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Strength properties of nylon- and polypropylene-fiber-reinforced concretes

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Abstract

The strength potential of nylon-fiber-reinforced concrete was investigated versus that of the polypropylene-fiber-reinforced concrete, at a fiber content of 0.6 kg/m^3. The compressive and splitting tensile strengths and modulus of rupture (MOR) of the nylon fiber concrete improved by 6.3%, 6.7%, and 4.3%, respectively, over those of the polypropylene fiber concrete. On the impact resistance, the first-crack and failure strengths and the percentage increase in the postfirst-crack blows improved more for the nylon fiber concrete than for its polypropylene counterpart. In addition, the shrinkage crack reduction potential also improved more for the nylon-fiber-reinforced mortar. The above-listed improvements stemmed from the nylon fibers registering a higher tensile strength and possibly due to its better distribution in concrete.

Keywords: Mechanical properties; Concrete; Fiber reinforcement; Shrinkage

1. Introduction

Concrete is a tension-weak building material, which is often crack ridden connected to plastic and hardened states, drying shrinkage, and the like. The cracks generally develop with time and stresses to penetrate the concrete, thereby impairing the waterproofing properties and exposing the interior of the concrete to the destructive substances containing moisture, bromine, acid sulfate, etc. The exposure acts to deteriorate the concrete, with the reinforcing steel corroding. To counteract the cracks, a fighting strategy has come into use, which mixes the concrete with the addition of discrete fibers [1,2]. Because of the mixing action, the fibers are uniformly distributed throughout the concrete in all directions. In the fresh concrete, the uniformly distributed fibers reinforce against the formation of plastic shrinkage cracks. In the hardened concrete, the uniformly distributed fibers disallow the microcrack from developing into macrocracks and potential troubles. In addition, these fibers bridge and therefore hold together the existing macrocracks, thus reinforcing the concrete against disintegration. The concrete-reinforcing fibers include metal, polymer, and various others. Among the polymer fibers, the polypropylene fibers enjoy popularity in the domain of concrete [3–13] and the nylon fibers show a rising acceptance [14,15]. The polypropylene fibers claimed contribution to the concrete performance subjected to crack opening and slippage [4]. Furthermore, the fibers reinforced the performance under not only compression, flexure, and tension [7], but also under impact blows [9] and plastic shrinkage cracking [10]. On the other hand, the nylon fibers stepped up the performance after the presence of cracks [14] and sustained high stresses [15]. However, the establishment was awaiting as to how the polypropylene fibers compete with the nylon rivals in advancing the performance of concrete under compression, tension, flexure, etc., and in shrinkage cracking control.

In this paper, the strength properties and shrinkage cracking control of nylon-fiber-reinforced concrete were under investigation, in comparison with those of the polypropylene-fiber-reinforced concrete counterpart.

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2. Experimental program

2.1. Materials

The materials used for the nonfibrous control concrete mixture consisted of the normal Type I Portland cement, the gravel having a maximum size of 2.54 cm, and the river sand having a fineness modulus of 2.9. Approximately 300 kg/m^3 of cement and 194 kg/m^3 of mixing water were used with 1050 kg/m^3 gravel and 850 kg/m^3 sand for the nonfibrous concrete mixture. To the nonfibrous mixture, the nylon and polypropylene fibers were both added at the concentration of 0.6 kg/m^3 for the nylon- and polypropylene-fiber-reinforced concretes. The properties of the two types of fibers appear in Table 1.

2.2. Mixing and curing

The procedures for mixing the fiber-reinforced concrete involved the following. Firstly, the gravel and sand were placed in a concrete mixer and dry mixed for 1 min. Secondly, the cement was spread and dry mixed for 1 min. Thirdly, the mixing water was slowly added and mixed for 2 min. After which, the specified amount of fibers was distributed and mixed for 3 min. Lastly, the freshly mixed fiber-reinforced concrete was fed into the cylinder molds for the compressive and splitting tensile strength specimens measuring 15×30 cm, and into the beam molds for the flexural specimens measuring 15×15×53 cm.

