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Durability performance of latex modified nylon fiber reinforced concrete for precast concrete pavement applications

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The mechanical and durability characteristics of latex-modified nylon fiber-reinforced concrete (LMNFRC) are investigated with a view to precast concrete pavement applications. Precast concrete pavement can mitigate various problems in the field, e.g., eliminating the need for concrete casting and curing on-site. Compared with conventional concrete, using precast concrete pavement minimizes the wait time following repairs, thus enabling the earliest movement of traffic. Concrete cracking is an issue in the field. In this study, the nylon fiber volume fraction (0, 0.05, and 0.1%) and the amount of added latex (0, 5, 10, and 15% of the cement weight) are varied, and the slump, compressive strength, flexural strength, chloride ion penetration, abrasion resistance and impact resistance are measured. Increasing the latex content improved the flexural strength, permeability resistance, abrasion resistance, and impact resistance of the LMNFRC. Increasing the volume fraction of the nylon fiber improves the same properties. These improvements are attributed to stronger bonding and greater impact absorption capability by the nylon fiber and latex.

Keywords: Latex, Mechanical properties, Nylon fiber, Precast concrete pavement, Permeability, Durability

Concrete pavement is widely used in many structures, including roads, highways and airport runways.[1,2] However, it is susceptible to rapid deterioration caused by the influx of water and moisture that penetrates through the concrete surface. This leads to scaling, erosion, and abrasion.[3,4] A variety of maintenance methods have been applied to cope with these problems.[1,5-7] However, fresh concrete pavement requires about 28 days to cure.[1,2,8] During this time, traffic must be rerouted, thus introducing significant delays.[1,2] Because of this long curing time, it is not possible to use ASTM Type I cement on a roadway or airport runway in need of urgent rehabilitation.[3,4] Concrete mixtures made with fast-setting cement or rapid-hardening cement can be used, but only temporarily because of their limited durabilities.[5-8] Concrete pavement made with such cements has diminished durability and shortened maintenance intervals because of rapid generation of micro-cracks resulting from the heat of hydration.[4-6] Latex addition to the concrete mix has been explored as a way to use high early-strength concrete in pavement formulations because of the ability of latex to improve the concrete's permeability resistance.[6] However, the fast-setting, rapid hardening property of such cement makes it difficult to precisely measure its properties.[6] Using precast concrete pavement can significantly reduce problems in the field by eliminating the need for concrete casting and curing on-site.[1,2] Moreover, it allows the earliest traffic openings after replacement or repair.[1,2] Precast concrete pavement has excellent durability; previous studies have shown little evidence of deterioration resulting from a rapidly developing heat of hydration.[1,2] Also, precast concrete pavement is plant-based and can be manufactured with excellent quality control.[1,2] In fact, precast concrete structures are more likely to become cracked by impact during delivery and installation. Fiber-reinforced concrete (FRC) is concrete that contains or is reinforced with dispersed, randomly oriented, unconnected fibers.[9,10] Concrete is intrinsically brittle, but such brittleness is rectified if it is reinforced with fibers within its structure; its ductility is improved by the suppression of crack growth by the reinforcing fibers.[11,12] Pavement made from fiber-reinforced precast concrete has a high resistance to cracking and to fracturing that can occur during transportation and installation.[9,10] Adding latex improves the fluidity of the concrete mix, even at low water-to-cement ratios.[13-15] This is because of interactions of cement

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materials with the surfactant present in the latex.[14,15] The formation of a latex film improves the bond strength and mechanical properties of concrete, and increases the concrete's resistance to water permeability.[11,12,15] This study evaluated the strength of latex-modified nylon fiber-reinforced concrete (LMNFRC) and its resistance to permeability, impact, and abrasion with a view to using it in precast concrete pavement applications.

