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EXPERIMENTAL EVALUATION ON ENGINEERING PROPERTIES AND MICROSTRUCTURE OF THE HIGH-PERFORMANCE FIBER-REINFORCED MORTAR WITH LOW POLYPROPYLENE FIBER CONTENT

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Abstract. Recently, high-performance fiber-reinforced mortar/concrete (HPFRM) has been researched and developed in many fields such as repair, maintenance, and new construction of infrastructure works due to its high strain capacity and tight crack width characteristics. Optimizing the design of mixture proportions and structures using HPFRM is still a complex mechanical and physical process, depending on the design principles, specific site conditions, and their local materials. This study aims to develop an HPFRM with low polypropylene fiber content by using locally available ingredients in Southern Vietnam to address the deficiencies commonly observed in traditional cement grout mortars. Three mixture proportions were prepared with different water-to-binder (w/b) ratios of 0.2, 0.25, and 0.3. Then, the performance of HPFRM was evaluated in both fresh and hardened stages. Additionally, the microstructural characteristics of each mix design were also assessed through scanning electron microscope observation. The experimental results showed that the optimum w/b of 0.25 and a fixed dosage of 0.6% polypropylene fiber produced positive impacts on the rheological, mechanical properties, and also ductility of the high-performance mortar. It was concluded that HPFRMs are promising for cost-effective and sustainable cement mortars.

Keywords: high-performance fiber-reinforced mortar, engineered cementitious composite, drying shrinkage, mechanical strength, microstructure.

1. INTRODUCTION

Mortar, a bonding agent between building materials, is normally a mixture of water, fine aggregate, and binding material like cement, lime, etc. One of the most popular applications of mortar in practice is used for filling voids under machines or other structural elements, sealing joints/openings in surfaces, and reinforcing existing structures, especially applied in pavement overlay, link-slab for bridge expansion joints, thin-wall structures, etc. In Vietnam, on the commercial market, there are several cementitious products for concrete pavement structures such as cement-based grout (Sikagrout) and high-performance polymer-modified, fiber-reinforced mortar (Sika Monotop®R) of Sika Limited (Vietnam); Delpatch™ elastomeric concrete of D.S. Brown (USA); DOM1-17, a kind of polymer concrete, which was developed by University of Transport and Communications; GM-F self-leveling non-shrink grout of Vietnam Institute for Building Science and Technology (IBST), along with conventional cement grout/mortar, etc. Moreover, in recent years, high-/ultra-high performance concrete has attracted a lot of attention in engineers and scientific communities and is usually developed based on using steel fiber reinforcement and mineral additives (industrial by-products such as fly ash, slag, etc.) [1,2]. For example, high-strength concrete reinforced with steel fiber was used to retrofit the pavement of historical monuments [3], the aircraft Hangar [4], the surface of Thang Long Bridge's top deck [5], etc. The practical reality has shown that the current cementitious materials have not brought high efficiency [6]: mainly focuses on developing early high strength, improving bond strength, limiting shrinkage, and the production cost is still quite expensive (due to most of them are exclusive products developed by foreign companies), little or no attention has been paid to the environmental friendliness and the limitation of crack development of cementitious materials. Therefore, the long-term durability and environmental friendliness of these materials still need to be continuously monitored and evaluated for the long term.

At present, one of the most promising approaches in terms of cement-based materials is high-performance fiber-reinforced mortar, namely Engineered Cementitious Composite (ECC for short herein, invented by Professor Victor Li, University of Michigan, USA) which has been researched and developed in many fields such as repair, maintenance, and new construction of infrastructure works [6]. Due to its high strain capacity and tight crack width characteristics (typically below 100 μm), in contrast to conventional cement mortar/concrete (Fig. 1), this material can be used for structural components requiring high energy absorption capacity, control of crack propagation, and opening under the effect of large deformation, etc. Particularly, ECC ultra-thin white topping has been successfully applied to achieve greater performance on the deteriorated hot mix asphalt (HMA): reducing the maintenance work while increasing the durability of the HMA pavement [9].

Several studies have already presented the unique properties of ECC. In general, the two main research directions of ECC are the selection of mixture ingredients, evaluation of basic mechanical properties, and some related-durable aspects of ECC [9]. Typically, standard ECC consists of cement, fly ash, micro silica sand, and a fiber content of 2% by volume: fiberglass [10], or polypropylene (PP) fibers [10, 11], or polyvinyl alcohol (PVA) fibers [12], etc. with a common fiber length of 12 − 19 mm, in addition with appropriate chemical admixture (i.e, superplasticizer). ECC can possess high deformability of 3 − 7% (compared to conventional concrete of 0.01 − 0.1%) and can achieve a compressive strength of 25 MPa within 12 hours, 35 MPa in 24 hours, 48 MPa after 7 days, 55 MPa at 28 days, and 56 MPa at 60 days [13]. Thus, ECC ensures the durability and load-carrying capacity of the wearing/surface material layer [9,14]. Furthermore, it is important to note that the different mechanical properties of ECC could be achieved by modifying the proportions and ingredients of mixtures based on practical requirements.

