Uniaxial Tensile Behavior of Engineered Cementitious Composites (ECC): A Review

Qing Wang and Boyu Yao

ABSTRACT

The high ductility and multiple cracking characters of Engineered Cementitious Composites (ECC) is particular for cementitious materials. In the present paper, recent progress in the uniaxial tensile behavior of ECC is reviewed. Raw materials, mix proportion, tensile specimen size, testing procedure and tensile properties of ECC are summarized according to literature from the last decade. It is conclude that with the addition of ductile fiber, ECC possesses the ability to stretch after the initial elastic stage and due to the bridging effect of decentralized fiber in matrix, crack failure was well controlled which leads to small and tight cracks at the ultimate condition. On the whole, uniaxial tensile strength ranges from 3.2-16.0MPa, ultimate tensile strain from 0.5-8.0%, average crack width controlled below 100μm.¹

INTRODUCTION

Concrete is normally a typical brittle material, as first crack occurs, immediate localization of deformation followed under tension, accompanied by suddenly decreasing load which may cause catastrophic damage. To overcome the brittleness nature of traditional concrete, a class of high performance fiber reinforced cementitious composite, called engineered cementitious composite (ECC), has been developed in recent years [1-3]. Since the initial mesomechanical design with short fibers in 1990s by V.C. Li from University of Michigan [4], scientific research on ECC becomes more thorough and extensive mainly because of its strain hardening

¹Qing Wang, Boyu Yao, Guangzhou University, No. 230 Outer Ring West Road, Higher Education Mega Center, Panyu District, Guangzhou City, Guangdong Province, China, 510006
and multiple cracking properties. In order to enhance the behavior of cementitious composite, polyvinyl alcohol (PVA) fiber was most commonly utilized in producing ECC due to its better disperse ability and interface adhesive property [5-7]. Polyethylene (PE), steel fiber and other kind of fibers were introduced to the cement-based system as well aiming at improving ductility and crack controllability [8]. While keeping the fiber volume fraction no greater than 2%, ECC has large tensile strain capacity in the range of 1-7% against 0.01% of conventional concrete, a tensile strength of 3-8MPa at the level of 30-80MPa compressive strength, which enables ECC to possess much more ductility than concrete [9-11]. When subjected to tension, ECC exhibits multiple cracking with crack width less than 100 μm, making it a highly reliable and durable material under structural load and environmental impacts [12-13]. Therefore, the present review tries to summarize the recent progress about tensile behaviors of ECC to provide some insights and suggestions for further research and construction applications of ECC.

**RAW MATERIALS AND MIX PROPORTIONS**

By eliminating coarse aggregate from traditional concrete, ECC mainly consists of cement, fine aggregate and fiber. As research approaches, fly ash, silica fume and blast furnace slag was incorporated as supplemental cementitious materials (SCMs) to lower the cement dosage and enhance the performance of ECC at the same time [14-15]. For fine aggregate, quartz sand was largely adopted with an average particle size between 0.075-0.400mm [16]. After mixing cement, supplemental cementitious materials and quartz sand together, fiber was added to improve ductility and fracture toughness. Till now, many kinds of fiber were employed for various engineering consideration such as polyvinyl alcohol (PVA) fiber, polyethylene (PE), steel fiber, carbon fiber, basalt fiber etc [17-18].

With components mentioned above, ECC for high ductility applications can be produced by precise proportion design. Usually the cement to binder ratio was in a range of 0.2-0.6, sand to cementitious materials ratio 0.35-0.90, and SCMs to cement ratio 0-3 according to ECC performance demands. When in low cement to binder ratio, superplasticizer was introduced mainly to improve flowability and fiber distribution. Additionally, fiber is crucially essential for ECC and the volume fraction of fiber is around 2% in average. Typical mix proportions of ECC was shown in TABLE I.
### TABLE I. MIX PROPORTIONS AND SPECIMEN SIZE OF ECC FROM LITERATURE.

