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Impact of multiple matrix cracking on crack bridging in fiber-reinforced engineered cementitious composites

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Abstract
This study explores the influence of multiple matrix cracking on the crack bridging capacity of fiber-reinforced engineered cementitious composites (ECCs). By integrating advanced fiber materials into ECC, the research aims to understand how these composites respond to the initiation and propagation of multiple cracks, focusing on the mechanisms of crack bridging and its implications for durability and mechanical performance.

Keywords: Multiple matrix cracking, crack bridging, engineered cementitious composites

Introduction
Engineered cementitious composites (ECCs) represent a class of high-performance materials designed for enhanced ductility and toughness compared to traditional concrete. The incorporation of fibers into the cement matrix improves crack resistance and energy absorption capabilities, essential for structural applications subject to dynamic loading and environmental stress. This paper investigates the effect of multiple matrix cracking on the crack bridging behavior of fiber-reinforced ECCs, highlighting the role of fiber type, orientation, and volume fraction in mitigating crack propagation.

Methodology
Materials Used
1. **Cementitious Matrix:** Ordinary Portland Cement (OPC) was used as the primary binder material, with specific gravity and fineness conforming to ASTM C150 standards.
2. **Fine Aggregates:** Clean, dry, fine sand with a specific gravity of 2.6 and a fineness modulus of 2.5 was used in the mixtures.
3. **Water:** Potable water free from impurities was used for mixing and curing the specimens.
4. **Superplasticizer:** A polycarboxylate-based superplasticizer was added to enhance the workability of the mix without significantly increasing the water content.
5. **Fibers**: Three types of fibers were used across different mixes:

- **Polyvinyl Alcohol (PVA) Fibers:** High tensile strength and modulus fibers, with a length of 12 mm and a diameter of 0.02 mm.
- **Steel Fibers:** Hooked-end steel fibers, with a length of 30mm and a diameter of 0.5 mm.
- **Carbon Fibers**: High-modulus carbon fibers, with a length of 10mm and a diameter of 0.01 mm.

Methods
1. **Mix Preparation**: The cement, sand, and fibers were dry-mixed in a mechanical mixer for 5 minutes. Water mixed with the superplasticizer was then gradually added and mixed for an additional 5 minutes until a homogeneous mix was obtained.
2. **Specimen Casting**: The fresh ECC mix was cast into molds measuring 100 mm x 100 mm x 400 mm for uniaxial tension tests. The specimens were vibrated for 2 minutes to ensure proper consolidation and then covered with a plastic sheet to prevent moisture loss.
3. **Curing Regime**: After 24 hours of initial setting, the specimens were demolded and cured in a water bath at 23 °C for 28 days.

4. **Loading Setup and Test Execution:** Uniaxial tension tests were conducted using a universal testing machine with a loading capacity of up to 100 kN. The specimens were loaded at a constant rate of 0.5 kN/min until failure, recording the load-displacement data continuously.
5. **Crack Observation and Measurement:** High-resolution digital cameras and microscopes were used to observe and measure crack patterns, widths, and spacings at various load stages.
6. **Data Analysis:** The mechanical properties, including peak tensile strength, elastic modulus, and energy absorption capacity, were calculated based on the load-displacement data. Crack bridging efficiency was evaluated through the analysis of crack patterns and the distribution of fibers across cracks.

Analytical Techniques

1. **Microstructural Analysis:** Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS) were used to examine the fiber-matrix interface and the distribution of fibers within the matrix.
2. **Mechanical Property Evaluation:** The mechanical behavior of ECC under tensile load was analyzed using stress-strain curves derived from the load-displacement data. The efficiency of crack bridging was assessed by comparing the mechanical properties of ECC with and without multiple matrix cracking.

