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Engineering Performance of a Rapid Hardening Hydraulic Binder with Hybrid Fiber

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Abstract

The fundamental performance of any construction material should cover at least two phases: safety and serviceability. Safety commonly represents adequate strength, while serviceability encompasses the control of cracking and deflections at service loads. With respect to rapid hydraulic binders as a construction material, the above two phases should also be considered. Recent research on rapid cooling ladle furnace slag (RC-LFS) has drawn much attention, particularly given that it shows remarkable rapid hydraulic ability to pulverize to a fineness of 6,300cm^2/g. This industrial byproduct could contribute to developing the sustainability of the rapidly hardening cementitious material system. This paper aims to expand upon the applicability of an RC-LFS-based binder that is composed of two parts. It also seeks to illustrate the engineering performance of an RC-LFS-based hybrid fiber-reinforced composite and to increase the strength of the RC-LFS-based composite. Each step of this experiment followed ASTM standards. The engineering performance, in both fresh state and hardening state, was tested and discussed in this paper. According to the experimental results for fresh concrete, the air content increased following the addition of polypropylene fiber. For hardened concrete, the toughness and strength improved following the addition of a hybrid fiber. The hybrid fiber mixture, which contains 0.75% of steel fiber and 0.25% of polypropylene fiber, shows even better engineering performance than other mixtures.

Keywords : rapid hardening cement, rapid cooling LFS, hybrid fiber reinforced mortar

1. Introduction

The sustainability of the use and construction of hydraulic binders has been in the limelight for several years, and the issues involved will further intensify over the course of the 21st century. During the last century, global materials use increased 8-fold, and as a result, humanity currently uses almost 60 billion tons (Gt) of materials per year (Krausmann et al., 2009); thus, it is a formidable challenge to explore and apply new ways to reduce its ecological and environmental impact. In comparison, the embodied energy and carbon per unit volume of concrete are much smaller than any other construction material. Given concrete's low environmental imprint, it is more difficult to find a breakthrough in a single step or with a specific technology[1]. By gaining more control over energy and resource consumption, and by bringing them to their lowest levels, it is imperative that industrial byproducts be recycled; this will serve as a key strategy to achieve this aim.

Nowadays, a special material known as rapid-hardening hydraulic cement, produced from a calcium aluminate-rich industrial byproduct, has drawn much attention due to its chemical composition.

Among all the industrial byproducts, slag offers many advantages, as it can be reused as raw materials for cement production. One of the top reasons for

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this is that the chemical composition of slag is relatively close to that of clinker. Electric arc furnace slag (EAFS) is slag discharged from an electric arc furnace in the steel-making industry. As a byproduct, EAFS has been wasted in landfills or used as low-value materials, such as fillers in pavement. EAFS actually represents two different types of slag, depending on the working conditions involved: oxidizing slag and reducing slag. Given the different properties and chemical compositions of each slag, the separation of slag is of significance when recycling it; currently, slag is dumped without any separation. Furthermore, ladle furnace slag (LFS) (hereafter, LFS refers to reduced slag) has not been separated from oxidizing slag, and it has been slowly cooled on the dumping field. For this reason, cooled LFS exhibits crystallized phases and contains high levels of free CaO and free MgO, which cause excessive expansion with water. Therefore, when recycling LFS as construction material, it is inevitable that its volume stability be secured. LFS itself contains a large portion of calcium, alumina, and silica, which are main components of cementitious materials; hence, LFS's chemical composition can be further used as useful elements for hydraulic materials[2,3,4,5,6,7,8].

