

## Article

# Strength and Durability of Hybrid Fiber-Reinforced Latex-Modified Rapid-Set Cement Preplaced Concrete for Emergency Concrete Pavement Repair

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**Abstract:** The benefits of using reinforcing fibers in latex-modified rapid-set cement preplaced concrete for emergency pavement repairs were examined in terms of strength, permeability, and durability as functions of the type of fiber. Single-type fibers, including jute, poly (vinyl alcohol) (PVA), and nylon fibers, as well as hybrid fiber mixtures prepared with two of the aforementioned fibers at a 1:1 weight ratio, were evaluated. Fibers were incorporated into the concrete mixture at 1.2 kg/m<sup>3</sup>. A vibratory press compactor that simulates roller compaction was used to increase compaction and densification of the resulting pavement repair material. The hybrid fiber-reinforced latex-modified rapid-set cement preplaced concrete (HFLMC) was manufactured to satisfy the criteria for opening traffic, i.e., compressive strength of 21 MPa or higher, and flexural strength of 3.5 MPa or higher after 4 h. Pavement requiring repair was removed and replaced with coarse aggregate. The rapid-set binder, fibers, and latex were then mixed and placed onto the coarse aggregate layer. The repair was considered complete after compaction. The resulting HFLMC satisfied all of the test criteria. Furthermore, concretes made with hybrid fibers were more mechanically sound than those made with a single fiber variety. Hybrid fiber concretes made with PVA and nylon fibers exhibited the best properties for emergency pavement repair. These results indicate that HFLMC is suitable for emergency pavement repair.

**Keywords:** durability; emergency pavement repair; hybrid fiber; latex-modified rapid-set cement preplaced concrete



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## 1. Introduction

The materials and methods used to repair aged pavement are evolving [1,2]. Because pavement repair requires a short-term interruption of traffic flow, there is considerable interest in the use of rapid-set concrete-based repair materials [3,4]. However, the high heat of hydration during the development of early strength in rapid-set concrete can result in microcracks that compromise the durability of the entire repaired layer [5,6]. Specifically, microcracks increase the permeability of the repaired pavement structure, resulting in rapid degradation [7,8]. To mitigate this issue, a latex-modified rapid-set cement concrete was developed as a pavement material for emergency repair [9,10]. The addition of latex reduces the risk of cracking due to the heat of hydration [11,12]. During the hydration process, latex bonds to hydrated cement particles to form an interconnected network and continuous material as latex solids fill micropores within the concrete structure. This significantly reduces the occurrence of cracks and material deterioration [13,14]. However, the on-site preparation of such a mixture requires a mobile mixer truck. Self-leveling latex-modified prepacked concretes that do not require a mobile mixer truck have been studied as alternative materials [2,3]. In such a system, an emergency pavement repair is initiated with the removal of the old pavement. A coarse aggregate is then placed into the excavated hole.

The latex and rapid-set binder are mixed using a standard mixer and then poured into the voids within the coarse aggregate. A vibratory press compactor is used instead of a roller compactor. Once the pour and compaction are complete, the pavement repair is finished [2]. A large mobile mixer is not required provided that the coarse aggregate is deposited into the repair area before adding the self-leveling latex-modified rapid-set cement concrete [2]. Furthermore, the use of a vibratory press compactor significantly enhances the durability of the repaired pavement layer [2]. However, self-leveling latex-modified preplaced concrete does not completely solve the problem of microcrack formation and subsequent concrete degradation. This study addresses this problem with the addition of reinforcing fibers to effectively reduce crack formation, thereby increasing the strength and durability of the concrete mixture. Crack formation in materials containing reinforcing fibers occurs by separation of the fibers from the cement matrix, fiber pull-out, or fracture of the fiber itself [15–18]. This study investigated natural jute, poly (vinyl alcohol) (PVA), and nylon fibers, as well as hybrid fiber mixtures consisting of two types of reinforcing fiber at a 1:1 weight ratio. The effects of fiber type on the properties of latex-modified rapid-set cement preplaced concrete were evaluated toward the improvement of current materials used for emergency pavement repair.

## 2. Materials and Methods

### 2.1. Materials

Rapid-set cement is manufactured by mixing rapid-hardening calcium sulfoaluminate clinker minerals with Type 1 cement components. The chemical properties of rapid-set cement (Jungang Polytech Co., Ltd., Yangsan City, Gyeongnam, Korea) are shown in Table 1. The coarse aggregate consisted of crushed stone with a maximum size of 25 mm and a density of 2.61 g/mm<sup>3</sup> (Table 2). The fine aggregate consisted of river sand with a density of 2.58 g/mm<sup>3</sup> (fineness modulus: 2.80). The properties of the styrene–butadiene (SB) latex (Jungang Polytech Co., Ltd.) are provided in Table 3. The styrene content of the latex was 34 ± 1.5% and the butadiene content was 66 ± 1.5%. The latex mixture consisted of 46.5% solids. The properties of the natural jute, PVA, and nylon fibers (Nycon Materials Co., Ltd., Asan City, Chungnam, Korea) are shown in Table 4. The densities of these fibers were 1.26, 1.26, and 1.16 g/mm<sup>3</sup> with lengths of 6, 3, and 3 mm and diameters of 0.015, 0.015, and 0.023 mm, respectively. The types of the fibers are shown in Figure 1.

