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Review Article

BENDABLE CONCRETE: A REVIEW

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Bendable concrete also known as Engineered Cementitious Composites abbreviated as ECC is class of ultra-ductile fiber reinforced cementitious composites, characterized by high ductility and tight crack width control. This material is capable to exhibit considerably enhanced flexibility. An ECC has a strain capacity of more than 3% and thus acts more like a ductile metal rather than like a brittle glass. A bendable concrete is reinforced with micromechanically designed polymer fibres. In this paper literature survey of fresh and mechanical properties of different ECC mixtures are evaluated by incorporating supplementary cementitious material, i.e., fly ash and different aggregate type considering various parameters, i.e., types of fibers, compressive strength, flexural strength and deflection.

Keywords: Bendable Concrete, ECC-Engineered Cementitious Composites, Deflection, Compressive strength, Flexural strength

INTRODUCTION

Conventional concretes are almost un-bendable and have a strain capacity of only 0.1% making them highly brittle and rigid. This lack of bendability is a major cause of failure under strain and has been a pushing factor in the development of an elegant material namely, bendable concrete also known as Engineered Cementitious Composites abbreviated as ECC. This material is capable to exhibit considerably enhanced flexibility. A bendable concrete is reinforced with micromechanically designed polymer fibres.

ECC is made from the same basic ingredients as conventional concrete but with the addition of High-Range Water Reducing (HRWR) agent is required to impart good workability. However, coarse aggregates are not used in ECCs (hence it is a mortar rather than concrete). The powder content of ECC is relatively high. Cementitious materials, such as fly ash, silica fume, blast furnace slag, silica fume, etc., may be used in addition to cement to increase the paste content. Additionally, ECC uses low amounts, typically 2% by volume, of short, discontinuous fibres. ECC incorporates super fine silica sand and tiny Polyvinyl Alcohol-fibres covered with a very thin (nanometer thick), slick coating. This surface

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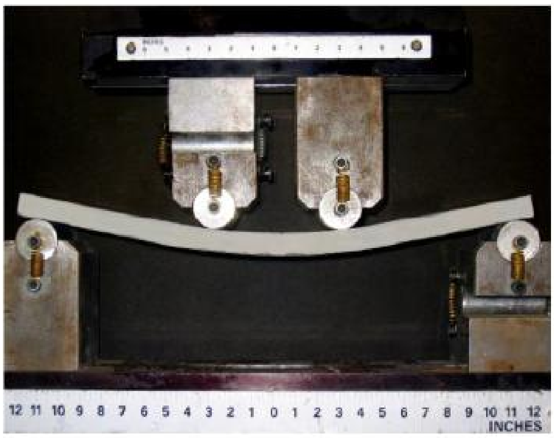
coating allows the fibre to begin slipping when they are over loaded so they are not fracturing.

Figure 1: Response of ECC under Flexural Loading



It prevents the fibre from rupturing which would lead to large cracking. Thus an ECC deforms much more than a normal concrete but without fracturing. Figure 1 represents the behavior of ECC under flexural loading and it can be seen that the beam can deform well without direct failure. The different ingredients of ECC work together to share the applied load. ECC has proved to be 50 times more flexible than traditional concrete, and 40 times lighter, which could even influence design choices in skyscrapers. Additionally, the excellent energy absorbing properties of ECC make it especially suitable for critical elements in seismic zones.

LITERATURE REVIEW

Qian *et al*. (2010) carried out experimental study to investigate the self-healing behavior of ECC with focus on the influence of curing condition and precracking time. Four-point bending tests was used to pre crack ECC beams at different age, followed by different curing conditions, including air curing, 3% CO_2 concentration curing, cyclic wet/dry (dry under 3% CO_2 concentration) curing and water curing. For all curing conditions, deflection capacity after self-healing can recover or even exceed that from virgin samples with almost all precracking ages. After self-healing, flexural stiffness was also retained significantly compared with that from virgin samples, even though the level of retaining decreases with the increase of precracking time. The flexural strength increases for samples pre-cracked at the age of 14 days and 28 days, presumably due to continuous hydration of cementitious materials afterwards. Furthermore, it was promising to utilize nanoclay as distributed internal water reservoirs to promote self-healing behavior within ECC without relying on external water supply.

Victor C Li *et al.* (2012) carried out experimental study to improve the fibre distribution by adjusting the mixing sequence. With the standard mixing sequence, fibres are added after all solid and liquid materials are mixed. The undesirable plastic viscosity before the fibre addition may cause poor fibre distribution and results in poor hardened properties. With the adjusted mixing sequence, the mix of solid materials with the liquid material is divided into two steps and the addition of fibres is between the two steps. In this paper, the influence of different water mixing sequences was investigated by comparing the experimental results of the uniaxial tensile test and the fibre distribution analysis.

The result was concluded that compared with the standard mixing sequence, the adjusted mixing sequence increases the tensile strain capacity and ultimate tensile strength of ECC and improves the fibre distribution.

