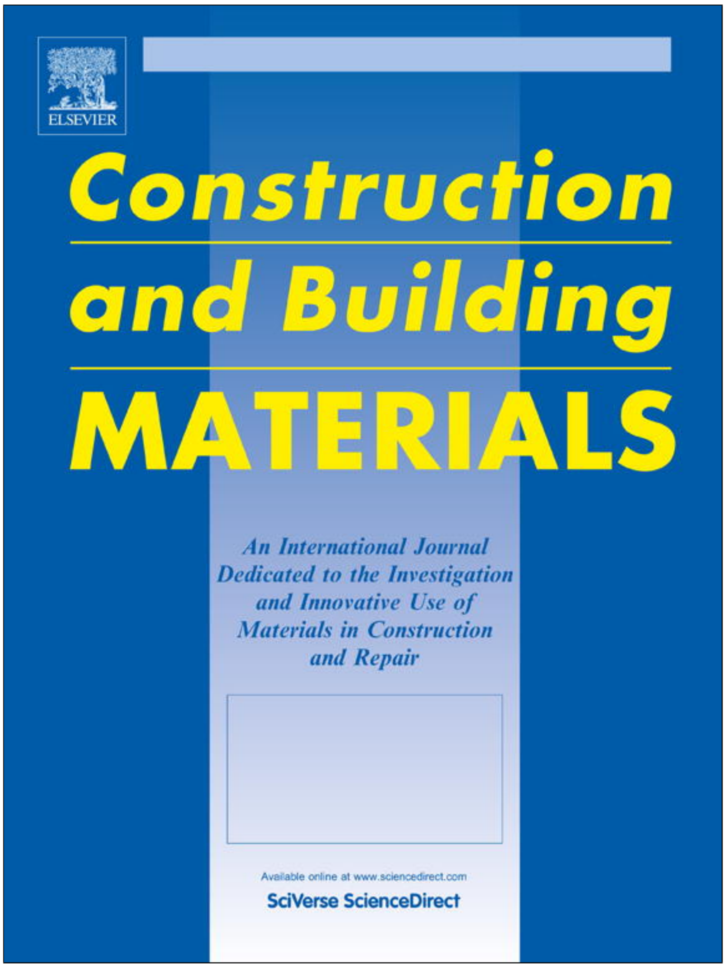
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On the use of recycled tire rubber to develop low E-modulus ECC for durable concrete repairs

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HIGHLIGHTS

- Tire rubber was used as aggregate to prepare low modulus ECC repair material.
- Using tire rubber in ECC reduces cracking tendency due to restrained shrinkage.
- The use of tire rubber in ECC mixtures improves the material tensile ductility.
- High tire rubber content tends to reduce the crack width in ECC material.

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ABSTRACT

The durability of concrete repairs is often limited due to restrained drying shrinkage. In this study, recycled tire rubber is used to develop deliberately low elastic modulus and highly ductile ECC repair material so as to alleviate repair failure induced by restrained drying shrinkage. Emphasis of this study is placed on the influence of tire rubber on the mechanical properties and cracking tendency of ECC repair material. It is revealed that the addition of tire rubber in ECC mixtures dramatically improves the tensile ductility but lowers the compressive strength, tensile strength, and elastic modulus. In spite of the increase in free drying shrinkage deformation, the reduction in elastic modulus of ECC containing tire rubber is demonstrated to be effective in reducing the cracking tendency of ECC repairs, which suggests that an improved durability of concrete repairs can be achieved by ECC material containing recycled tire rubber.

1. Introduction

It has been estimated that almost half of all concrete repairs fail prematurely and about three-fourths of the failures are attributed to lack of durability of concrete repairs [1]. One of the major reasons associated with the poor durability of concrete repairs is non-uniform volume change under restrained drying shrinkage [1]. The drying shrinkage deformation under restraint causes tensile stress development within the repair material and tensile and shear stresses at the interface between the repair material and concrete substrate. If the repair material is brittle, material cracking and interface delamination may occur, which allows easy penetration of aggressive chemicals eventually resulting in concrete disintegration, spalling, and loss of structural integrity. Therefore, alleviating the tensile failure of repair material and preventing delamination at the repair/substrate interface due to restrained drying shrinkage are of vital importance in improving the durability of concrete repairs.

