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Effect of fiber type on performance of fiber reinforced concrete applied for hydraulic construction

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ABSTRACT

This study aims at evaluating effect of fiber types on comprehensive property of a practical fiber reinforced concrete (FRC) applied for hydraulic construction. Three fiber types including polypropylene, glass, and steel fiber were used to replace concrete volume at 0.3 vol.%. Experimental results illustrated that when compared with the reference concrete, the fiber reinforced concretes with steel or glass fiber had comparable or slight changes on the fresh properties. But, addition of polypropylene fiber induced the fresh FRC with decreased slump flow and significantly increased air entrained volume. Although using various types of fibers led to unbeneficial effect on the compressive strengths of the FRCs, presence of fiber induced the FRCs with significant enhancements on the flexural strength, drying shrinkage, and water absorption and slightly increased UPV at 28 days. In this study, steel fiber was considered as the best choice for improving the mechanical properties of the hardened concrete while, as the volume stability and durability performance of the concrete were primarily considered, polypropylene seemed to be a preferable selection. According to standardized requirements, all concrete proportions were in classification of M40(28)-M45(28), being assigned to concretes suitably applied for widespread on-site hydraulic constructions.

1. INTRODUCTION

Concretes have been the dominant construction materials due to tripled benefits on technical, economical, and also ecological in comparison with other common materials such as aluminum and steel. Traditional concretes are composed of a high volume of fine and coarse aggregate glued by cementitious binder, particularly ordinary Portland cement. Mechanical performance of the hardened concrete crucially depends on the bonding properties of the hydration products. Although fracture mechanism of concrete has been highly agreed to be quasi-brittle, resistance of concrete to tension stress induced by bending moment or longitudinal tension force is significantly smaller than the compression resistance and thus tension resistance of concrete is normally neglected in structural design progress. Consequently, reinforced concrete instead of plain concrete is commonly applied for structural construction. Therefore, with effort to reduce the crucial role of steel reinforcement and to increase resistance of the concrete structures, particularly emphasized on the hydraulic structures, to crack appearance and propagation, enhancement on the concrete tensile strength seems to be a key solution. In both laboratory and practical sites, addition of fibers into concrete matrix to create a novel concrete so-called fiber reinforced concrete (FRC) has been realized to be an efficient way to approach achievement. Typically, various fiber types sourced from either metallic such as steel fiber (Köksal et al., 2022; Wang et al., 2022), or synthetic such as polypropylene and glass fibers (Lei et al., 2020; Wu et al., 2023) are illustrated good compatibility as working along with the plain concrete. Currently, tremendous literature considering the properties and productions of FRCs with different kinds of fibers used due to previous compilations (Afroughsabet et al., 2016; Sanya and Shi, 2023; Vairagade and Dhale, 2023) but performance of the FRC applied for hydraulic constructions seems to be undisclosed. Therefore, this study attempts to initially realize the impact of fiber types, including steel, polypropylene, and glass fibers, on properties and productions of the practical hydraulic concretes. This aspect has not been previously considered.

2. EXPERIMENTAL PROGRAM

2.1. Materials and mix proportions

Portland cement (PC) and fly ash (FFA) available in Vietnam were applied as the main binder and filler, respectively. The physicochemical properties and mineral compositions of the raw materials were conducted and shown in Table 1 and Figure 1, respectively. Accordingly, alite and belite crystals were the primary ingredients of PC, which was normally assigned to the hydraulic property while quartz and mullite crystals induced FFA fundamentally stable in the alkali pore solution of hydrated cement at early or even long time ages. Additionally, the particle shapes of the raw materials were illustrated in Figure 2 which showed that the FFA particles were spherical, which was different from the granular-shape of PC particles. For fabricating concrete, natural stone with maximum size of 10 mm and water absorption of 1.0% and crushed sand with specific gravity of 2.43, fineness modulus (FM) of 3.29, and water absorption of 6.89% were used as the fine and coarse aggregates, respectively. To achieve desired workability of the fresh concretes, commercial Type G superplasticizer (SP) was also used. In this study, commercial fibers including polypropylene, glass fiber, and steel fiber were used to estimate influence of fiber type on enhanced performance of the fiber reinforced concrete (FRC). The characteristics of three types of fibers were shown in Table 2.

