2.4. Test methods

To evaluate the application of CC using local materials in Southern Vietnam, the long-term mechanical properties and durability were examined. In detail, the long-term mechanical properties were assessed through flexural, compressive strength, and ultrasonic pulse velocity (UPV) tests. The durability was evaluated using porosity measurement, chloride ion penetration (CIP), and sulfate resistance tests. The detailed descriptions of these tests are presented in Table 4, while the images of these tests are displayed in Fig. 2.

Table 4. Summarisation of test methods

No.	Test name	Sample size (mm)	Testing age (days)	Reference standards
1	Flexural strength	40 × 40 × 160	28, 56, 120	TCVN 3121-11:2003 [27]
2	Compressive strength	40 × 40 (using broken prisms from flexure)	28, 56, 120	TCVN 3121-11:2003 [27]
3	Porosity	50 × 50 × 50	28, 56, 120	ASTM C1403 [28]
4	CIP	∅100 × 50 (cutting from ∅100 × 200)	28, 56, 120	TCVN 9337:2012 [29]
5	UPV	∅100 × 200	28, 56, 120	ASTM C597 [30]
6	Sulfate resistance	25 × 25 × 285	0, 7, 28, 56, 120	ASTM C1012 [31]


(a) Compressive strength test

(b) Flexural strength test


(c) Sulfate resistance


(d) CIP test


(e) UPV test

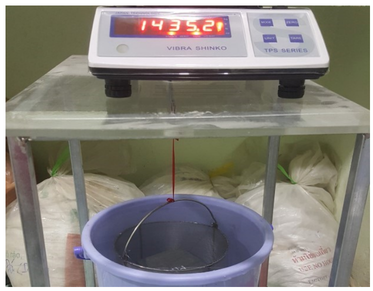

(f) Porosity test

Figure 2. Apparatus for the experimental programs

3. Results and discussion

3.1. Porosity

It is well-known that porosity strongly affects both the mechanical strength and durability of CC [32]. Generally, the higher porosity causes lower mechanical strength and durability performance. Fig. 3 shows the porosity values of various CC samples designed with different w/b ratios up to 120 days.

It can be seen from Fig. 3 that the porosity of CC containing low fiber content, ranging from 6.06 to 8.03%, was relatively higher than those of no-fiber samples (normally < 5% by volume) due to the addition of fibers [33]. In addition, it is observed that the WB30 mix with w/b of 0.3 had the highest porosity of 6.71–8.03%, whereas the porosity of the WB25 was the lowest in the range of 6.06–7.13%. This can be explained by the fact that the fine particles in the sample were well compacted together under the optimal conditions of natural compaction and hydration process (optimal water content), resulting in a homogeneous mixture with lower porosity once hardening. Moreover, due to the latent pozzolanic reaction of FA in the hydrated cementitious composite, the size and discontinuity of the pores improved over time, contributing to a denser matrix [34].

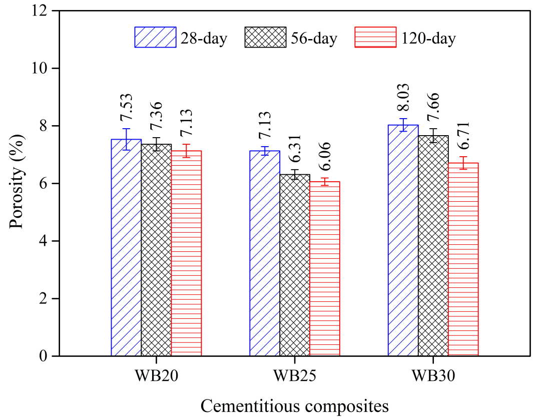
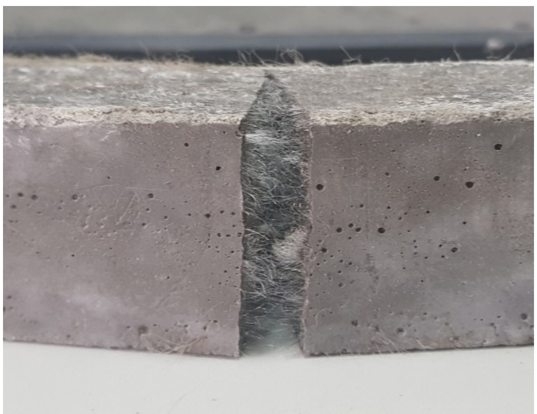