The concept of elevating the durability of concrete repairs by replacing a brittle repair material with highly ductile Engineered cementitious composites (ECC) that can suppress fracture failures caused by restrained drying shrinkage was introduced by Li [2]. Such concept has been numerically and experimentally verified in ECC repairs subjected to drying shrinkage [3–5]. The benefit of ECC repairs for the durability of repaired systems is attributed to the high tensile ductility of ECC in the form of inelastic strain capacity and multiple micro-cracking. To illustrate the influence of inelastic strain capacity on the shrinkage deformation behavior of repair material, Li and Henrik [7] considered a 2-D slab under restraint at its ends and defined a restrained shrinkage cracking potential parameter P as

$$P = \varepsilon_{sh} - (\varepsilon_e + \varepsilon_i + \varepsilon_{cp}) \qquad (1)$$

where ε_{sh} is the free shrinkage strain of the repair material, ε_e is its elastic tensile strain capacity, ε_i is its inelastic tensile strain capacity, and ε_{cp} is its tensile creep strain. ε_{sh} is the maximum strain

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Table 1
Typical properties of normal concrete and ECC [7].

Properties	ε_{sh} (%)	ε_e (%)	ε_i (%)	ε_{cp} (%)	P
Concrete	0.04–0.1	0.01	0	0.02–0.06	(−0.03) to 0.07
ECC	0.1–0.15	0.015	2–5	0.07	(−4.99) to (−1.94)

demand due to shrinkage, while $\varepsilon_e + \varepsilon_i + \varepsilon_{cp}$ is the total material strain capacity. If strain demand exceeds strain capacity, fracture failure occurs in the repair material.

Table 1 lists the typical properties of normal concrete and ECC. The cracking potential P for normal concrete is in a narrow range around zero. Under service loads, the imposed deformations show more variations than this narrow range causing brittle fracture as soon as the cracking potential becomes positive (greater than zero). In comparison, ECC has a highly negative cracking potential P, a direct result of its large inelastic strain capacity, allowing shrinkage deformation to be fully accommodated into the multiple microcracks maintaining the integrity of the repair layer.

In addition to material ductility, a low elastic modulus in the repair material is also desirable for durable concrete repairs, as it lowers the tensile stress build up due to shrinkage restrained by existing concrete. This reduces the cracking tendency in the repair material and lowers the magnitude of delamination at the repair/substrate interface. A cracking resistance parameter R is introduced to illustrate the influence of elastic modulus on cracking resistance ability of ECC repairs under restrained drying shrinkage. Cracking resistance R is defined as the ratio of first cracking strength to shrinkage stress assuming full restraint at 28 days,

$$R = \sigma_f / \sigma_{sh} \tag{2}$$

where shrinkage stress σ_{sh} is the elastic modulus $^*\varepsilon_{sh}$, and σ_f is the first cracking strength. Therefore, a high first cracking strength, low elastic modulus, and low free shrinkage strain are desirable properties for high cracking resistance.

A repair material with high cracking resistance R would delay first cracking. A repair material with a large negative cracking potential P would delay final fracture failure. Clearly a material with both high R and large negative P would be most desirable for durable concrete repair.

In this paper, recycled tire rubber was used to partially replace rigid aggregate in ECC mixture for reducing the elastic modulus of ECC so as to reduce the stresses developed due to restrained drying shrinkage. The effects of tire rubber on the tensile properties, elastic modulus, free drying shrinkage, and compressive strength of ECC mixtures were investigated. Cracking resistance R and cracking potential P (defined above) were used as durability indicators to theoretically assess the effect of tire rubber on the cracking tendency of ECC repairs under restrained drying shrinkage. Restrained shrinkage ring tests of ECC mixtures with and without tire rubber were used to evaluate the influence of tire rubber on the cracking behavior of ECC repairs. The experimental results were used to validate the theoretical concepts behind the two repair durability indicators.

2. Experimental procedures

2.1. Materials and mix proportion

The ECC mixtures investigated in this study consist of Type I Portland cement (PC) and Class F fly ash (FA) as cementitious materials, iron ore tailings (IOTs) as very fine aggregates, recycled tire rubber as fillers, Poly-Vinyl Alcohol (PVA) fibers, water, and a polycarboxylate-based high range water reducing admixture (HRWRA). Chemical composition and physical properties of fly ash are given in Table 2. IOTs have an average size of 135 μm and nominal maximum size of 300 μm. The detailed investigation on the use of these IOTs in the production of ECC can be found in Huang et al. [8]. PVA fibers with a surface oil coating of 1.2% by weight have a diameter of 39 μm and a length of 8 mm. The nominal tensile strength, elastic modulus and maximum elongation (at break) of PVA fibers are 1620 MPa, 42.8 GPa, and 6%, respectively.

Table 2
Chemical and physical properties of fly ash (%).

