CAIT-UTC-REG75

# Mitigating cracks in concrete members for durable bridge construction

FINAL REPORT
April 2025

Submitted By:

Ravi Ranade
Associate Professor

Pinar Okumus
Associate Professor

University at Buffalo
212 Ketter Hall, Buffalo, NY 14260

External Project Manager:

John Picard, PE
Resident Engineer
LaBella Associates, Rochester, NY
Former Regional Bridge Maintenance Engineer
New York State DOT - Region 5 (Buffalo)

In cooperation with

Rutgers, The State University of New Jersey
And
U.S. Department of Transportation
Federal Highway Administration

## Disclaimer Statement



The Center for Advanced Infrastructure and Transportation (CAIT) is a Regional UTC Consortium led by Rutgers, The State University. Members of the consortium are Atlantic Cape Community College, Columbia University, Cornell University, New Jersey Institute of Technology, Polytechnic University of Puerto Rico, Princeton University, Rowan University, SUNY - Farmingdale State College, and SUNY - University at Buffalo. The Center is funded by the U.S. Department of

| 1. Report No.<br>CAIT-UTC-REG75 | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| 4. Title and Subtitle<br>Mitigating cracks in concrete members for durable bridge construction | | 5. Report Date<br>April 2025<br>6. Performing Organization Code<br>CAIT/University at Buffalo |
| 7. Author(s)<br>Ravi Ranade (https://orcid.org/0000-0001-6030-8371)<br>Pinar Okumus (https://orcid.org/0000-0002-2197-3261) | | 8. Performing Organization Report No.<br>CAIT-UTC-REG75 |
| 9. Performing Organization Name and Address<br>University at Buffalo<br>212 Ketter Hall, Buffalo, NY 14260 | | 10. Work Unit No.<br>11. Contract or Grant No.<br>69A3551847102 |
| 12. Sponsoring Agency Name and Address<br>Center for Advanced Infrastructure and Transportation<br>Rutgers, The State University of New Jersey<br>100 Brett Road<br>Piscataway, NJ 08854 | | 13. Type of Report and Period Covered<br>Final Report<br>10/1/2022-3/31/2025<br>14. Sponsoring Agency Code |
| 15. Supplementary Notes<br>U.S. Department of Transportation/OST-R<br>1200 New Jersey Avenue, SE<br>Washington, DC 20590-0001 | | |

16. Abstract

As a brittle material with low tensile capacity, concrete is prone to cracking under service-level loads. Typical approaches for improving concrete's cracking resistance involve either increasing the compressive strength, which also leads to greater brittleness, or adding fibers, which controls crack widths but has little effect on the cracking strength. In this research, the primary objective was to enhance the fracture toughness of concrete by employing steel wool. Unlike conventional steel fibers, steel wool provides micro-scale reinforcement to the concrete matrix, which increases its tensile cracking strength under tension. Optimum volume fractions of steel wool in two different concretes were determined considering its effect on fracture toughness and modulus of rupture. Standard compressive strength tests were performed for flexure, and fracture toughness tests were performed at the material-scale specimens. The findings demonstrated remarkable improvements in flexural strength and fracture toughness when steel wool was incorporated, compared to reference specimens without steel wool.

| 17. Key Words<br>Cracking; Service life; Steel wool; Steel fibers<br>Fracture toughness; Tensile strength | | 18. Distribution Statement | |
|---|---|---|---|
| 19. Security Classification (of this report)<br>Unclassified | 20. Security Classification (of this page)<br>Unclassified | 21. No. of Pages<br>31 | 22. Price |

**Form DOT F 1700.7** (8-69)

## Acknowledgments

This research was financially supported by the Region 2 University Transportation Center, funded by the US Department of Transportation and the University at Buffalo (UB), the State University of New York. Financial support was also provided by the Institute of Bridge Engineering at UB. These financial supports are gratefully acknowledged. The opinions, findings, and views expressed in this study are the ones of the authors only and do not necessarily reflect the views, policies, standard specifications, or regulations of the parties acknowledged above. Funding agencies do not assume any liability for the contents or the use thereof.

# Table of contents

## List of figures

## List of tables

## Background and motivation

Concrete structures are prone to cracking under service loads and environmental exposure mainly due to the brittleness (low fracture toughness) and low tensile strength of concrete. Cracks negatively affect the durability of exposed concrete members typically used in bridge construction [1, 2]. Although prestressed concrete bridge members are designed not to crack under service loads, the low tensile strength of concrete necessitates large prestressing forces and member cross-sections to meet this design criterion. Eliminating concrete cracks or reducing their number and width is essential for extending infrastructure service life [3].

Various fibers have been used in concrete to manage the problem of cracking. Steel fibers have been the most commonly employed fibers to enhance concrete's tensile and flexural strengths, improve post-cracking ductility, and limit crack openings. Straight, smooth steel fibers form a weak bond with concrete, and therefore, their surface and geometry are often modified to enhance stress transfer between the fibers and concrete [4]. Commercially, steel fibers are available in various length/diameter aspect ratios ranging from 10 to 100. Fibers with diameters less than 0.3 mm are referred to as "microfibers", whereas larger fibers are referred to as "macrofibers" [5]. While steel microfibers are more effective in reducing crack openings and are often used for improving durability in volume fractions of up to 1%, steel macrofibers at volume fractions larger than 1% (but usually not more than 3%) are used for improving flexural and shear capacities of reinforced concrete structural elements [6-8]. Despite these positive effects of steel fibers on post-cracking behavior of concrete, their influence on the cracking strength of concrete under tension is marginal, as the fiber-reinforcement mechanisms are activated only after cracking [4, 5, 9].

Preventing or delaying concrete cracking under service loads requires increasing its fracture toughness. From a fracture mechanics standpoint, fracture toughness can be improved by either reducing flaw size/porosity or reinforcing the matrix at a much smaller scale. However, the former approach increases the compressive strength of concrete, making it more brittle with worse post-cracking behavior than normal strength concretes. Fiber reinforcement at a smaller scale to delay crack formation through greater energy dissipation in the fracture process zone can be achieved using smaller fibers such as polymer microfibers, carbon nanotubes, or steel wool. Although polymer microfibers and carbon nanotubes have been demonstrated to enhance the cracking strength of concrete, their high cost and specialized equipment needs for achieving good dispersion in concrete limit their practical applications [10]. This research focuses on using steel wool to improve the fracture toughness of concrete for crack prevention under service loads.

Steel wool (or chopped steel fibers) is commonly used in the form of rolls or pads for applications in brake pad linings (as thermal shields), automobile exhaust pipes (as acoustic shields), metal separation, water and air filtration, cleaning, and many more [11]. Figure 1 shows a sample of steel wool used for prior research at the University at Buffalo (UB). Due to the random chopping process, the lengths of individual fibers of this steel wool vary between 0.4 and 4.0 mm, and their diameters vary between 0.04 and 0.20 mm. Steel wool is manufactured using bundle drawing technology, wherein a single-sheath composite wire is annealed and drawn multiple times to reduce the cross-section to a desired fineness. Steel wool is widely available worldwide in various sizes and grades. There are several suppliers of steel wool in the USA, including American Metal Fibers, Inc. (IL), International Steel Wool, Inc. (OH), IntraMicro, Inc. (AL), Global Material Technologies, Inc. (IL), etc. The physical properties of the steel wool used for research at UB are shown in Table *1* below. At 1% volume fraction, the added cost of steel wool in concrete is about \$100/yd$^3$. This research utilized stainless steel wool with the same physical properties as those shown in Table 1, but it is highly corrosion-resistant and costs approximately \$2.5/lb.