Experimental Procedure

Materials

The properties of the latex (Dow Chemical Company, USA) used in this study are given in Table 1. Latex is a semi-transparent, milky liquid containing colloidal (0.5-5.0 µm diameter) organic polymer microparticles that are stabilized by surfactant.[9-12] When latex is added to a cement formulation, the surfactant in the latex delays solidification and increases the workability at low water/cement (W/C) ratios; the latex particles meanwhile form a film during cement hydration.[9-12] Air voids in the cement are filled in such a way that a semi-continuous plastic film is formed on the aggregate surface, resulting in poorer permeability but improved bond and tensile strengths.[9-12] The compressive strength of cement-based composites depends on the W/C ratio; a higher W/C ratio results in decreased strength and increased shrinkage. The W/C ratio should be low to achieve high strength in a short time with minimum shrinkage; however, these conditions decrease the workability.[9-12] The surfactant introduced with the latex can compensate for this.[12-14] Latex has been widely used in bridge deck overlays with excellent results.[16-21] Bridge deck overlay is more exposed to environmental changes than general road pavement. The overlay cannot be greatly affected by temperature, and must be treated with waterproofing materials to protect the bridge slabs.[16-21] Latex has been used in many concrete bridges because it provides excellent workability, waterproofing, and durability.[16-21] The properties of the ASTM Type 1 cement used here are shown in Table 2. The fine aggregate had a specific gravity of 2.62. The maximum size of the coarse aggregate used in this study was 25 mm; it had a specific gravity of 2.65. Abrasion testing according to the ASTM C131 standard gave a wear rate of 17.8%. The grading distribution curves of the aggregates are shown in Fig. 1. The properties of the nylon fiber (length: 6 mm; diameter: 0.013 mm) used are given in Fig. 2 and Table 3.

Mix proportions

This study focused on improving the resistance of LMNFRC to permeability, impact, and abrasion for potential application in precast concrete pavement structures. This study varied the nylon fiber volume

Table 1 – Properties of latex

Solids content (%)	Styrene content (%)	Butadiene content (%)	pH	Density (g/mm^3)	Surface tension (dyne/cm)	Particle size (A)	Viscosity (cPs)
49	34 ± 1.5	66 ± 1.5	11.0	1.02	30.57	1700	42

Table 2 – Properties of cement

	Fineness (cm^2/g)	Density (g/mm^3)	Stability (%)	Setting time		Compressive strength (MPa)		
				Initial (min)	Final (min)	3 days	7 days	28 days
Physical properties	3,200	3.15	0.02	220	400	20	30	38

Table 3 – Properties of nylon fiber

Modulus of elasticity (GPa)	Density (g/mm^3)	Fiber diameter (mm)	Fiber length (mm)	Tensile strength (MPa)
3.5	1.16	0.023	6	800

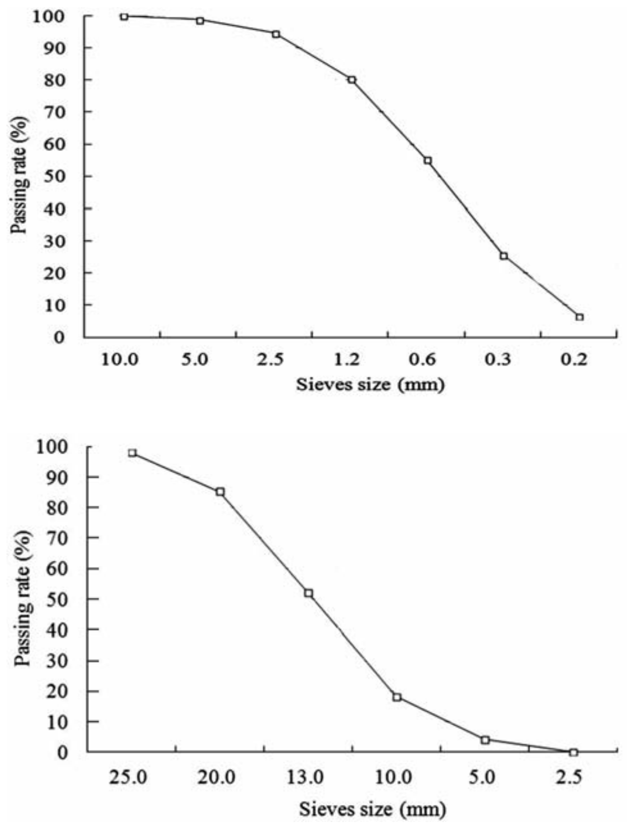

Fig. 1 – Grading distribution curve of the fine and coarse aggregates

fraction (0, 0.05, and 0.1%) and the latex content (0, 5, 10, and 15% of the cement weight). Precast concrete pavement applications require a flexural strength of 4.5 MPa after 28 days of curing. This study target slump for this application was 180 mm. The mix compositions are given in Table 4.