**Table 1.** Chemical compositions of rapid-set cement.

SiO <sub>2</sub> (%)	Al <sub>2</sub> O <sub>3</sub> (%)	Fe <sub>2</sub> O <sub>3</sub> (%)	CaO(%)	MgO(%)	K <sub>2</sub> O(%)	SO <sub>3</sub> (%)
13 ± 3	17.5 ± 3	3>	50 ± 3	2.5>	0.21	14 ± 3

**Table 2.** Physical properties of coarse aggregate.

Density (g/mm <sup>3</sup> )	Absorption (%)	Fine Modulus
2.61	0.35	6.92

**Table 3.** Properties of styrene–butadiene latex.

Solids Content (%)	Styrene Content (%)	Butadiene Content (%)	pH	Density (g/mm <sup>3</sup> )	Surface Tension (dyne/cm)	Particle Size (Å)	Viscosity (cps)
46.5	34 ± 1.5	66 ± 1.5	11.0	1.02	30.57	1700	42

**Table 4.** Fiber properties.

Properties	Jute Fiber	PVA Fiber	Nylon Fiber
Elastic modulus (GPa)	61	45	35
Tensile strength (MPa)	510	1600	800
Density (g/mm <sup>3</sup> )	1.26	1.26	1.16
Fiber length (mm)	6	3	3
Fiber diameter (mm)	0.015	0.015	0.023



(a)



(b)



(c)

**Figure 1.** Type of fibers. (a) Jute fiber. (b) PVA fiber. (c) Nylon fiber.

## 2.2. Mix Proportions and Test Specimen Preparation

This study adopted the specifications of the American Association of State Highway and Transportation Officials, the Road Traffic Bureau of each state in the United States, and the Korea Expressway Corporation for repairing pavement using rapid-set cement [19,20]. The standards specify a traffic opening time of 4 h, at which point the material must reach a compressive strength of at least 21 MPa and a flexural strength of at least 3.5 MPa. Furthermore, these specifications require a minimum compressive strength of 35 MPa, a flexural strength of 4.5 MPa, and a splitting tensile strength of 4.2 MPa after 28 days of curing. Permeability, which strongly affects pavement service lifetime in terms of durability, was evaluated according to the ASTM C1202 chloride ion penetration test [21]. The acceptance criterion for permeability was a maximum of 2000 coulombs after 28 days of curing, as recommended by the Korea Expressway Corporation. Moreover, the durability acceptance criterion was a relative dynamic modulus of 80% or higher after 300 freeze–thaw cycles. The mix proportions of latex-modified rapid-set cement preplaced concretes containing single fiber types or hybrid fiber mixtures are provided in Table 5. Rapid-set cement was used at 400 kg/m<sup>3</sup> per mixture. The deployment of hybrid fiber-reinforced latex-modified rapid-set cement preplaced concrete (HFLMC) involves the use of a pressurized vibrating compactor. However, filling the voids in a coarse aggregate is only possible if the HFLMC has sufficient fluidity. Therefore, pressurized vibration compaction was used together with a rapid-set cement mortar with sufficient fluidity to allow self-leveling. Latex was added at a 15% weight ratio to rapid-set cement to ensure fluidity upon compaction. A water–cement ratio of 0.28 was applied. Fibers (single or hybrid mixtures) were added at a rate of 1.2 kg/m<sup>3</sup>.

**Table 5.** Mix proportions of HFLMC materials for pavement repair.

Design Compressive Strength: 4 h (MPa)	Maximum Size of Coarse Aggregate (mm)	W */C (%)	Unit Weight (kg/m <sup>3</sup> )								
			Water	Rapid Set Cement	Fine Aggregate	Coarse Aggregate	Latex		Reinforcing Fibers		
							Solid	Water	PVA	Jute	Nylon
21	25	28	43	400	1015	832	60	69	0	0	0
									1.2	0	0
									0	1.2	0
									0	0	1.2
									0	0.6	0.6
									0.6	0.6	0
									0.6	0	0.6

\* water and water in latex.

The specimen dimensions for testing mechanical properties and durability were as follows: cylindrical specimens measuring  $\varnothing 100 \times 200$  mm were used for compressive strength, splitting tensile strength, and chloride ion penetration tests; prism-shaped specimens with dimensions of  $100 \times 100 \times 400$  mm were used for flexural strength and freeze-thawing testing, and cylindrical specimens measuring  $\varnothing 150 \times 150$  mm were used in abrasion tests. Figure 2 shows the manufacturing process for HFLMC specimens. First, molds were filled with coarse aggregate (Figure 2a). Second, water, rapid-set cement, sand, latex, and fiber were mixed in a mixer for 1.5 min and then poured into a mold containing the coarse aggregate (Figure 2b). Finally, the surface of the specimen was compacted using a special vibratory press compactor (Figure 2c). Figure 2d shows manufactured compression and flexural strength specimens. Vibratory press compaction ensured that the latex-modified rapid-set cement material filled the voids in the coarse aggregate. No signs of insufficient compaction, such as persistent voids, were observed. In addition, no material separation of fibers from the latex-modified rapid-set cement was observed.



