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Effect of Plate Thickness on Crack Propagation Characteristics of Engineered Cementitious Composites

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ABSTRACT

Engineered Cementitious Composites (ECC) is a ductile fiber reinforced material developed in the 1990s suitable in repair and retrofit applications. However, its widespread use is currently limited by the elevated cost of the material. Optimization of overall dimensions of elements within specified crack width limits can be an effective cost cutting tool. Therefore, it was the objective of this study to investigate the effect of varying plate thickness on the crack propagation characteristics of ECC by monitoring the crack width and crack distribution on 10, 20 and 30 mm ECC plates. ECC plates were cast and water cured for 28 days at 20°C. Cracks were then generated using a bending machine, accentuated by fluorescent paint and imaged by a digital camera. Crack distribution was analyzed from the images using AutoCad software while crack widths were directly measured on the plates by a Crack-Viewer FCV-30. It was found that all ECC plates developed multiple fine surface cracks measuring 0.08 mm average width and no significant variation in the crack width or crack distribution with variation in thickness was observed. Therefore, the characteristic fine surface cracks of restricted widths produced by ECC are independent of thickness of the plates. Since, a 10 mm reduction in thickness of unit area of ECC results in a 33% reduction in volume of the material required, application of smaller thicknesses of ECC significantly reduces cost of material and increases its economic viability.

Key words: ECC, repair, retrofit, crack width, crack distribution

INTRODUCTION

Plain cement materials such as cement pastes, mortars and concretes are commonly used for construction. In spite of their ubiquity, these materials have several inherent deficiencies such as brittleness originating from their material structure (ACI 301-05, 2005; Neville, 1996) which diminish both early age performance and long-term durability. Modern concepts of fiber reinforcement and interface engineering emanated from efforts to address the deficiencies of these materials (Li *et al.*, 1995) producing High Performance Fiber Reinforced Cement Composites (HPFRCC) such as Engineered Cementitious Composites (ECC) in the 1990s (Li, 2003). ECC is a ductile fiber reinforced cement based composite material that has been found to be excellent at crack dispersion. Formed primarily from cement and sand with fiber and certain chemicals as additives, ECC is systematically engineered to achieve high ductility under tensile and shear load. It can achieve maximum ductility in excess of 3% under uniaxial loading with only 2% volume of fiber content (Li, 2005). Moreover, due to its strain hardening capacity, ECC develops fine cracks of less than 0.1 mm width which are limited to the surface in contrast to the through cracks developed by plain cement materials (Kunieda *et al.*, 2006).

Durability concerns of plain cement materials also exist in retrofit or repair works especially on the substrate/repair layer interface. In some cases, the drying shrinkage of the new material restrained by the old material leads to cracking and interface de-lamination introducing water and other deteriorative agents into the repaired system thereby invoking fresh deterioration and necessitating a new and certainly uneconomical repair cycle. However, it has been verified experimentally, that when an adequate bond is provided, the high ductility of ECC can relieve shrinkage induced stresses in the ECC repair layer and at the ECC/concrete interface, suppressing the development of large through cracks and interface de-lamination (Li and Li, 2006). Therefore, in retrofit and repair applications, based on properties only, ECC is a more suitable material than traditional plain cement materials. However, in practice the use of ECC is currently limited to less than 10 countries worldwide. This is mainly due to its elevated cost emanating from its requirement of special fibers, very high cement content and a high performance super-plasticizer (Patodi and Rathod, 2008). Certainly, cost and sustainability of ECC are two aspects that need to be addressed to make the use of ECC widely acceptable. While optimization of the composite to minimize the fiber content is critical to cost reduction, optimization of the overall dimensions of ECC elements can reduce the volume of material required thereby reducing the overall material cost.

In repair and retrofit applications, there is usually little flexibility regarding the length and width of the original structure but thickness tends to be adjustable depending on the structural requirements. Even though it is possible to apply ECC layers of thickness as low as 10 mm using the direct spraying method (Kanda *et al.*, 2002), the selection of the optimum thickness for a particular element depends on the structural requirements such as expected crack widths since design codes specify crack width limits based on functional use of the structure. For instance, the British Code BS 8007 of 1987 states that a maximum crack width of 0.2 mm is deemed adequate for water tightness in water retaining structures and a more stringent 0.1 mm is necessary where aesthetic appearance is of particular importance. Hence, it is imperative for a repair layer to meet this standard to be deemed adequate. Inevitably, variations in material content, dimensions and external loads in turn vary the size and distribution of cracks developed by any material. It is therefore, the objective of this study to elucidate the impact of variations in thickness, on the size and distribution of cracks propagated by ECC.