Slump test

Slump tests were carried out according to the ASTM C 143 standard, to determine the effect of the added latex and reinforcing fibers on the workability of the LMNFRC. [22]

Compressive strength

Compressive strength testing was done in accordance with the ASTM C39 standard.[23] The specimens were 100 mm in diameter and 200 mm in length. The tests were performed after 28 days of curing.

Flexural strength

Flexural tests were conducted in accordance with the ASTM C496 standard.[24] Specimens with dimensions of 100 × 100 × 400 mm^3 were cured in water at 23 ± 2°C. The tests were performed after 28 days of curing.

Fig. 2 – Shape of nylon fibers

Table 4 – Mix proportions of nylon fiber latex modified concrete for precast pavements

No. of mix	W/C (%)	S/a (%)	Unit weight (kg/m^3) W	C	S	G	Admixture	Nylon fiber	latex
No. 1							3.22	0	0
No. 2							3.22	0.58	0
No. 3							3.22	1.16	0
No. 4							0	0	24.4
No. 5							0	0.58	24.4
No. 6							0	1.16	24.4
No. 7	35	38.28	171	488	620	1015	0	0	48.8
No. 8							0	0.58	48.8
No. 9							0	1.16	48.8
No. 10							0	0	73.2
No. 11							0	0.58	73.2
No. 12							0	1.16	73.2

Chloride ion penetration

Chloride ion penetration tests were conducted in accordance with the ASTM C1202-94 standard.[25] The specimens were 100 mm in diameter and 50 mm in length. The test apparatus is shown in Fig. 3.

Abrasion resistance

Abrasion tests were conducted in accordance with the ASTM C944 standard.[26-28] Specimens with dimensions of 150 × 60 mm^2 were tested after 28 days of curing. The test apparatus is shown in Fig. 4.

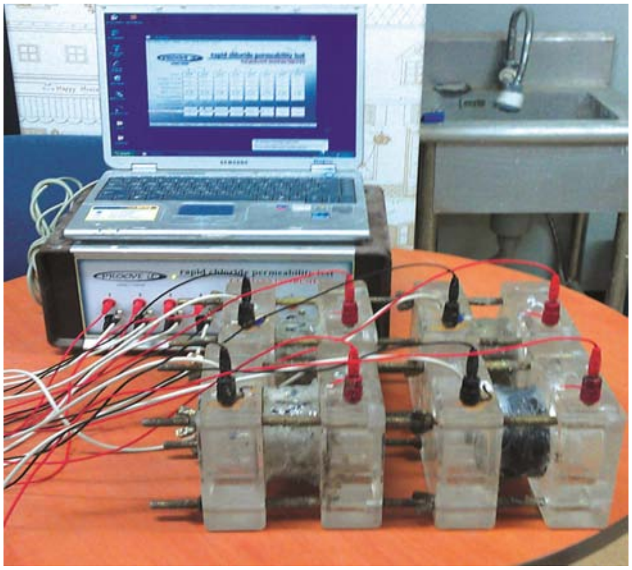

Fig. 3 – Chloride ion penetration test set-up

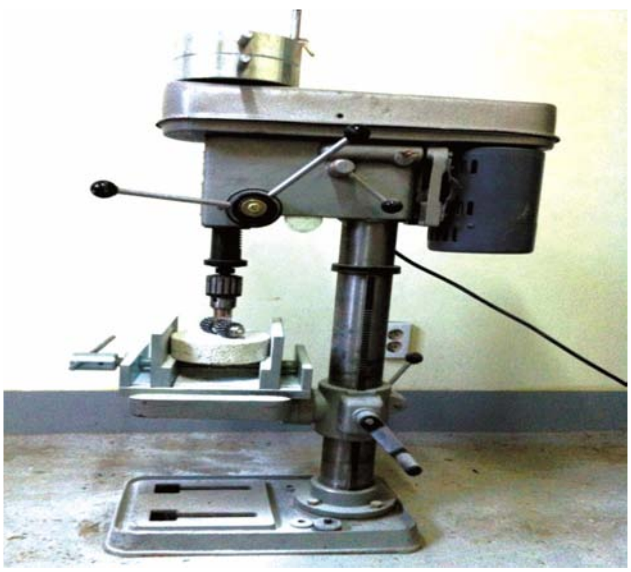

Fig. 4 – Abrasion test set-up

Impact resistance

Impact tests were conducted in accordance with the specifications of the ACI Committee 544.[29] Specimens with dimensions of 150 × 60 mm^2 were cured in water at 23 ± 2°C. Each test was performed after 28 days of curing.