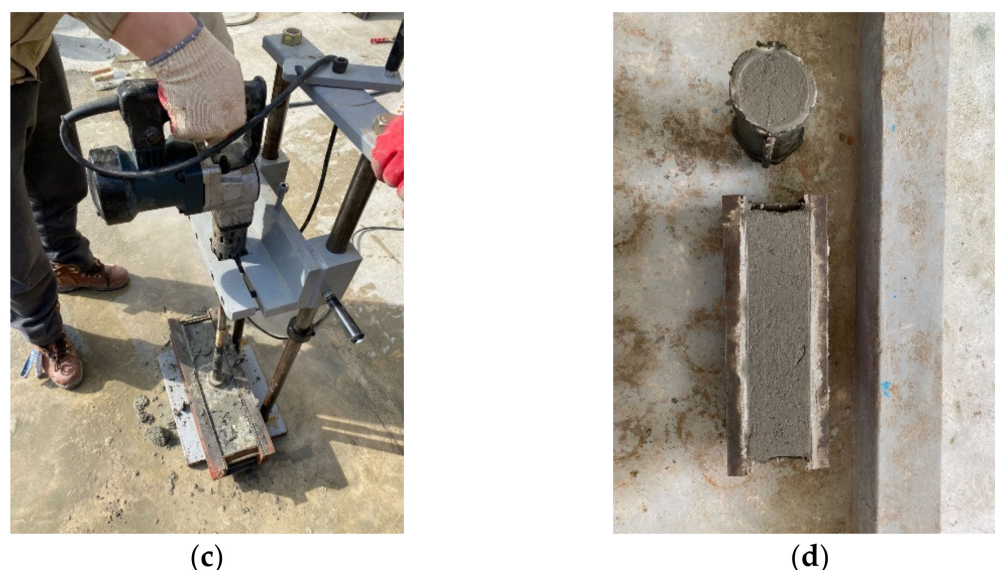
(a)



(b)

**Figure 2.** Cont.





**Figure 2.** Test specimen manufacturing process. (a) Filling of coarse aggregate in the mold. (b) Fiber-reinforced rapid-set latex-modified materials pouring. (c) Pressurized vibration compaction, (d) Completion of manufacture of test specimen.

### 2.3. Test Methods

#### 2.3.1. Mechanical Properties

The compressive, flexural, and splitting tensile strengths of HFLMC were evaluated in accordance with ASTM C 39 [22], C 78/C78M [23], and C 496/C496M [24], respectively, after 4 h, 7 days, and 28 days of curing. Test specimens for evaluating mechanical properties were manufactured twice in batches of three, resulting in a total of six specimens for each mechanical property being evaluated.

#### 2.3.2. Durability

The durability of HFLMC materials was evaluated via chloride ion penetration, abrasion, and repeated freeze–thaw tests. Chloride ion penetration tests were conducted in accordance with ASTM C1202 after 28 days of curing [18]. Abrasion tests were conducted in accordance with ASTM C944 after 7 days of curing [25]. Repeated freeze–thaw tests were performed in accordance with ASTM C666/C666M [26]. Specimens were manufactured for durability testing in two batches of two, giving a total of four specimens.