| Literature   | SCMs          | w/b     | Volume Fraction | Shape     | Dimensions (mm) |
|--------------|---------------|---------|-----------------|-----------|-----------------|
| Kim (2007)[19] | BFS           | 0.35-0.60 | 2.0%            | dumbbell  | 350*84*20       |
| Mustafa (2009)[20] | 55-70%FA   | 0.27    | 2.0%            | prism     | 152.4*76.2*12.7 |
| Zhou (2012)[21]  | 30%LP+35%BFS | 0.30-0.35 | 2.0%            | dumbbell  | 240*60*13       |
| Xiao (2013)[22]  | 68.7%FA      | 0.26    | 2.0%            | dumbbell  | 305*76*38       |
| Khin (2013)[23]  | 34%FA        | 0.25    | 1.5-1.75%       | dumbbell  | 320*60*12.79    |
| Prakash (2014)[24]| 65%FA       | 0.20    | 2.0%            | prism     | 228.6*76.2*12.7 |
| Galal (2015)[25] | 55%FA       | 0.29    | 1.1%            | dumbbell  | 240*65*40       |
| Pan (2015)[26]   | 54-78%FA    | 0.26-0.32 | 1.2-2.0%       | dumbbell  | 240*60*30       |
| Zhang (2016)[3]  | 10%FA+10%SF +10%BFS | 0.20 | 2.0%            | prism     | 200*100*20      |
| Lu (2017)[27]    | 80%FA+2%SF  | 0.20    | 2.0%            | dumbbell  | 152.4*76.2*12.7 |
| Namratha (2017)[28]| -           | 0.40    | 1.0%            | dumbbell  | 240*60*13       |
| Pourfalah (2018)[29]| 53%FA+18%SF | 0.23    | 2.0%            | dumbbell  | 330*60*13       |
| Jing (2018)[30]  | 72%FA       | 0.30    | 0.5-1.5%        | dumbbell  | 330*60*30       |
| Shu (2018)[31]   | 50-80%FA    | 0.25-0.41 | 0.5-2.0%       | dumbbell  | 240*60*13       |
| Yu (2018)[32]    | 44%BFS+8%SF | 0.14    | 2.0%            | dumbbell  | 330*60*30       |
| Li (2019)[33]    | 50%FA       | 0.30    | 0.41-3.12%      | dumbbell  | 330*60*13       |

### TENSILE SPECIMEN AND TESTING PROCEDURES

After the preparation of fresh cementitious composites, they were cast into several types of mould to form specific test specimens for mechanical property determinations. As for compressive and flexural strength, standard size of 100mm cubic and prism specimen were commonly used. While for tensile behavior, different dimensions were adopted by investigators partly shown in TABLE I. According to present review, specimen in dumbbell shape was employed most frequently for direct tensile tests. After removing the tensile specimens from molds, they were stored in curing room at around 20°C, 95% relative humidity or in water for presupposed days. Direct tensile tests were conducted with displacement control at a rate of 0.015-0.050 mm/min. Strain was measured by extensometers and the stress was recorded in the hydraulic testing machine.

### RESULTS AND ANALYSIS

**Tensile Stress-strain Curve**

Tensile stress-strain curves of ECC were obtained from direct tensile tests. According to the results, three stages could be divided: I-elastic stage, II-strain...
hardening process and III-stress decreasing stage, shown in Figure 1. In stage I, tensile stress maintains a continuous increasing trend as strain extends, while after that, tensile stress keeps at a certain level with further stretch in deformation and then declines slowly in stage III.

Since the first decade of 21th century, direct tensile tests of various ECC have been carried out by many researchers for separate purpose. In 2007, Jin et al.[19] studied about tensile performance of ECC produced with ground granulated blast furnace slag. All specimens exhibit apparent multiple cracking patterns accompanying pseudo strain-hardening behavior with strain capacity ranging from 1.0% to nearly 3.6%. Representative curves were displayed in Figure 1.

Mustafa[20] investigated ECC with high-volume Fly Ash, exhibiting a strain capacity of more than 3.5% at 7 days and tensile strength above 4.0MPa. Zhou et al.[21] researched uniaxial tensile stress-strain behaviors of ECC with a tensile strain capacity of 2.2% and ultimate tensile strength of 3.5 MPa. Huang et al.[22] explored the feasibility of incorporating iron ore tailings (IOTs) as environmental friendly alternative aggregates, and results indicated that when tensile strength was at a level of 4.50-5.80MPa, tensile capacity was 4.70-2.80% respectively.

Figure 1. Stress-strain curves in uniaxial tension (Kim, 2007)[19].

Khin et al.(2013)[23] studied the mechanical properties of a new hybrid fiber-reinforced engineered cementitious composite with 1.75% PVA and 0.58% steel fibers. Prakash et al.[24] researched the possibility for ECC to substitute concrete materials, which proved to be 4.50-5.20MPa tensile strength and 1.90-2.60% strain capacity. Furthermore, in 2015, Galal et al.[25] studied about evaluation of PVA and PBI-based engineered cementitious composites under different environments. Lu et al (2017)'s[27] researched different thickness on ECC mechanical behavior, and increasing thickness from laboratory scale (10-15 mm) to over 100 mm, tensile strength decreases by nearly 20% from 5.20MPa to 4.40MPa while the ductility decreases almost by half from 5.06% to 2.49%. Jing Yu et al.(2018)[30] replaced...
polyvinyl alcohol (PVA) fibers by recycled polyethylene terephthalate (PET) fibers. The tensile strength for these compositions is over 4.3 MPa. Even with 50% of PVA fibers replaced by recycled PET fibers, the ultimate tensile strain reached 1.83%.