The traditional methods used to cool and treat LFS include dumping it into a field and cooling it slowly using air, as mentioned above[4,5]. This method could increase the environmental burden with the occupation of huge areas of working yard. Furthermore, the slowly cooled slag has very low activity since it is easily crystallized, even though it has a chemical composition that enables it to solidify. When using LFS as a binder, it must be cooled rapidly. The rapid cooling of melting slag results in amorphous phases and can provide good reactivity. Rapidly cooled (RC)-LFS contains a high amount of $12CaO \cdot 7Al_2O_3$ ($C_{12}A_7$) and $\beta-C_2S$. Given the rapid cooling procedure used, $C_{12}A_7$ exists in a glass phase, and C_2S is expected to have high reactivity in its $\beta-C_2S$ phase, not $\alpha-C_2S$. The existence of glass-phase $C_{12}A_7$ will provide great strength early on in the process. However, given that the hydration rate at very early stages is so strong, it can also generate large amounts of heat during the hydration process. Therefore, hydration heat has to be controlled with the help of gypsum in the composite[1,2,3]. In addition to $C_{12}A_7$, $\beta-C_2S$ also contributes to the development of LFS's long-term strength[2,3,4,5,6].

Recycled materials have to be strongly supported for sustainable development. In the cement industry, the reuse of industrial byproducts as raw materials has served as a functional method to decrease the environmental imprint.

Pulverized RC-LFS as a kind of rapidly setting and hardening cementitious material has higher activity when compared to ordinary Portland cement (ASTM type 1). It is widely accepted that the rapid hardening of cementitious material plays a critical role in the construction field. The use of rapidly hardening cement will speed up construction activities, thus lowering the costs and improving the efficiency of shotcrete or repair construction. To increase flexural strength and to modify strain-stress behaviors, various types of fibers are generally combined with rapidly hardening cement in these types of construction processes. Similarly, the use of a hybrid fiber-reinforced system has not been fully studied, particularly when a rapidly hardening binder (specifically, pulverized RC-LFS) served as the matrix.

As cementitious materials, low resistance to open and developing cracks also influence the safety and serviceability of various structures. The most common way to increase flexural strength and toughness is to add fibers. This method can be traced back to thousands of years ago, when humans used straw to reinforce mud[7,8]. In modern society, reinforcing the cementitious matrix has been a widely accepted approach. A fiber-reinforced composite can be classified as mono-fiber-reinforced concrete or hybrid fiber—reinforced concrete according to how many fiber types are contained in the system. The mono—fiber—reinforced system uses a fiber that shares the same morphological characteristics and materials, while hybrid fiber—reinforced concrete always uses several types of fiber[8]. For modern concrete, natural fibers are not commonly compared to artificial fibers. Artificial fiber offers the benefits of stable output, increased durability, and easy quality control. Of the types of artificial fiber, carbon fiber has remarkable engineering performance but is somewhat expensive. Steel fiber (SF) and polypropylene fiber (PPF) are reasonable for use in construction work due to their engineering performance and economic efficiency. Thus, it was decided that SF and PPF would be used to form the hybrid fiber system featured in this experiment.

Therefore, the fundamental purpose of this research is to study the engineering performance, including compressive strength, flexural strength, and strain-stress behaviors, of a hybrid fiber—reinforced composite with pulverized RC—LFS.

2. Experiment setup

2.1 Experimental plan

The experimental plan is shown in Table 1. The experimental purpose is to illustrate the different engineering properties of different hybrid fiber—reinforced, rapidly hardening mortars.

Different hybrid fiber systems will be identified by examining the various proportions of PPF and SF, as shown in Table 1. The total fiber content was controlled within 1 percent of 1 cubic meter of concrete.

The water—to—binder ratio was decided as 0.4, the curing was performed in water at 16.5˚C, equally, in all tests.

For fresh concrete, the flow, air content, and unit weight were measured. For hardening concrete, the engineering performance (including compressive and flexural strength) was tested and recorded at 4 hours, 1 day, 7 days, and 28 days after being cast. Additional performance measures such as stress-strain behavior and length change were also detailed in this paper.

The mixing design is shown in Table 2. According to the experimental plan and purpose, five mixtures were examined in this experiment. These mixtures were named according to the different hybrid proportions of both SF and PPF. The control mixture is a mixture without additional fiber.