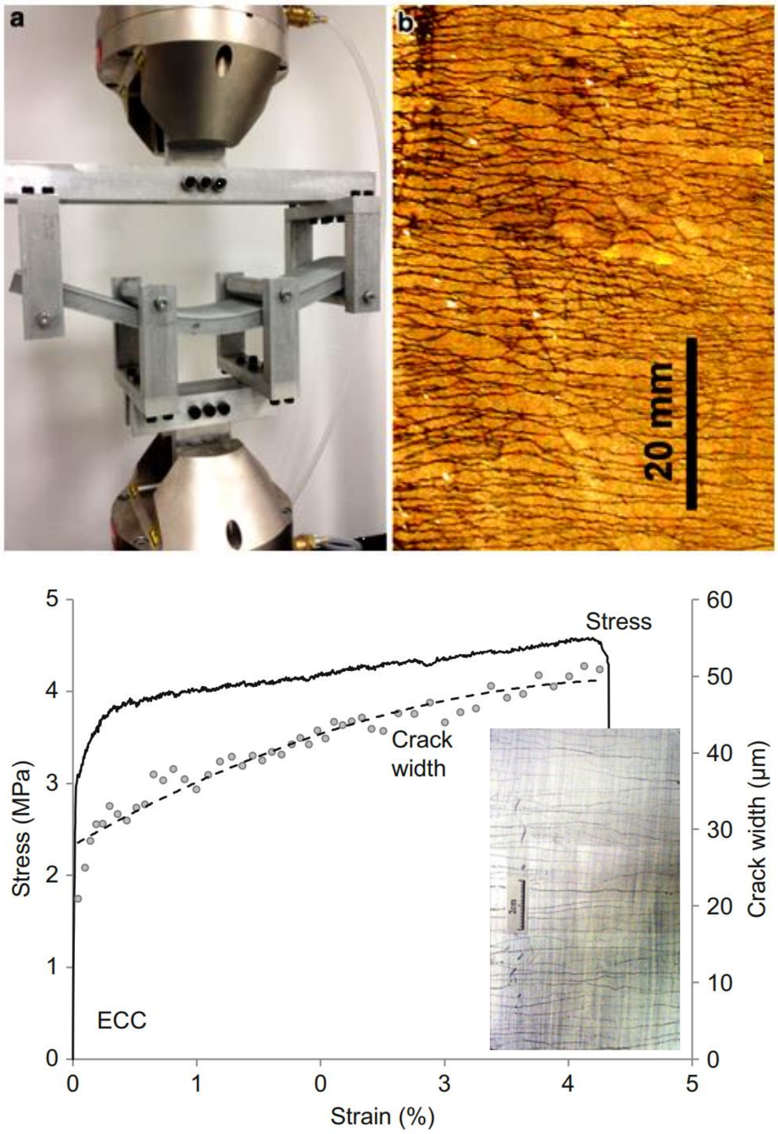


Figure 1. Basic characteristics and differences of ECC compared to conventional cement mortar/concrete: (above) under tensile [7] & (below) flexure [8].

ECC with very promising characteristics and performance, however, the application of this relatively new material still has many issues for further improvements, such as high initial material cost due to the use of fiber, silica fine sand, and a large amount of cement (less environmental friendliness); a reduction in abrasion resistance (using very fine sand as aggregate), and typically higher requirements on field construction techniques (difficult to mix and ensure uniform distribution of fiber in the matrix). To make ECC a viable construction material, several approaches have been developed to solve these above problems according to the open literature review. Replacing ordinary Portland cement with supplementary cementitious materials, i.e. fly ash, slag appeared to be the effective and environmental way to reduce the amount of cement required and drying shrinkage risk, improving the workability but will influence the early strength of ECC. It was recommended that the fly ash to cement ratio (FA/C) can range from 0.11 to 2.8 [15]. And a lower FA/C ratio is often used once the early and fast strength is required. Presently, in Vietnam, FA sources are available/abundant by-products in localities with existing thermal power plants (i.e. Tra Vinh, Binh Thuan provinces, etc.) that have not been effectively processed and are often occupied by very large areas. Thus, such a study on the effective use of FA in concrete/mortar is an important, timely, and sustainable contribution to construction technology and materials [16]. Moreover, locally available ingredients (i.e. river or local fine sands, PP fibers) also should be applied to reduce the initial high cost of materials. For instance, the medium-sized river sand of a maximum grain size of 625 μm and an average grain size of 300 μm was employed in [17]. Lee et al. [11] also investigated the feasibility of using local river sands below 600 μm and available PP fibers (Malaysia) in producing the new version of ECC which can perform well in compression and flexure. A research group in the Transportation Consortium of South-Central States (USA) developed a cost-effective ECC with locally available two types of river sands (coarse and fine) providing minor effects in the mechanical properties of ECCs evaluated [18]. Another study tried to use white quartz sand with different particle size distributions, naturally available in the Arabian Gulf, to produce strain-hardening cementitious composites [19]. A modified ECC mixture containing concrete sands conforming to ASTM C33 as the only aggregate was prepared at Nevada University [15]. The use of locally available concrete sands would not only reduce the cost of ECC but also allow to development of various ECC mixes for a bridge deck overlay material. It could be confirmed from previous research that it is possible to produce ECC having good mechanical performance when larger sand particles are used. Therefore, this research sought to incorporate a larger amount of abundant fine river sands in the Mekong Delta (Southern Vietnam) having a larger particle size than the standard micro sand commonly used in ECC to create HPFRM, a kind of modified ECC that is expected to compete with the traditional cement grout/mortar or available commercial products.

