Hindawi
Advances in Civil Engineering
Volume 2019, Article ID 3658125, 10 pages
https://doi.org/10.1155/2019/3658125

Research Article

Mechanical and Durability Characteristics of Latex-Modified Fiber-Reinforced Segment Concrete as a Function of Microsilica Content

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Received 22 October 2018; Revised 13 December 2018; Accepted 19 December 2018; Published 13 January 2019

Academic Editor: Constantin Chalioris

This study evaluated the performance of latex-modified fiber-reinforced concrete (RC) segments as a function of the substitution level of microsilica and type of reinforced fiber, to address the problem of corrosion of steel segments and steel-reinforced fiber segments, which are commonly used to shield tunnel-boring machine (TBM) tunnels in urban spaces. Our study compared macro synthetic, steel, and hybrid (macro synthetic fiber + polypropylene fiber) reinforcing fibers. The substitution levels of microsilica used were 0, 2, 4, and 6%. The target strengths were set at 40 and 60 MPa to test compressive strength, flexural strength, chloride ion penetration resistance, and impact resistance. Testing of latex-modified and fiber-reinforced segment concrete showed that the compressive strength, flexural strength, and chloride ion penetration resistance increased with an increasing substitution level of microsilica. These improvements were attributed to the densification of the concrete due to filling micropores with microsilica. Micro synthetic fiber was more effective in terms of improved compressive strength, flexural strength, and chloride ion penetration resistance than steel fiber. These results were due to the higher number of micro synthetic fibers per unit volume compared with steel fiber, which reduced the void volume and suppressed the development of internal cracks. The optimal microsilica content and fiber volume fraction of micro synthetic fiber were 6% and 1%, respectively. To evaluate the effects of the selected mixtures and hybrid fibers simultaneously, other mixing variables were fixed and a hybrid fiber mixture (combination of macro synthetic fibers and polypropylene fibers) was used. The hybrid fiber mixture produced better compressive strength, flexural strength, chloride ion penetration resistance, and impact resistance than the micro synthetic fibers.

1. Introduction

As underground tunnel construction in urban spaces usually causes severe environmental problems, complaints because of noise and vibration, and infrastructural effects, the shielded tunnel-boring machine (TBM) construction method is generally used for urban tunnel cutting [1, 2]. Currently, TBM is used widely for constructing various tunnels, not only for roads and railways but also for subways, electric power, communications, and waterworks [1, 2]. For shielded TBM tunnels, steel and segment concrete are used for support. Steel segments were used initially in TBM construction, but because concrete performance has improved, reinforced concrete (RC) segments are now used widely because of the lower risk of corrosion and higher cost-effectiveness versus steel [3]. However, the edges of RC segments may be damaged by TBM thrust forces. In particular, the edges may be severely damaged in terms of eccentricity during the construction of sharp curves [4]. Thus, steel segments have been constructed primarily via the arrangement of steel bars to reduce segment width and segment damage due to thrust forces. However, steel segments may be subject to corrosion; severe corrosion may result from water leakage if welding is done without a water stop [5]. Consequently, studies are in progress with the goal of minimizing the need for steel reinforcement of RC segments, as well as segments using steel fibers [6]. In particular, a steel fiber-reinforced segment may be more advantageous than an RC segment for sharp curve construction because arranging steel bars is difficult when the segment is narrow [7–10]. Steel fiber can show excellent ductile behavior when used in concrete [11–19]. Studies on steel fiber-reinforced concrete have evaluated and predicted flexural behavior by the shape, length, and fiber volume fraction of the steel fiber [11], and the behavior of steel fiber-reinforced concrete exposed to shear and repeated load, among other parameters [12–17]. Additionally, studies have also been conducted to determine the fiber volume fraction to meet the targeted flexural behavior, shear behavior [11, 15, 18], and strength, and enhance flexural performance by hybridizing steel fibers differing in length and diameter [19].

However, segments constructed using steel fiber may have poor durability due to internal corrosion of the steel fibers, in addition to a decreased life span resulting from corrosion of the steel fibers and steel bars in steel-reinforced fiber segments [10]. Corrosion has been observed in RC and steel fiber-reinforced concrete segments exposed to a chloride ion environment. Possible solutions to the issue of corrosion of reinforcing steel bars and steel fibers include compacting concrete structures to improve water permeability resistance and using a stiffener that cannot corrode [10].

There are also studies on the application of high-strength concrete in segment concrete. Using high-strength concrete can enable a reduction in the thickness of the segment and improves water permeability resistance and other properties [6–10]. In contrast to general concrete, high-strength concrete uses smaller-sized aggregate, which tightens pores to strengthen the microtexture; this makes it a useful material, given current trends toward large, high-rise constructions [20, 21]. Although high concrete strength is achieved through tightening the cement matrix, the most widely used strengthening method is lowering the water-cement ratio and adding a mineral admixture, including microsilica, to lower the CaO-SiO_2 ratio [22–25]. However, high-strength concrete has the accompanying issue of brittleness. As a brittle material, concrete has low tensile strength and energy-absorbing capacity. When it is highly strengthened, concrete is extremely brittle [22–25]. Various studies are underway to address this issue; one widely used approach employs steel fibers [10].