The reference concrete mixture without fiber addition was produced with a mass ratio of FFA to mixture of the fine aggregate and FFA of 13.7% and a mass ratio of mixture of FFA and fine aggregate to total amount of FFA, fine and coarse aggregates of 54.4%, which were obtained by adapting the particle packing theory as previously reported (Chao-Lung et al., 2011). For manufacturing the FRCs, each of various types of fibers including polypropylene, glass fiber, and steel fiber was used as partial replacement of concrete mixture at 0.3% by volume. A ratio of water to cement (w/c) of 0.4 was fixed for all concrete mixtures. The mixture proportions of the reference and FRC mixtures were illustrated in Table 3.

Table 1. Physico-chemical properties of raw materials

	Fly ash	Portland cement
Specific gravity	2.13	3.05
SiO_2, %	58.77	22.45
Al_2O_3, %	26.11	6.81
Fe_2O_3, %	5.61	3.15
CaO, %	2.07	60.03
MgO, %	1.66	2.08
SO_3, %	0.21	2.77
Na_2O, %	0.27	0.55
K_2O, %	1.48	0.79
TiO_2, %	0.66	0.41
L.O.I, %	3.11	0.95

Table 2. Characteristics of fibers

Properties	Polypropylene	Glass fiber	Steel fiber
Specific gravity	0.91	2.50	7.85
Diameter, μm	30	9-13	0.5- 1.0
Length, mm	18-19	12	50

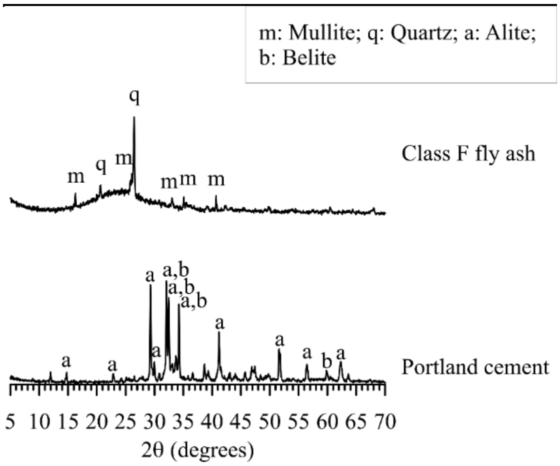

Figure 1. XRD patterns of the raw materials

Table 3. Mix proportions for the concretes, kg/m^3

Mixtures	Stone	Sand	Fly ash	Cement	Water	Fiber	SP
Reference	663	683	108	574	230	-	3
FRC with glass fiber	661	681	108	573	229	3	4
FRC with polypropylene	661	681	108	573	229	8	3
FRC with steel fiber	661	681	108	573	229	24	3

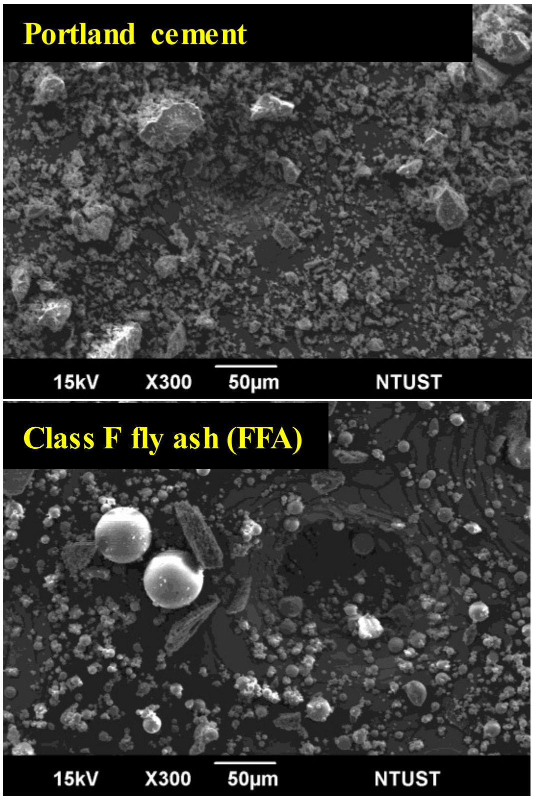

Figure 2. SEM images of the raw materials

2.2. Specimen preparation and test methods

Fresh properties of concretes were assessed by means of slump test, unit weight, and air entrained volume in accordance to TCVN 3106, TCVN 3108, and TCVN 3111, respectively. Immediately after the assessment on the fresh properties, concrete cubes with dimensions of 150×150×150 mm^3 and concrete prisms with dimensions of 150×150×600 mm^3 were cast for the tests on compressive and flexural strengths accordant to TCVN 3118 and TCVN 3119, respectively. The cubic specimens were also used for assessing water absorption of concretes in accordance to TCVN 3113. Additionally, the concrete prisms with dimensions of 75×75×285 mm^3 were also cast for the drying shrinkage and ultrasonic pulse velocity (UPV) tests complying with TCVN 8824 and TCVN 9357, respectively. After 24 hours being cured in the molds at ambient temperature, all concrete samples were remolded and cured in air at 27 ± 2ºC and 65% of RH until the tests. In this study, the compressive strength test was conducted at 7 and 28 days while the tests of flexural strength, water absorption, and UPV were conducted at 28 days. In addition, the drying shrinkage test was monitored up to 28 days of curing.