It should be noted that the critical variable in the ECC mixture design was found to be the water-to-binder (w/b) ratio. Various previous researches showed that the ideal w/b ratio is 0.25 ± 0.05 [15]. ECC mixes are designed with w/b ratios outside of this range will have reduced tensile strengths and strains. For example, a decrease of the w/b ratio from 0.42 to 0.20 resulted in an improvement of the compressive strength of ECC [17]. Ye et al. [20] found that in the w/b ranges of 0.13 – 0.24, along with the increase of sand/binder ratio from 0.3 to 0.8, the compressive strength and tensile strength were enhanced, however, the ductility of ECC was reduced. Yang et al. [21] also examined the effects of w/b ratios of 0.25, 0.31, 0.33, and 0.37 on the mechanical properties of ECC at 7 and 28 days. The experimental result showed that the compressive strength and flexural strength of the ECC decreased with the increase of w/b. It can be concluded that the effect of w/b ratios on the properties of ECC has been examined carefully. Moreover, fiber contents of 1.5 – 2.5% were evaluated (typically 2% by volume) and test results showed that higher fiber contents will result in higher tensile strengths and strains of ECC [15]. Note that, higher fiber contents increase the unit cost of ECC and compromise ease in production, and an especially significant reduction in workability of fresh mortar/concrete. Though there are a lot of researches on the impact of w/b on ECC properties, very few studies have been carried to examine the influence of this critical variable on the low fiber content cementitious composite (less than 1% fiber content) but still perform well in compression and flexural, namely HPFRM. Optimizing the design of mixture proportions and structures using HPFRM is still a complex mechanical and physical process, depending on the design principles, specific site conditions, and their local materials. Thus, the development and application of this material is still an important research direction in the construction field.

Based on the short overview above, this study aims to investigate the feasibility of using locally available ingredients in Southern Vietnam and incorporating a lower polypropylene fiber content for producing a modified, cost-effective version of ECC, namely HPFRM in this study, that can perform better or comparable as compared to conventional cement grout/mortar or available commercial products. Furthermore, the effect of w/b ratios on the engineering properties and microstructure of the HPFRMs is also discussed.

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

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

2. EXPERIMENTAL DETAILS

2.1. Properties of materials

Locally available ingredients were utilized in this study to produce HPFRM: Vicem Ha Tien PC40 Cement (certified to TCVN 2682-2009 and ASTM standard C150 Type I), class-F FA, which is a by-product of Duyen Hai thermal power plant (Tra Vinh province), and washed fine river sands (RS) with density, water absorption, and fineness modulus of 2.69 g/cm^3, 1.12%, and 1.45, respectively. The specific gravities and chemical compositions of cement and fly ash are presented in Table 1. The particle size distribution of river sand is shown in Fig. 2 (left). PP fiber conforming to ASTM C1116 was used in this study with its properties as shown in Table 2. The average length and diameter of the PP fiber were 12 mm and 30 μm, respectively, resulting in an aspect ratio of 400 (Fig. 2, right). A local sourcing polycarboxylate-based superplasticizer (SP) type G in yellow liquid form with a density of 1.15 g/cm^3 was used to ensure the required flowability of the mortar mixtures.

2.2. Mix design and proportions

Table 3 shows the designed HPFRM mix proportions for laboratory evaluation based on the findings of the literature review. Three different w/b ratios of 0.20, 0.25, and 0.30 were selected for the HPFRM mixtures to better understand the influence of w/b ratios on the HPFRM properties with locally sourced river sand, FA, and lower commonly used fiber content in ECC. The specimen ID was nominated by two capital letters WB representing the water-to-binder ratio by mass, and a number indicating the percentage of w/b used. As an example: the WB20 mix refers to the HPFRM mixture with a w/b of 0.2. In this trial, cement and fly ash were used at 85% and 15% by the total weight of binder (including cement and FA), respectively. The ratio of fine river sand: binder was 1:1. And the dosage of SP was adjustable to control that each of the mix proportions had a similar slump flow from 250 to 270 mm. Based on the results of the previous study [22], the percentage of PP fibers selected for all mixes was 0.6% by mass of the total binder. Particularly, the purpose of adding PP fibers into the HPFRM mortar with lower content as compared to that of ECC is to provide a lesser reduction of workability while still maintains a reasonable improvement of mechanical properties and drying shrinkage-reducing effect.