After the feeding operation, each of the specimens was allowed to stand for 24 h before demolding, stored in lime water at 23 °C for 28 days, and then removed and kept at room temperature until the time of testing. Following the removal, some of 15×30 cm specimens were employed for assessing the impact strength of the control and fiber-reinforced concretes. For the assessment, each of the specimens was cut into four cylindrical discs for the impact specimens, each measuring 15×6.4 cm.

2.3. Drop weight test

The impact strength assessment followed the ACI committee 544 recommendations [16], which subjects an impact specimen to repeated blows. The number of blows to the first visible crack on the specimen top served as the first-crack strength; the number of blows to the ultimate failure of the specimen, the failure strength. The stage of the failure is clearly recognized by the fractured specimens butting against the lugs on the base plate.

Table 1
Physical properties of nylon and polypropylene fibers

Fiber type	Fiber length (mm)	Specific weight	Elastic modulus (GPa)	Tensile strength (MPa)	Melting point (°C)
Nylon	19	1.14	5.17	896	225
Polypropylene	19	0.91	4.11	413	160

2.4. Fiber distribution

The in-concrete distribution of nylon and polypropylene fibers was approximated through the distribution of these fibers in the mixing water. To approximate the distribution, 3 g of nylon and polypropylene fibers were respectively introduced into a 5×40 cm cylindrical glass measure filled with 1000 g of the mixing water. After the introduction, the measure was stopped, vigorously agitated, and allowed to stand for 2 h. Next to the standing procedure, the volume of the suspension containing the fibers was measured.

2.5. Shrinkage crack reduction potential test

The shrinkage crack reduction potential of nylon and polypropylene fibers in concrete was evaluated by assessing the potential of these two types of fibers in the rich and no-coarse-aggregate cement mortar consisting of cement and sand at the ratio of 1:1.5. The fibrous mortar was molded into the 60×60×6 cm test slab by using a steel mold. The interior faces of the mold and the base plate received a thin layer of lubricant to eliminate the friction between the mortar and the base plate. Immediately after the molding operation, the slab was exposed to an air stream at a speed of 12 to 16 km/h. The exposure lasted 24 h, followed by the measurements of width and length of the plastic shrinkage cracks appearing on the slab face. According to the widths, the cracks fell into four categories: large, medium, small, and hairline. The cracks about 3 mm wide were the large ones, assigned a weighted value of 3. The cracks about 2, 1, and 0.5 mm wide were the medium, small, and hairline ones, respectively, and the corresponding weighted values were 2, 1, and 0.5.

To each crack, the crack length multiplied by the weighted value was the weighted average value. The sum of the weighted average values for the cracks in a slab was the total weighted value. Comparing the total weighted values between the fibrous and nonfibrous slabs quantified how the nylon and polypropylene fibers reduced the sensitivity of the concretes to plastic shrinkage cracks.

3. Results and discussion

3.1. Dispersion characteristic

The volume of the nylon fiber containing suspension was about 25% of the capacity of the glass measure, which was a 5% increase over that of the polypropylene fibers containing suspension. The increase indicates that compared to the polypropylene fibers, the nylon fibers claimed a slightly increased ability to distribute themselves throughout the concrete, thus distributing the unfavorable stresses within a greater volume of concrete and improving the concrete's properties in the plastic and hardened state.

3.2. Compressive strength

The experimental results on the strengths of the two fiber-reinforced concretes and the nonfibrous control concrete appear in Table 2, including the compressive and splitting tensile strengths and modulus of rupture (MOR). Each of the results was the average of 18 test specimens. Following the table, the compressive strength of the nylon-fiber-reinforced concrete improved by 12.4% over the nonfibrous control counterpart, followed by the polypropylene-fiber-reinforced concrete at 5.8%. Both of the improvements came principally from the fibers interacting with the advancing cracks. When withstanding an increasing compression load, the fibrous concrete cylinders may develop lateral tension, thus initiating cracks and advancing those cracks. As the advancing crack approached a fiber, the debonding at the fiber–matrix interface began due to the tensile stresses perpendicular to the expected path of the advancing crack. As the advancing crack finally reached the interface, the tip of the crack encountered a process of blunting because of the already present debonding crack. The blunting process reduced the crack-tip stress concentration, thus blocking the forward propagation of the crack and even diverting the path of the crack. The blunting, blocking, and even diverting of the crack allowed the fibrous concrete cylinders to withstand additional compressive load, thus upgrading its compressive strength over the nonfibrous control concrete.