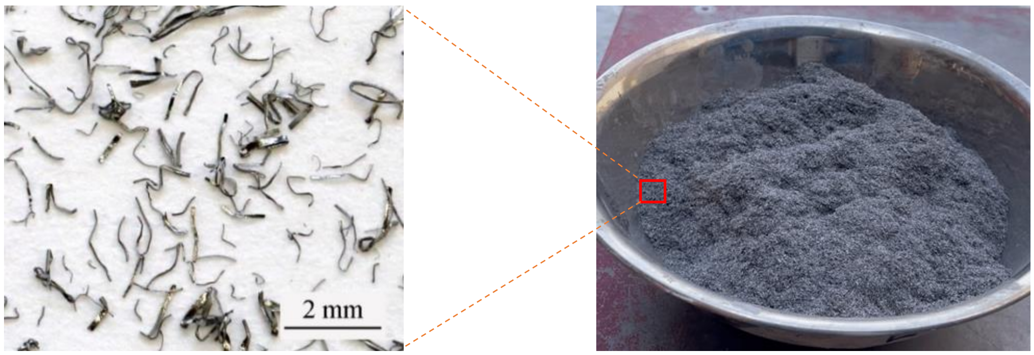



Figure 1: Steel wool particles

Table 1: Properties of steel wool

| **Material** | **Color** | **Specific Gravity** | **Tensile strength** | **Elastic modulus** | **Average length** | **Average diameter** | **Cost** |
|---|---|---|---|---|---|---|---|
| Mild steel | Gray | 7.85 | 44 ksi (300 MPa) | 30,000 ksi (210 GPa) | 0.06″ (1.5 mm) | 0.003″ (0.07 mm) | \$0.75/lb |

We conducted a preliminary study to investigate the effect of steel wool on the fresh and hardened properties of a high-strength mortar (compressive strength ~18 ksi). Five mixes were prepared with the volume fraction ($V_f$) of steel wool ranging from 0% to 2% of the total mix volume with increments of 0.5%. Figure 2 shows the change in properties relative to the mix that did not contain steel wool. The workability was reduced slightly due to the addition of steel wool, but it was improved by increasing the amount of plasticizer used. The main observation was that although the compressive strength increased only by about 20% at $V_f = 1.5\%$, the flexural strength increased by about 70%, and the fracture toughness increased by about 50% at $V_f = 1.5\%$. This shows the effectiveness of the micro-reinforcement provided by the steel wool, which improves the crack resistance under tension. A closer examination of the fracture surface in the fracture toughness specimens revealed that the tortuosity of the crack path increased with the increase in steel wool content, which supports the approach proposed in this research to increase the crack resistance of conventional concrete.

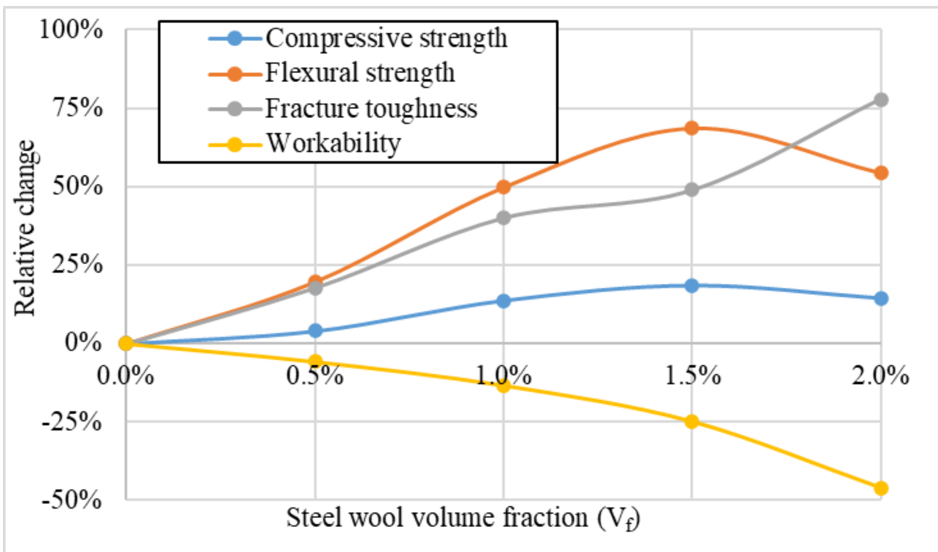



Figure 2: Effect of steel wool on concrete properties

## Problem description, approach, and methodology

The primary problem addressed in this research is the cracking of reinforced and prestressed concrete structural elements under service loads. The goal of this research was to investigate the use of steel wool in concrete to increase its crack resistance. An experimental approach was employed wherein several concretes with increasing volume fractions of steel wool were produced, and corresponding mechanical properties, including compressive strength, flexural strength, and fracture toughness, were evaluated using standard test methods. Fracture toughness and flexural strength were used as indicators for concrete's cracking resistance and tensile capacity. Finally, an optimum volume fraction of steel wool in concrete was determined based on the test results. The research tasks completed in this research are as follows:

**1. Preparation of base concrete mixtures and specimens**

The investigators obtained two mixture designs in Table 2 for concretes used by two different precast concrete manufacturers in their products. These two mixtures served as the base concrete mixtures (without steel wool) for this study. The precast concrete manufacturers also provided the constituent materials for these concretes. Both the mixtures were designed to attain a slump of 6-9 inches and an average compressive strength of 6,000 psi at 28 days. The investigators prepared the two base mixtures in their laboratory using a concrete gravity mixer with a volumetric capacity of 3.5 $ft^3$, following the procedure in ASTM C192 [12].