Yu Zhu *et al*. (2012) carried out an experimental study to develop a kind of green ECC with high tensile ductility and strong enough matrix strength, especially at early age. A series of investigations was carried out to evaluate mechanical properties and drying shrinkage of ECC with 70% combination mineral admixtures of FA and ground granulated blast furnace slag (SL). Four ECC mixtures with constant W/B of 0.25 are prepared with combined inclusion of FA and SL as constant cement replacement level of 70%. The laboratory measurements are carried out, including direct tensile test, four-point bending test, and compressive strength and drying shrinkage.

The experimental results show that ECC with combination mineral admixtures can achieve strain hardening behavior, tensile capacity of ECC can be more than 2.5% at 90 days. Meanwhile, compared to ECC only with fly ash, slag and fly ash can effectively increase compressive strength of ECC, especially at early age. Incorporating SL into matrix can slightly increase drying shrinkage of ECC. However, among four ECC mixtures, ECC with 30% SL and 40% FA presents the lowest drying shrinkage at later ages.

Jun Zhang *et al*. (2013) carried out an experimental study on the potential applications of the fibre reinforced engineered cementitious composite with characteristic of low drying shrinkage (LSECC) in concrete pavements for the purpose of eliminating joints that are normally used to accommodate temperature and shrinkage deformation. It was found that a composite slab containing both plain concrete and LSECC, with steel bars at the LSECC/concrete interface, and designed construction procedures, it is possible to localize the tensile cracks into the LSECC strip instead of cracking in adjacent concrete slab. The crucial problem that interfacial failure in composite slab was prevented by using reinforcing bars across the interfaces. Due to the strain-hardening and high strain capacity of the LSECC, the overall strain capacity and the integrity of the composite slab can be significantly improved. The temperature and shrinkage deformations can be accommodated by adequate selection on the length ratio of LSECC strip and concrete slab.

Mustafa Sahmaran *et al.* (2013) carried out experimental work for 36 different ECC mixtures to evaluate the combined effects of the following factors on workability and rheological properties: water-binder (w/b), sand-binder (s/b), superplasticizer-binder (SP/b) ratios and maximum aggregate size (Dmax). A mini-slump cone, a Marsh cone and a rotational viscometer was used to evaluate the workability and rheological properties of ECC mixtures. Compressive strength and four point bending tests was used for mechanical characteristics of ECC mixtures at 28 days. The effects of studied parameters (w/b, s/b, SP/b and Dmax) was characterized and analyzed using regression models, which can identify the primary factors and their interactions on the measured properties. Statistically significant regression models was developed for all tested parameters as function of w/b, s/b, SP/b and Dmax. To find out the best possible ECC mixture under the range of parameters investigated for the desired workability and mechanical characteristics, a multi-objective optimization problem was defined and solved based on the developed regression models.

Experimental results indicate that w/b, s/b and SP/b parameters affect the rheological and workability properties. On the other hand, for the range of studied aggregate sizes, Dmax is found to be statistically insignificant on the rheological and workability properties of ECC, also in addition to that the mid-span beam deflection capacities, which reflect material ductility, of ECC mixtures varied noticeably with the change of s/b and Dmax design parameters. Both of these two parameters negatively affect the deflection capacity of the ECC mixtures. The other parameters have almost no effect on the mid-span beam deflection capacities of ECC mixtures.

Yu Zhu *et al.* (2014) carried out experimental study to investigate the mechanical properties of ECC produced by high volume mineral admixtures which are fly ash, slag and silica fume. Emphasis of this study is placed on building the correlation between compressive strength and the parameters obtained in load–deflection curves of 12 different ECC mixtures in binary and ternary system of binder materials with different mineral admixtures (FA, SL and silica fume) and to build the correlation between compressive strength and durability of ECC. The water-binder materials ratio (W/B) is kept at 0.25 for various ECC mixtures. The replacement levels of different mineral admixtures in all ECCs in binary systems of binder materials are 50%, 60%, 70% and 80%, respectively (FA + cement and SL + cement). In ternary system (FA + SL + cement and FA + SF + cement), the total replacement of mineral admixtures is 70%, the ratios of FA/SL and FA/SF are different in ECC mixture proportions. The toughness behavior and compressive strength of 12 different ECC mixtures are firstly measured by fourpoint bending test and compressive strength test, respectively.

The results indicate that the compressive strength has an inverse relationship with deflection, toughness index and fracture energy, respectively; but the compressive strength have an direct proportional relation with flexural strength, first cracking load, and peaking load, respectively.

Additionally, in the binary system of binder materials, the ductility of ECC can be obviously improved by introducing high volume fly ash and slag replacing the cement, respectively. However, the compressive strength of ECC with fly ash and slag can reduce 40% and 14%, respectively. For the ternary system of binder materials with replacement 70% of cement, the combination of fly ash and slag can keep not only the excellent ductility of ECC, but also enough stronger matrix strength. Meanwhile, the combination of fly ash and silica fume only increase the compressive strength, but weaken the toughness of ECC.