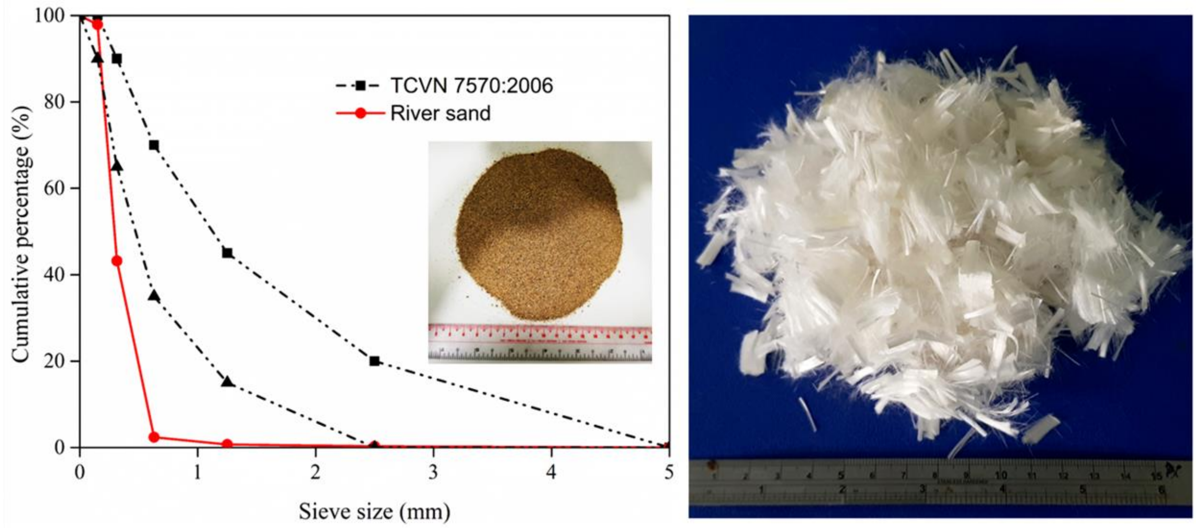


Figure 2. Gradations for local river sand and TCVN standard sand (left) & PP fibers (right).

Table 2. PP fiber properties.

Properties	**Value**
Diameter	0.03 mm
Length	12 mm
Melting point	160 − 170^{o}C
Elongation at break	15 − 20%
Tensile strength	> 500 MPa
Acid and alkali resistance	High
Reference standard	ASTM C1116
Density	0.91 g/cm^3

2.3. Samples preparation and test methods

The HPFRM samples were prepared in the laboratory using a vertical shaft planetary forced mortar mixer (Fig. 3, left) as the following procedures: (1) Before being used, water and SP were mixed in a separated container; (2) Cement and FA were mixed dry for about one minute to obtain a uniform dry powder; (3) While the mixer was running, slowly add a part of the water-SP solution, continue mixing for two minutes to assure a homogeneous paste; (4) Add all the sand and some water-SP solution, mix for two minutes; (5) Slowly add all PP fibers and remaining water-SP solution, mix additional two minutes until the fibers were well-dispersed in a homogeneous mixture. Right after mixing, the fresh mixture was tested for slump flow, fresh unit weight, and then poured into molds to prepare testing samples. After casting, the samples were kept in the laboratory for 24 hours, then de-molded and cured in water until the necessary experiments were performed.

Table 3. Mixture proportions of HPFRM samples.

Mix ID.	w/b	Materials (kg/m^3)					
		Cement	**FA**	**RS**	**Water**	**SP**	**PP**
WB20	0.20	905.9	159.9	1,065.8	213.2	21.3	6.4
WB25	0.25	866.2	152.9	1,019.0	254.8	12.2	6.1
WB30	0.30	827.0	145.9	972.9	291.9	7.8	5.8

Table 4. Summary of tests performed in the laboratory evaluation of HPFRM.

State of HPFRM	Properties	Testing age (days)	Sample size (mm)	Reference standard
Fresh	Slump flow	-	-	TCVN 3121-3:2003
	Unit weight	-	-	TCVN 3121-6:2003
Hardened	Water absorption	28	50 × 50 × 50	TCVN 3121-18:2003
	Porosity	28	50 × 50 × 50	ASTM C1403
	Microstructure (Scanning electron microscope, SEM)	28	Broken sample extracted from a compression test	SEM of ZEISS [23]
	Flexural strength	1, 7, 28, 56	40 × 40 × 160	TCVN 3121-11:2003
	Compressive strength	1, 7, 28, 56	Portions of prisms broken in flexure	TCVN 3121-11:2003
	Dry shrinkage	1, 7, 28, 56	25 × 25 × 285	ASTM C596

To investigate the feasibility of producing HPFRM using locally available ingredients in Southern Vietnam, the fresh HPFRM mixtures and samples were subjected to several tests as shown in Table 4 to determine their fresh and hardened properties.

Figure 3. Laboratory mortar mixer (left) & freshly mixed HPFRM mixture (right)

3. RESULTS AND DISCUSSION

3.1. Flowability and fresh unit weight

The values of slump flow and unit weight of the fresh HPFRM mixtures are recorded and presented in Table 5. In this study, as abovementioned, the slump flow value of all HPFRM mixtures was controlled in the range of 250 − 270 mm to ensure the requirements of high-quality construction mortar, including suitable consistency and excellent workability with self-leveling capability (Fig. 3, right below).

Table 5. Flowability and unit weight of fresh HPFRM mixtures.

Mix ID.	**w/b**	**Slump flow (mm)**	**Unit weight (kg/m^3)**	**SP dosage (%)**
WB20	0.20	250	2,290	2.0
WB25	0.25	270	2,285	1.2
WB30	0.30	270	2,244	0.8

It could be seen from Table 5 that to maintain the desired slump flow values, different amounts of SP have been added to the mixtures. The SP content was found to decrease significantly as increasing the w/b ratio. In detail, the dosage of SP used in the mixtures increased from 0.8% to 2.0% when the w/b ratio was reduced from 0.3 to 0.2. On the other hand, the experimental results also showed that the unit weight of fresh HPFRM mixtures decreased with an increasing w/b ratio. This can be explained as follows: once increasing the w/b ratio, the volume of water occupied in the same volume of mortar increases, while the water density is much lower than that of other ingredients in the mixture resulted in a reduction of unit weight of the material.

3.2. Flexural strength

Flexural characteristic plays important role in the performance of HPFRM because it can reflect the tensile ductility (due to fiber incorporation) without conducting a direct tensile test.

Therefore, a three-point bending test (Fig. 4) was carried out for evaluation of the mechanical properties of the HPFRM in this study.