The mixture named S25P75 represents a mixture that contains 0.25 percent SF and 0.75 percent PPF. Other mixtures are referred to in accordance with the same naming rule.

Since calcium aluminate cement is sensitive to ambient temperatures, the experimental temperature was adjusted to about 20˚. After the temperature reaches the designed set, the experiment will start. The mixing method is illustrated in Figure 1. Sand and binder were first mixed for 30 seconds, and then 90% of the water was added and it was mixed for another 30 seconds. Following that, SF and PPF were added into the composite and mixed for another 30 seconds. Finally, superplasticizer and the remaining 10% of water were added and mixed for a final 3 minutes.

Table 1. Experimental plan

Binder	Mixture	Fiber content (%)		w/b (%)	Test items
		SF**	PPF***		
CAC* + gypsum	Control S25P75 S50P50 S75P25 S100P0	0 0.25 0.5 0.75 1	0 0.75 0.5 0.25 0	40	- Flow - Air content - Unit weight - Compressive strength (4h,1.7.28d) - Flexural strength (4h,1.7.28d) - Stress-strain curve - Length changes ratio - SEM - XRD

* CAC : Hereafter means pulverized RC-LFS
** SF : Hereafter means steel fiber
*** PPF : Hereafter means polypropylene fiber

Table 2. Mixing proportions

Mixture	Fiber weight (kg/m^3)		Water (kg/m^3)	Binder (kg/m^3)		Sand (kg/m^3)	Total(kg/m^3)
	SF	PPF		CAC	Gypsum		
Control	0	0	270	506.25	168.75	1278.59	2223.59
S25P75	19.65	6.83					2250.07
S50P50	39.30	4.55					2267.44
S75P25	58.95	2.28					2284.82
S100P0	78.60	0					2302.19

Table 3. The basic physical and chemical properties of pulverized RC-LFS and gypsum

Binder	Physical properties		Oxide content (Wt. %)					
	Density (g/cm^3)	Fineness (g/cm^3)	SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	SO_3
LFS	2.97	6300	10.9	44.5	26.6	4.3	6.6	-
Gypsum	2.72	1100	2.6	40	0.9	0.4	0.3	55.8

To test the setting and hardening time and to ensure that ample time was provided for placing and to perform the necessary tests, a 1.7% chemical retarder by binder mass was used; it was dissolved in water in advance. The chemical retarder used in this experiment was citric acid, which was provided from the Korean market. Since the additional fibers would influence the workability of fresh concrete, in order to reach the target flow, a superplasticizer was also involved. The concentration of the superplasticizer was decided based on the different amounts of fibers used in the pre-test. There were two kinds of molds used during the experiment: one was 100×100×400mm for the stress-strain curve test, while the other was 40×40×160mm to assess flexural strength, compressive strength, and length change. The tests for fresh concrete were performed simultaneously by placing the samples. The samples were moved into the curing room at a constant temperature of 20˚C, right after casting; demolding occurred after a waiting period of 3 hours. Then, the samples were molded and immersed into the water at 16.5˚C until they were tested.