3. RESULTS AND DISCUSSIONS

3.1. Fresh properties

The fresh properties of the reference and FRC samples were conducted and shown in Table 4. Accordingly, the slump value, unit weight, and air entrained volume were in ranges of 7.7-9.2 cm, 2497-2574 kg/m^3, and 1.8-2.4%, respectively. Addition of fiber induced the fresh FRC concretes with increased unit weight due to high specific gravity of the fiber. When compared with the reference concrete without fiber addition, the FRC with polypropylene addition had lower slump value and higher air entrained volume, which was assigned to the concrete with reduced fresh properties. Such a result could be due to the fresh FRC mixture was vulnerable to block issue as polypropylene fiber was used. The previous studies (Yap et al., 2014; Alwesabi et al., 2020) indicated that large surface area of polypropylene fiber was possibly the crucial reason inducing the fresh concrete with increased viscosity and thus decreased the slump value. On the other hand, addition of either glass or steel fiber enhanced the workability of the fresh FRC mixtures due to the comparable or slightly increased slump value and reduced air entrain volume.

Table 4. Fresh properties of the concretes

	Reference	Fiber reinforced concrete (FRC) with		
		Polypropylene fiber	Glass fiber	Steel fiber
SP, %	0.8	0.8	0.8	0.7
Slump, cm	8.8	7.7	8.6	9.2
Air entrained volume, %	2.0	2.4	1.8	1.9
Unit weight, kg/m^3	2497	2512	2513	2574

3.2. Flexural strength

The flexural strengths of the hardened concretes were illustrated in Figure 3.

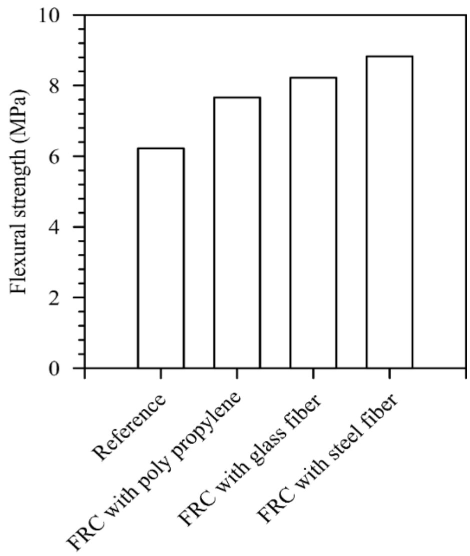

Figure 3. Flexural strengths of the hardened FRCs

As being expected, incorporation of fiber with irrespective of fiber type significantly improved the flexural strength of the FRCs as compared with the reference concrete without fiber addition. The 28-day flexural strength of the FRC with three types of fibers was in average of 8.2 MPa which was higher than value of 6.2 MPa of the reference concrete up to approximately 32.3%. Such a result was due to the contribution of the fiber to resisting crack operation. In this study, steel fiber was considered being the most efficient selection to enhance the flexural strength of the hardened FRCs. The flexural strength of the FRC with steel fiber was 8.8 MPa which was higher than that of the reference concrete up to 41.9%. The mechanism behind the flexural strength enhancement of the FRCs was due to a phenomenon of crack bridging and interfacial bonds generated among fibers and cement hydrates (Alwesabi et al., 2020; Yap et al., 2014). As previously indicated (Li et al., 2018), combined addition of steel and polypropylene fibers remarkably enhanced the mechanical properties of FRC implied synergistic effect observed, which was visualized in this study.