Tahir Kemal Erdem (2014) carried out experimental work to study size effect on the residual properties of ECC was investigated on the specimens exposed to high temperatures up to 800°C. Cylindrical specimens having different sizes were produced with a standard ECC mixture. Changes in pore structure, residual compressive strength and stress–strain curves due to high temperatures were determined after air cooling. Standard ECC mixture (M45) with a fly ash-cement ratio (FA/C) of 1.2 by mass was used in this investigation which was prepared in a standard mortar mixer at water to cementitious material ratio of 0.27.

Experimental results indicate that despite the increase of specimen size, no explosive spalling occurred in any of the specimens during the high temperature exposure. Increasing the specimen size and exposure temperature decreased the compressive strength and stiffness. Percent reduction in compressive strength and stiffness due to high temperature was similar for all specimen sizes.

Bensaid Boulekbache *et al*. (2012) carried out experimental study to examining the influence of the paste yield stress and compressive strength on the behavior of Fibre-Reinforced Concrete (FRC) versus direct shear. The parameters studied are the steel fibre contents, the aspect ratio of fibres and the concrete strength. Prismatic specimens of dimensions 10 * 10 * 35 cm made of concrete of various yield stress reinforced with steel fibres hooked at the ends with three fibre volume fractions (i.e., 0%, 0.5% and 1%) and two aspects ratio (65 and 80) were tested to direct shear. Three types of concretes with various compressive strength and yield stress were tested, an Ordinary Concrete (OC), a Self-Compacting Concrete (SCC) and a High Strength Concrete (HSC). The concrete strengths investigated include 30 MPa for OC, 60 MPa for SCC and 80 MPa for HSC.

The results show that the shear strength and ductility are affected and have been improved very significantly by the fibre contents, fibre aspect ratio and concrete strength. As the compressive strength and the volume fraction of fibres increase, the shear strength increases. The ductility was much higher for ordinary and self-compacting.

Soutsos *et al.* (2012) carried out experimental study on commercially available steel and synthetic fibres. Flexural stress – deflection relationships have been used to determine: flexural strength, flexural toughness, equivalent flexural strength, and equivalent flexural strength ratio.

The flexural toughness of concrete was found to increase considerably when steel and synthetic fibres were used. However, equal dosages of different fibres did not result in specimens with the same flexural toughness.

Pajak and Ponikiewski (2013) carried out experimental study to investigate the flexural behavior of self-compacting concrete reinforced with straight and hooked end steel fibres at levels of 0.5%, 1.0% and 1.5% and compare it to Normally Vibrated Concrete (NVC). The laboratory tests were determined according to RILEM TC 162-TDF recommendation.

The flexural behavior of SCC appeared to be comparable to NCV, where the increase of fibres volume ratio cause the increase in pre peak and postpeak parameters of SCC. Nevertheless, the type of steel fibres influences much this dependency. However, the SCC achieves the maximum crack mouth displacement for lower deflections than NVC.

Albert *et al.* (2014) carried out experimental study on Polyolefin fibre-reinforced concrete enhanced with steel-hooked fibres in low proportions. Four types of conventional fibrereinforced concrete with steel and polyolefin fibres were produced on the basis of the same self-compacting concrete also manufactured as reference. These concrete mixtures were manufactured separately with the same fibre contents being subsequently used for two more hybrid mixtures. Fracture properties, in addition to fresh and mechanical properties, were assessed.

The result revealed that it is possible to produce a hybrid fibre reinforced self-compacting concrete with a combination of hooked steel fibres and macro polyolefin fibres, preserving the high performance fresh properties within the most common self-compacting requirements. It should also be noted that the addition of Fibres did not noticeably change the compressive strength, indirect tensile strength or modulus of elasticity of the reference SCC for any of the amounts, types or combination of fibres used.

LITERATURE SUMMARY

- Compressive strength is directly related to the Flexural strength and inversely related to deflection but if the compressive strength is kept in limited ranges, the desirable value of related parameters can be obtained.
- Compressive strength decreases with the increase in the cementitious material i.e. fly ash, silica fume, LP etc.
- Incorporation SL into matrix can effectively increase compressive strength at all ages, especially at early age
- The water to cementitious material (w/c) ratio 0.27 gives the best result.
- Compared with the standard mixing sequence, by adjusting mixing sequence increases the tensile strain capacity and ultimate tensile strength of ECC and improves the fibre distribution.
- Increasing the specimen size and exposure temperature decreased the compressive strength and stiffness.
- In Hybrid fibres mixture the compressive strength decreases with decreasing flexural strength.
- The ductility in direct shear depends on the fibre orientation and is significantly improved when the fibres are perpendicular to the shear plane.
- The Polycarboxylate based superplasticizer mortar mixes give more workability and higher compressive strength at all ages compare with sulphonated melamine formaldehyde based SP.

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