The compressive strength of the nylon fiber concrete topped that of the polypropylene fiber concrete by a 6.3% increase. The increase stemmed from the nylon fibers recording the higher tensile strength, which resulted in greater tensile stresses being transferred from a cracked matrix to the nylon fibers than to the polypropylene fibers, thus leading to the increase in the compressive strength of the nylon fiber concrete. Additionally, the nylon fibers carried a more marked dispersion in the mixing water, implying that the nylon fibers distributed themselves more thoroughly throughout the concrete, which also backed the increase.

In Table 2, the coefficient of variation V compares the uniformity of strength data on the fiber-reinforced and plain concretes. The two V values for compressive strength of fiber-reinforced concretes come in vicinity of that of plain concrete, declaring that the presence of nylon and polypropylene fibers went without undesirable effects on compressive strength variability.

3.3. Splitting tensile strength

Following Table 2, the splitting tensile strengths of the nylon- and polypropylene-fiber-reinforced concretes were 17.1% and 9.7% higher, respectively, than that of the unreinforced control concrete. Once the splitting occurred and continued, the fibers bridging across the split portions of the matrix acted through the stress transfer from the matrix to the fibers and, thus, gradually supported the entire load. The stress transfer improved the tensile strain capacity of the two fiber-reinforced concretes and, therefore, increased the splitting tensile strength of the reinforced concretes over the unreinforced control counterpart.

Because of the slightly increased dispersion in the mixing water, a greater number of nylon fibers intersected the split sections, accordingly declaring the splitting tensile strength to be 6.7% higher for the nylon fiber concrete than for the polypropylene fiber concrete. This declaration was consistent with the statement that the splitting tensile strength of fiber-reinforced concrete behaved in proportion to the number of fibers intersecting the fracture surfaces [17]. As with the compressive strength, the declaration came partially from the nylon fiber carrying the higher tensile strength.

In Table 2, the V values on splitting tensile strength run near to each other, manifesting that the incorporation of the two types of fibers invited improvement in absence of unfavorable effect on the variability of splitting tensile strength.

Table 2
Strength test result on nylon- and polypropylene-fiber-reinforced concretes versus plain control concrete

Concrete type	Descriptive statistics	Compressive strength[a] (MPa)	Splitting tensile strength[a] (MPa)	Modulus of rupture[a] (MPa)	Slump (cm)
Nylon-fiber-reinforced concrete	Mean[a]	25.88	2.54	6.24	12.5
	Standard deviation	1.86	0.18	0.38	
	Coefficient of variation (V)	7.2	7.1	6.1	
Polypropylene-fiber-reinforced concrete	Mean[a]	24.35	2.38	5.98	12
	Standard deviation	1.83	0.16	0.36	
	Coefficient of variation (V)	7.5	6.7	6.0	
Plain control concrete	Mean[a]	23.02	2.17	5.89	16
	Standard deviation	1.77	0.15	0.36	
	Coefficient of variation (V)	7.7	6.9	6.1	

[a] Each strength value is the average of 18 samples.

3.4. Modulus of rupture

The MOR of the nylon fiber concrete posted a 5.9% increase over the nonfibrous control concrete, with the polypropylene fiber concrete registering 1.5%. The increase resulted primarily from the fibers intersecting the cracks in the tension half of the reinforced beam. These fibers accommodated the crack face separation by stretching themselves, thus providing an additional energy-absorbing mechanism and also stress relaxing the microcracked region neighboring the crack-tip. Apart from the fiber–crack intersection, the nylon fibers topped the polypropylene fibers in the in-concrete fiber dispersion and the tensile strength. The topping also led the MOR of the nylon fiber concrete to a 4.3% increase over the polypropylene fiber concrete.

As stated for compressive and splitting tensile strengths, the nylon and polypropylene fiber additions made bearable differences in the variability carried by the MOR for the two fibrous concretes, compared to the plain concrete counterpart.