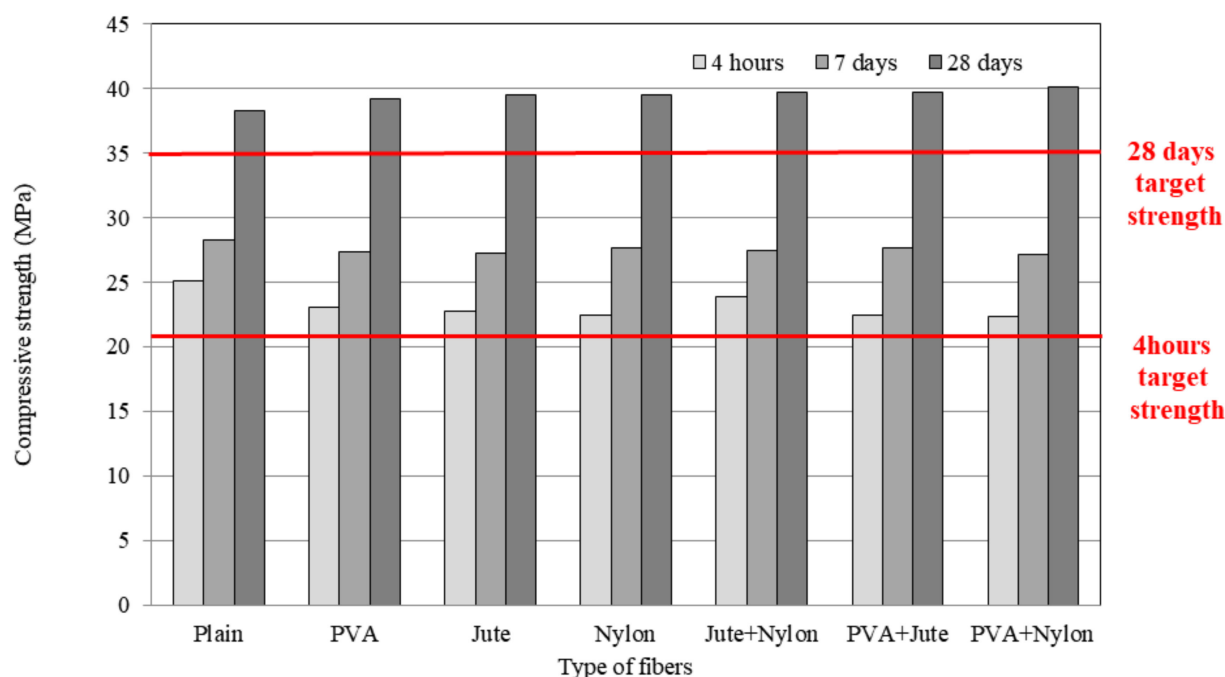
## 3. Test Results

### 3.1. Compressive Strength

The compressive strengths of each HFLMC material are shown in Figure 3. Mixtures containing fibers exhibited slightly lower compressive strengths after 4 h. This is due to the surface hydrophilicity of the fibers, which tend to absorb water and suppress evaporation during the early stages of curing.

All of the mixtures created in this study satisfied the requirement of 21 MPa compressive strength after 4 h. After 7 days, the fiber-reinforced and plain mixtures had similar compressive strengths. After 28 days, all mixtures met the target compressive strength of 35 MPa. After 28 days, the fiber-reinforced materials showed greater splitting tensile strengths than the plain mixtures, with enhancements of 2.62%, 3.31%, 3.39%, 3.83%, 3.91%, and 5.01%, respectively, for mixtures containing PVA, jute, nylon, jute+nylon, PVA+jute, and PVA+nylon fibers. The compressive strengths of fiber-reinforced mixtures were 2.62–5.01% higher than those of plain mixtures. Furthermore, hybrid fiber mixtures were more effective than single fiber mixtures in terms of strength enhancement. This can be attributed to the greater diversity in fiber length and diameter of the hybrid mixtures, which was more effective for filling voids within the concrete, thereby suppressing crack

formation and growth [27,28]. Notably, the PVA+nylon hybrid fiber mixture developed the highest compressive strength. The variety in fiber dimensions suppressed both macro and micro-crack formation. However, batch-to-batch variation in concrete quality is a concern. From a quality control perspective, synthetic nylon and PVA fibers are preferred because their properties can be readily controlled by the manufacturer. In contrast, the properties of jute fibers, as a natural material, are difficult to control.



**Figure 3.** Compressive strength of HFLMC mixtures.

### 3.2. Flexural Strength

The flexural strengths of the HFLMC mixtures for emergency pavement repair are shown in Figure 4. All of the mixtures attained the minimal traffic-opening criteria of flexural strength of 3.5 and 4.5 MPa at 4 h and 28 days, respectively. The hybrid fiber-reinforced mixtures had higher flexural strengths than those of the single-fiber reinforced mixtures. Fiber reinforcement had a greater influence on flexural strength than on compressive strength. Notably, the PVA–nylon hybrid fiber-reinforced mixture had the highest flexural strength among the studied HFLMC mixtures. After 28 days of curing, the flexural strengths of mixtures containing PVA, jute, nylon, jute+nylon, PVA+jute, and PVA+nylon fibers increased over those of the plain mixtures by 11.03%, 13.21%, 12.31%, 19.23%, 17.89%, and 22.30%, respectively. These data show that the hybrid systems are more effective for reinforcing concrete materials. As discussed above, the hybrid fibers were better able to suppress crack formation due to the variability in fiber length and diameter [29].