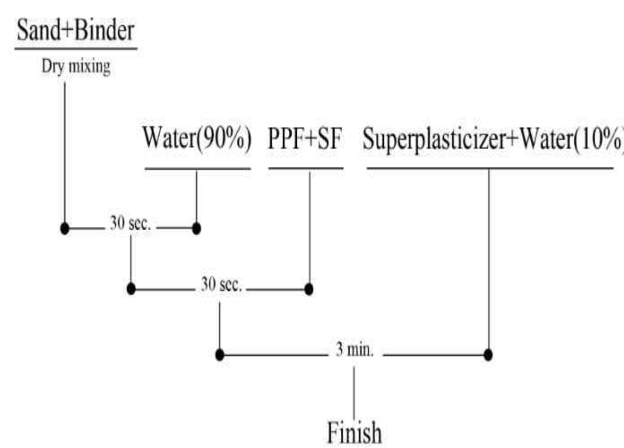


Figure 1. Mixing procedures for the fresh mixture

2.2 Materials

The materials used in this experiment are pulverized RC-LFS, gypsum, river sand, PPF, SF, superplasticizer, and a retarder. The binder used in this experiment was combined with pulverized RC-LFS powder and replaced by 25% gypsum (see Figure 2). The gypsum was replaced based on the results of previous studies[3,4]; gypsum controls the heat and rate of hydration, and it also yields a positive effect on the formation of hydrates[2,3]. The basic physical and chemical properties are shown in Table 3.

Pulverized RC–LFS Gypsum

Figure 2. Binder material in its natural state

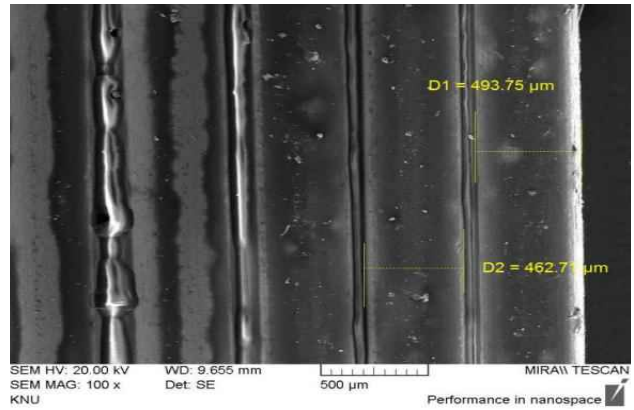
Steel fiber Polypropylene fiber

Figure 3. Fiber condition in its natural state

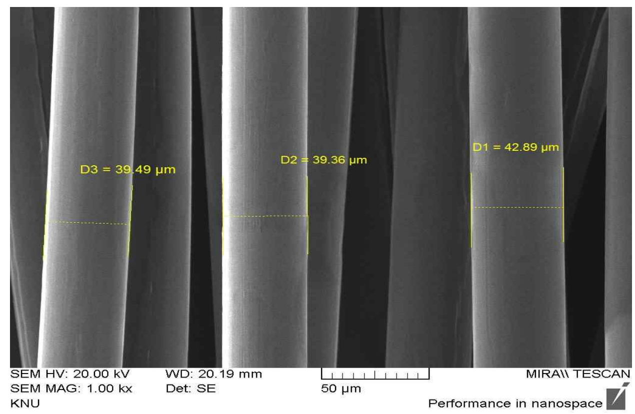
The fine aggregate for this experiment was common river sand; after it was washed and sieved using a 4.75mm sieve, that sand was submerged in water for 48 hours and then dried to saturated surface dry(SSD) condition as per ASTM standard C128–15. The composite was subsequently safely stored in sealed condition until the experiment.

Since evaporation may occur at room temperature, the sand has to be tested again for SSD conditions just before the experiment starts. The fibers involved in this experiment were 12mm PPF and 30mm hooked–end SF. The fiber conditions are illustrated in Figure 3. Glued and hook–end types of SF can prevent the generation of fiber balls.

To clearly illustrate the various fiber conditions, the images generated from SEM are provided in Figure 4. According to the results from the SEM images, PPF has a relatively smooth surface when compared with SF. For more detail, Table 4 is available.



Surface condition of steel fiber



Surface condition of polypropylene fiber

Figure 4. Surface condition of steel fiber and polypropylene fiber, as imaged by scanning electron microscopy (SEM)

Table 4. Physical and mechanical properties of polypropylene fiber and steel fiber

ID	Section	Tensile Strength (MPa)	Aspect Ratio	Length (mm)	Type
PPF	Round	500	300	12	Single
SF	Round	1250	60	30	Glued

2.3 Test methods

2.3.1 Fresh properties

For a fresh–state composite, flow, air content, and unit weight were tested to illustrate these properties. Each test method complied with the following ASTM standards: ASTM C1437, C185, and C138 for flow, air content, and unit weight, respectively.