This study evaluated the performance of microsilica, which can serve as a highly strengthening, noncorrosive polyolefin macro synthetic fiber substitute for the steel fibers and steel-reinforcing bars traditionally used in segment concrete. Compared with steel fiber, polyolefin macro synthetic fibers have better impact/static strength ratio and cannot corrode. These properties have encouraged its use in various structures such as marine structures, shotcrete, and concrete linings [16–29]. Those applications have demonstrated that macro synthetic fibers provide excellent resistance to corrosion and have better rebound stability than steel fibers when used in shotcrete [26–29]. However, poorer fiber dispersibility results in fiber balls that decrease the performance of fiber-reinforced concrete segments [30, 31]. Latex may be added to concrete to improve fluidity and water permeability resistance. Such effects improve the fluidity of fiber-reinforced concrete and, subsequently, fiber dispersibility, thus increasing water permeability resistance via the formation of a latex film on the concrete [32–35].

Previous studies have focused on the application of latex-modified reinforced segment concrete with blends of polyolefin and polypropylene fibers [34]. It has been used with blast furnace slag fine powder in segment concrete [34]. Herein, we evaluated the performance of segment concrete as a function of fiber type and content and identified the composition providing the best performance [34]. The performance testing was carried out with constant loading of 0.9 kg/m^3 of polypropylene fiber [34]. The substitution levels of microsilica were set as variables to test the compressive strength, flexural strength, chloride ion penetration, and impact strength. We also evaluated the effects of hybrid fiber and microsilica use (mixture of macro synthetic fibers and polypropylene fibers).

2. Materials and Methods

2.1. Materials. The cement used in this study was ASTM Type 1; its properties are listed in Table 1. Microsilica was used to ensure durability and water tightness of the segment concrete; its properties are listed in Table 2. This study used crushed aggregate (25 mm maximum size) and fine aggregate having a density of 2.62 g/mm^3. The physical properties of the coarse aggregate are listed in Table 3 [35]. The following reinforcing fibers were used: bundle-type steel fibers (length of 30 mm and diameter of 0.5 mm) and micro synthetic fibers (length of 30 mm and diameter of 1 mm) [34, 36]. Polypropylene fibers (length of 3 mm) were also used to evaluate the effects of a hybrid fiber mixture [34]. The properties and forms of the reinforcing fibers are shown in Table 4 and Figure 1.

A technical report published by the Technical Committee 548 of the American Concrete Institute (ACI) indicated that pores ranging from 10 to 1,000 nm in diameter damage concrete over the long term through a capillary tube effect. Polymers with a particle size of 100 nm can effectively fill these internal concrete pores. In this study, it was difficult to achieve sufficient mixing and compaction during mixing and segment fabrication because of low initial fluidity, in turn due to the fiber reinforcement method applied. This study used styrene-butadiene (SB) latex to improve durability and the initial fluidity. Table 5 lists the main ingredients of the SB latex.

2.2. Mixture Proportions. The study evaluated the performance of latex-modified fiber-reinforced segment concrete as a function of microsilica addition. Macro synthetic fibers

Table 1: Properties of cement [34].

Type of cement	Fineness (cm^2/g)	Specific gravity	Stability (%)	Setting time		Compressive strength (MPa)		
				Initial (min)	Final (min)	3 days	7 days	28 days
Portland	3,200	3.15	0.02	220	400	20.3	30.2	38.7

Table 2: Properties of microsilica.

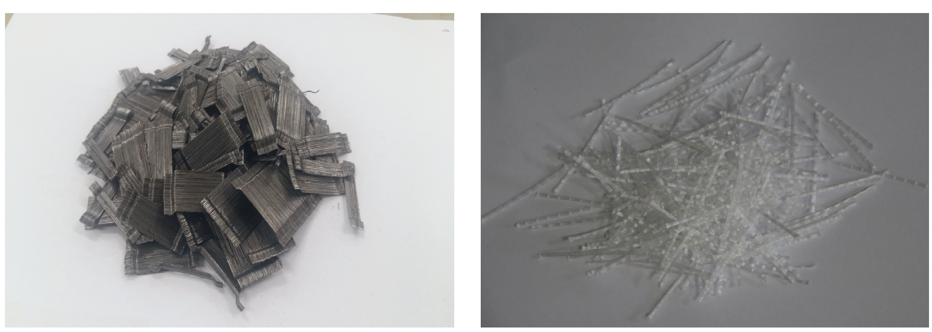
Chemical composition (%)				
SiO_2	Al_2O_3	Fe_2O_3	CaO	Others
90–98	0.4–0.9	1-2	0.2–0.7	2-3

Table 3: Physical properties of coarse aggregate [34, 35].

Type of aggregate	Specific gravity			Absorption (%)	FM
	Bulk	Bulk (SSD)	Apparent		
Crushed coarse aggregate	2.80	2.65	2.83	0.35	6.92

Table 4: Properties of fibers [34, 36].