MATERIALS AND METHODS

Repair and retrofit structures are usually applied in layers or plate-like elements and hence in this study, plates were used as the target elements. ECC plates of varying thickness were cast and cracks artificially generated followed by the determination of crack width and crack density. The study was carried out at Tottori University, Japan from August 1st, 2008 to September 30th, 2009.

Materials: ECC premix powder was used in this experiment. The major components of the ECC premix powder were cement, sand and water soluble Poly-vinyl Alcohol (PVA) fiber of length 12 mm, diameter 0.04 mm, tensile strength 1690 Tottori and modulus of elasticity 40,600 MPa. The mix proportions of ECC are shown in Table 1. At a room temperature of 20°C, the premix ECC powder was added to an electric mixer. Water and 3 admixtures: Type A (super-plasticizer), Type B (anti-shrinkage agent) and Type C (expansive agent for air content adjustment) were mixed

Table 1: Mix proportion of ECC (1 m^3)

ECC pre-mix* (kg^{-1})	Water (20°C) (kg^{-1})	Admixture type A (kg^{-1})	Admixture type B (kg^{-1})	Admixture type C (kg^{-1})
1,562.50	350.00	16.88	15.25	3.13 (diluted 25 times)

*ECC premix composition: Sand/cement = 0.65, Fly ash/cement = 0.3 PVA, Fiber volume fraction = 2%

together and added to the premix powder. The mixer was covered and run for 2 min to avoid losses of the mix components. While the mixer was running, its cover was removed and mixing was continued until 10 min elapsed. The ECC paste was then transferred into a tray. The homogeneity of the mix was further corroborated by hand mixing.

Experimental procedure

Determination of crack distribution: ECC plates of dimensions 40×400 mm and thicknesses of 10, 20, 30 mm were cast and cured in water for 28 days at 20°C. The dimensions 400×400 mm were selected to fit the limits of the device used for generation of cracks. The upper dimension of 30 mm was selected since it is the common thickness used in ECC repair applications while the lower dimension of 10 mm coincides with the minimum ECC thickness that can be placed using the direct spraying technique. Three sets of ECC plates were prepared for each thickness, each set comprising 3 plates. Using the Third-Point Loading test configuration (ASTM, 2004) on a bending machine, the first set was loaded to ultimate failure to determine the average ultimate failure load for each thickness. Using 80% of the determined average ultimate failure load, cracks were generated on the second set. The third set was kept intact as the control. A 100 mm wide strip was marked on the central portion of the set of plates with cracks. A thin film of fluorescent paint was used to accentuate the cracks and in a dark room, each plate was illuminated under black light which caused the fluorescent paint-packed cracks to glow yellow. Using a digital camera, pictures were taken at 3 positions on the strip. Images from the camera were viewed using the computer-aided drafting software, AutoCAD 2002. The number of cracks along the 100 mm wide strip was then physically counted from the images and multiplied by 10 to obtain the average number of cracks per unit meter.

Determination of crack width: Crack widths were measured using a crack width-measuring device, the Crack Viewer FCV-30. The average crack width was determined by taking measurements on 3 cracks from each of the 10, 20 and 30 mm plates used for determination of crack distribution. Images and data of each crack were recorded as shown in Fig. 1.

RESULTS AND DISCUSSION

During mixing of the material, it was observed that the ECC fresh mix had very high workability which enabled easy placing. The behavior of the 10, 20 and 30 mm plates under load was similar to ductile material i.e., gradual bending into a visible curve in contrast to instant rupture of plain Cementitious materials. Moreover, multiple fine surface cracks were observed on the surface of the plates. As shown in Table 2, the average crack widths for the 10, 20 and 30 mm plates were 0.9, 0.8 and 0.8 mm, respectively while the average crack densities were 126, 115 and 135 cracks m^{-1}.