Results and Discussion

Slump test

Figure 5 shows the results of slump testing for samples with varying amounts of added latex and nylon fiber. The slump value decreased as the nylon fiber volume fraction increased for a given latex level.

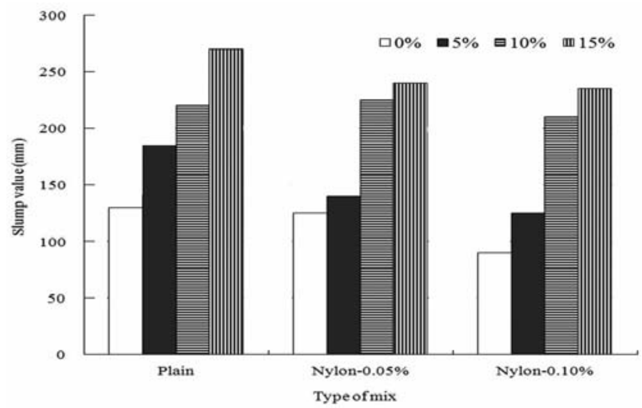

Fig. 5 – Slump test results

The slump value increased as more latex was added for a fixed nylon fiber volume fraction. In the case of plain concrete, as the latex additive level increased from 0 to 5, 10, and 15%, the slump value increased from 130 to 185, 220, and 275 mm, respectively. For the mix with a nylon fiber content of 0.5%,_as the latex level increased from 0 to 5, 10, and 15%, the slump increased from 125 to 140, 225, and 240 mm, respectively. Additionally, for the mix with a nylon fiber content of 0.1%, as the latex level increased from 0 to 5, 10, and 15%, the slump value increased from 90 to 125, 210, and 235 mm, respectively. Hydrophilic nylon fibers absorb the mix water and thus lower the slump value, worsening the workability of the concrete through a bridging effect.[32-34] Latex initially greatly improves the workability of concrete through an interfacial effect. It can be used to offset the workability reduction with increasing nylon fiber content, i.e., the workability of nylon fiber-reinforced precast concrete for pavement can be improved in this way[9-12.] In this study, the target slump value was 180 mm for application as precast concrete pavement. This was achieved by latex loadings of at least 10%, regardless of the amount of added nylon fiber. Therefore, the latex loading must be at least 10% to ensure the workability of precast concrete containing reinforcing nylon fiber and intended for pavement.

Compressive strength

Figure 6 shows the compressive strength test results for LMNFRC containing varying amounts of added latex and nylon fiber. For plain concrete, as the latex content increased from 0 to 5, 10, and 15%, the compressive strength steadily decreased from 40.2 to 33.30, 31.80, and 25.83 MPa, respectively. At a nylon fiber loading of 0.05%, as the latex level increased