3.5. Impact resistance

The drop weight test results reportedly exhibit dispersion [18], which was detectable in the current work. In view of the dispersion, the current drop weight test results were evaluated statistically. The statistical evaluation of the 48 discs in this work appears in Table 3. According to the evaluation, the mean first-crack and failure strengths of nylon-fiber-reinforced discs increased 19.0% and 30.5%, respectively, over the plain control discs, whereas the figures for the polypropylene-fiber-reinforced discs were 11.9% and 17.0%, respectively. All these figures mirrored the benefit of nylon and polypropylene fiber additions and displayed the nylon fiber addition outperforming the polypropylene counterpart in benefiting the two strengths. In Table 3, the term PINPB is the percentage increase in the number of postfirst-crack blows, representing the potential of a disc to delay the ultimate failure after the first crack appears. The mean PINPB value of nylon fiber concrete was 1.6 times higher than that of the polypropylene fiber concrete, indicating that the nylon fiber addition was more effective than its polypropylene counterpart in delaying the ultimate failure. The values for the coefficients of variation V on the two strengths and on the PINPB, respectively, reached their maxima for the plain control concrete discs, followed by the polypropylene fiber concrete discs, and the nylon fiber concrete discs. The descending order declares the two fiber additions narrowing the dispersion in the two strengths and in the PINPB. The minimum V value for the nylon fiber concrete arose because the nylon fiber addition worked better in overshadowing the local weakness of the disc and, thus, prompted the redistribution of stresses through the disc during the millisecond period of each impact event.

Table 3
Statistical evaluation for the impact test results on nylon- and polypropylene-fiber-reinforced concretes and plain control concrete

Concrete type	Descriptive statistics	First-crack strength (blows)	Failure strength (blows)	PINPB[a] (blows)
Nylon-fiber-reinforced concrete	Mean	200	231	16
	Standard deviation	62	63	2
	Coefficient of variation (V)	31	27	13
Polypropylene-fiber-reinforced concrete	Mean	188	207	10
	Standard deviation	65	67	3
	Coefficient of variation (V)	35	32	30
Plain control concrete	Mean	168	177	5
	Standard deviation	60	61	2
	Coefficient of variation (V)	36	34	40

[a] Percentage increase in number of postfirst-crack blows to ultimate failure.

3.6. Shrinkage cracking control

The plain control mortar carried the highest value of 3800 for the total weighted value, followed by the polypropylene fiber mortar with 1120, and the nylon fiber mortar with 870. Obviously, the nylon fibers performed better in reducing the incubating of early plastic shrinkage cracks because of their higher tensile strength resulting in better load transfer across the cracks. This, along with the more marked in-concrete distribution, progressed the crack-friendly concrete from the plastic to hardened state with a pronounced integrity, also contributing to the above-discussed strength improvements achieved by nylon fiber concrete over its polypropylene counterpart.

4. Conclusions

The nylon fiber-reinforced concrete outperformed its polypropylene companion in the upgrading of compressive and splitting tensile strengths, MOR, and impact resistance. The outperforming arose from the higher tensile strength of nylon fibers and probably the better distribution of the fibers through the concrete mass.

The compressive strength variability of two fibrous concretes tended to come in neighborhood of that of the plain concrete; the tendency was detectable for splitting tensile strength and MOR. For impact resistance, the tendency remained with the variability of first-crack and failure strengths of the fibrous concretes, whereas the PINPB variability was less pronounced for the polypropylene-fiber-reinforced concrete and much less pronounced for the nylon-fiber-reinforced concrete counterpart.

The splitting tensile strength of nylon-fiber-reinforced concrete tended to improve most, followed by the compressive strength, and the MOR. The tendency repeated itself for the polypropylene fiber concrete.

Compared to the plain concrete base, the improvement to the PINPB of nylon-fiber-reinforced concrete had an advantage over those to first-crack and failure strengths, but the advantage narrowed for the polypropylene-fiber-reinforced concrete.

The shrinkage crack reducing potential of the nylon fibers in mortar went moderately ahead of that of the polypropylene fibers.

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