Figure 4. Flexural characteristics of HPFRM samples

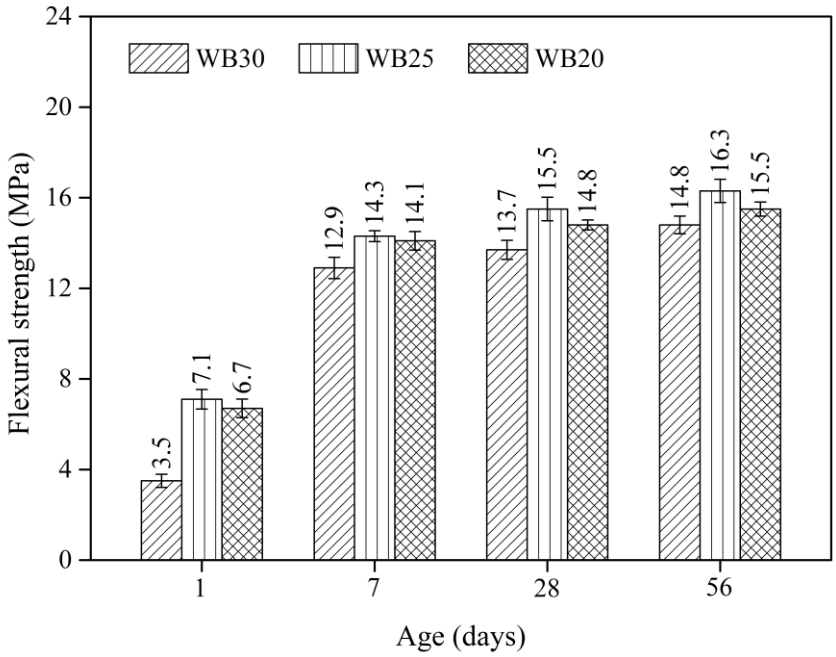


Figure 5. Flexural strength of the HPFRM samples.

The flexural strength development of the HPFRM samples over time is shown in Fig. 7. For pavement/surface material requirements, the early gain strength is considered an important factor due to the urgent traffic opening situation in practice. Thus, the more delay in strength gains of the construction materials, the more adverse effect on traffic conditions becomes. As seen in Fig. 5, the flexural strength values at 1 day were 6.7, 7.1, and 3.5 MPa, corresponding to the w/b ratios of 0.2, 0.25, and 0.3. Similar trends were also observed as evidenced by the significant increase at 7, 28, and 56 days. Specifically, the flexural strengths of the HPFRM with w/b of 0.2, 0.25, and 0.3 at the age of 56 days were 15.5, 16.3, and 14.8 MPa, respectively. When increasing the w/b ratio from 0.2 to 0.25, the flexural strength increases. However, the flexural strength is reduced when the w/b ratio is increased from 0.25 to 0.3. It can be realized that, if the amount of water is less than the optimal content, part of the binder has not yet been fully involved in the chemical reactions. As a result, fewer hydration products are formed, and the unreacted particles make the sample heterogeneous, thereby reducing the sample strength. In the case of too much water in the mixture, the increased pore volume results in lower strength of the specimen [24].

3.3. Compressive strength

The time-dependent compressive strength development of HPFRM at 1, 7, 28, and 56 days old with different w/b ratios is presented in Fig. 6. Accordingly, the 1-day compressive strength values were 41.6, 46.6, and 37.8 MPa with w/b ratios of 0.20, 0.25, and 0.30, respectively. As aforementioned, this early strength development is very important and necessary for pavement/surface construction materials. A similar result can be found in the literature performed by Zhang et al. [13], which also conforms to TCVN 9204:2012. From Fig. 8, it can be seen that the obtained compressive strength is inversely proportional to the w/b ratio, which agrees well with the known effects of concrete/cementitious materials as the compressive strength of the HPFRM is inversely related to the water content. For example, when the w/b ratio is at 0.2, the amount of SP required for the mix to achieve the required workability was very high (2% of binder mass), leading to certain difficulties once shaping/handling the HPFRM sample in the molds. This obstacle was fixed by increasing the w/b ratio to 0.25, where the fine particles in the sample well compacted together under the optimal conditions of natural compaction and hydration reaction, forming a homogeneous mixture with low porosity after hardening. However, when the w/b ratio is at 0.3, the compressive strength tends to decrease significantly. At this ratio, more pore volume could be formed and pore size in the matrix is also predicted to be larger, which contributes to a decrease in compressive strength [25].