Type of fiber		Elastic modulus (GPa)	Density (g/mm^3)	Length (mm)	Diameter (mm)	Tensile strength (MPa)	Aspect ratio (L/D)
Steel	Bundrex type	200	7.8	30	0.5	1100	60
Macro synthetic	Crimped type	10	0.91	30	1	550	30



(a) (b)

Figure 1: Geometry of the reinforcing fibers [34, 36]. (a) Steel fibers. (b) Macro synthetic fibers.

Table 5: Properties of SB latex [34–36].

Solids content (%)	Styrene content (%)	Butadiene content (%)	pH	Density (g/mm^3)	Surface tension (dyne/cm)	Particle size (Å)	Viscosity (cps)
49	34 ± 1.5	66 ± 1.5	11.0	1.02	30.57	1,700	42

Table 5 is reproduced from the Kim and Park [35] (https://www.mdpi.com/2071-1050/8/4/386/html).

and steel fibers were mixed at the volume ratio of 1.0%, and 0.0, 2.0, 4.0, and 6.0% of the cement weight was substituted by microsilica to evaluate changes in the mechanical properties and chloride ion penetration resistance of the segment. The performance evaluation results are listed in Table 6. The target compressive strengths of the latex-modified fiber-reinforced segment concrete based on the previous work were 40 and 60 MPa for a material age of 28 days [34].

2.3. Test Methods. This study evaluated the compressive strength, flexural strength, and chloride ion penetration resistance of latex-modified fiber-reinforced segment

Table 6: Mix proportions.

Design strength (MPa)	Unit weight (kg/m^3)							
	W	C	S	G	Microsilica	Latex	Steel fiber	Macro synthetic fiber
40	150	500 490 480 470	1184	466	0 10.0 20.0 30.0	50	80	—
	150	500 490 480 470	1184	466	0.0 10.0 20.0 30.0	50	—	9
60	143	625 612.5 600 587.5	1087	467	0.0 12.5 25.0 37.5	62	80	—
	143	625 612.5 600 587.5	1087	467	0.0 12.5 25.0 37.5	62	—	9

concrete as a function of the substitution level of microsilica and identified the mixture having the optimal performance. Polypropylene fiber was added to the mixtures at the unit volume of 0.1% to test for impact resistance, compressive strength, flexural strength, and chloride ion penetration resistance.

2.3.1. Compressive Strength. Compressive strength was determined using the ASTM C 39 standard "Testing Methods for Compressive Strength of Concrete." Specimens of dimensions 100 mm (diameter) × 200 mm (length) were prepared, and the test was repeated twice for three specimens, which were tested at a material age of 28 days. Each specimen was cured for 1 day in a curing room at $23 \pm 2^{\circ}C$ and a relative humidity of 50%, followed by water curing at a constant temperature of $23 \pm 2^{\circ}C$ [37].

2.3.2. Flexural Strength. Flexural strength was determined using the ASTM C 496 standard "Testing Methods for Flexural Strength of Concrete." Concrete was placed directly in a rectangular mold ($100 \times 100 \times 400$ mm) to fabricate three specimens, which were tested at a material age of 28 days. After initial curing, the specimens were immersed in a constant temperature water bath at $23 \pm 2^{\circ}C$. Testing was done in duplicate [38].

2.3.3. Chloride Ion Penetration. Water permeability is the most important property affecting the strength and durability of a segment concrete [34]. Increased water permeability decreases the strength (due to expanding cracks) and durability (due to freezing, melting, and abrasion). The study conducted permeability tests in accordance with the ASTM C 1202-94 standard [38]. Two cylindrical specimens (100 mm (diameter) × 200 mm (length)) were fabricated for each material and tested at an age of 28 days. The center of each specimen was cut to a thickness of 50 mm and then placed in a desiccator. Vacuum was applied for 3 h to remove any air trapped inside, and water was then added to the desiccator to saturate the specimen before running the pump for a further 1 h [34, 36, 39]. The vacuum pump was then turned off, and the specimen was maintained for 18 ± 1 h under conditions of full saturation with water [34, 36, 39]. After preparing for the water permeability test as described above, the specimen was fixed on an applied voltage (AV) cell, where the (+) pole was filled with NaOH solution (0.3 N) and the (−) pole was filled with NaOH solution (3%) [34, 36, 39]. Then, a potential of 60 V was applied to the specimen and the direct current was measured over a 6-h period [34, 36, 39]. Table 7 lists the qualitative chloride permeability descriptors of concrete as a function of the electric charge passed, as stipulated in the ASTM Standard C 1202 [34, 36, 39]. The test was repeated twice for three specimens having a material age of 28 days. Table 8 lists the water permeability according to chloride ion penetration, as suggested by ASTM standards.

2.3.4. Impact Resistance. Impact resistance was determined according to the test method of the ACI Committee 544, whereby a rigid body of dimensions 150 mm (diameter) × 60 mm (length) is freely dropped [40]. Three specimens were produced for each mix ratio; they were cured for 1 day in a curing room ($23 \pm 2^{\circ}C$, 50% relative humidity), and then water curing was performed at a constant temperature of $23 \pm 2^{\circ}C$. The test was repeated twice for three specimens with a material age of 28 days.