When tensile strength and strain capacity of ECC were extracted from literature shown in Figure 2. Conclusion can be drawn that physical properties of ECC under tension are as follows: ultimate tensile strength ranges from 3.2-16.0MPa, ultimate tensile strain from 0.5-8.0%. Furthermore, tensile strength tends to decrease when tensile strain capacity starts to grow according to the fitting line.

Multiple Cracking Characters

Besides the strain hardening effect brought by small amount of fiber, multiple cracking is another important character of ECC. As fibers makes great effort in bridging adjacent cement paste together, cracks initial from cementitious materials are well controlled in certain degree.

Pan et al.(2015)[26] found the phenomenon of multiple cracking of specimens and the recorded stress-strain curves of compositions M17 and M21 are shown in Figure 3 respectively. Both compositions exhibited multiple cracking with many sub-parallel cracks during strain hardening. The average value of measured first crack strength fc, strain fc, peak stress cu and ultimate tensile strain tu are 3.02MPa, 0.022%, 3.51MPa, 2.61% and 3.44MPa, 0.023%, 4.39MPa, 4.46% respectively.

In addition, S. Pourfalah(2018)[29] believed although cracks propagated on the specimens (see Figure 4) were small and tight, the comparison showed a reduction in crack numbers in the H13ECC series compared to the H6ECC series due to the use of longer steel fiber. Gao et al.(2018)[31] have researched on the influences of shrinkage-reducing agent content and PVA fiber volume fraction on the tensile properties and crack resistance of ECC. Yu et al.(2018)[32] have investigated on the Ultra-high performance engineered cementitious composites (UHP-ECC), the average tensile strength of the dumbbell specimens approached 17.42 MPa and corresponding average rupture strains was 8.17%. Li et al.(2019)[33] found that TR-ECC have better crack-width controlling and tensile performance when the tensile properties of textile grid, Young's modulus and cracking strength of matrix were close.

As mentioned above, the formation of multiple cracking is necessary to achieve high composite tensile ductility which is critically important for durability of both material and structure. Unlike normal concrete, the steady state crack width is an intrinsic material property independent of loading, structure size and geometry. This observation has important implications in service life, maximum member size, structure safety and architectural aesthetics.
CONCLUSIONS

In the present paper, recent progress in the uniaxial tensile behavior of ECC has been reviewed. ECC was typically composed of cement, supplementary cementitious materials, quartz sand, superplasticizer, and ductile fiber. Of all the types of fiber utilized in ECC, PVA fiber had an advantage of easy dispersion in cementitious matrix and was dominantly adopted in producing ECC. According to present review, specimen in dumbbell shape was employed most frequently. From the results reviewed on uniaxial tensile behavior, two main characters of ECC had been observed, strain hardening and multiple cracking. With the addition of ductile fiber, ECC possesses the ability to stretch after elastic stage and due to the bridging effect of decentralized fiber, crack failure was well controlled which leads to small and tight cracks at the ultimate condition. On the whole, uniaxial tensile strength ranges from 3.2-16.0MPa, ultimate tensile strain from 0.5-8.0%, average crack width controlled below 100μm. Another interesting phenomenon was noticed that with the increase of strain capacity, tensile strength seems to decrease according to summary of separate tests results.

ACKNOWLEDGEMENTS

Support from Scientific Research Startup Project of Guangzhou University (No.69-18ZX10356) is gratefully acknowledged.