2.3.2 Property evaluation of hardened concrete

To evaluate the properties of hybrid fiber-reinforced, LFS-based mortar, its compressive strength, flexural strength, volume stability (as estimated by the length change ratio), and toughness (as estimated by the strain-stress curve) were measured. Compressive strength and flexural strength as basic engineering properties were tested by following the ASTM C39 and ASTM C293 standards, respectively. The compressive strength tests followed the flexural strength tests.

The dimension of the specimens used in these tests was 4cm×4cm×16cm (Figure 5).

Flexural strength   Compressive strength

Figure 5. Flexural strength and compressive strength test

To illustrate the toughness of these mixtures, stress-strain curves were measured by attaching a strain gauge and linear variable differential transformer (LVDT), as can be seen in Figure 6.

3. Results and discussion

3.1 Fresh properties

Flow, air content, and unit weight were measured during the test, and the results are shown in Figures 7 and 8.

Strain gauge   LVDT

Figure 6. Toughness test

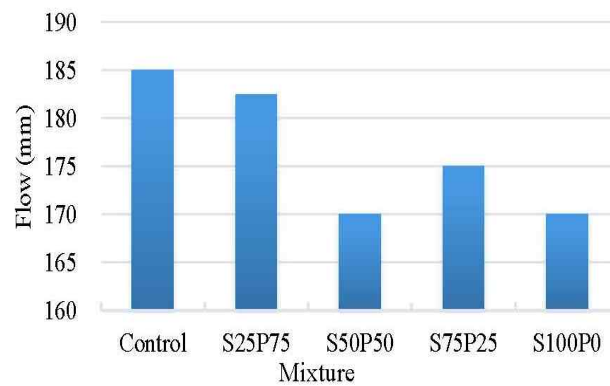


Figure 7. Flow of the various mixtures

According to the results, flow was controlled by the different amount of superplasticizer used to obtain the target value.

In terms of the air content of the fresh composite, a number of changes were also evident; these trends are clearly shown in Figure 8. Higher PPF content increased the air content of the fresh composite. This may aggravate the inborn flow of the cement composite and result in a negative influence on its durability and mechanical properties, such as its compressive strength and flexural strength. Unlike PPF, SF did not have too great an influence on the air content. This finding can be clearly seen with S100P0 (which contains 1% of SF) when compared with the control mix with no fiber. The air content results of these two groups are very close. The unit weights in both PPF and SF are different. This is due to the different densities of SF, PPF, and pure cement mortar. The huge difference in the unit weight of mixture S25P75 may also be caused by the large amount of PPF (Figure 8).