3. Results and Discussion

3.1. Compressive Strength. Figure 2 shows the compressive strength test results as a function of the microsilica addition ratio. The results show that the compressive strength increased with increasing substitution level of microsilica. The same trend was observed with steel fiber and macro synthetic fiber. The compressive strengths achieved using macro synthetic fiber in the mixtures were not significantly

Table 7: Standard of permeability levels by ASTM.

Charge passed (coulombs)	Chloride permeability
>4,000	High
2,000~4,000	Moderate
1,000~2,000	Low
100~1,000	Very low
<100	Negligible

different. This trend was attributed to void reduction in the concrete via filling of the micropores by fine microsilica particles into the latex-modified fiber-reinforced segment concrete. The mixture containing macro synthetic fibers had a slightly higher compressive strength than that containing steel fibers because the density of the macro synthetic fibers was markedly lower than that of the steel fibers. Thus, the number of fibers in the same volume was relatively higher with macro synthetic fibers, which effectively suppressed cracking of the concrete. However, because compressive strength is affected more by the internal concrete strength than by reinforcing fibers, the difference in compressive strength was not significant for any microsilica substitution level.

3.2. Flexural Strength. Figure 3 shows the flexural strength test results as a function of the microsilica loading. Segment concrete is subjected to deflection loads, particularly in utility tunnels. Thus, flexural strength is more important than compressive strength. The flexural strength increased with increasing substitution of microsilica, for both the steel and macro synthetic fiber cases; the strength of mixtures containing macro synthetic fibers increased only slightly. The fine microsilica particles filled the micropores in the concrete, reducing the void volume, and thereby increasing the compaction. The compressive strength of the mixture containing macro synthetic fibers was slightly higher than that of the mixture containing steel fibers because the density of the macro synthetic fibers ($0.91\,g/mm^3$) was much lower than that of the steel fibers ($7.8\,g/mm^3$). Thus, the number of macro synthetic fibers per unit volume was relatively higher. The higher number of fibers in the concrete increased the crack-suppressing effect. However, the low density of the macro synthetic fibers decreased their dispersibility compared with steel fibers. The target strengths for this study were 40 and 60 MPa, that is, high strengths, along with a low water-cement ratio and low water content in the mixtures. The poorer dispersibility of the macro synthetic fibers was resolved by adding latex to improve the initial fluidity. In this way, the flexural strength of latex-modified fiber-reinforced segment concrete was improved with the inclusion of macro synthetic fibers.

Generally, concrete is brittle, and has low tensile strength, energy absorption, and crack resistance [14, 22, 26, 27, 31, 41–43]. Adding reinforcing fiber to the concrete is one approach to overcoming these issues. The reinforcing fiber mitigates brittleness and induces ductile behavior by modifying energy absorption via bridging effects [14, 22, 26, 27, 31, 41–43]. The improved energy absorption of fiber-reinforced cement concrete is determined by the bonding between the fiber and concrete [14, 22, 26, 27, 31, 41–43]. The bonding mechanism includes the bridging action, fiber debonding, fiber pullout, and fiber fracture [14, 22, 26, 27, 31, 41–43]. The energy absorption capability of the concrete is affected by the bonding of each individual fiber [14, 22, 26, 27, 31, 41–43]. Fiber bridging decreases the stress intensity factor and causes crack closure at the crack tip [14, 22, 26, 27, 31, 41–43]. Additionally, fiber debonding and pullout at the fiber-concrete interface affect the total energy absorption during crack propagation [14, 22, 26, 27, 31, 41–43]. Therefore, the bonding between the fiber and concrete greatly influences crack growth stabilization [14, 22, 26, 27, 31, 41–43]. The bonding behavior of the fiber-reinforced concrete is largely determined by the shape and surface of the reinforced fiber [22, 26, 27, 31, 41–43]. One way to improve the bonding characteristics between the fiber and concrete is to deform the fiber shape into crimped, hooked, or twisted forms. Another approach enhances bonding by making the fiber's surface hydrophilic [22, 26, 27, 31, 41–43]. We used crimped-type fibers in this study. Our mixes containing crimped-type macro synthetic fiber had good bond strength and interfacial toughness, even when compared with previous results for hooked-type steel fibers [26, 40]. This suggests that macro synthetic fibers could be used concurrently with steel fibers for segment concrete reinforcement [41].

This compared the results of previous studies using steel fiber with the current studies using crimped macro synthetic fiber [41]. The flexural load-displacement curves revealed that the deformation rate declined after the initial crack loading with the macro synthetic fiber ($9\,kg/m^3$) compared with the steel fiber ($40\,kg/m^3$) [41], and the strain hardened; that is, load increased with further deformation [41]. The concrete made with the steel fiber showed lower load, and decreasing load after initial crack loading, than the macro synthetic fiber, and strain softening occurred [41]. However, the flexural toughness of mixes made with steel fiber at the same fiber volume fraction was greater [44, 45]. Hence, for equivalent flexural toughness, the fiber volume fraction of the macro synthetic fiber must be higher than that of the steel fiber [44, 45]. In this study, the target performance for segment concrete was only design compressive strength. But, further research evaluated the ductile behavior of the steel fiber-reinforced concrete members to establish the flexural and shear capacities and to determine the minimal fiber volume fraction of steel fiber that would satisfy the strength and ductility required for safety. Replacing a portion of the steel fiber with macro synthetic fiber may reduce the risk of corrosion of the steel fiber, but a long-term study needs to also consider concrete strength, span-to-depth ratio, tensile stiffness, and the number of stirrups.