Table 2: Composition of base concrete mixtures

| **Constituents** | **Mix 1 (lb/yd³ concrete)** | **Mix 2 (lb/yd³ concrete)** |
|---|---|---|
| Cement | 799 | 720 |
| Coarse aggregates | 1,648 (NMAS* = 0.50″) | 1,600 (NMAS = 0.75″) |
| Fine aggregates | 10,540 | 1,279 |
| Water | 320 (w/c** = 0.40) | 259 (w/c = 0.36) |
| Air-entraining admixture | 0.3 | 0.4 |
| Plasticizer | 2.8 | 2.5 |

* NMAS = Nominal maximum aggregate size
** w/c = water/cement weight ratio

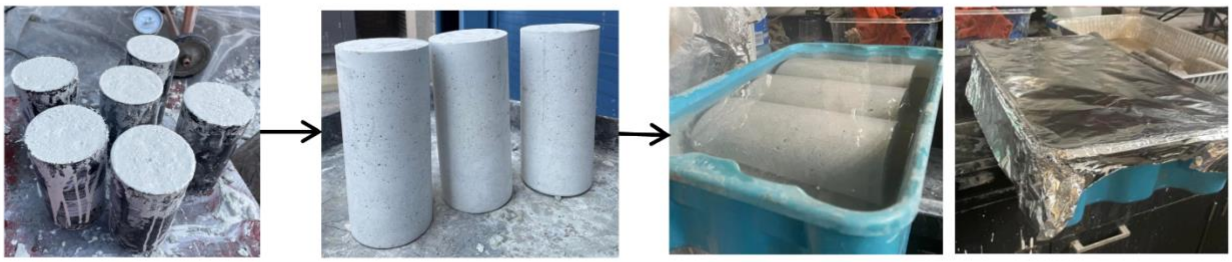
## 2. Evaluation of slump and compressive strength of base mixtures

Slump and compressive strength of the base mixtures were evaluated as quality control to ensure that these properties determined at UB were consistent with those observed at the precast manufacturers' facilities. Following the ASTM C143 [13] procedure, the measured slump for Mixes 1 and 2 was 7″ and 9″, respectively, which was similar to that observed by the precast concrete manufacturers at their facilities.

For measuring the 28-day uniaxial compressive strength, four cylindrical specimens of diameter 3″ and height 6″ were prepared for Mix 1, and four cylindrical specimens of diameter 4″ and height 8″ were prepared for Mix 2. Larger cylinders were used for Mix 2 considering the larger nominal maximum aggregate size of 0.75″ in Mix 2 compared to 0.50″ in Mix 1. Four additional cylinders of respective sizes were cast for each mixture to determine the early-age compressive strength. The curing procedure followed for each mixture is described below.

To characterize the early age strength, the Mix 1 specimens were demolded 12 hours after casting and then kept submerged in water at 90°C in an oven for 12 hours. The container holding the water and specimens was covered with aluminum foil to minimize water loss. This curing procedure accelerates the cement hydration reactions and simulates the 12-hour steam curing procedure typically used at precast concrete production facilities. A similar procedure was used for characterizing the early age strength of Mix 2, but instead of demolding the specimens 12 hours after casting, they were demolded 24 hours after casting as Mix 2 specimens took longer to gain the strength and stiffness necessary for demolding. The curing procedure for determining the 28-

day strength of both the mixtures involved demolding the specimens 24 hours after casting, submerging them in water for 21 days, and then leaving them exposed to air for 7 days. Figure 3 below shows the aforementioned steps.



Casting Demolded specimens Specimen submerged in water

Figure 3: Specimens through various stages of curing

Immediately after curing, the cylindrical specimens were tested under uniaxial compression following the procedure in ASTM C39 [14]. The average compressive strengths of Mix 1 and 2 were 3,977 psi and 4,845 psi at early-age, respectively, which increased to 7,139 psi and 7,262 psi at 28-days. These strengths were consistent with those obtained at the respective precast concrete manufacturers' facilities, enabling us to proceed with the next steps.

### 3. Preparation of concrete mixtures with steel wool

Four concrete mixtures with increasing steel wool volume fractions of 0.5%, 1.0%, 1.5%, and 2.0% (percentage of concrete volume) were prepared corresponding to each base mixture to investigate the influence of steel wool content on the mechanical properties of concrete. The mixing and curing procedures were similar to the base concrete mixtures, as detailed in Tasks 1 and 2 above. The only addition in these mixtures was stainless steel wool, which was added at the end after mixing the rest of the base concrete ingredients. The plasticizer amount was regulated (up to ±20% of the plasticizer amounts in Table 2) to maintain slump in the range of 6-9 inches while accounting for the additional steel wool and laboratory's environmental conditions (temperature and humidity) on the days of mixing.

## 4. Specimen preparation and testing of concrete mixtures with steel wool

Three different types of specimens were cast for each of the 10 mixtures investigated in this study. These included specimens for determining uniaxial compressive strength, modulus of rupture (flexural strength), and fracture toughness. Table 3 shows the number, type and dimensions of specimens cast for each mixture. The details of experiments are given below.

Table 3: Test matrix

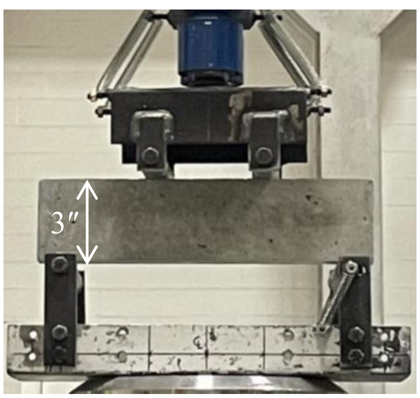
| | **Steel wool volume fraction →** | **0%** | **0.5%** | **1.0%** | **1.5%** | **2.0%** |
|---|---|---|---|---|---|---|
| | **Experiment type (Specimen dimensions)** | **Number of specimens** | | | | |
| **Mix 1** | Compression (3″×6″ cylinders) | 4 | 4 | 4 | 4 | 4 |
| | Flexure (1.5″×3″×12″ beams) | 4 | 4 | 4 | 4 | 4 |
| | Fracture Toughness (1.5″×3″×12″ notched beams) | 4 | 4 | 4 | 4 | 4 |
| **Mix 2** | Compression (4″×8″ cylinders) | 4 | 4 | 4 | 4 | 4 |
| | Flexure (4″×4″×14″ beams) | 3 | 3 | 3 | 3 | 3 |
| | Fracture Toughness (4″×4″×14″ notched beams) | 3 | 3 | 3 | 3 | 3 |

Uniaxial compression tests: Although the focus of this study was to investigate the effect of steel wool on the cracking and tensile behavior of concrete, change in the tensile behavior influences the passive confinement of concrete, which in turn affects the compressive strength. Therefore, uniaxial compressive strength of each mixture was characterized following the procedure in ASTM C39 [14]. Besides, it is customary to report the compressive strength of concrete as it serves as a good data point for quality control and most other properties of concrete can be correlated to compressive strength. Figure 4 shows sample specimens of base Mixes 1 and 2 at the end of their uniaxial compression tests. As explained above, larger specimens (4″ dia × 8″ height cylinders) were used for Mix 2 compared to Mix 1 (3″ dia × 6″ height cylinders) due to larger nominal maximum aggregate size used in Mix 2 compared to Mix 1. The loading rate in all the uniaxial compression tests was maintained between 28 and 42 psi/s as per ASTM C39 [14].