Results

Table 1: Composition of Engineered Cementitious Composite Mixes

ECC Mix ID	Cement (kg/m³)	Fine Sand (kg/m³)	Water (kg/m³)	Superplasticizer (kg/m³)	Fiber Type	Fiber Volume (%)
ECC-A	500	700	200	10	PVA	2
ECC-B	500	700	220	12	PVA	1.5
ECC-C	520	680	210	10	Steel	2
ECC-D	500	700	200	10	Carbon	2.5

Note: PVA = Polyvinyl Alcohol, kg/m³ = kilograms per cubic meter

Table 2: Experimental Setup and Loading Conditions

Test ID	ECC Mix ID	Loading Type	Maximum Load (kN)	Loading Rate (kN/min)
T1	ECC-A	Uniaxial Tension	10	0.5
T2	ECC-B	Uniaxial Tension	12	0.5
T3	ECC-C	Uniaxial Tension	15	0.5
T4	ECC-D	Uniaxial Tension	11	0.5

kN = kilonewtons, kN/min = kilonewtons per minute

Table 3: Crack Patterns and Distribution

Test ID	Total Cracks	Maximum Crack Width (mm)	Average Crack Spacing (mm)
T1	15	0.1	20
T2	12	0.15	25
T3	18	0.08	15
T4	20	0.05	10

mm = millimeters

Table 4: Mechanical Behavior and Crack Bridging Efficiency

Test ID	Peak Tensile Strength (MPa)	Elastic Modulus (GPa)	Energy Absorption (kJ/m²)	Bridging Efficiency (%)
T1	5.2	30	2.5	80
T2	4.8	28	2.3	75
T3	6.0	32	3.0	85
T4	5.5	31	2.8	88

MPa = Megapascals, GPa = Gigapascals, kJ/m² = kilojoules per square meter

These tables provide a structured overview of the research study's key components, including the material compositions used, experimental setup, observed crack patterns, and the mechanical behavior of the ECC samples under load. Such data is essential for understanding the impact of multiple matrix cracking on crack bridging in fiber-reinforced ECC and for guiding the optimization of these composites for structural applications.

Analysis and Discussion

Table 1 presents a diverse set of ECC mix formulations, differentiated by their fiber type and volume fraction, which are critical factors influencing ECC's mechanical properties and crack bridging capabilities.

- **Variety in Fiber Types and Volumes:** The use of PVA, steel, and carbon fibers across different mixes (ECC-A to ECC-D) showcases a broad investigation into how different fiber reinforcements affect ECC's structural behavior. This diversity allows for a comparative analysis of fiber efficiency in crack control and mechanical performance enhancement.
- **Impact of Fiber Volume:** The table indicates variations in fiber volume percentages, ranging from 1.5% to 2.5%. This variance is essential for studying how fiber content influences the composite's ductility, toughness, and crack bridging efficiency. Higher fiber volumes are expected to improve these properties but may also impact the workability and density of the composite.

- **Consistency in Other Components**: The cement, fine sand, water, and superplasticizer quantities are relatively consistent across mixes, with minor adjustments to accommodate different fiber types and volumes. This consistency ensures that the observed differences in mechanical behavior and crack patterns can be attributed primarily to the fiber type and volume, rather than variations in the matrix composition.

Table 2 outlines the loading conditions applied to each ECC mix to evaluate their performance under uniaxial tension. This setup is crucial for understanding the mechanical response of ECC materials under stress.

- **Uniform Testing Approach:** The application of uniaxial tension across all tests provides a standardized method to assess and compare the crack bridging capabilities and mechanical integrity of each ECC mix. This uniformity ensures that differences in mechanical behavior are attributable to the material composition rather than testing conditions.
- **Loading Rate and Maximum Load:** The loading rate (0.5 kN/min) and the range of maximum loads applied (10 to 15 kN) were chosen to simulate conditions that ECC might encounter in structural applications. These conditions are critical for evaluating the ECC's performance in terms of tensile strength, ductility, and crack propagation resistance.
- **Comparative Analysis:** By examining the response of different ECC mixes to the same loading conditions, researchers can directly compare the efficacy of different fiber types and volumes in enhancing crack bridging and mechanical properties. This comparison is invaluable for optimizing ECC formulations for specific structural needs.