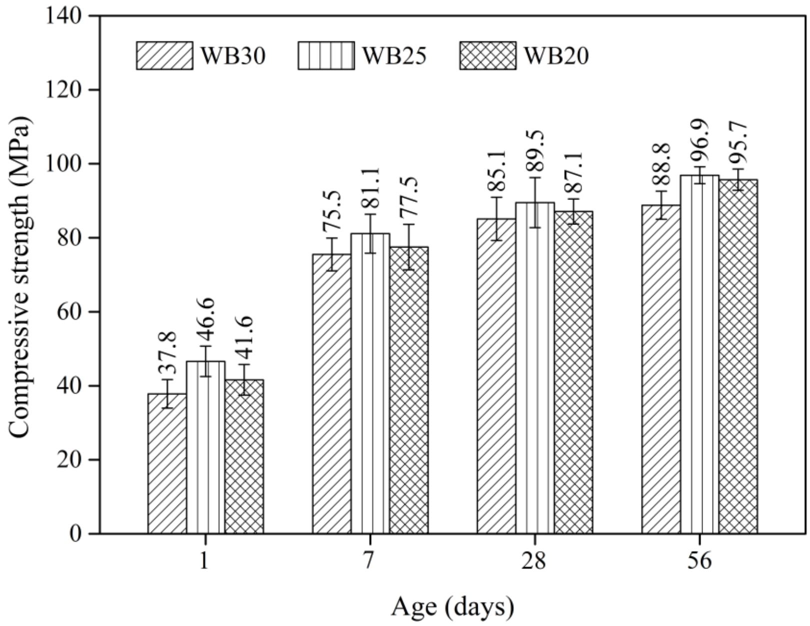


Figure 6. Compressive strength of the HPFRM samples.

Moreover, the addition of PP fibers at a dosage of 0.6% to the HPFRM in this study did not cause any adverse effect on the value and development of the compressive strength of the matrix. All HPFRM samples registered a compressive strength of over 80 MPa at 28 days or even higher up to 96.9 and 95.7 MPa at 56 days for WB20 and WB25 mixes, respectively.

Furthermore, it was interestingly found that the fiber-reinforced specimen continues to compress with increases in both length and width without disintegrating (Fig. 7). Overall, the HPFRM shows significantly ductile behavior under compression due to fiber-bridging effects until failure. The compressive ductility of HPFRM is in sharp contrast with conventional cementitious material's brittle behavior, contributing to sustainability performance for repair and rehabilitation applications of this material.

Figure 7. Compressive ductility of the HPFRM samples under compression.

3.4. Water absorption and porosity

Table 6 presents the water absorption and porosity values of the HPFRM samples at 28 and 56 days. In general, all HPFRM samples in this experiment have relatively low water absorption of 3.35 − 3.56% at 28 days, and a slight decrease in the range of 3.16 − 3.40% after 56 days. Thus, the lowest water absorption is 3.16 − 3.35% in the mixture using the ratio w/b of 0.25. Increasing the w/b ratio to 0.3 leads to the water absorption up to 3.40 − 3.56%. It is also observed that mix WB30, which has the highest w/b, also has the highest porosity of 7.66 − 8.03%, whereas the porosity of the WB20 is higher than that of the WB25. Therefore, a w/b ratio of 0.25 is considered an optimum ratio in this study. Chung et al. [26] explained that when the w/b ratio decreased, the voids in the homogenous and compacted samples were reduced and the discontinuity of the pore system in the sample increased, making the water adsorption process becomes more difficult. Furthermore, due to the pozzolanic reaction of FA in the hydrated cement mortar, the size and discontinuity of the pores improved over time, contributing to a denser mortar.

Table 6. Water absorption and porosity of HPFRM samples at 28 and 56 days.

Mix ID.	**Water absorption (%)**		**Porosity (%)**	
	28-day	**56-day**	**28-day**	**56-day**
WB20	3.46	3.28	7.53	7.36
WB25	3.35	3.16	7.13	6.31
WB30	3.56	3.40	8.03	7.66

3.5. Drying shrinkage

Fig. 8 shows the drying shrinkage of HPFRM samples with different w/b ratios. The drying shrinkage of the HPFRM samples was found to increase with an increasing w/b ratio. However, the shrinkage increased slightly when increasing the w/b ratio from 0.2 to 0.25 and more significantly when the w/b ratio increased up to 0.3. The large length variation of samples containing more water can be attributed to an imbalance in the relative humidity between the mortar and the ambient environment. The more water evaporates, the stronger the drying process takes place. One reason for the sample's tendency to shrink more might be due to the formation of more voids when the w/b ratio is high, which induces a greater surface tension in the pores [27]. However, the degree of length change due to drying shrinkage of the HPFRM samples in this research is relatively low, ranging from -0.037% to -0.048% due to the presence of fibers and FA addition in the mixture.