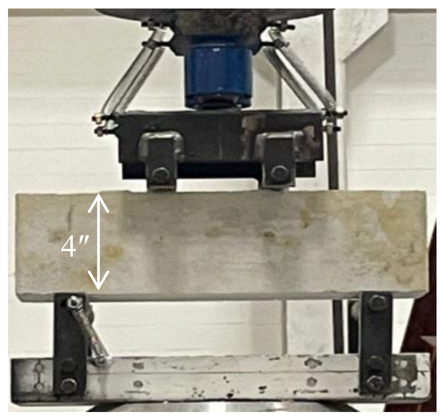

(a) Base Mix 1 specimen (b) Base Mix 2 specimen

Figure 4: Sample specimens under uniaxial compression

Four-point flexure tests: This test assesses the flexural strength or modulus of rupture of concrete and provides information about the concrete's ability to resist cracking and failure under bending loads. The four-point bending experiments were conducted according to ASTM C78 [28] and the average modulus of rupture was determined for each mixture. Figure 5 shows sample specimens of base Mixes 1 and 2 during the four-point flexure experiments. These tests were performed with beam specimens of dimensions 1.5″ (width) by 3″ (height) by 12″ (length) for Mix 1 and with beams specimens of dimensions 4″ (width) by 4″ (height) by 14″ (length) for Mix 2. Larger specimens were used for Mix 2 due to its larger aggregate size. A constant machine head displacement rate of 0.015 inch/minute was used for Mix 1 and that of 0.020 inch/minute was used for Mix 2, accounting for the difference in heights of the specimens.



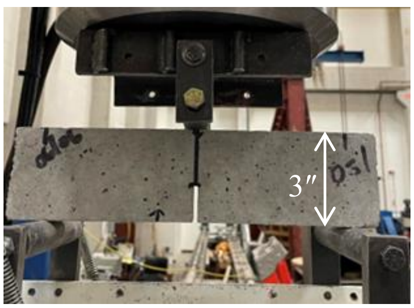

(a) Base Mix 1 specimen



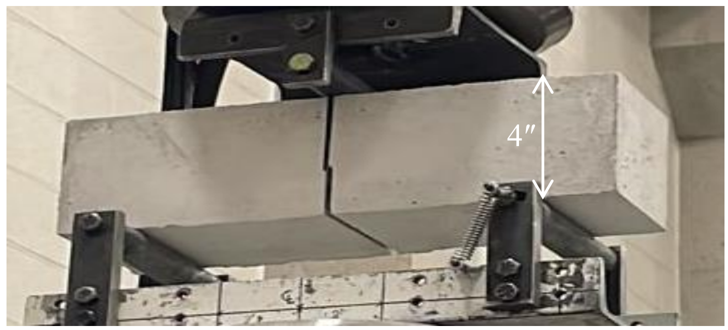

(b) Base Mix 2 specimen

Figure 5: Sample specimens under four-point flexure

Fracture toughness tests: Fracture toughness is an indicator of a material's ability to resist crack initiation and is a critical property for estimating concrete's durability and resistance to cracking. In this study, three-point bending experiments were performed on notched beam specimens to determine fracture toughness according to ASTM E399 [15]. Figure 5 shows sample specimens of base Mixes 1 and 2 during the four-point flexure experiments. The notched beam specimens had the same overall dimensions as the beams used for the four-point flexure tests. A notch of depth equal to approximately 40% of the beam depth was precut in each specimen before performing the tests. A vertical load was applied at a constant displacement rate of 0.0075 inch/minute for Mix 1 and that of 0.010 inch/minute for Mix 2.




(a) Base Mix 1 specimen




(b) Base Mix 2 specimen

Figure 6: Sample specimens in three-point bending for fracture toughness test

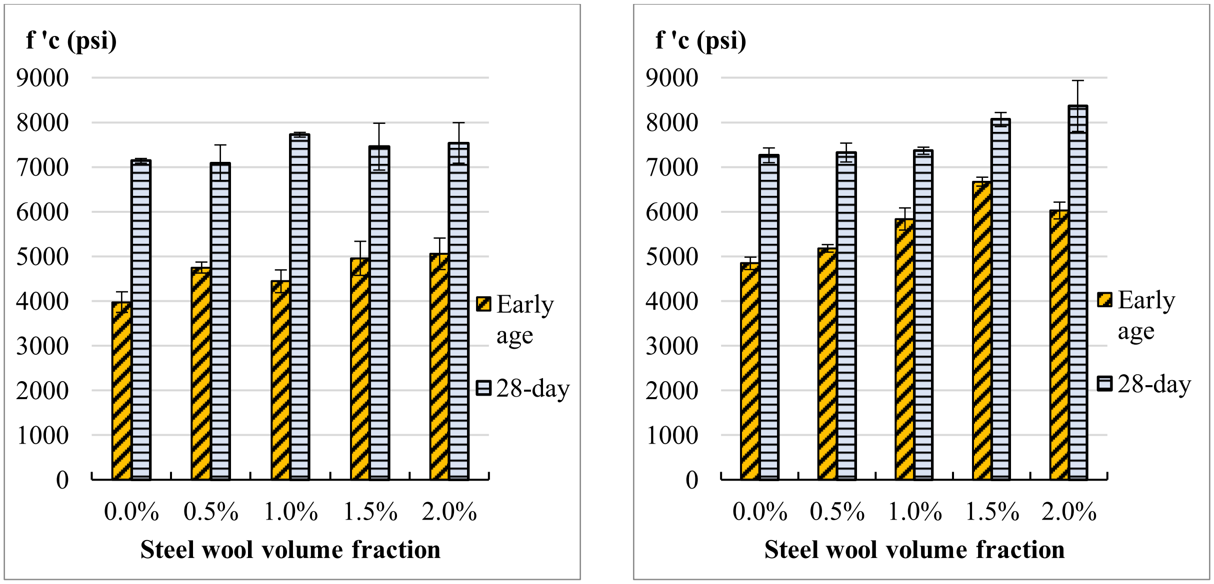
## Results and discussion

### Compressive strength

The average compressive strength ($f'_c$) of all concrete mixtures and corresponding standard deviations (as error bars) are shown in Figure 7 at early age and at 28-days. Figure 8 shows the change in compressive strength of mixtures containing steel wool compared to the respective base mixtures at early age and at 28-days.

The addition of steel wool in concrete led to substantial improvements in early-age compressive strength. Mix 1 with 2.0% (by volume) steel wool had the highest increase in compressive strength of 27% relative to the base Mix 1. Similarly, using 1.5% steel wool in Mix 2 led to a maximum increase of 38% in compressive strength relative to base Mix 2. In contrast, the effect of steel wool on 28-day compressive strength was significantly smaller (less than 10% for most cases). Furthermore, it is interesting to note that even the absolute gains in compressive strength due to steel wool addition were lower at 28-days compared to early age. This could be due to the reduced effectiveness of passive confinement provided by the steel wool at 28-days compared to early age, which in turn could be caused by the greater lateral strain in concrete cylinders near peak compressive stress at 28-days compared to early age. In other words, steel wool fibers might be too small to bridge the vertical microcracks formed in concrete cylinders near the peak compressive stress at 28-days.