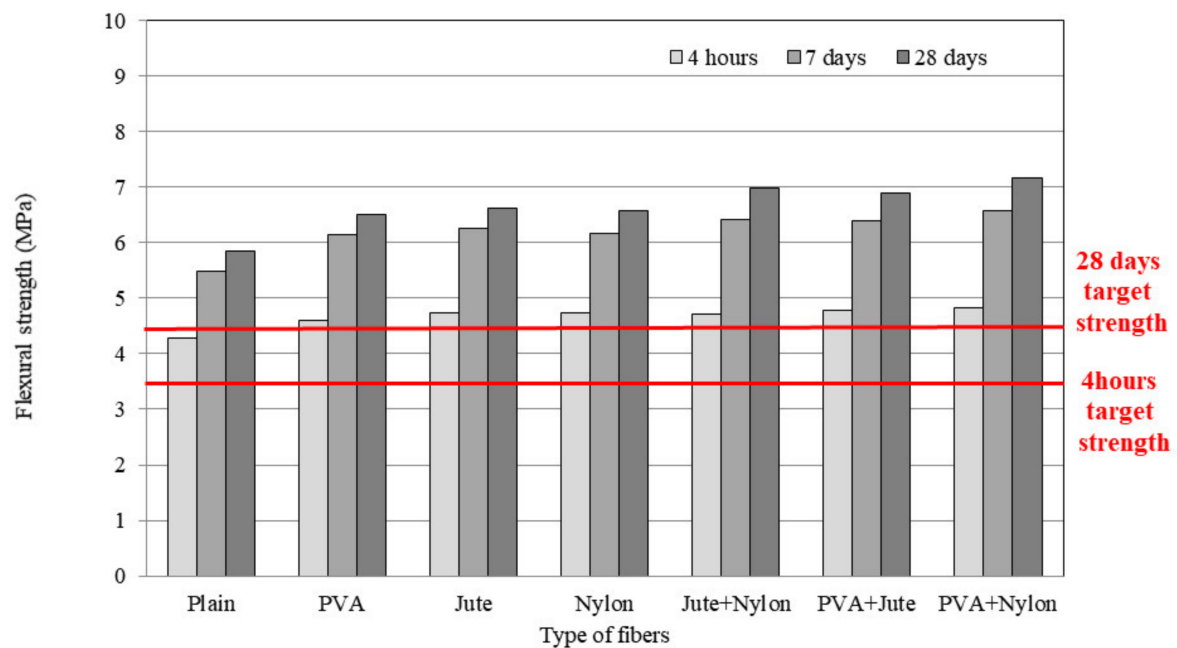


Figure 4. Flexural strength of HFLMC mixtures.

### 3.3. Splitting Tensile Strength

According to the Korea Expressway Corporation standard, an emergency pavement repair material must attain a splitting tensile strength of at least 4.2 MPa after 28 days. This criterion was met by all of our HFLMC mixtures with no significant differences in performance (Figure 5). However, the splitting tensile strengths of the fiber-reinforced mixtures were higher than those of plain mixtures. Again, hybrid fiber systems were more effective than single fiber systems in terms of strength enhancement.

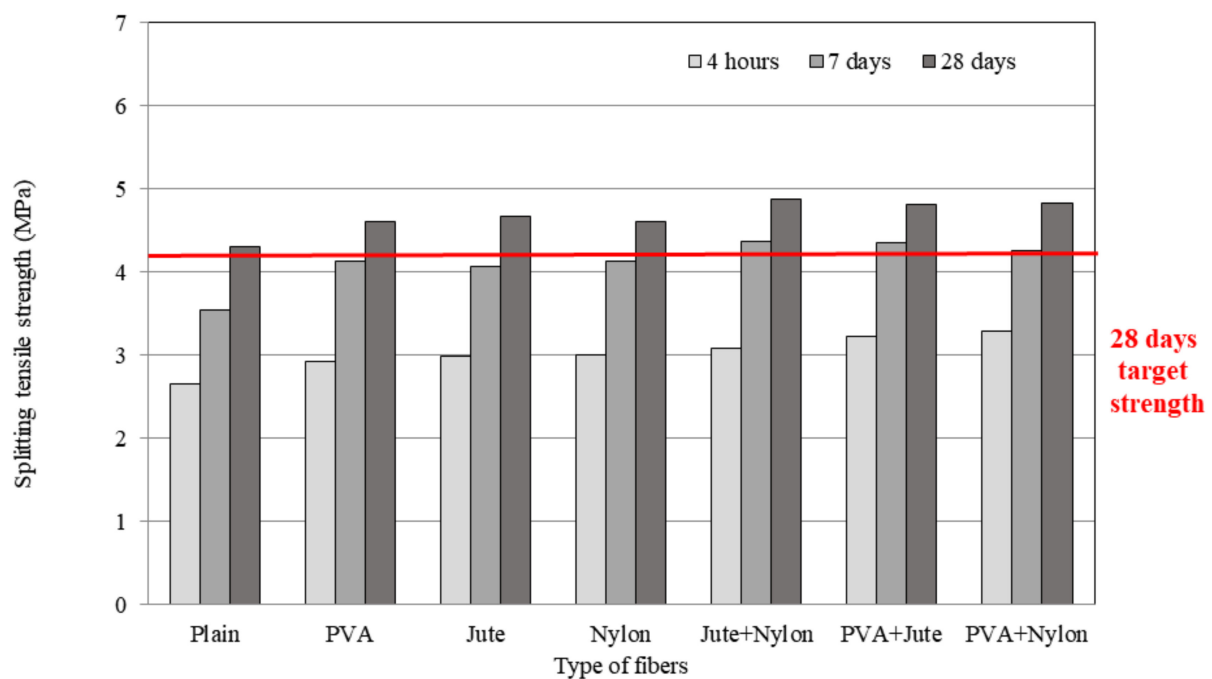


Figure 5. Splitting tensile strength of HFLMC mixtures.