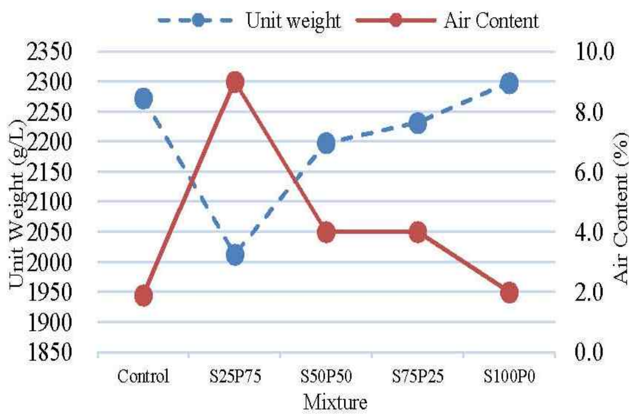


Figure 8. Unit weight and air content of the various mixtures

3.2 Length change

Length change was measured over the course of several hours (Figure 9). A discussion on expansion could be traced in two different ways: one is via the cementing matrix, and the other is to assess the fiber-reinforced effect. According to the experimental results, all five mixtures expanded at various levels. These expansions are aligned with the behaviors of calcium aluminate cement featuring gypsum, which may be caused by the formation of AFt. The formation of AFt in its early stages will increase the matrix's early strength. However, with continuing hydration, the formation of AFt will cause expansion of the matrix and lower its long-term strength by generating microcracks. Pulverized RC-LFS was replaced by 25% gypsum as the binder material for this experiment. The expansion of this matrix should also be caused by the formation of AFt using a similar procedure. The control mixture showed less expansion than S25P75, while it showed higher expansion than the S50P50, S75P25, and S100P0 composites. Given that the control mixture contains no fibers, the expansion level of this mixture could be controlled using the same standard as other mixtures. The relatively higher expansion level of S25P75 may be caused by the additional increase of PPF content, provided that the air content is high and that a large amount of space is given for the formation of AFt. On the other hand, a high level of air content attenuates the interfacial transition zone (ITZ) between the matrix and fibers. A mixture of S50P50, S75P25, and S100P0 showed relatively similar expansion levels; however, some differences were also noted in the results. For mixture S100P0, the expansion rate peaked 72 hours after mixing it with water. Its expansion rate was rapid in the initial 72 hours, and it then started to decrease; it began to exhibit similar patterns to mixture S75P25 after 600 hours. Mixtures S75P25 and S50P50 appeared to be more stable than the other mixtures in their early stages, while mixture S75P25 showed the lowest expansion out of all the fiber-containing mixtures until 800 hours. This result indicates that the hybrid fiber exhibits a positive function in that it can stabilize these expansive mixtures. SF has higher tensile strength than PPF, although the reinforcement effect of fibers depends not only on the tensile strength of the fiber itself, but also on the physical shapes, aspect ratio, and so on. In mono-fiber-reinforced concrete, SF is much more commonly used in load-bearing members. Unlike mono-fiber-reinforced concrete, the hybrid fiber-reinforced composite featuring PFF and SF achieves combined effects to contribute to the performance of the hardened concrete. Since PPF is a microfiber, it will prevent the generation and expansion of microcracks. However, the PPF involved in this experiment has a smooth surface and low tensile strength. These characteristics will attenuate the bonding strength between the fiber and the matrix. After it is combined with SF, which has a high tensile strength and a hook-end physical shape, PPF can provide stronger bonding strength to resist expansion. This phenomenon occurred in mixture S75P25. SF provided good bonding strength, while PPF increased the matrix's toughness, so the mixture was more stable than the mono-fiber-reinforced composite or plain concrete. Based on the test results of this experiment, the hybrid fiber featuring 0.25% of PPF and 0.75% of SF per 1 cubic meter of concrete showed the best result out of the five mixtures.

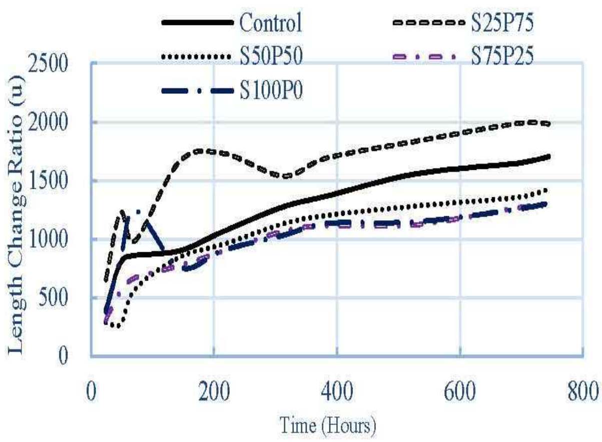


Figure 9. Length changes ratio of various mixtures

3.3 Compressive and flexural strength

The most important characteristics in hardened concrete - flexural and compressive strength - were illustrated in Figures 10 and 11.