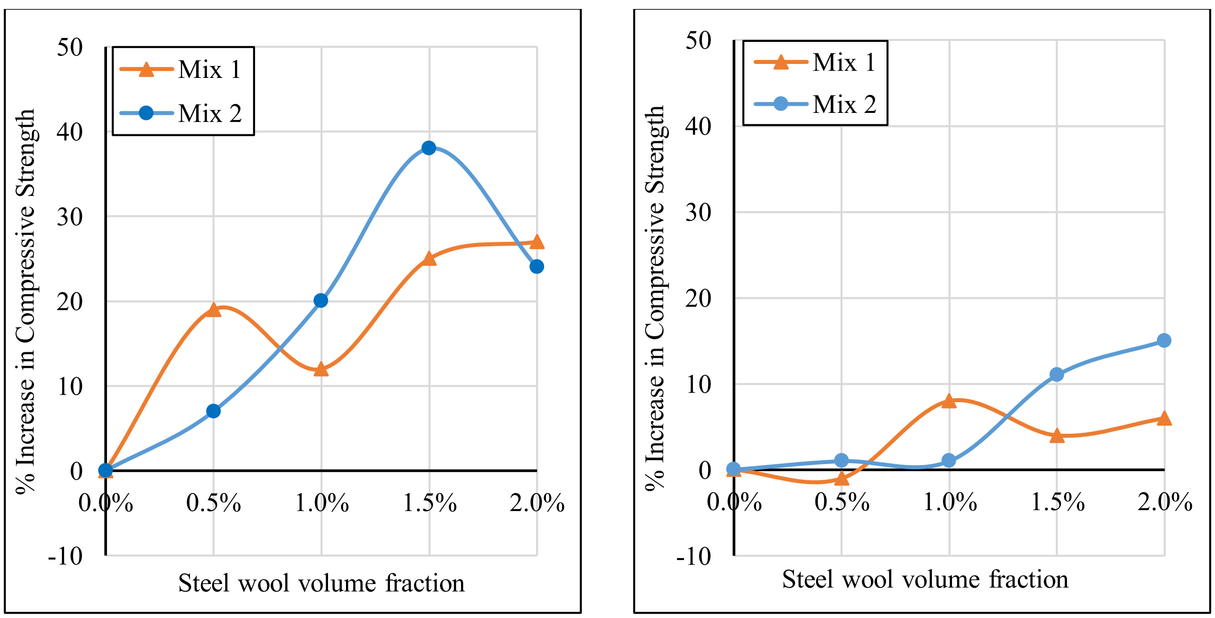
The 28-day results compressive strength results in this study are comparable to those in the literature for steel fibers [8, 16-18], which show that although adding steel fibers increases ductility and post-peak performance, it does not significantly affect compressive strength. When higher volumes of steel fibers are used, the compressive strength could decrease due to inadequate dispersion of the fibers within the concrete matrix creating discontinuities in concrete. We could not find a study in the literature that systematically shows the effect of steel wool on the compressive strength of concrete.




(a) Mix 1 series

(b) Mix 2 series

Figure 7: Compressive strength




(a) Early-age

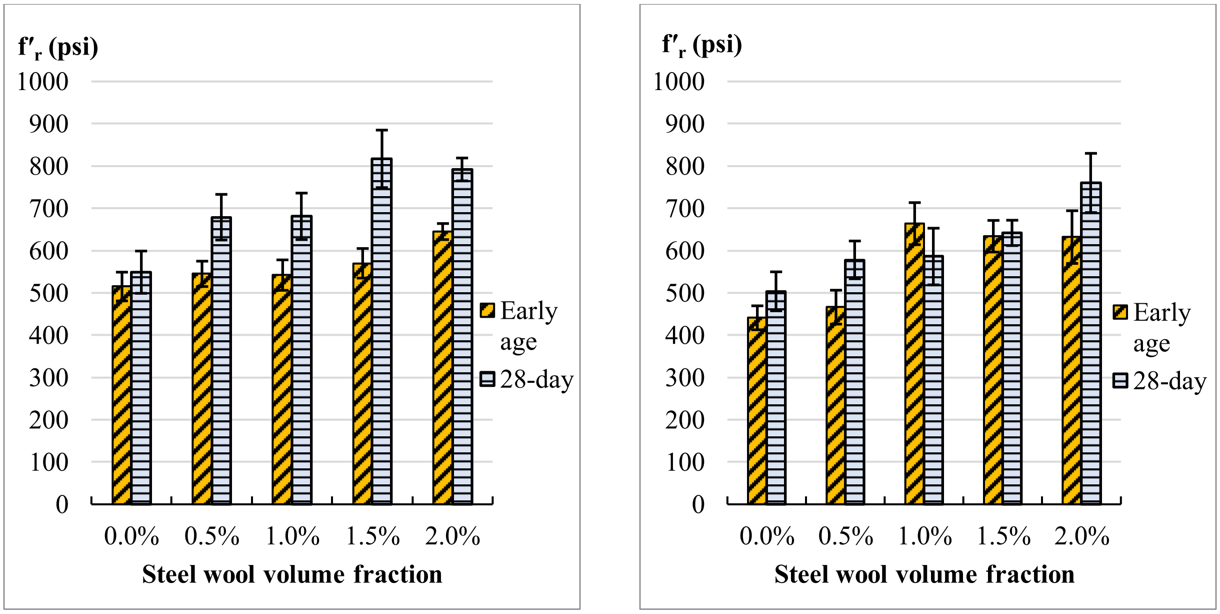
(b) 28-days

Figure 8: Percentage change in compressive strength

**Modulus of rupture**

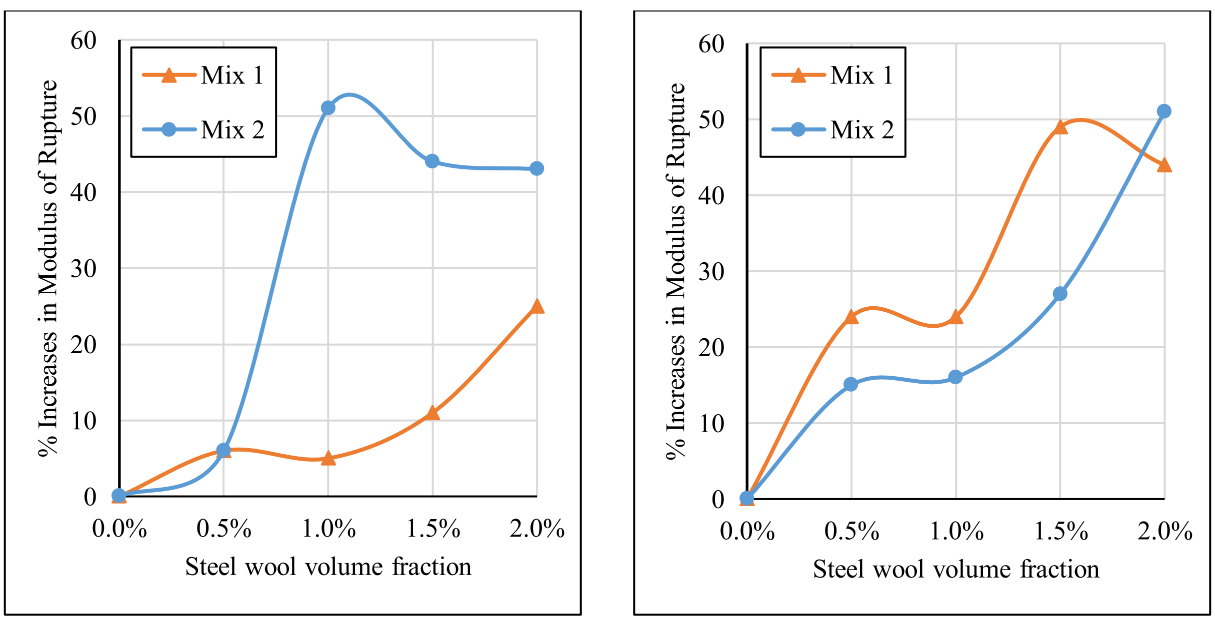
The base Mixes 1 and 2 exhibited average modulus of rupture (MOR) of 515 psi and 441 psi, respectively, at early age, and that of 549 psi and 504 psi, respectively, at 28 days. The MOR of these mixes at both early age and 28-days were consistent with their compressive strengths. The ACI 318 formula of $7.5\sqrt{f'_c}$ provides a good estimate for the experimentally obtained MOR.