In general, adding fibers to concrete is more effective for increasing tensile strength than compressive strength [30]. This is because fiber reinforcement suppresses crack formation and growth, the main factors responsible for concrete fracture [31]. In addition, crack suppression is more effective with hybrid fiber mixtures than with single-type fibers [27–30]. In the current study, the hybrid fiber system satisfied the 4.2 MPa requirement after only 7 days. After 28 days, the splitting tensile strengths of mixtures containing PVA, jute, nylon, jute+nylon, PVA+jute, and PVA+nylon fibers increased over those of plain mixtures by 7.27%, 8.65%, 7.19%, 12.24%, 12.12%, and 13.31%, respectively. The PVA+nylon hybrid fiber system yielded the highest splitting tensile strength.

### 3.4. Chloride Ion Penetration Resistance

Figure 6 shows the amount of charge passed during chloride ion permeation tests on the HFLMC mixtures. The solid line corresponds to the permeability criteria specified by the ASTM C1202. Fiber-reinforced mixtures had less charge passed compared to plain mixtures, and those containing hybrid fibers were less permeable than those containing single-type fibers. The single-type fiber system passed about 1500–2000 coulombs, corresponding to “low” permeability according to ASTM C1202. In contrast, the hybrid fiber system passed only 1000 coulombs or less, corresponding to “very low” permeability. After 28 days, the permeabilities of mixtures containing PVA, jute, nylon, jute–nylon, PVA+jute, and PVA+nylon fibers decreased compared to those of plain mixtures by 20.4%, 22.9%, 37.5%, 50.2%, 49.8%, and 56.0%, respectively.

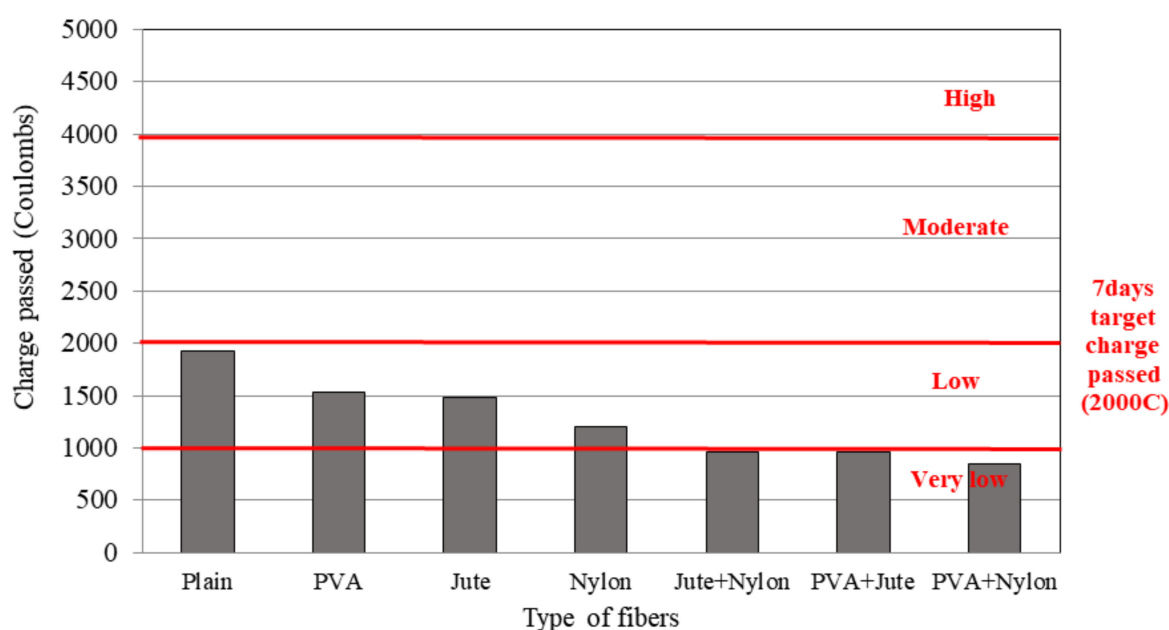


Figure 6. Permeability of HFLMC mixtures.

Latex creates a thick impermeable layer within the concrete, resulting in decreased permeability [29]. This explains the excellent permeability resistance shown by all mixtures. In addition, fiber reinforcement further reduced permeability by suppressing the occurrence and growth of microcracks within the concrete [28,29]. Microcracks likely occur in rapid-set concrete because of the high heat of hydration that occurs during the early stage of curing [1,2]. This is largely eliminated by incorporating both latex and fiber reinforcements. Of the various mixtures evaluated, the PVA+nylon hybrid fiber-reinforced concrete passed the smallest amount of charge, corresponding to “very low” permeability.



### 3.5. Abrasion Resistance

Figure 7 shows the abrasion resistance of the HFLMC mixtures for emergency pavement repair. Compared to mixtures without fibers, those containing PVA, jute, nylon, jute–nylon, PVA+jute, and PVA+nylon fibers showed 7.31%, 10.64%, 7.30%, 16.95%, 19.51%, and 22.60% increases in abrasion resistance, respectively. This is because the fibers prevent particles from breaking free of the concrete surface. Furthermore, the fibers suppressed the occurrence and growth of surface microcracks and created denser concrete structures [2,3]. The abrasion resistance of HFLMC was much greater than that of the plain mixtures. As with the other mechanical properties, the hybrid fiber system was more effective than the single-type fiber-reinforced system at suppressing the formation and growth of cracks within and on the surface of the concrete. Notably, the PVA+nylon hybrid fiber-reinforced mixture exhibited the greatest resistance to abrasion.