3.3. Chloride Ion Penetration. Figure 4 shows the test results for chloride ion penetration resistance as a function of the substitution level of microsilica. The purpose of this study was to address the issue of the corrosion of steel segments, reinforced segment concrete, and steel fiber-reinforced

Table 8: Mixing ratio for optimal mix proportions determination.

Design strength (MPa)	Type of mix	Unit weight (kg/m³) W	C	Microsilica	G	S	Latex	Macro synthetic fiber	Polypropylene fiber
40	Control	150	470	30	1184	466	50	—	—
	Macro synthetic fiber							9	—
	Hybrid fiber							9	0.9
60	Control	143	587.5	37.5	1087	467	62	—	—
	Macro synthetic fiber							9	—
	Hybrid fiber							9	0.9

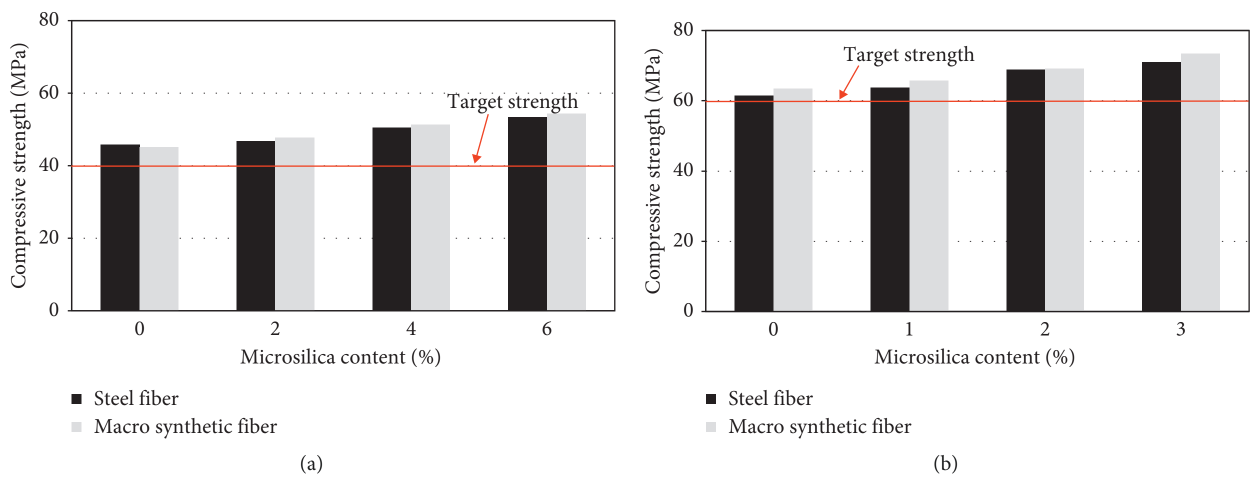


Figure 2: Compressive strength by microsilica content. Target strength of (a) 40 MPa and (b) 60 MPa.