Steel wool yielded significant increases in MOR both at early age and at 28-days. Figure 9 shows the average MOR ($f'_r$) and corresponding standard deviations for all mixtures at the two ages. Figure 10 shows the percentage increase in MOR relative to the respective base mixtures as a function of steel wool volume fraction. The early age MOR of Mix 1 increased by up to 27% with 2.0% steel wool. The maximum increase in the early age MOR of Mix 2 was 51% and occurred when 1.0% steel wool was added by volume. At 28-days, the MOR increased by up to 49% with 1.5% steel wool for Mix 1 and increased by up to 51% with 2.0% steel wool for Mix 2. For Mix 2, when the steel wool dosage was increased from 1.5% to 2.0%, there was a slight reduction in the percentage increase of MOR. This decrease can be attributed to a less effective dispersion of steel wool, likely because of the larger aggregate size.




(a) Mix 1 series (b) Mix 2 series

Figure 9: Modulus of rupture



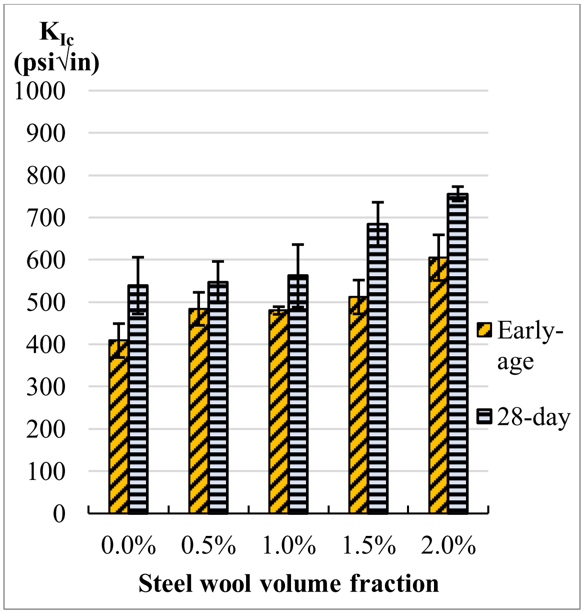

(a) Early-age (b) 28-days

Figure 10: Percentage change in modulus of rupture

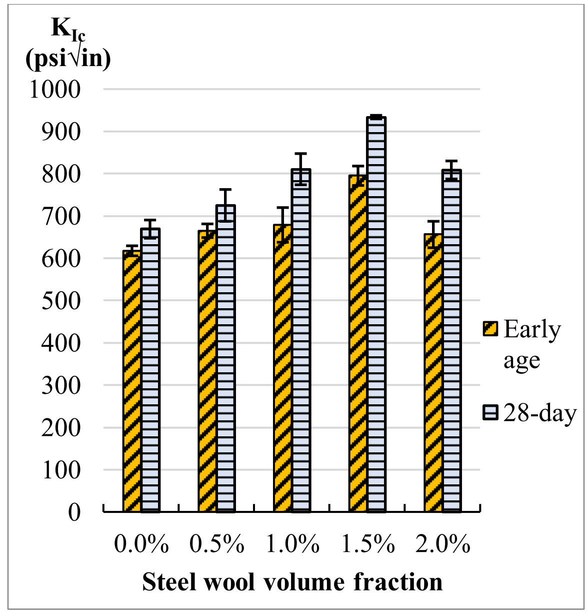
These notable improvements can be attributed to the steel wool's bridging effects, which prevent the formation and propagation of microcracks [19]. While there are no comparable studies in the literature on concrete containing steel wool, studies on concrete containing conventional steel micro- and macro-fibers [20-23] reported higher (up to 120%) increases in MOR compared to concretes without fibers. This significant increase is attributed to the larger length of steel fibers compared to steel wool. Longer fibers can increase the post-cracking tensile strength and ductility more due to a stronger bridging effect [21, 24]. Nevertheless, the gains in MOR with steel wool are significant considering their much lower cost and minimal impact on workability due to its significantly smaller size than conventional steel fibers.

**Fracture toughness**

Figure 11 shows the average fracture toughness ($K_{Ic}$) and the corresponding standard deviations for all the mixtures at an early age and at 28 days. Figure 12 depicts the change in the fracture toughness compared to the base mixtures. The base Mixes 1 and 2 exhibited early-age fracture toughness of 409 psi√in and 618 psi√in, respectively. Mix 1 with 2% steel wool by volume showed the highest increase in early-age fracture toughness (48%) compared to the base Mix 1. For Mix 2 series, the highest increase (29%) in early-age fracture toughness was achieved at steel wool volume fraction of 1.5%. At 28-days, the fracture toughness of base Mix 1 and 2 were 549 psi√in and 669 psi√in, respectively. Similar to their early age trend, Mix 1 and 2 achieved maximum increases in fracture toughness at 2.0% and 1.5% steel wool by volume, respectively.