CaO	14.04
SiO_2	44.09
Al_2O_3	23.21
Fe_2O_3	8.39
SO_3	1.46
Moisture	0.05
Loss on Ignition	0.56
Available Alkalis, as Na_2O	0.99
Retained on 45 microns, %	16.85
Water Requirement, %	97
Specific gravity	2.45

The tire rubber used in this study is a post-consumer recycled material produced by grinding tires at their end-of-life. The particle size distribution of tire rubber is given in Fig. 1. Micronized tire rubber (henceforth, referred as tire rubber) is used in the ECC mixtures of this study, instead of crushed tire rubber with diameter of the order of a few millimeter that are typically used as fine or coarse aggregate in concrete production. The fine size of the tire rubber ensures homogenous dispersion of PVA fibers and also limits the fracture toughness of the matrix. Both these factors are essential for achieving tensile ductility in ECC [9,10]. The density of tire rubber is 1.14 kg/m^3, as provided by the manufacturer. The elastic modulus of tire rubber ranges from 1.2 MPa to 5.2 MPa [11].

To investigate the effect of tire rubber on the mechanical and physical properties of ECC, five different mixtures were prepared. In these mixtures, cement, FA, and water content were kept constant (Table 3). PVA fiber volume fraction was fixed at 2% for all mixtures. For the control mixture (R0), IOTs were used as aggregates with aggregate to cementitious material ratio of 0.36 by weight. Four different ECC mixtures (R10–R40) were prepared by replacing 10%, 20%, 30%, and 40% volume of IOTs in the control mixture with the same volume of tire rubber. The HRWRA content was adjusted to maintain the viscosity of all matrix mixtures at a constant level (30 ± 5 s) flow time in marsh cone flow test for maintaining the degree of homogeneity of fiber dispersion [12].

2.2. Specimen preparation and testing

The mixtures were prepared following a typical ECC mixing procedure [13]. For each mixture, three cube specimens measuring 50 × 50 × 50 mm^3 were prepared for compression tests, and three dogbone specimens were prepared for tension tests. The geometry of a dogbone specimen used in this study can be found in Ranade et al. [14]. In addition, four notched beam specimens measuring 305 × 76 × 38 mm^3 for each mixture were cast without adding fiber to determine the influence of tire rubber on the matrix fracture toughness. All specimens were demolded after 24 h of casting and then cured in a plastic bag for 27 days at a room temperature of about 23 ± 3 °C before testing.

Uniaxial tensile tests on dogbone specimens were performed to characterize the tensile behavior of the ECC mixtures described above. Tests were conducted under displacement control with a loading rate of 0.5 mm/min as recommended by the

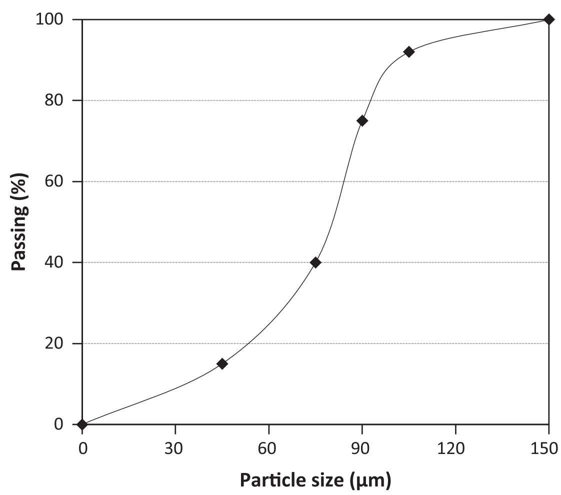

Fig. 1. Particle size distribution of tire rubber.

Table 3
Mixture proportions of ECC (kg/m^3).

Mix ID	Replacement ratio (vol.%)	Tire rubber	IOTs	Cement	FA	Water	PVA	HRWRA
R0	0	0	444.1	471.6	754.5	331.0	26	10.8
R10	10	19.7	397.2	471.6	754.5	331.0	26	13.5
R20	20	39.3	353.1	471.6	754.5	331.0	26	15.5
R30	30	59.0	309.0	471.6	754.5	331.0	26	18.1
R40	40	78.6	264.8	471.6	754.5	331.0	26	19.8

Japan Society of Civil Engineers (JSCE) for direct tension testing of High Performance Fiber Reinforced Cementitious Composite [15]. Two LVDTs were attached on each dogbone specimen with gauge length of approximately 100 mm to measure the tensile extension. During the tensile testing, multiple cracks through the thickness of the specimen accompanied the strain-hardening deformation process.

After the uniaxial tension tests, residual crack widths on the surface of dogbone specimens were measured using an optical microscope, following the method recommended by JSCE [15]. For each dogbone specimen, one central line parallel to the loading direction was drawn on the specimen surface. Using an optical microscope with 1 micron resolution, the widths of cracks crossing the central line within the dogbone specimen's gauge length were measured. The average residual crack width for each ECC mixture was then calculated by averaging the measured crack widths in three dogbone specimens.