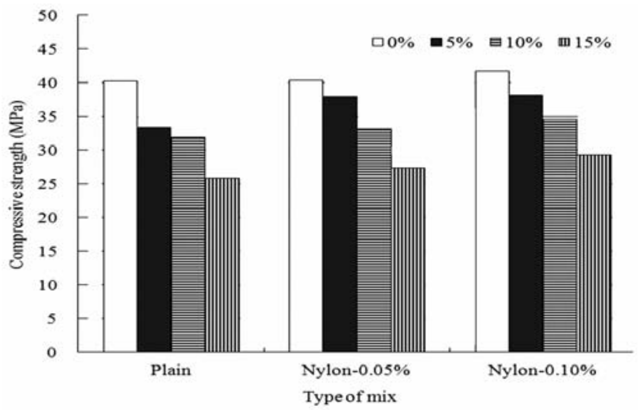

Fig. 6 – Compressive strength test results

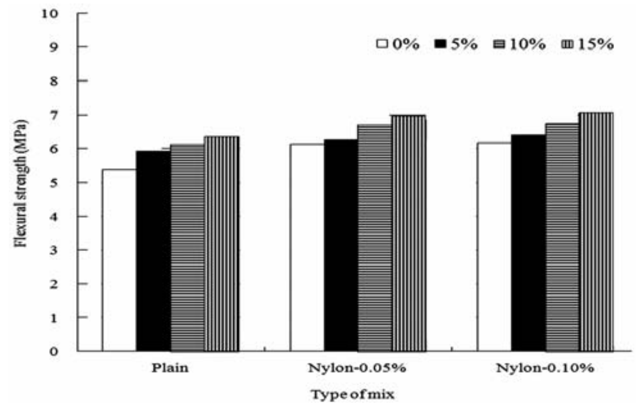

Fig. 7 – Flexural strength test results

from 0 to 5, 10, and 15%, the compressive strength decreased from 40.40 to 33.29, 33.04, and 27.24 MPa, respectively. Additionally, at a nylon fiber loading of 0.1%, as the latex level increased from 0 to 5, 10, and 15%, the compressive strength decreased from 41.67 to 38.13, 34.53, and 29.20 MPa, respectively. The compressive strength decreased as more latex was added (for a given nylon fiber volume fraction). The addition of latex is known to improve the tensile strength of concrete, rather than its compressive strength.[9-12] This has been explained in terms of the latex film interfering with the hydration reaction.[30,31] At a fixed latex level, however, there was at most a slight increase in the compressive strength as the nylon fiber volume fraction was increased. Generally, if the volume fraction of fiber in fiber-reinforced concrete is increased, the compressive strength only increases slightly.[31-33] This is because the fiber dispersion worsens with increasing fiber volume fraction, which generates pores at the bonding interface between fibers and the concrete because of balling of the fibers.[9-12] Nylon is a hydrophilic fiber and has an excellent bonding capacity through hydrogen bonding with the concrete, and can reduce the number of pores generated at the interface between the fibers and the concrete.[31-33] In this research, adding latex prevented the strength reduction resulting from fiber balling because the latex improved the dispersion of the fibers. Using both hydrophilic nylon fiber and latex together is more advantageous when attempting to improve the compressive strength of concrete than using nylon fiber or latex individually.

Flexural strength

Figure 7 shows the flexural strength test results of LMNFRC made with varying amounts of latex additive and nylon fiber. For plain concrete, as the latex level increased from 0 to 5, 10, and 15%, the flexural strength steadily increased from 5.38 to 5.93, 6.12, and 6.36 MPa, respectively. At a nylon fiber loading of 0.05%, as the latex level increased from 0 to 5, 10, and 15%, the flexural strength also increased from 6.12 to 6.26, 6.70, and 6.96 MPa, respectively. At a nylon fiber loading of 0.10%, as the latex level increased from 0 to 5, 10, and 15%, the flexural strength increased from 6.18 to 6.39, 6.75, and 7.08 MPa, respectively. The addition of latex has a greater effect on the tensile and flexural strengths of the concrete than on its compressive strength. The latex film enhances the bond strength between materials when concrete is subjected to flexural or tensile loading.[16-21] The results of this study are consistent with this: the flexural strength increased as more latex was added. The tests with varying nylon fiber volume fraction showed that the flexural strength also increased with the nylon fiber volume fraction. Using a hydrophilic fiber such as nylon in fiber-reinforced concrete, rather than a hydrophobic fiber, can clearly improve the performance of concrete through improved bonding.[32-34] Improvements in bonding are seen through improved fiber pullout, fiber bridging, fiber fracture and fiber debonding. Fiber-reinforced concrete has improved flexural strength because the generation and growth of cracks are suppressed during flexural loading.[32-34] Film formation by the added latex improves bonding and thereby the flexural strength of concrete. Thus, using nylon, a hydrophilic fiber, and latex greatly improved the flexural strength of the concrete: all of the mixes with co-addition of latex and nylon fiber exceeded the target flexural strength of 4.5 MPa for precast concrete pavement applications.