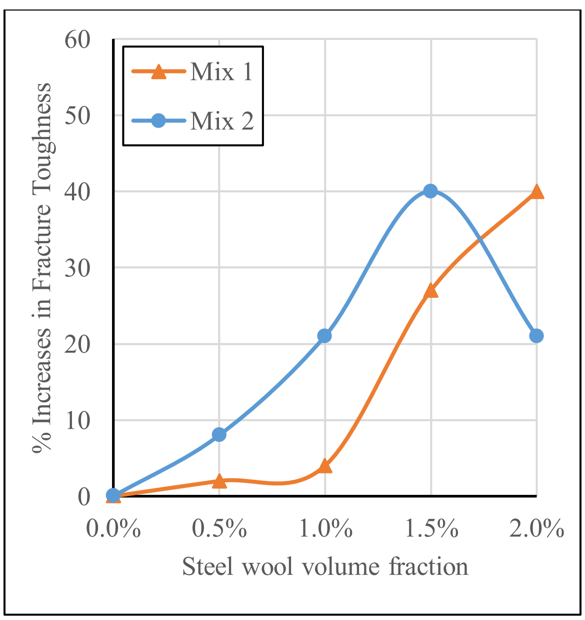



(a) Mix 1 series

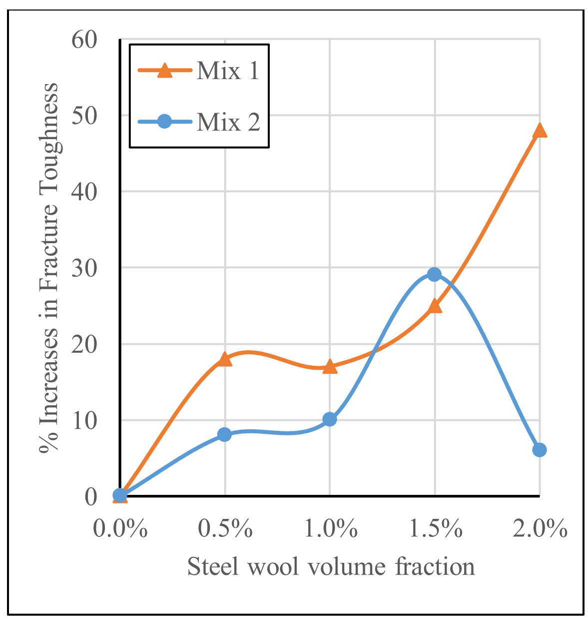



(b) Mix 2 series

Figure 11: Fracture toughness




(a) Early-age




(b) 28-days

Figure 12: Percentage change in fracture toughness

Previous research [19, 25, 26] has reported a similar increase in fracture toughness of cementitious materials with the addition of microfibers. The explanation provided in the literature for the underlying toughening mechanism due to microfibers is as follows. All concretes contain inherent flaws in the form of entrapped air bubbles, porosity, and weak aggregate/cement paste interfaces. Under an applied tensile load, stress concentrations are developed at the ends of these flaws. The stress intensity factor ($K_I$) mathematically represents the magnitude of stress concentration at each flaw. $K_I$ increases with the applied tensile stress, and according to linear-elastic fracture mechanics, a crack is formed at the flaw where $K_I$ equals the fracture toughness ($K_{Ic}$). However, before such formation of a crack (or a "macro" crack), several microcracks are formed near each flaw in a region of high tensile strain called the fracture process zone (FPZ), as shown in Figure 13. The added fibers in concrete can bridge these microcracks in the FPZ, but only if the added fibers are sufficiently small and bond well with the cementitious matrix [27]. The bridging of the microcracks allows stress redistribution and energy absorption in the FPZ, as well as increases the size of the FPZ [28], which in turn increases $K_{Ic}$ as it is related to the energy a material absorbs before crack formation.

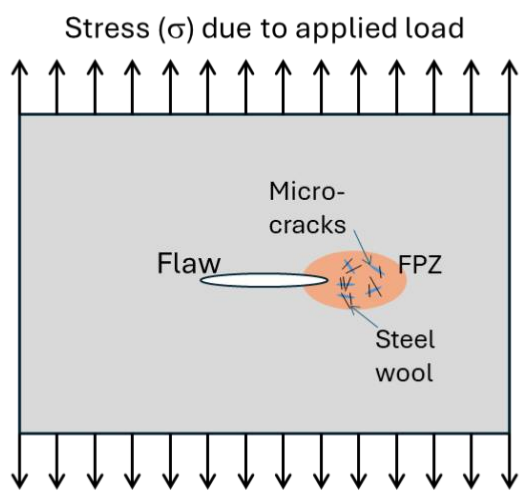
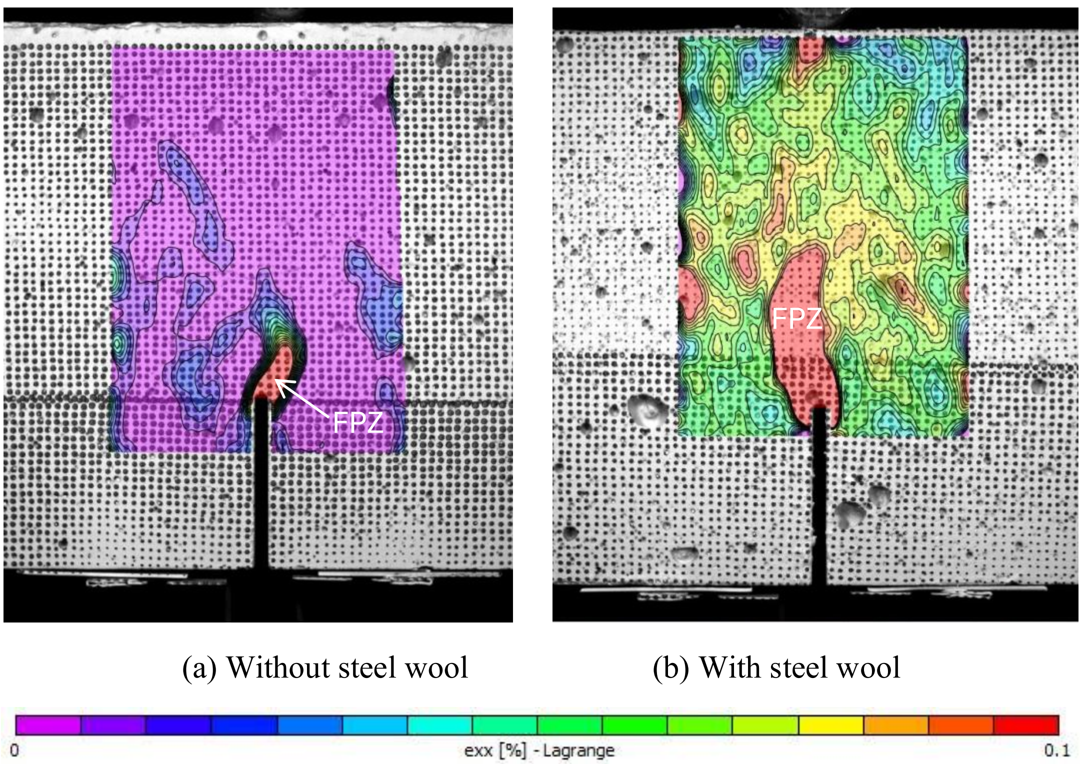



Figure 13: Steel wool bridging microcracks in FPZ

Typically used steel fibers in fiber-reinforced concrete cannot bridge the microcracks in the FPZ due to their large diameter and weak bond with the cementitious matrix, which, therefore, do not improve the cracking strength of concrete. On the other hand, due to their small size (thickness), steel wool can bridge the microcracks in the FPZ, increasing the size of the FPZ and $K_{Ic}$. Figure 14 from Scott et al. [28] depicts a larger FPZ for a notched concrete beam specimen containing steel wool compared to a specimen without steel wool.