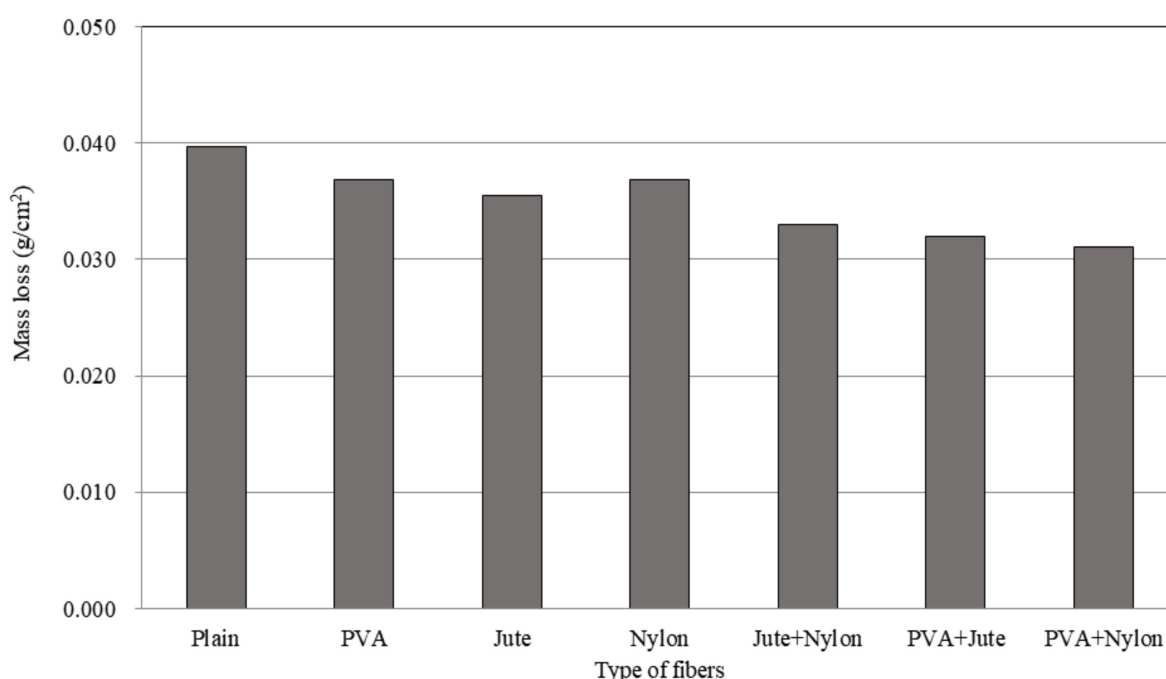


Figure 7. Mass loss of HFLMC mixtures.

### 3.6. Repeated Freezing and Thawing Resistance

The relative dynamic moduli of the HFLMC mixtures are shown in Figure 8. All mixtures satisfied the target relative dynamic modulus of 80% after 300 cycles of freezing and thawing. However, plain mixtures showed a marked decrease in relative dynamic modulus after 90 cycles with further decreases up to 300 cycles. In contrast, the fiber-reinforced mixtures had relative dynamic moduli exceeding 95% or higher, indicating greater freeze–thaw resistance than the plain mixtures. Note that the single-type fiber systems also exhibited decreases in relative dynamic modulus, although the cycle at which the decreases began varied with the type of fiber: 120 cycles for PVA fiber, 180 cycles for nylon fiber, and 210 cycles for jute fiber. After 300 cycles, the relative dynamic moduli of mixtures containing PVA+nylon, PVA+jute, jute+nylon fiber, PVA, jute, and nylon fibers were 98.30%, 97.82%, 96.32%, 94.36%, 94.34%, and 94.26%, respectively. By comparison, the relative dynamic modulus of the plain mixture was 93.37%. The relative dynamic moduli of hybrid fiber-reinforced mixtures remained nearly constant. In particular, the PVA+nylon hybrid fiber-reinforced mixture exhibited the highest freeze–thaw resistance. This was attributed to the presence of latex in the mixture [29]. It is also likely that the fibers suppressed the formation and growth of microcracks induced by repeated freezing

and thawing. Note also that the hybrid fiber mixtures were more resistive to freeze–thaw cycles than the plain mixtures.