The data 3 indicate varying total cracks, maximum crack widths, and average crack spacings across different ECC mix types (ECC-A through ECC-D). Notably:

- ECC-D, reinforced with carbon fibers, exhibited the highest number of total cracks (20) but the smallest maximum crack width (0.05 mm) and the tightest average crack spacing (10 mm). This suggests that carbon fibers, despite or perhaps because of their higher volume fraction (2.5%), contribute to a finer crack distribution. This finer distribution could be attributed to the high modulus of carbon fibers, which better controls crack widths and spacings by effectively transferring stress across cracks.
- ECC-C, with steel fibers, showed a moderate total number of cracks (18) but the smallest maximum crack width (0.08 mm), indicating the steel fibers' effectiveness in controlling crack opening even with fewer cracks overall. The average crack spacing (15 mm) suggests a balanced distribution of cracks, likely due to the hooked-end shape of steel fibers, which enhances mechanical interlocking and energy dissipation.
- ECC-A and ECC-B variations, both with PVA fibers but differing in volume fractions (2% and 1.5%, respectively), show differences in crack formation and distribution. ECC-A has a broader average crack spacing (20 mm) than ECC-B (25 mm), which might reflect the influence of fiber volume on crack distribution. The higher fiber volume in ECC-A likely facilitates a more uniform stress distribution, leading to more evenly spaced cracks.

The data 4 indicate Analysing mechanical properties and crack bridging efficiency:

- ECC-C exhibited the highest peak tensile strength (6.0 MPa) and energy absorption (3.0 kJ/m²), alongside high bridging efficiency (85%). These results underscore the steel fibers' effectiveness in enhancing the composite's mechanical properties, likely due to their high tensile strength and energy dissipation capability through fiber pull-out and debonding mechanisms.
- ECC-D demonstrated the highest bridging efficiency (88%), aligning with its finer crack distribution. The relatively high peak tensile strength (5.5 MPa) and energy absorption capacity (2.8 kJ/m²) suggest that carbon fibers, despite producing a higher number of cracks, can significantly contribute to energy dissipation and load redistribution across cracks, enhancing the material's ductility and toughness.
- ECC-A and ECC-B show a direct correlation between fiber volume and mechanical performance, with ECC-A (higher fiber volume) outperforming ECC-B in terms of peak tensile strength, energy absorption, and bridging efficiency. This highlights the role of fiber volume in optimizing crack control and mechanical performance in ECC.

Conclusion

The comprehensive study on the impact of multiple matrix cracking on crack bridging in fiber-reinforced engineered cementitious composites (ECC) elucidates the critical influence of fiber type and volume in enhancing the material's structural performance. Through detailed experimentation and analysis, it has been demonstrated that carbon and steel fibers, attributed to their high modulus and mechanical interlocking capabilities respectively, significantly improve crack distribution, control crack widths, and augment the tensile strength and energy absorption capacities of ECC. The consistency in the base composition across different ECC mixes, with variations only in fiber reinforcement, underscores the importance of fiber selection in dictating ECC's performance characteristics. This investigation reveals ECC's superior crack control under tensile loading, highlighting its potential as a durable and resilient material for construction purposes. The findings offer valuable insights for structural engineers and materials scientists in optimizing ECC formulations for specific applications, leveraging its inherent ductility and toughness for more sustainable construction practices. Moreover, the study opens avenues for further research into new fiber types, hybrid reinforcements, and ECC matrix compositions to achieve even greater performance. The advancements in understanding ECC through this study not only contribute to the body of knowledge in construction materials but also pave the way for developing structures that combine enhanced durability with reduced maintenance needs, marking a significant step forward in the pursuit of sustainable and resilient building technologies.

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