(a) Without steel wool (b) With steel wool

Figure 14: Fracture process zone in notched beam specimens [28]

For Mix 2, there was a noticeable decline in fracture toughness when the dosage of steel wool was increased from 1.5% to 2.0%. This is attributed to less efficient steel wool dispersion, likely due to the larger aggregate size in Mix 2 compared to Mix 1, resulting in poor workability and larger air voids.

## Conclusions and recommendations

Adding steel wool up to 2% volume fraction in two different concrete mixtures (obtained from two different precast concrete manufacturers) significantly enhanced their fracture toughness, thus improving their resistance to crack formation. Like other microfibers, steel wool's bridging of the microcracks in the FPZ around a flaw redistributes stress, increases energy absorption, and increases the size of the FPZ before crack formation, thus increasing the fracture toughness. Steel wool addition also improved the MOR of concrete substantially, signifying their post-cracking contribution to the tensile capacity of concrete through crack bridging. However, the beneficial effects of steel wool on MOR and fracture toughness diminished at a volume fraction greater than 1.5% due to adverse effects on workability (especially in Mix 2 with larger coarse aggregates) and homogeneity of the material. Therefore, this study recommends using 1.5% volume fraction of steel wool in concrete for optimum mechanical properties and good workability. The maximum gains in concrete properties at early age and at 28 days and the corresponding steel wool content are summarized in the tables below.

Early-age:

| | Compressive strength | MOR | Fracture toughness |
|---|---|---|---|
| Mix 1 | +27% with 2% SW* | +25% with 2% SW | +40% with 2% SW |
| Mix 2 | +38% with 1.5% SW | +51% with 1% SW | +40% with 1.5% SW |

* SW = steel wool

28-days:

| | Compressive strength | MOR | Fracture toughness |
|---|---|---|---|
| Mix 1 | +8% with 1% SW* | +49% with 1.5% SW | +48% with 2% SW |
| Mix 2 | +15% with 2% SW | +51% with 2% SW | +29% with 1.5% SW |

* SW = steel wool

## References


1. Fanous, F., *Impact of deck cracking on durability*. 2000, Center for Transportation Research and Education, Iowa State University: Ames, IA.
2. Okumus, P., R.P. Kristam, and M.D. Arancibia, *Sources of Crack Growth in Pretensioned Concrete-Bridge Girder Anchorage Zones after Detensioning.* Journal of Bridge Engineering, 2016. **21**(10): p. 04016072.
3. Wang, L., *Strand corrosion in prestressed concrete structures*. 2023, Singapore: Springer.
4. Bentur, A. and S. Mindess, *Fibre reinforced cementitious composites*. 2nd ed. 2014, Milton Park, UK: CRC Press.
5. ACI, *544.4R-18: Guide to Design with Fiber-Reinforced Concrete*. 2018, American Concrete Institute: USA.
6. Ouyang, C. and S.P. Shah, *Toughening of high strength cementitious matrix reinforced by discontinuous short fibers.* Cement and Concrete Research, 1992. **22**(6): p. 1201-1215.
7. Beaudoin J, J., *Microstructural Modifications of Macro and Micro-Fiber Reinforced Hydrated Portland Cement Matrices*, in *1st Can. University-Industry Workshop on Fiber Reinforced Concrete*. 1991: Quebec City. p. 129-139.

8. Bhutta, A., M. Farooq, and N. Banthia, *Performance characteristics of micro fiber-reinforced geopolymer mortars for repair.* Construction and Building Materials, 2019. **215**: p. 605-612.

9. Jayasooriya, D., P. Rajeev, and J. Sanjayan, *Tensile stress-strain models for steel fiber reinforced concrete.* Journal of Building Engineering, 2024. **96**: p. 110533.

10. Ahmad, J. and Z. Zhou, *Properties of concrete with addition carbon nanotubes: A review.* Construction and Building Materials, 2023. **393**: p. 132066.

11. American Metal Fibers Inc. *Applications of steel wool*. [cited 2018 Dec 29]; Available from: http://www.amfi-usa.com/applications.

12. ASTM, *Standard practice for making and curing concrete test specimens in the laboratory*, in *ASTM C192/C192-M*. 2019, ASTM International: West Conshohocken, PA.

13. ASTM C143/C143M-20, *Standard Test Method for Slump of Hydraulic-Cement Concrete*. 2020, ASTM International: West Conshohocken, PA.

14. ASTM C39/C39M-21, *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*. 2021, ASTM International: West Conshohocken, PA.

15. *ASTM E399—17*, in *Standard test method for linear-elastic plane-strain fracture toughness kic of metallic materials*. 2017, American Society for Testing and Materials: West Conshohocken, Pennsylvania.

16. Dopko, M., et al., *Strength and Crack Resistance of Carbon Microfiber Reinforced Concrete.* ACI Materials Journal, 2020. **117**.

17. Yoo, D.-Y., et al., *Effects of fiber shape, aspect ratio, and volume fraction on flexural behavior of ultra-high-performance fiber-reinforced cement composites.* Composite Structures, 2017. **174**: p. 375-388.

18. Usman, M., et al., *Axial Compressive Behavior of Confined Steel Fiber Reinforced High Strength Concrete.* Construction and Building Materials, 2020. **230**.

19. Ragalwar, K., et al., *On enhancing the mechanical behavior of ultra-high performance concrete through multi-scale fiber reinforcement.* Cement and Concrete Composites, 2019. **105**: p. 103422.

20. Zhou, F., et al. *Uniaxial Tensile Behavior of Carbon Textile Reinforced Mortar*. Materials, 2019. **12**, DOI: 10.3390/ma12030374.

21. Kayali, O., M.N. Haque, and B. Zhu, *Some characteristics of high strength fiber reinforced lightweight aggregate concrete.* Cement and Concrete Composites, 2003. **25**: p. 207-213.

22. Libre, N.A., et al., *Mechanical properties of hybrid fiber reinforced lightweight aggregate concrete made with natural pumice.* Construction and Building Materials - CONSTR BUILD MATER, 2011. **25**: p. 2458-2464.

23. Mohammadi, Y., S.P. Singh, and S. Kaushik, *Properties of steel fibrous concrete containing mixed fibres in fresh and hardened state.* Construction and Building Materials, 2008. **22**: p. 956-965.

24. Khan, M. and M. Ali, *Use of glass and nylon fibers in concrete for controlling early age micro cracking in bridge decks.* Construction and Building Materials, 2016. **125**: p. 800-808.

25. Banthia, N. and J. Sheng, *Fracture toughness of micro-fiber reinforced cement composites.* Cement and Concrete Composites, 1996. **18**(4): p. 251-269.

26. Li, V.C. and M. Maalej, *Toughening in cement based composites. Part II: Fiber reinforced cementitious composites.* Cement and Concrete Composites, 1996. **18**(4): p. 239-249.

27. Nelson Patricia, K., C. Li Victor, and T. Kamada, *Fracture Toughness of Microfiber Reinforced Cement Composites.* Journal of Materials in Civil Engineering, 2002. **14**(5): p. 384-391.

28. Scott, D.A., et al., *Fracture process zone characterizations of multi-scale fiber reinforced cementitious composites.* Construction and Building Materials, 2023. **408**: p. 133713.