Figure 3. Porosity results of different mixtures

3.2. *Flexural and compressive strengths*

In this study, the purpose of the addition of PP fiber at a low dosage of 0.6% (by total binder weight) to the CC samples is to increase the flexural ability and ductility (see Fig. 4). Overall, this ductility of CC is significantly different from conventional cementitious material's brittle behavior due to fiber-bridging effects until failure.



(a) Flexural characteristic

(b) Compressive ductility of CC

Figure 4. (a) Flexural characteristic and (b) compressive ductility of CC

It can be found in Figs. 5 and 6 that the WB25 mix, which has the smallest porosity, demonstrated the highest strengths in both flexure and compression at all ages even though the differences are not remarkable. For instance, the flexural and compressive strengths of WB25 were 17.8 and 114.9 MPa, respectively at the age of 120 days, while those of WB20 and WB30 were 16.1 and 112.5 MPa and 15.7 and 110.6 MPa, respectively. Similar trends were also observed as evidenced in Figs. 5 and 6 at 28 and 56 days old. Therefore, it can be considered that a w/b ratio of 0.25 was an optimum ratio in terms of strengths or mechanical properties in this study. It can be explained that, if the amount of water is less than the optimal content, not the whole of the binder has yet been fully hydrated. As a result, fewer hydration products are formed, more pore volume could be formed, and pore size in the matrix is also larger, thereby reducing the sample strength. Inversely, in the case of too much water in the mixture, the looser matrix leads to lower strength of the specimen [35]. Furthermore, it is postulated that relatively good adhesion between the PP fiber and the cementitious matrix supported the strength gain and higher deformation of the CC samples [34].

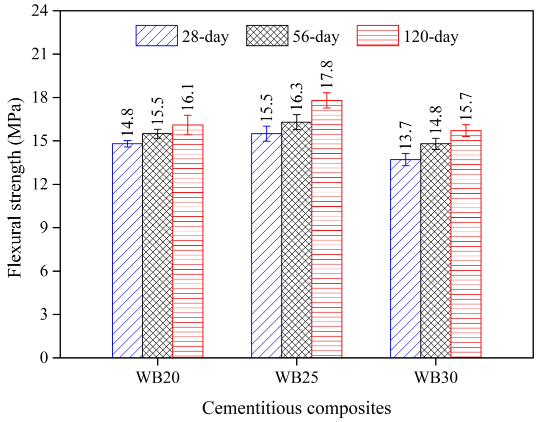


Figure 5. Flexural strength results

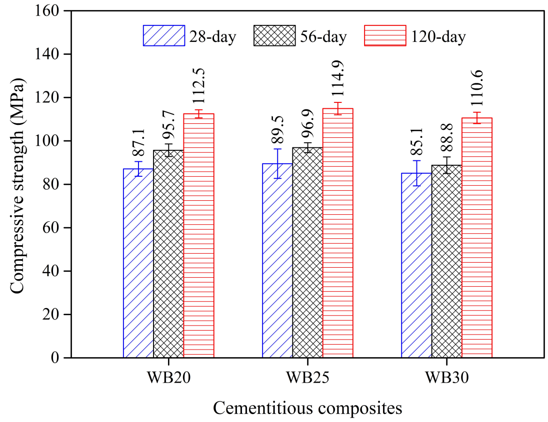


Figure 6. Compressive strength results

The flexural and compressive strengths of the CC samples over time are shown in Figs. 5 and 6, respectively. As mentioned in the previous section, it is observed that there was an increasing tendency in strengths of CC up to 120 days due to the pozzolanic reaction of FA with cement hydrate products. However, the increasing rates at a later period were more pronounced in the case of the compression test, which was in the range of 28–30%, whereas in the case of flexural strength, the increment just ranged from 8 to 15% as compared to 28-day-old strengths. The results show that the inclusion of low PP fiber content insignificantly affected the flexural strength improvement of CC as compared to that of compressive strength, but similar to the compression, the failure state of the two halves of the beam was not completely separated. It is caused by the fibers being broken or pulled out at the crack plane of the beam when gradually increasing the applied force until complete failure [32].