The crack widths and crack densities obtained in this research agree with data obtained by previous researchers. For instance, the multiple fine surface cracks observed on the ECC plates are typical and the values of crack widths of 0.8 to 0.9 mm agree with findings by Li *et al*. (1995) and

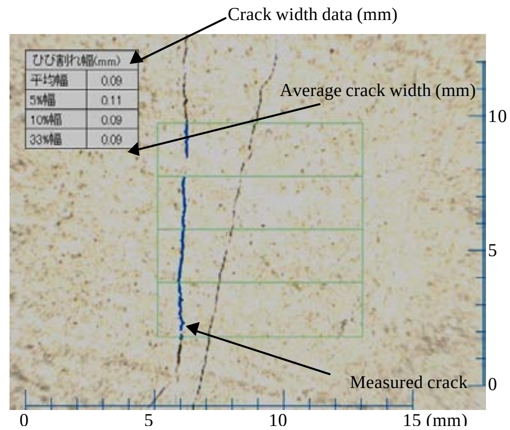

Fig. 1: Image and data from the crack viewer FCV-30

Kanda *et al.* (2002). The unique property of ECC relative to other fiber reinforced composites is its ductility and confinement of crack widths to less than 0.1 mm. The high workability of ECC is due to the moderate amount of short discontinuous fibers which allows flexibility in construction execution, including self consolidation casting (Kong *et al.*, 2003), a property that is very useful in repair and retrofit applications. The bending behavior in response to loading is typical ductile behavior characteristic of ECC (Li, 2003) enabling failure of ECC structures to be less catastrophic than plain cement structures which are brittle.

The matrix of fibres evenly distributed within ECC slide within the cement forming matrix cracks when loaded whose density increase until composite peak load resulting in the bending of ECC under excessive strain. From Table 2, there was no significant variation in crack patterns, crack density and crack width for the 10, 20 and 30 mm thicknesses. Ultimate failure of all the plates was gradual and was preceded by bending in typical ductile behavior. The multiple micro cracking observed at the crack generation load (80% of ultimate failure load) is due to the characteristic strain hardening after the first cracking of the ECC. The fibers which are evenly, distributed within the material bridge the cracks thereby restricting the crack width. This tight crack width by ECC is self-controlled and a material characteristic independent of rebar reinforcement ratio (Li, 2005) or plate thickness. The restriction of crack width to an average size of 0.8 mm obtained in this study is important in water storage facilities applications where a maximum, crack width of 0.2 and 0.1 mm are deemed necessary for water tightness and aesthetic appearance respectively. Since the reduction in thickness of the plates does not significantly affect crack width or crack density, ECC layers of small thickness can be applied in repair and retrofit works where minimal distortion of the dimensions and aesthetic appearance of the original structure is crucial.

So far, researchers have focused on the crack dispersion properties and structural aspects of ECC and there is very little focus on the issue of cost reduction which to date has limited the use of an otherwise excellent repair material. While previous researchers (Kunieda *et al.*, 2006; Swift *et al.*, 2000) have elucidated the effectiveness of ECC as a repair material, the optimization of the dimensions of ECC elements as a cost reduction measure has not been investigated. While technically it is possible to apply 10 mm thick ECC layers, in practice most applications are 30 mm thick. This research investigated the reduction in thickness of ECC repair layer as a material

Table 2: Average crack density and crack width

Thickness (mm)	Average density (cracks m^{-1})	Average crack width (mm)
10	125	0.07
20	115	0.08
30	135	0.08

volume reduction and consequent cost cutting measure and proved that it is possible to decrease the thickness of an ECC repair layer and still obtain its unique and desirable properties of ductility and multiple surface fine cracks of widths less than 0.1 mm. In terms of volume of material, a 10 mm reduction in thickness results in a 33% reduction of volume per unit area which is significant in the reduction of cost of material. This is important in addressing the current limitation in the use of ECC due to the high cost of the material.

CONCLUSION

From the study the following conclusion are made:

- The thickness of plates has no significant effect on the crack width and crack distribution on ECC. This enables smaller thicknesses of ECC elements to be applied where structurally possible, thereby reducing the material volume and subsequently lowering overall material costs
- ECC can restrict crack widths to less than 0.1 mm despite reduction in thickness from 30 to 10 mm making ECC suitable for use in water storage facilities
- The ability of ECC to maintain small widths despite reduction in thickness is important for repair and retrofit applications where adherence to the structural integrity and minimal distortion to aesthetic appearances of the original structure are crucial
- Reduction in thickness of ECC results is significant reduction in the volume and material cost which addresses the issue of the high cost currently associated with the material. Moreover, the ductility and production of fine surface cracks as opposed to the brittleness and production of through cracks by plain cementitious material makes ECC a more durable repair or retrofit material since it curtails the cycle of repairs imminent with the use of other plain cement materials thereby also increasing economic viability

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