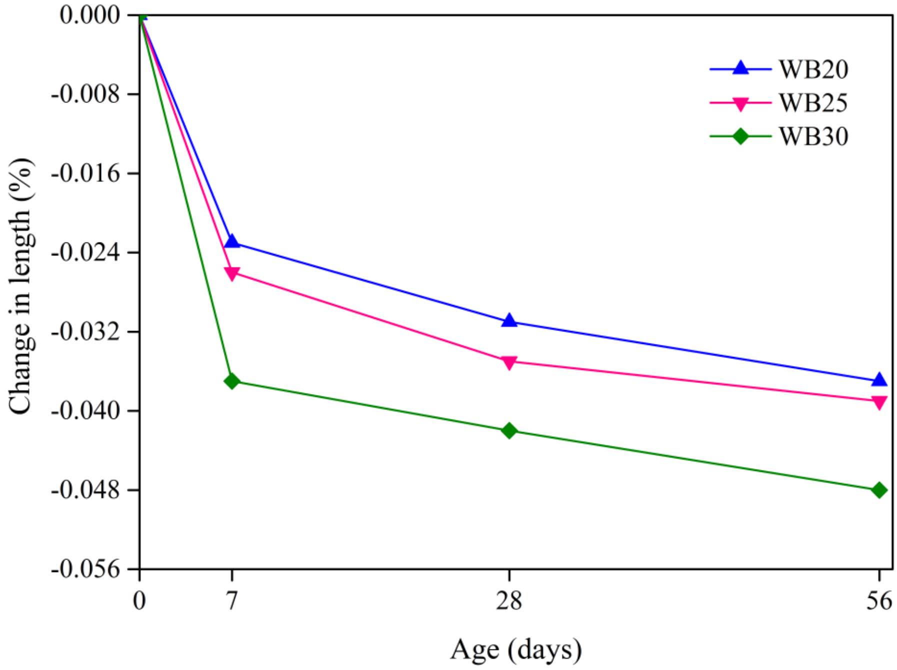
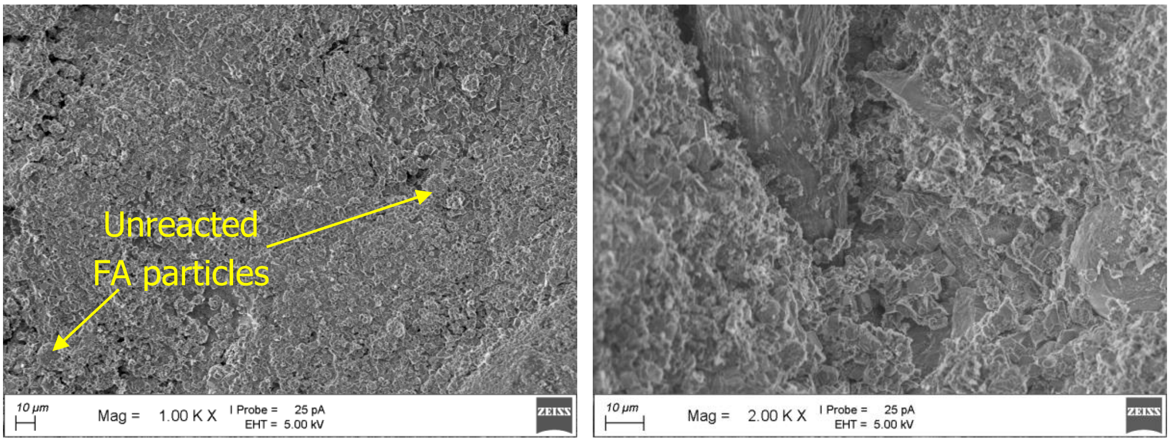


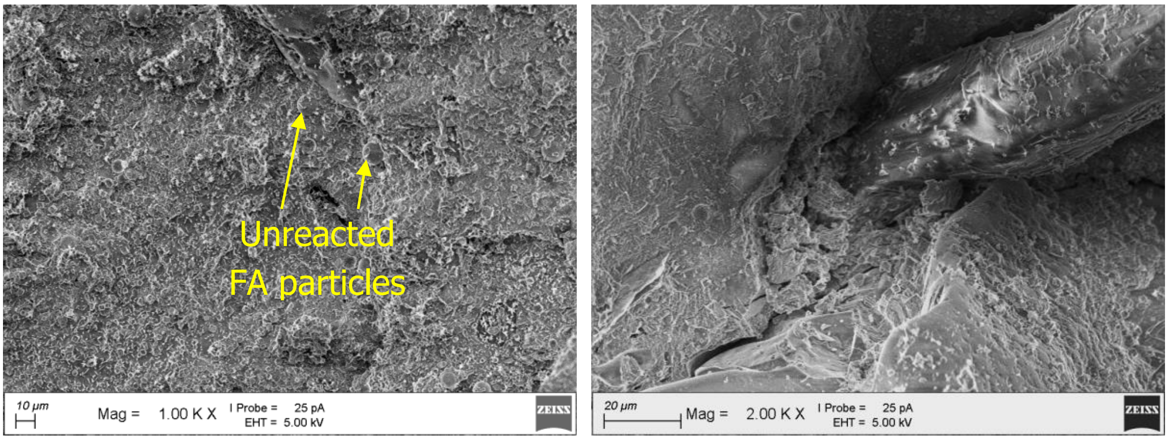
Figure 8. Drying shrinkage of the HPFRM samples.