3.3. *Chloride ion penetration*

Fig. 7 shows the effect of w/b ratios on total charges passed through various CC samples in terms of the exposure period as long as 120 days. CIP value is one of the experimental approaches to represent the pore system in the CC specimens. The higher the CIP value is obtained, the more connecting voids/ pores exist in the structure [36].

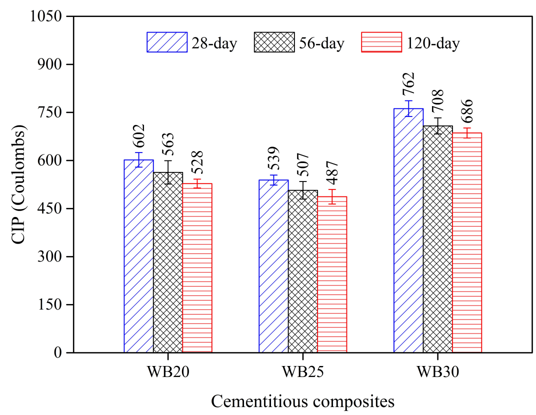


Figure 7. Chloride ion penetration results

It could be seen from Fig. 7 that the WB25 mix had the lowest CIP value and tended to decrease gradually throughout the experimental period up to 120 days, demonstrating the best resistance to CIP in this experiment. Following was the WB20 mix and the lowest performance was observed in the WB30 mix. This trend was similar to the measured porosity value and has been explained in Section 3.1. For example, the CIP values obtained in sample WB20 were 539, 507, and 487 coulombs at 28, 56, and 120 days, respectively; while the corresponding values measured in sample WB30 were 762, 708, and 686 coulombs. These values were relatively 40% higher than those of the WB20. This demonstrated that the w/b ratio not only affected the total porosity but also influenced the linking/connecting properties of the pores in the structure of CC samples [24]. However, the maximum charges passed in this experiment were less than 1000 coulombs and, as per ASTM C1202, as a result, all CC mixtures in this study showed very low chloride ion penetrability. A similar result has also been reported in another previous study [37].

3.4. Ultrasonic pulse velocity

One of the recent popular non-destructive tests applied in the assessment of the durability of cementitious composites is UPV measurement based on the principle of the propagation of a pulse of the ultrasonic wave passing through the sample [38]. In general, the denser specimen has a higher value of UPV, which indicates the smaller the porosity. Due to the presence of FA in the composition of CC samples, it is expected that the measured UPV values will tend to increase gradually due to the improvement in the structure of the sample over time, especially at a later age (i.e., after 28 days). Fig. 8 shows the measured UPV values in samples with different w/b ratios over time. Similar to the porosity value, the WB30 sample gave the lowest UPV value (4467, 4517, 4625 m/s at 28, 56, and 120 days, respectively), followed by the WB20 (4533, 4617, and 4796 m/s), and the highest was of the WB25 (4566, 4687, and 4884 m/s). However, it can be seen that the measured UPV values after 28 days old ranged from 4517 to 4884 m/s were in the range of above 4500 m/s, proving that the CC samples are classified as excellent quality grade according to [39, 40].