Chloride ion penetration

Figure 8 shows the chloride ion penetration test results. This test indirectly assesses the permeability of concrete. The chloride penetration rate decreased as the amount of latex increased. This is consistent with the filling of voids inside the concrete with the latex, which eventually forms a thick film that reduces the ion penetration. The penetration was greatest for the plain concrete, and then decreased as the amounts of latex and nylon fiber increased. In general, reinforcing fiber in fiber-reinforced concrete suppresses the formation of connecting pores and the generation and growth of cracks inside the concrete; this improves the water permeation resistance.[32-34] A hydrophilic fiber is better than a hydrophobic one at improving the water permeation resistance of concrete because of enhanced bonding with the concrete.[32-34] A hydrophilic fiber suppresses the formation of fine cracks inside the concrete because of this improved bonding. Although using a hydrophobic fiber improves the water penetration resistance relative to conventional concrete, these fibers generate pores at the bonding interface because of the weaker bonding between the concrete and the fiber.[32-34] Thus, the water permeability can increase through this interface. A hydrophilic nylon fiber is more effective at improving the water permeation resistance than a hydrophobic fiber.[32-34] In this study, concurrent addition of latex and nylon fiber improved the water permeation resistance significantly; similar behavior would be expected in a precast concrete application. Better water permeation resistance should also improve durability.

Abrasion resistance

Figure 9 shows the abrasion resistance test results for LMNFRC. This property also improved with the amount of added latex. This behavior is attributed to coating of the concrete surface by the latex film, thereby strengthening the abrasion resistance of the surface. Additionally, the bonding between materials was improved by the latex addition. The test results also indicate that the abrasion resistance increased with the nylon fiber volume fraction.

Traffic load wears out the surface of precast concrete pavement. Fine cracks can form inside the concrete, which accelerates the destruction of a structure. Fiber-reinforced concrete has an improved abrasion resistance because the bridging action of the reinforcing fibers limits concrete particles from falling off the main body of the pavement.[33] If the fiber is not well dispersed, however, fiber balling occurs, which accelerates surface abrasion. Latex addition improves fiber dispersion and can suppress surface wear by improving the bridging action of the reinforcing fiber through the formation of a latex film.[16-21] Co-addition of latex and nylon fiber was more effective at improving the wear resistance than using latex or nylon fiber alone.

Impact resistance

Figure 10 shows the impact resistance test results. The number of impacts required for the initial appearance of cracking and for final breaking increased with the amount of added latex. This is because the latex film improved the bond strengths between the materials and limited the crack formation and propagation resulting from impacts. The number of impacts required for the initial appearance of cracking and for final breaking also increased with the nylon fiber volume fraction. Fiber reinforcement improves the fracture toughness or the energy absorption capacity of concrete.[9-12,33] A higher fiber volume fraction increased the fracture toughness and