3.6. Microstructure

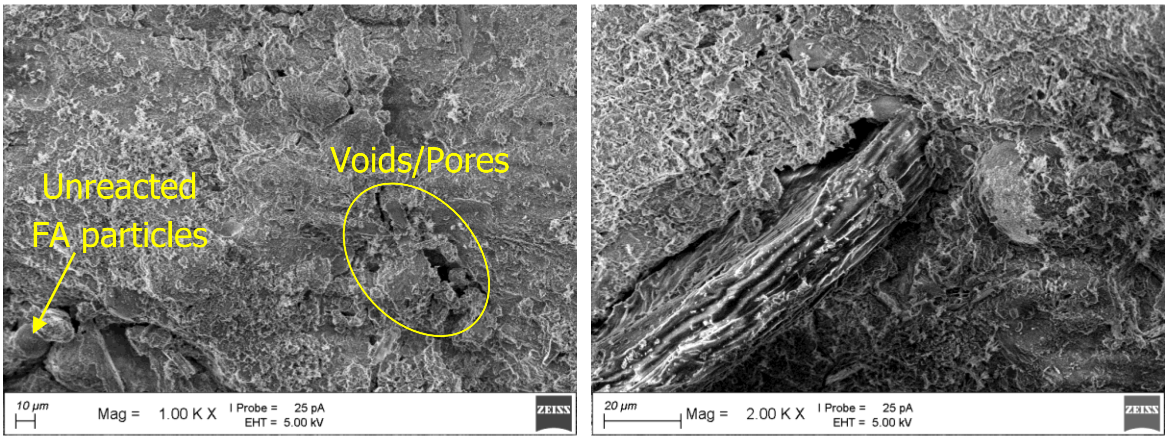
Fig. 9 displays the microstructure of a representative fractured surface from failed HPFRM samples prepared with different w/b ratios. It could be observed that most of the FA was involved in the chemical reaction with the presence of cement. However, a closer observation in Fig. 9 shows the presence of unreacted FA particles in the HPFRM samples. The higher number of unreacted FA particles indicates a moderate degree of reaction in the system [28]. Moreover, the microstructure of the HPFRM samples with a w/b ratio of 0.25 was denser than that of other samples. As mentioned in the previous section, it is fact that there was some difficulty in shaping/handling the HPFRM samples in the molds due to the relatively high viscosity of the mixture at w/b of 0.2. Therefore, the microstructure of the WB20 sample was less compact than that of the WB25 one. In the case of increasing the w/b to 0.3, the presence of high water content introduces more micro-voids and pores within the system due to the water evaporation during the hardening process, leading to the increase in porosity and consequently reduced strength of the HPFRM. Furthermore, SEM micrographs of the HPFRM samples (Fig. 9, right) reveal a relatively good adhesion between the PP fibers and the HPFRM, which supports the strength gain of the HPFRM samples. The SEM observation also supports the results of strength, porosity, water absorption, and drying shrinkage of the HPFRM samples as in the previous discussion.



(a) WB20



(b) WB25



(c) WB30

Figure 9. SEM micrographs of the HPFRM samples with different w/b ratios.

3.7. Comparison between HPFRM and other commercial grouts/mortars

To evaluate the potential production and application of the proposed HPFRM in this study, a comparison between the HPFRM and some other commercial grouts/mortars has been performed in terms of performance (i.e. density, flowability, compressive strength, flexural strength, and shrinkage) and cost. It is noted that the data of the Sika grout® 212, Sika Monotop®R, and SACA-G M80 (VIBM) as shown in Table 7 are easily obtained from the website of the suppliers. As can be seen, the fresh HPFRM mixture provides a comparable flowability and unit weight to other commercial grouts/mortars. Remarkably, the compressive and flexural strength values of the HPFRM are superior among the compared mortars. Besides, the total cost of HPFRM is calculated considering the costs of raw materials, the production processes (i.e. dry mixing, package, and quality control), and the profit of both producer and supplier. As a result, the commercial cost of each HPFRM bag (25 kg) ranges from 120,000 to 150,000 VND, which is much competitive than other commercial grouts/mortars. The information presented in Table 7 further demonstrates a high potential use of HPFRM in real practice.

Table 7. Comparison between HPFRM and some typically commercial grouts/mortars available on the market.

Criteria	Sika grout® 212	Sika Monotop® R	SACA-G M80 (VIBM)	HPFRM (this research)
Material base	Cement-based grout	High-performance polymer-modified, fiber-reinforced mortar	Cement-based grout	High-performance cement-based, low content fiber reinforced mortar
Fresh unit weight (kg/l)	~2.20	~2.15	~2.10 − 2.20	2.24 − 2.29
Flow (mm)	250 − 320	-	≥ 270	250 − 270
Compressive strength (MPa)				
1-day	≥ 25	~ 15	32	37.8 − 46.6
7-day	≥ 52	-	65	75.5 − 81.1
28-day	≥ 60	~ 45	80	85.1 − 89.5
56-day	-	-	-	88.8 − 96.9
Flexural strength (MPa)				
1-day	-	-	-	3.5 − 7.1
28-day	~9.6	~ 8	-	13.7 − 15.5
56-day	-	-	-	14.8 − 16.3
Drying shrinkage at 28 days (%)	+0.021	-	+0.100	-0.030 − -0.042
Cost (×1,000 VND), (25 kg/bag)	310	1,240	225	~120 − 150

4. CONCLUSION

The potential application of locally available ingredients in Southern Vietnam in the production of HPFRM, a modified engineered cementitious composite was experimentally investigated in this study. The following conclusions can be drawn:

(i) HPFRM can be successfully developed using locally available ingredients, such as fine river sand, FA, PP fibers, etc. contributing to cost-effective and sustainable performance for construction materials and rehabilitation applications. HPFRM in this research demonstrated a slump flow of 250 − 270mm, an average 1-day and 28-day flexural strength of 5.8 and 14.7 MPa, and an average compressive strength of 42 MPa at 1 day age and 87.2 MPa at the age of 28 days, together with a dense and relatively ductile matrix mortar, characterized by relatively high deformability, low drying shrinkage of -0.037 − -0.048% and average water absorption as low as 3.5%.

(ii) Based on the design requirements of high-performance construction materials (i.e. early strength, self-leveling, high deformability, and low shrinkage, etc.), the HPFRM can be successfully designed and manufactured with a w/b ratio in the range of 0.2 – 0.3 and the reinforced PP fiber content is relatively low about 0.6% by total weight of the binder. In which, w/b ratio of 0.25 is considered to be the optimal level in this study in the balance between matrix strength, durability, and rheological requirements for creating good HPFRM.

(iii) However, further researches should be continuing conducted on this material to be more confident in practice. For example, the impacts of different materials selection and mix proportioning (i.e. different local river sands, PP fiber dosages, etc.) on the mechanical and related durable properties of the materials.

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