3.3. Compressive strength

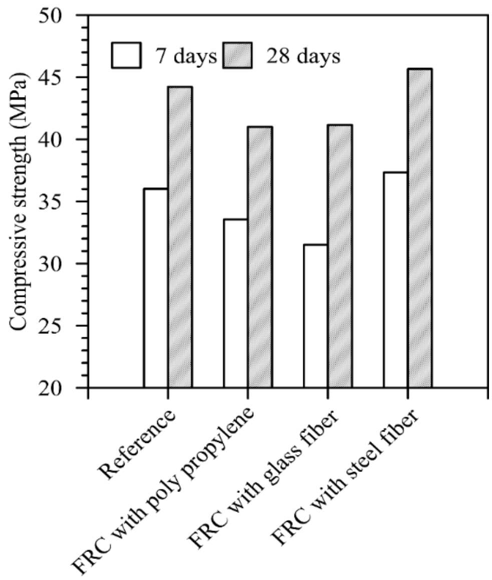

Figure 4. Compressive strengths of the hardened FRCs

Compressive strengths of the hardened concretes with/without fiber addition were conducted and illustrated in Figure 4. Accordingly, the compressive strengths of the concrete specimens increased with increased ages of curing. The 28-day compressive strengths of the concretes were in the range of 41.0-45.7 MPa which were assigned to the strength grades of M40(28)-M45(28) based on technical requirements for hydraulic concrete as shown in TCVN 8218. As indicated in TCVN 8218, these concretes were suitably applied for most of the serving conditions where hydraulic structures existed. Although the addition of polypropylene or glass fiber slightly decreased the 28-day compressive strengths of the FRCs as compared with the reference concrete without fiber addition, the strength grade of the FRCs was maintained at M40(28). Particularly, when compared with the reference concrete without fiber addition, addition of steel fiber increased the 28-day compressive strength of the FRC to reach the upgraded strength grade of M45(28) and thus it was considered as the preferable choice to widen the applicability of the FRCs for job-site hydraulic structures based on the suggestions from TCVN 8218. Reasonably, the higher compressive strength grade was associated with the concrete with enhanced microstructural condensation and thus improved resistance to chemical attacks through penetration progress.

3.4. Water absorption

The water absorption performances of the hardened reference and modified FRCs were illustrated in Figure 5. Accordingly, addition of fiber resulted in the FRCs with water absorption of 5.5% in average which was smaller than value of 8.8% of the reference concrete at approximate 37.7%. Such a result was possibly attributed to increased resistance of the FRCs to crack penetration (Alwesabi et al., 2020; Yap et al., 2014). In this study, FRC with polypropylene fiber had the lowest water absorption, which implied presence of this type of fiber reduced continuous pore volume inside the concrete samples. In addition, the obtained result also allowed to predict the durability in term of chemical penetration of the FRC with polypropylene fiber will be enhanced and thus suggested a widened applicability of the concrete for hydraulic constructions.

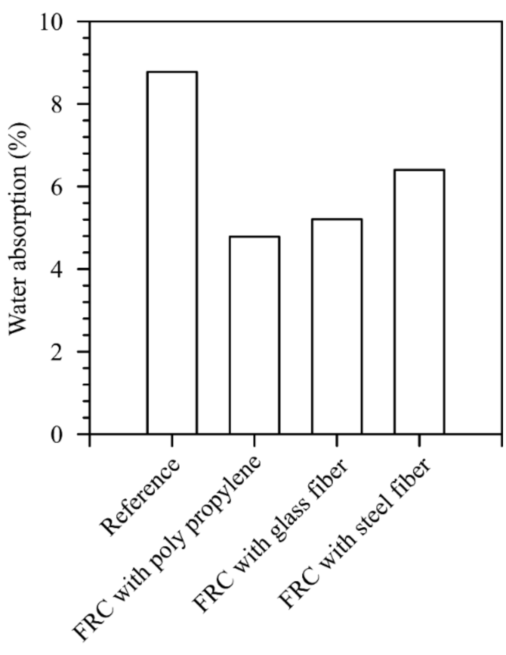

Figure 5. Water absorption performance of the hardened FRCs

3.5. Ultrasonic pulse velocity (UPV)

The UPV values of the hardened concretes were illustrated in Figure 6 which indicated the UPV values of the FRCs were slightly higher than that of the reference concrete without fiber addition. Addition of various types of fibers fluctuated the UPV values of the hardened concrete specimens. A comparison showed that the UPV value of the FRCs was highest as steel fiber was used. In this study, the UPV values of all concrete mixtures with/without fiber addition were in the range of 4334-4412 m/s which were assigned to the concretes with good durability (Hasbullah et al., 2017; Othman et al., 2020). When compared with the reference concrete with UPV value of 4334 m/s, the FRCs had the UPV value increased at 1.2% on average. As steel fiber was used, the UPV of the FRC reached the highest at 4412 m/s which was 1.8% higher than that of the reference concrete.