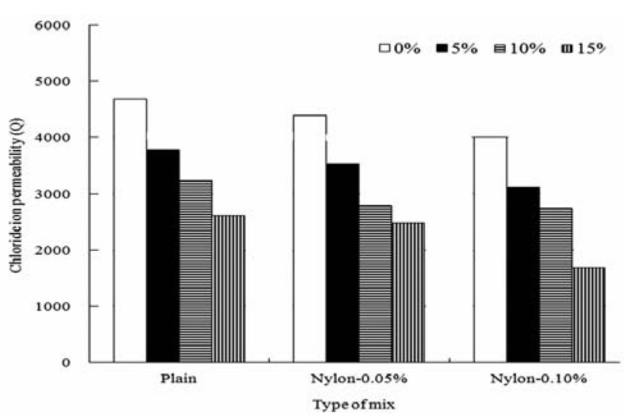

Fig. 8 – Chloride ion penetration test results

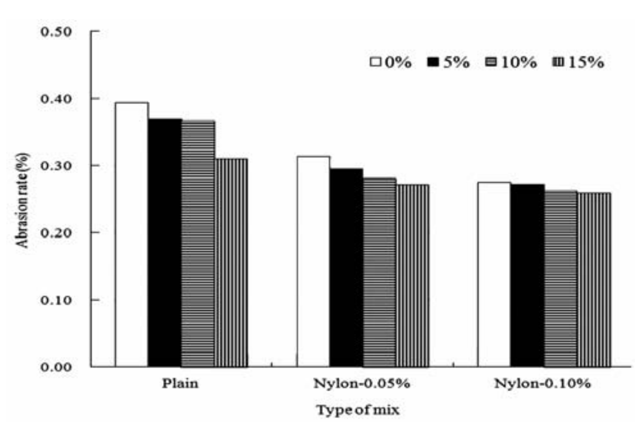

Fig. 9 – Abrasion test results

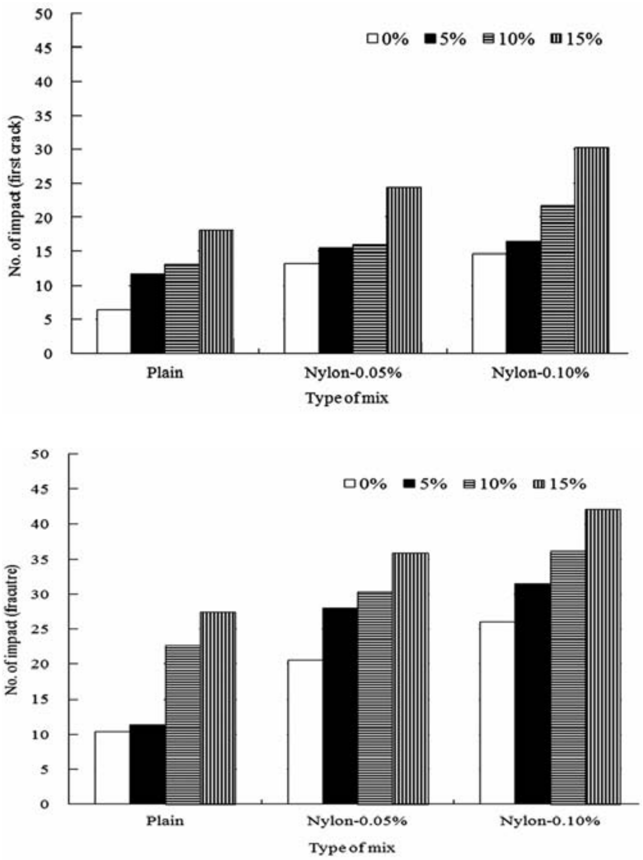

Fig. 10 – Impact test results (a) number of impacts for initial cracking and (b) number of cracks to failure

improved the impact resistance of precast concrete pavement by absorbing the impact energy. Latex addition improved the bonding between materials and thereby the resistance to impact. The improved fiber dispersion by the latex also assisted in delocalizing the impact energy from the point of impact. Latex is rubbery and can absorb some of the impact energy on a precast concrete pavement surface.[16-21] Therefore, as the latex addition level and the amount of nylon fiber increased, so did the impact resistance. Mixes containing both latex and nylon required more impacts to generate the first crack and fracture than the mixes made with only latex or nylon fiber.

Conclusions

In this study, the nylon fiber volume fraction (0, 0.05, and 0.1%) and the amount of added latex (0, 5, 10, and 15% of the cement weight) were varied for LMNFRC. Slump, compressive strength, flexural strength, chloride ion penetration, abrasion resistance, and impact resistance were measured. The following conclusions can be drawn from this study:

(i) Slump increased with increasing latex loading and decreased as the amount of nylon fiber increased. The target slump of 180 mm for ensuring adequate workability of LMNFRC was achieved for all nylon fiber contents for latex levels of 10% and higher.

(ii) Compressive strength decreased with increasing latex content, but increased with increasing nylon fiber content. Concurrent addition of the two materials can control this change in compressive strength.

(iii) Flexural strength increased with the latex content and amount of nylon fiber. Concurrent addition of latex and nylon fiber was more effective at improving the flexural strength than the addition of either material individually. This is because the addition of latex improved the bonding between materials through the formation of a latex film. The latex also improved the dispersion of nylon fibers, which helped to improve the mechanical properties of LMNFRC.

(iv) Chloride ion penetration resistance decreased with increasing latex loading and nylon fiber content. Concurrent addition of latex and nylon fiber showed better chloride ion penetration resistance than individual incorporation of latex or nylon fiber.

(v) Abrasion resistance improved with latex addition. The latex strengthened the surface of the concrete and nylon fiber suppressed spalling through the bridging action of the fiber. The added latex also improved the dispersion of the added nylon fiber and thereby amplified its reinforcing effect. Co-addition of latex and nylon fiber provided the best abrasion resistance improvement for LMNFRC.

(vi) Impact resistance improved with increasing latex and nylon fiber loadings. Concurrent addition of latex and nylon fiber especially improved the impact resistance, and was better than the individual addition of either latex or nylon fiber. It is expected that the combined use of latex and nylon fiber would improve the impact resistance of precast concrete pavement structures.

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