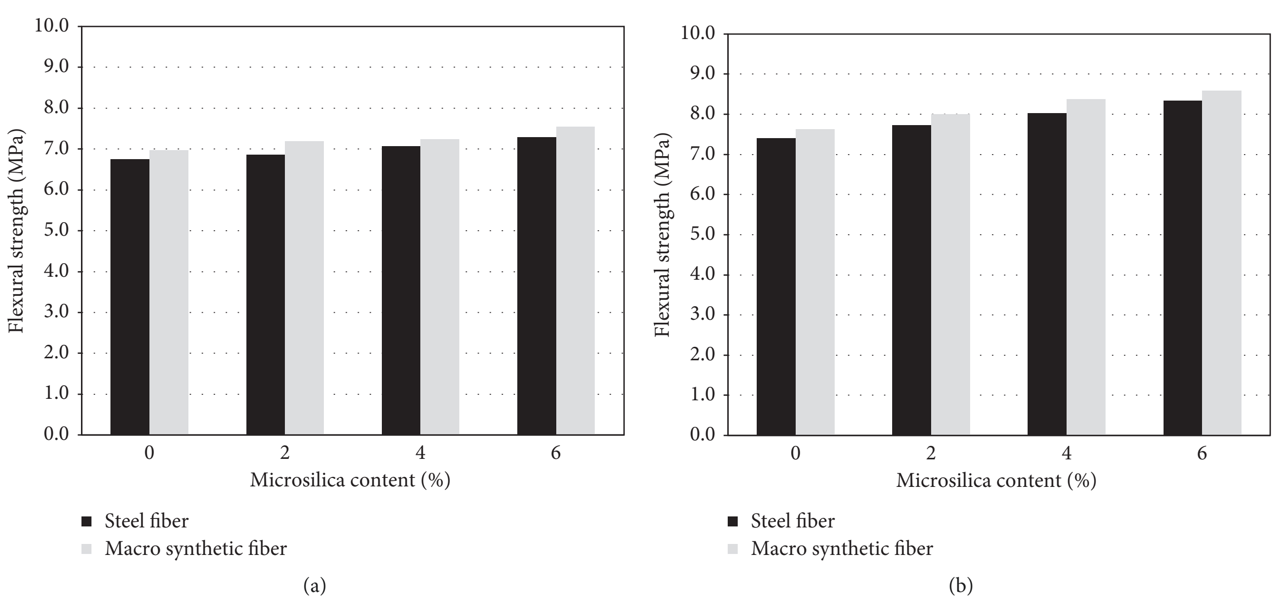


Figure 3: Flexural strength by microsilica content. Target strength of (a) 40 MPa and (b) 60 MPa.

segment concrete. Thus, corrosion was considered an important variable. We measured chloride ion penetration resistance as a function of the substitution level of microsilica and found increased chloride ion penetration resistance with increasing substitution level. This finding was consistent with those for steel fibers and structural synthetic fibers. Chloride ion penetration was lower for mixtures containing the structural synthetic fiber. Chloride ion penetration decreased with increasing microsilica substitution level because the fine microsilica particles filled

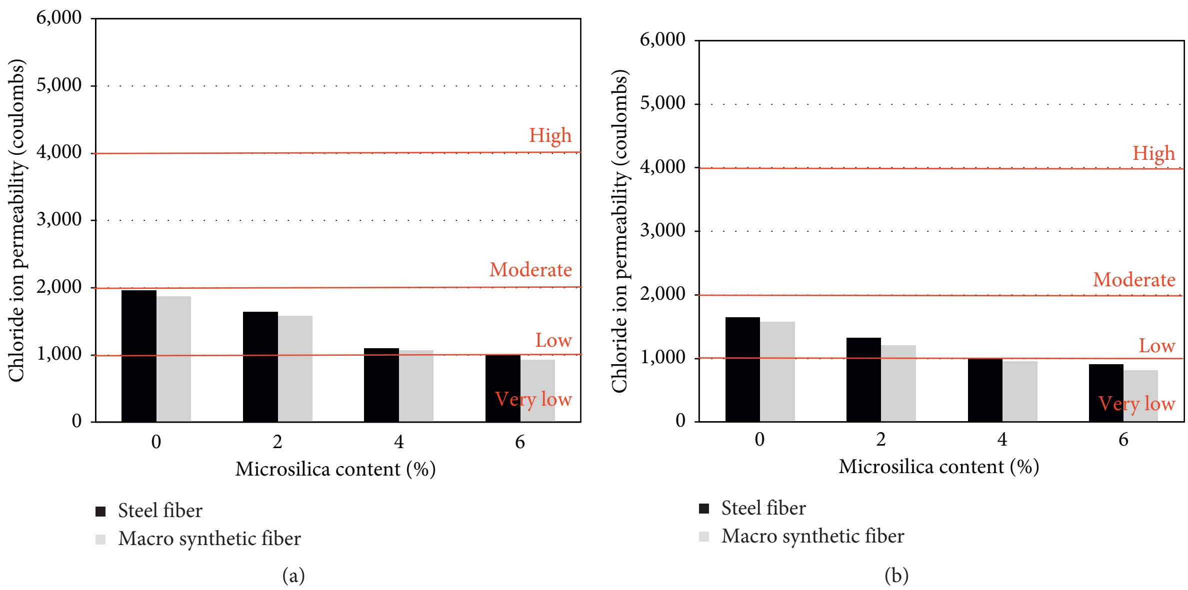


Figure 4: Chloride ion penetration by microsilica content: (a) 40 MPa and (b) 60 MPa.

voids in the segment concrete and thereby increased the compaction of the concrete. The measured water permeability at the target strength of 40 MPa was low in latex-modified fiber-reinforced segment concrete with steel fiber and macro synthetic fiber mixtures, up to the 2% substitution level of microsilica. According to the ASTM C 1202–94 standard descriptors, the water permeability was low at the 4% substitution level, and at 6%, it was low for the steel fiber mixture and very low for the macro synthetic fiber mixture. At the target strength of 60 MPa, the water permeability was low, regardless of the type of reinforcing fiber used, up to the 4% substitution level of microsilica, and it was very low with steel fibers and macro synthetic fibers at 6%. Analysis of the design strengths of 40 and 60 MPa revealed that the mixtures with macro synthetic fiber showed better chlorine ion permeation resistance than the steel fiber mixtures. This finding is consistent with greater packing of the macro synthetic fibers in the concrete voids with improved suppression of microcracks in the segment concrete.