3.6. Drying shrinkage

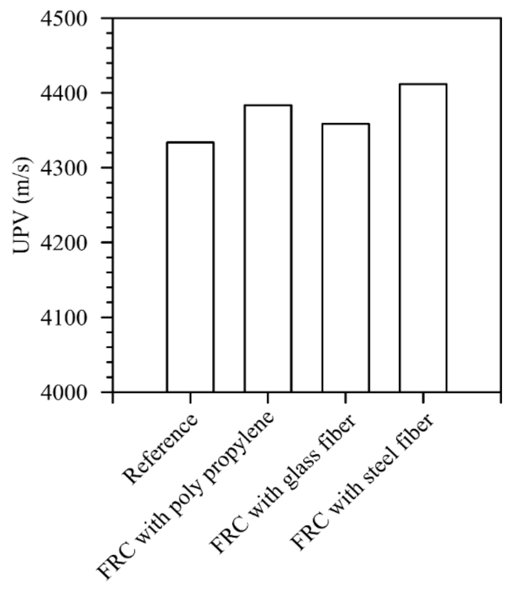

Figure 6. UPV of the hardened FRCs

The drying shrinkage of the hardened concrete was monitored and shown in Figure 7. As shown in Figure 7, the drying shrinkage increased as curing ages increased due to the accumulated water vaporization from the concrete specimens into the air. Apparently, Figure 7 indicated a significant reduction in drying shrinkage was obtained for the FRCs as compared with the reference concrete without fiber addition, which was possibly due to the high resistance of the FRCs to drying strain. At 28 days, the so-called stable drying shrinkage of FRC with polypropylene fiber was the lowest, followed by those of the FRCs with glass and steel fiber. As previously mentioned, the phenomenon of crack bridging and interfacial bonds generated among fibers and cement hydrates possibly contributed to the lowered drying shrinkage of the FRCs when compared with the reference concrete without fiber usage (Alwesabi et al., 2020; Yap et al., 2014).

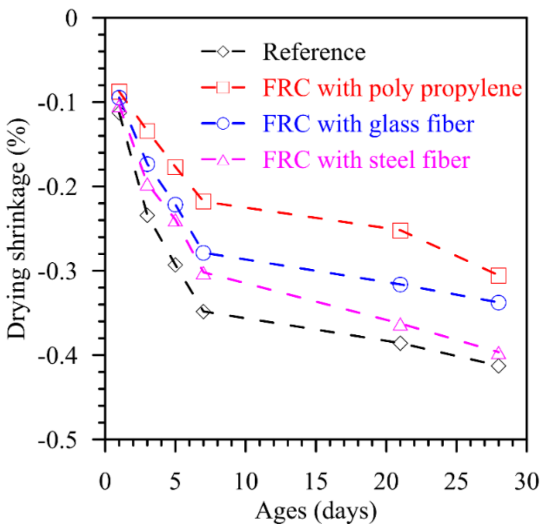

Figure 7. Drying shrinkage of the FRCs

4. CONCLUSIONS

The impact of various types of commercial fibers, including polypropylene fiber, glass fiber, and steel fiber, on comprehensive physical and mechanical properties of a practical hydraulic concrete was investigated. According to the experimental results, the following conclusions should be drawn:

– According to the standardized requirement for hydraulic concrete, all concrete proportions with or without fiber addition as conducted in this study were in the classification of M40(28)-M45(28), which implied the practical concretes suitably applied for most job-site conditions.

– Fiber addition as partial replacement concrete volume at 0.3 vol.% fluctuated the physical and mechanical performance of the fresh and hardened fiber reinforced concrete (FRC) in comparison with the reference concrete without fiber addition.

– Addition of either steel or glass fiber resulted in the FRCs with comparable or slightly increased slump and unit weight and slightly decreased volume of air entrained. In contrast, added polypropylene fiber induced the FRC with decreased slump flow and considerably increased air entrained volume.

– With irrespective of the fiber types, the flexural strengths of the hardened FRCs were remarkably enhanced. Incorporating steel fiber was the most effective way, followed by the glass and polypropylene fibers, to modify the flexural strengths of the hardened FRCs.

– Compared with the reference concrete without fiber addition, utilization of various fiber types led to an unbeneficial effect on the compressive strengths of the hardened FRCs.

– By considering the volume stability and durability performance, utilization of various fiber types not only slightly increased UPV but also significantly improved drying shrinkage and water absorption of the hardened FRCs at 28 days of curing, particularly when polypropylene was used.

– In this study, adding steel fiber as a partial replacement of concrete volume was considered as the best choice for improving the mechanical properties of the hardened concrete. On the other hand, as the volume stability and durability performance of the concrete were primarily considered, polypropylene seemed to be a preferable selection.

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