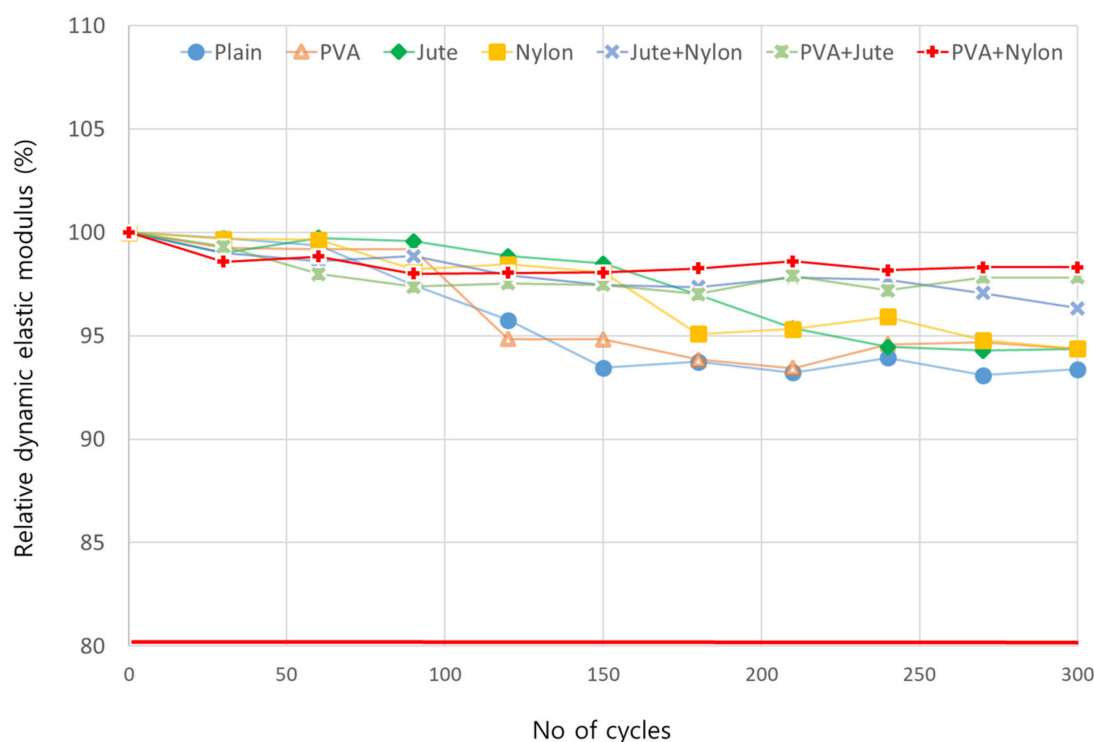


Figure 8. Relative dynamic modulus of HFLMC mixtures.

#### 4. Conclusions

This study evaluated the strength and durability of fiber-reinforced latex-modified rapid-set cement preplaced concrete for emergency pavement repair. A variety of fiber systems were evaluated. The test results are summarized as follows:

All HFLMC mixtures satisfied the compressive strength requirements of at least 21 MPa after 4 h and at least 35 MPa after 28 days; these are the criteria for opening traffic after an emergency pavement repair. The compressive strengths of fiber-reinforced mixtures were higher than those of mixtures without fibers. Furthermore, the hybrid fiber systems exhibited greater compressive strength than those incorporating a single type of fiber.

All of the HFLMC mixtures satisfied the flexural strength requirements of at least 3.5 MPa after 4 h and at least 4.5 MPa after 28 days. As with the compressive strength results, the hybrid fiber-reinforced mixtures had higher flexural strengths than the single-type fiber-reinforced mixtures. Notably, the hybrid fiber-reinforced mixtures had flexural strengths exceeding 4.5 MPa after only 7 days. The highest flexural strength was obtained with the incorporation of PVA+nylon hybrid fibers.

Similarly, all of the HFLMC mixtures satisfied the target splitting tensile strength of 4.2 MPa after 28 days. Hybrid fiber-reinforced materials showed higher splitting tensile strengths than those containing only single-type fibers. The highest splitting tensile strength was observed with the hybrid fiber-reinforced HFLMC containing PVA+nylon fibers.

All of the HFLMC mixtures met the target chloride ion permeability of under 2000 coulombs. The amount of charge passed decreased substantially to 1000 coulombs or less, indicating very low permeability, with the inclusion of hybrid fibers.

The inclusion of hybrid fibers also increased the abrasion resistance of the HFLMC mixtures over those with single-type fibers or no fibers. This was due to the denser structure created by the fibers and the suppression of crack formation on the surface of the concrete.

In freeze–thaw tests, all of the HFLMC mixtures met the target relative dynamic modulus of 80% or higher. A marked reduction in modulus was observed with plain mixtures after 90 cycles. This reduction was absent with mixtures containing either single or hybrid fibers. Incorporating hybrid fibers as reinforcement increased the relative dynamic modulus to 95% or higher, indicating excellent freeze–thaw resistance.

Thus, this study demonstrates the benefits of incorporating fiber reinforcements, and most notably, hybrid fiber mixtures, into latex-modified rapid-set concrete pavement repair materials. Clear advantages were observed in terms of strength and durability.

**Author Contributions:** S.-J.L. conceived and designed the experiments, H.-J.S. performed the experiments and analyzed data, and C.-G.P. analyzed data and wrote the manuscript. All authors have read and agreed to the published version of the manuscript.

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