4. Determination and Performance of the Optimal Mixture Compositions

4.1. Determination of the Optimal Mixture Proportions. This study used macro synthetic fibers, steel fibers, and microsilica as variables in our study and evaluated their applicability to segment concrete. In particular, we evaluated the applicability of macro synthetic fiber as a substitute for steel fiber in steel fiber-reinforced segment concrete. This study fixed the fiber volume fraction to 1 vol (%) and determined the appropriate replacement ratio of microsilica. The control specimens were steel fiber-reinforced segment concrete. Additionally, to study the application in tunnels, 1 vol% (9 kg/m^3) was used in shotcrete containing macro synthetic fiber. The appropriate mixing ratio was also determined.

Recent studies with steel fiber-reinforced concrete determined the optimal mixing ratio based on postcracking behavior [15, 18]. A similar approach was needed to evaluate the usability and practicality of concrete members containing reinforcing macro synthetic fiber.

Microsilica performed optimally at the 6% substitution level. The effects of blends of fibers (hybrid fiber reinforcement) were evaluated with respect to possible improvement of the performance of the latex-modified fiber-reinforced segment concrete. Blends of fibers of different lengths, diameters, and types are also known to improve the performance of concrete because they can effectively control the micro- and macrocracks that form in the concrete [19, 34, 45, 46]. Accordingly, using hybrid fibers in concrete can help to optimize the performance of the concrete [19, 34, 45, 46]. Previous studies showed that the flexural behavior and cracking are suppressed when the macro synthetic fiber and the micro PP fiber are hybridized and applied compared with cases where only a single type of fiber is used [34]. The current study also compared a hybrid fiber segment concrete mixture containing 0.1% of polypropylene fiber and macro synthetic fiber (fiber volume fraction 1.0%) with segment concrete including macro synthetic fiber and 6% substitution of microsilica, which showed the best results in terms of compressive strength, flexural strength, and chloride ion penetration resistance. The mixture used in this performance evaluation is detailed in Table 8.

4.2. Evaluation of the Optimal Mix

4.2.1. Compressive Strength. Figure 5 shows the compressive strength test results used to determine the optimal mixing ratio. The mixture made with the hybrid fiber mixture had a higher compressive strength that that made with just the macro synthetic fiber. However, the difference was not large. The same behavior was observed for target strengths of both

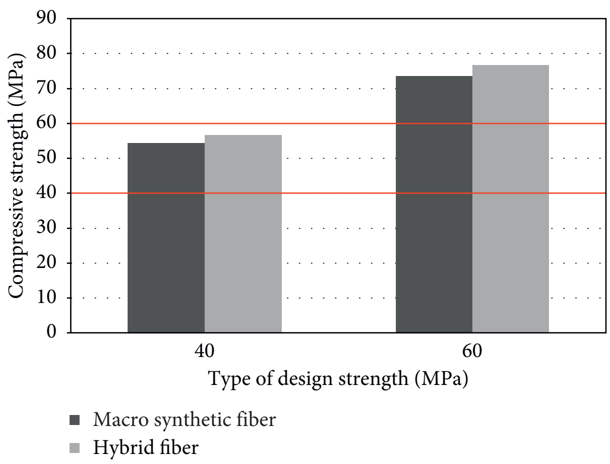


Figure 5: Compressive strength of the optimum mixture.

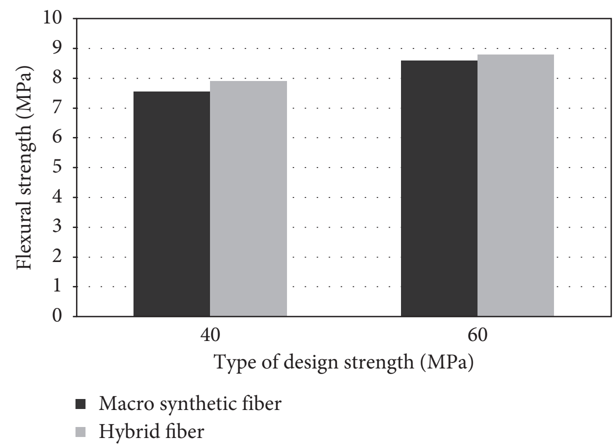


Figure 6: Flexural strength of the optimum mixture.

40 and 60 MPa. Generally, the reinforced fiber content affects flexural performance more than compressive strength. Hybrid fiber mixtures can control both wide and narrow cracks in concrete. Hence, they were more effective than macro synthetic fibers alone in increasing compressive strength, although the measured increase was not significant. All of the mixes met the design target strengths of 40 and 60 MPa.

4.2.2. Flexural Strength. The mixtures made with a hybrid fiber mixture had higher flexural strength than those made with a macro synthetic fiber. This is because the addition of polypropylene fibers increased the number of fibers per unit volume, subsequently increasing the internal tensile strength (Figure 6), suppressing internal crack formation and growth, and reducing the void volume of the concrete.