REFERENCES

1. Li V C, Mishra D K, Wu H C. 1995. Matrix design for pseudo-strain-hardening fibre reinforced cementitious composites. J. Materials & Structures, 28(10):586-595.
2. Li V C, Hashida T. 1993. Engineering ductile fracture in brittle-matrix composites. *J. Journal of Materials Science Letters*, 12(12):898-901.
3. Zhang J, Wang Q, Wang Z. 2016. Optimizing design of high strength cement matrix with supplementary cementitious materials. *J. Construction & Building Materials*, 120:123-136.
4. Li V C, Wang Y, Backer S. 1990. Effect of inclining angle, bundling and surface treatment on synthetic fibre pull-out from a cement matrix. *J. Composites*, 21(2):132-140.
5. Mechtcherine V, et al. 2012. Coupled strain rate and temperature effects on the tensile behavior of SHCC with PVA fibers. *J. Cement & Concrete Research*, 42(11):1417-1427.
6. Ahmed, Mihashi H. 2011. Strain hardening behavior of lightweight hybrid polyvinyl alcohol (PVA) fiber reinforced cement composites. *J. Materials & Structures*, 44(6):1179-1191.
7. Kamile Tosun, Burak Felekoğlu, et al. 2014. The role of flaw size and fiber distribution on tensile ductility of PVA-ECC. *J. Composites Part B Engineering*, 56(1):536-545.
8. Said S H, Razak H A. 2015. The effect of synthetic polyethylene fiber on the strain hardening behavior of engineered cementitious composite (ECC). *J. Materials & Design*, 86:447-457.
9. Bashar S, Mohammed et al. 2018. Optimization of hybrid fibers in engineered cementitious composites. *J. Construction & building Materials*, 190: 24-37.
10. Yu J, Li H, Leung C K Y, et al. 2017. Matrix design for waterproof Engineered Cementitious Composites (ECCs). *J. Construction & Building Materials*, 139:438-446.
11. Meng D, Huang T, Zhang Y X, et al. 2017. Mechanical behaviour of a PVA-ECC using local ingredients. *J. Construction & Building Materials*, 141:259-270.
12. Qiu J, Tan H S, Yang E H. 2016. Coupled effects of crack width, slag content, and conditioning alkalinity on autogenous healing of engineered cementitious composites. *J. Cement & Concrete Composites*, 73:203-212.
13. Yu K, Li L, Yu J, et al. 2018. Direct tensile properties of engineered cementitious composites: A review. *J. Construction & Building Materials*, 165:346-362.
14. Fischer G, Wang S, Victor C. Li. 2003. Design of Engineered Cementitious Composites (ECC) for processing and workability requirements. *J. Brittle Matrix Composites*:29-36.
15. Zhu Y, et al. 2014. Measurement and correlation of ductility and compressive strength for ECC produced by binary and ternary systems of binder materials: Fly ash, slag, silica fume and cement. *J. Construction & Building Materials*, 68(3):192-198.
16. Ma H, Qian S, Zhang Z, et al. 2015. Tailoring Engineered Cementitious Composites with local ingredients. *J. Construction & Building Materials*, 101:584-595.
17. Wu C, Li V C. 2017. Thermal-mechanical behaviors of CFRP-ECC hybrid under elevated temperatures. *J. Composites Part B*, 110:255-266.
18. Zhou J, Gang W U, Zhi-Shen W U, et al. 2009. Study on the Mechanic Properties of Steel Wire-Continuous Basalt Fiber Composite Plates. *J. Hi-Tech Fiber & Application*.
19. Kim J K, et al. 2007. Tensile and fiber dispersion performance of ECC produced with ground granulated blast furnace slag. *J. Cement & Concrete Research*, 37(7):1096-1105.
20. Şahmaran M, Li V C. 2009. Durability properties of micro-cracked ECC containing high volumes fly ash. *J. Cement & Concrete Research*, 39(11):1033-1043.
21. Zhou J, et al. 2012. Improved fiber distribution and mechanical properties of ECC by adjusting the mixing sequence. *J. Cement & Concrete Composites*, 34(3):342-348.
22. Huang X, Ranade R, et al. 2013. Development of green engineered cementitious composites using iron ore tailings as aggregates. *J. Construction & Building Materials*, 44(44):757-764.
23. Soe K T, Zhang Y X, Zhang L C. 2013. Material properties of a new hybrid fiber-reinforced engineered cementitious composite. *J. Construction & Building Materials*, 43(3):399-407.
24. Bhat P S, Chang V, Li M. 2014. Effect of elevated temperature on strain-hardening engineered cementitious composites. *J. Construction & Building Materials*, 69(11):370-380.
25. Fares G, Khan M I, et al. 2015. Evaluation of PVA and PBI-based engineered-cementitious composites under different environments. *J. Construction & Building Materials*, 85:109-118.
26. Pan Z, et al. 2015. Study on mechanical properties of cost-effective polyvinyl alcohol engineered cementitious composites. *J. Construction & Building Materials*, 78:397-404.
27. Lu C, et al. 2017. Theoretical evaluation of fiber orientation and its effects on mechanical properties in ECC with various thicknesses. *J. Cement & Concrete Research*, 95:240-246.
28. Kumar A A. 2017. Evaluation of Mechanical Properties of Hybrid Engineered Cementitious Composite (HECC). *J. Materials Today Proceedings*, 4(2017):9856–9859.
29. Pourfalah S. 2018. Behavior of ECC and hybrid engineered cementitious composites at high temperatures. *J. Construction & Building Materials*, 158(C):921–937.
30. Yu J, et al. 2018. Tensile performance of sustainable SHCC with hybrid PVA and recycled PET fibers. *J. Cement & Concrete Research*, 107:110-123.
31. Gao S, et al. 2018. Effect of shrinkage-reducing admixture and expansive agent on mechanical properties and drying shrinkage of ECC. *J. Construction & Building Materials*, 179:172-185.
32. Kequan Yu et al. 2018. Development of ultra-high performance ECC using polyethylene (PE) fibers. *J. Construction & building Materials*, 158: 217-227.
33. Benben Li et al. 2019. Tensile behavior of basalt textile grid reinforced Engineering Cementitious Composite. *J. Composites Part B*, 156:185-200.