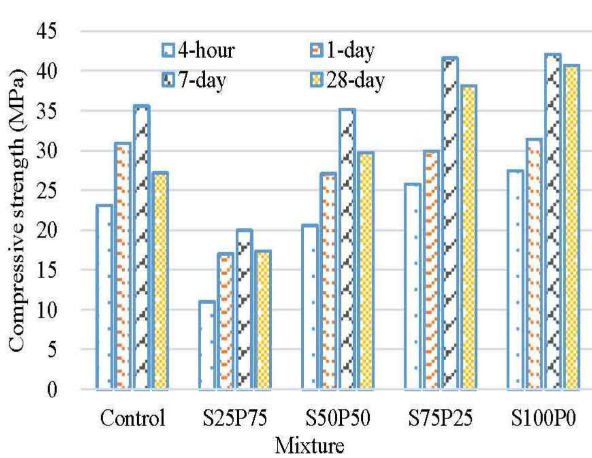


Figure 10. Compressive strength of the different mixtures

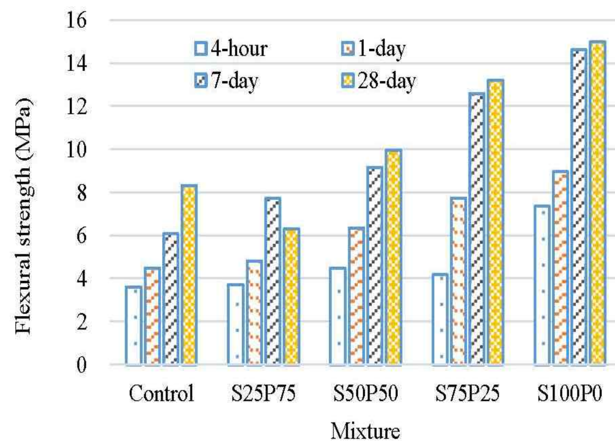


Figure 11. Flexural strength of the different mixtures

Those types of strength were measured at 4 hours, 1 day, 7 days, and 28 days. As rapidly hardening and setting cement, the 4-hour and 1-day strength measurements are illustrative of the matrix's early strength. Even though the compressive strength of S25P75 showed the lowest value of all five mixtures (Figure 10), its 4-hour strength showed the highest value at 11 MPa, which is an impossible value to achieve for ordinary Portland cement. The highest compressive strength belongs to mixture S100P0. Mixture S75P25 showed a similar result to S100P0, but it was a little lower than the average. The 4-hour compressive strengths of S75P25 and S100P0 were 25.8 MPa and 27.5 MPa, respectively, which are very remarkable values.

Another characteristic was noted whereby the compressive strength at 28 days showed the lowest value when compared to that at 7 days. Among all the factors that could lead to this decrease, the formation of AFt may be the most likely one. Its formation in the early stages may increase the compressive strength of the matrix; however, delayed AFt can jeopardize its strength. Conversely, even though the water-to-cement ratio and the curing conditions were controlled, the transformation from CAH_{10} to C_3AH_6 would still occur, thus decreasing the compressive strength. Unlike compressive strength, flexural strength does not exhibit a decrease at 28 days. According to the test results, mixtures S75P25 and S100P0 showed much higher flexural strength than the other mixtures (Figure 11). This may be due to the addition of fiber. When comparing S75P25 and S100P0, it is evident that SF may provide better reinforcement than PPF.

According to the test results, the reinforcement effect of the addition of fibers is clear. Mixture S100P0 showed a minimal decrease among all five mixtures (Figure 12).