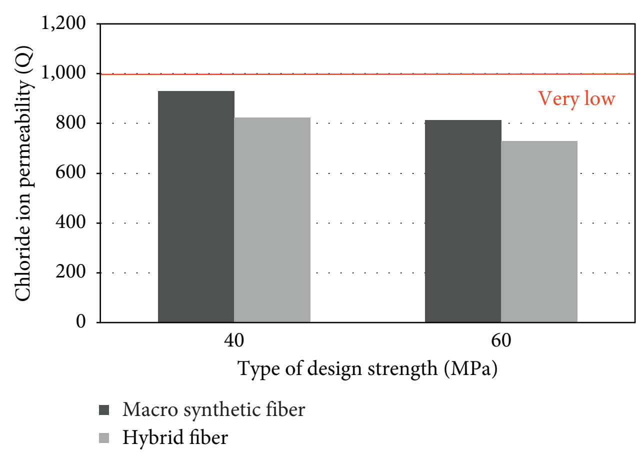


Figure 7: Chloride ion penetration of the optimum mixture.

4.2.3. Chloride Ion Penetration. Figure 7 shows the chloride ion penetration test results used to determine the optimal mixing ratio. Penetration was lower with the hybrid mixture than with the macro synthetic fiber mixture. However, all mixes had very low water permeability, regardless of the design strength of 40 or 60 MPa. Using a hybrid fiber mixture containing polypropylene fibers significantly improves the water permeability resistance.

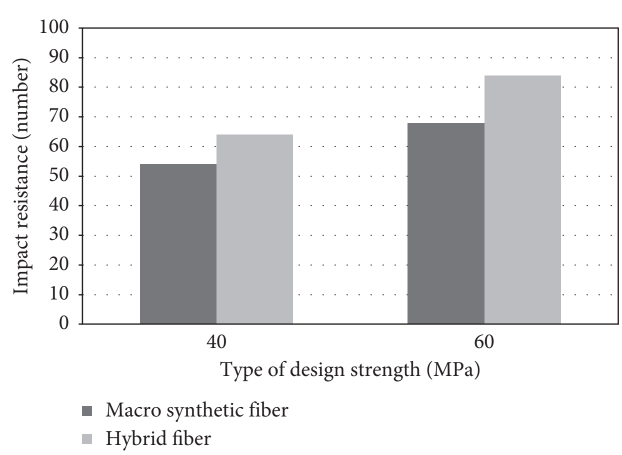


Figure 8: Impact resistance of the optimum mixture.

4.2.4. Impact Resistance. Figure 8 shows the impact resistance results used to determine the optimal mixing ratio. Better results were achieved with the hybrid fiber mixture than with the micro synthetic fiber mixture. When fiber-reinforced concrete receives an impact, it absorbs the load. This is because fiber-reinforced concrete improves the flexural toughness and energy absorption capacity through the complex steps of drawing, cross-linking, separating, and failure, thereby increasing impact resistance. Accordingly, the macro synthetic fiber mixture had better impact resistance than the mixture containing no fibers. The hybrid fiber mixture containing macro synthetic and polypropylene fibers suppressed both micro- and macrocracks, resulting in improved energy-absorbing capacity and impact resistance.

5. Conclusions

This study evaluated the mechanical properties and durability of fiber-reinforced, latex-modified segment concrete as a function of fiber type and microsilica substitution level.

Macro synthetic, steel, and hybrid fibers (macro synthetic fibers + polypropylene fibers) were used as reinforcing fibers. The substitution levels of microsilica were 0, 2, 4, and 6%. Ultimately, this study showed the utility of latex-modified segment concrete containing macro synthetic fibers and hybrid fibers as a replacement for corrodible steel fiber in TBM tunnels. The test results are summarized as follows:

(1) The compressive strength, flexural strength, and chloride ion penetration resistance of latex-modified fiber-reinforced segment concrete increased with increasing substitution level of microsilica. This was because the fine microsilica particles filled the internal concrete micropores to create a more compact concrete.

(2) The compressive strength of latex-modified fiber-reinforced segment concrete did not significantly increase when the macro synthetic fiber was used as the reinforcement.

(3) The macro synthetic fibers had better flexural strength and water permeability resistance than steel fibers. This is because the macro synthetic fibers had a higher number of fibers per unit volume, which effectively suppressed internal crack formation and formed a more compact concrete.

(4) The compressive strength, flexural strength, and chloride ion penetration resistance results demonstrated that the 6% substitution level of microsilica and the 1% volume fraction of macro synthetic fiber were the optimal mixing ratio. The effects of the selected mixture and hybrid fibers were compared by holding other variables constant.

(5) The mechanical properties and durability of a macro synthetic fiber mixture and a hybrid fiber mixture were compared. The hybrid fiber mixture had excellent compressive strength, flexural strength, permeability, and impact resistance.

(6) The addition of reinforcing fibers improved the performance of latex-modified concrete, and the hybrid fiber mixture effectively controlled the formation of wide and narrow cracks in segment concrete, thereby improving the performance.

(7) This study evaluated the use of macro synthetic fiber as a reinforcing fiber in segment concrete. Additional theoretical and experimental studies are needed to develop a predictive model of the flexural behavior and establish the minimum and optimal fiber volume fractions for practical use.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This research was supported by the basic science research program through the National Research Foundation of Korea (NRF) funded by Ministry of Education (NRF-2016R1D1A3A03918587 and NRF-2013R1A1A4A01011776).

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