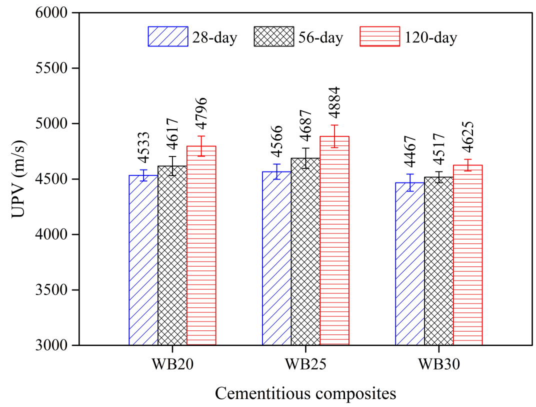


Figure 8. Ultrasonic pulse velocity results

3.5. Sulfate resistance

Another approach to evaluate the durability of the CC is the ability to resist the sulfate attack, usually determined in terms of the length change of the mortar sample in the sulfate environment as according to ASTM C596. Fig. 9 presents the length change due to the sulfate attack of the CC samples. Similar to previous durable properties, the sulfate resistance performances of CC samples with different w/b ratios were in the order: WB25 > WB20 > WB30. The WB25 specimens exhibited the smallest in terms of length change and time-dependent increment as compared to other samples, especially after 7 days of exposure. For example, the length change was measured as 0.076, 0.068, and 0.097% for the WB20, WB25, and WB30 specimens, respectively, at the 7-day test. In addition, it was also found that the changes in length were increased by 20.6, 18.2, and 23.3% in the

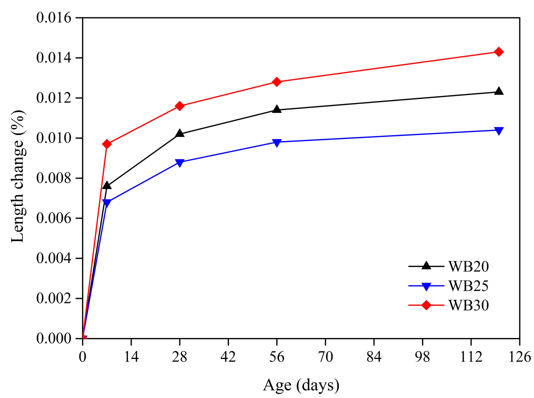


Figure 9. Length change due to sulfate attack

WB20, WB25, and WB30 samples, respectively, after 120 days exposed to a sulfate environment. Based on the obtained results, it could be inferred that the WB25 specimen was the best in terms of durability regardless of age. It can be attributed to the denser cementitious matrix due to pozzolanic reaction and the addition of low-volume of PP fiber [34].

4. Conclusions

The present study experimentally investigated the long-term strength and durability performance of CC with low PP fiber content. Although the general performance of CC with low PP fiber content may be less remarkable than standard ECC with higher fiber content (normally 2% by volume), the CCs investigated in this study were believed to be more economical and much easier to mix in practice. Based on the obtained results, the following conclusions could be drawn:

- All of the CC samples prepared in this study exhibited ductility and integrity characteristics under both compressive and flexural tests. Due to the smallest porosity, the WB25 mix presented the highest compressive and flexural strength in both the short and long term. Thus, it can be considered that a w/b ratio of 0.25 was an optimum ratio for preparing CC samples in terms of mechanical properties in this study. This behavior can be explained by the optimal conditions of natural compaction and water content during casting (short-term) and also the effect of the pozzolanic reaction of FA at later ages in the hydrated cementitious composite (long-term).

- Similar to strength development features, CC samples containing low PP fiber content showed excellent long-term durability performance in terms of CIP, UPV, and length change due to sulfate attack and were in the following order: WB25 > WB20 > WB30. It is because the size and discontinuity of the pores in CC mixtures improved over time due to latent pozzolanic reaction of FA and optimal hydration process with sufficient water content, contributing to a denser matrix and thus resulting in better durability in the WB25 mix.

- Further research should be done to clarify and provide much more scientific or reliable evidence (i.e., deformation capacity, SEM test for long-term evaluation, etc.) or other related durable performances of CC incorporating such various low fiber volumes. These future studies will contribute to the widespread and confident application of the modified engineered cementitious composites in practice.

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