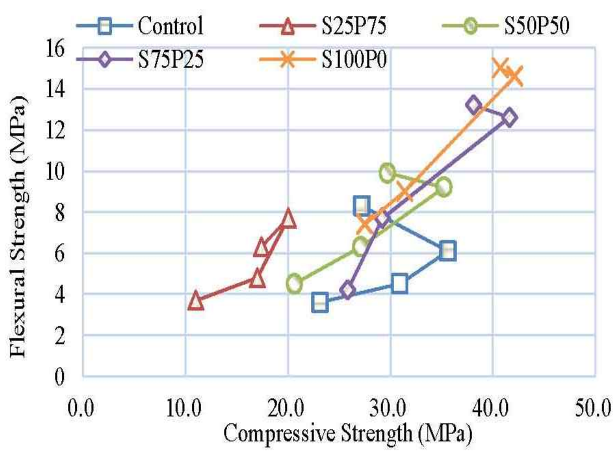


Figure 12. Relationship between compressive strength and flexural strength

The stress-strain curve and stress-strain ratio were tested 28 days after being mixed with water (Figures 13 and 14), which were generated from the strain gauge and LVDT, respectively. For the control mixture, which did not contain any fibers, the stress-strain behavior was found to be brittle. The members which content fibers have the ability to resist deformations that were generated during the loading process after the first crack was generated. In Figures 13 and 14, the different properties of the different fiber systems are illustrated. Among all four mixtures that contained fibers, mixtures S75P25 and S100P0 exhibited remarkable behaviors. With respect to their strength properties, these two mixtures showed similar behaviors. After the first crack was generated, mixture S75P25 showed better behavior than mixture S100P0. From this perspective, a hybrid fiber system featuring an appropriate fiber ratio can exhibit an enhanced performance when resisting deformations and cracks during the loading process.

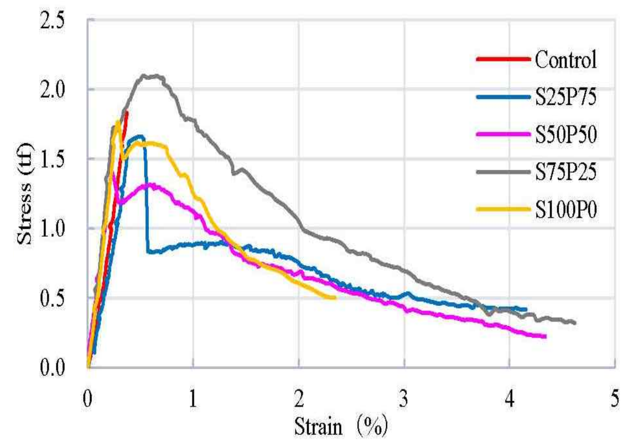


Figure 13. Stress-strain curve behaviors of the different mixtures

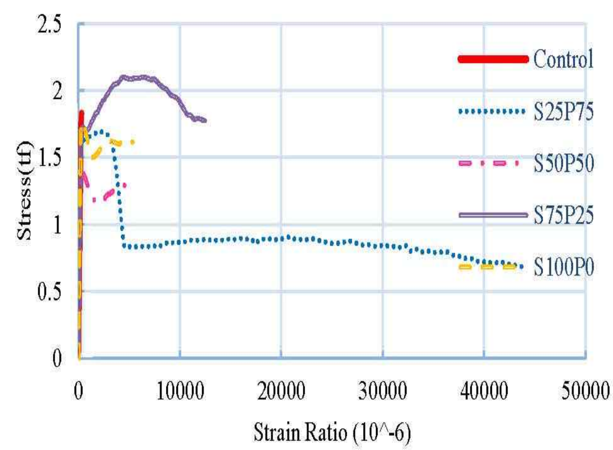


Figure 14. The stress-strain ratio curve behaviors of different mixtures

4. Conclusions

Some conclusion can be generated based on the test results.

1) Pulverized RC-LFS can hydraulic independently and rapid setting and hardening. Its early strength performance is also remarkable.

2) A high amount of PPF can increase the air content of fresh concrete; thus, it can lead to a decrease in the concrete's compressive and flexural strength.
3) A hybrid fiber containing both SF and PPF may increase the concrete's flexural strength, while the hybrid fiber system can modify the stress-strain behavior. The mixture content featuring 0.75% of SF and 0.25% PPF yielded the best performance during the stress-strain test.
4) According to the test results, some additional experiments are needed to clearly illustrate some behaviors, such as the decrease in compressive strength and fiber distribution.

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