The matrix fracture toughness was measured in accordance with ASTM E399 [16] using a three-point bending test setup. The span length of bottom support for the beam was 254 mm and the notch depth (at the longitudinal center of the beam) to beam height ratio was 0.4. Although ASTM E399 is a standard for testing the fracture toughness of metals, it is considered valid for determination of fracture toughness of brittle materials such the ECC matrices which show small scale yielding and, therefore, the assumptions of Linear Elastic Fracture Mechanics are valid [17].

Free drying shrinkage measurements were conducted on $250 \times 25 \times 25$ mm^3 bar specimens in accordance with ASTM C596. Three specimens were prepared for each mixture. All specimens were demolded after 24 h of casting and then cured in lime-saturated water for 48 h. Subsequently, the specimens were removed from water and stored in air at room temperature of 23 ± 3 °C and relative humidity of 25 ± 5%. Drying shrinkage deformation of bar specimens was then measured as a function of drying time.

Restrained ring test [18] was used to evaluate the restrained shrinkage cracking behavior of ECC mixtures. A 25.4 mm thick layer of ECC mixture was casted around a rigid steel ring with a height of 152.4 mm and inner and outer diameters of 279.4 mm and 304.8 mm, respectively. A detailed description of the restrained ring test setup can be found in Li [19]. The ring specimens were cured in the mold for 24 h and then stored in air at 23 ± 3 °C and 25 ± 5% RH after removing the outer mold. The crack initiation time, crack number, crack length, and crack width were recorded as a function of exposure time by using a portable microscope.

To observe the influence of tire rubber on the microstructure of ECC, specimen cross-sections of ECC with and without tire rubber were observed using Environmental Scanning Electron Microscopy (ESEM) equipped with X-ray Energy Dispersive Spectroscopy (XEDS).

3. Results and discussion

3.1. Tensile behavior

The uniaxial tensile test results in terms of first cracking strength, tensile strength, tensile strain capacity, and average residual crack width are summarized in Table 4. All the ECC mixtures were tested using three dogbone specimens at the age of 28 days. The representative (one out of three specimens) 28-day tensile stress–strain curves of ECC mixtures with different tire rubber content are presented in Fig. 2. It can be seen that all ECC mixtures exhibit strain hardening behavior under direct tension load. The tensile ductility of ECC mixtures increases with increase in tire rubber content. ECC mixtures with tire rubber exhibit tensile strain capacity of 2–3% at the age of 28 days (Table 4). This suggests that the incorporation of tire rubber is beneficial to the performance of ECC in terms of tensile ductility.

Fig. 3 shows the influence of tire rubber on the tensile first cracking and ultimate strength of ECC mixtures at 28 days. The first cracking strength significantly reduces in ECC mixtures with tire rubber, compared to the control mixture with no tire rubber (R0). This reduction in first cracking strength can be explained by the decrease of matrix fracture toughness as shown in Fig. 4. The incorporation of tire rubber leads to a substantial reduction in fracture toughness of about 50% in mixtures R1-4 compared to R0. Two possible mechanisms may cause the observeddecrease in matrix

Table 4
Tensile properties of ECC at 28 days.

Tire rubber replacement level (vol.%)	0	10	20	30	40
First cracking strength (MPa)	4.1 ± 0.2	3.2 ± 0.3	2.9 ± 0.2	2.9 ± 0.1	2.7 ± 0.2
Tensile strength (MPa)	4.9 ± 0.2	3.5 ± 0.1	3.4 ± 0.1	3.2 ± 0.4	3.1 ± 0.3
Tensile strain (%)	1.8 ± 0.1	2.0 ± 0.3	2.1 ± 0.4	2.6 ± 0.2	3.0 ± 0.1
Average residual crack width (μm)	~48	~27	~16	~5	~5

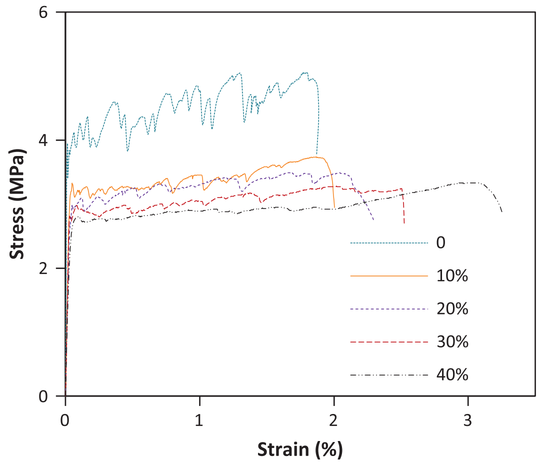

Fig. 2. 28 days tensile stress–strain curves of ECC with varying amounts of tire rubber.

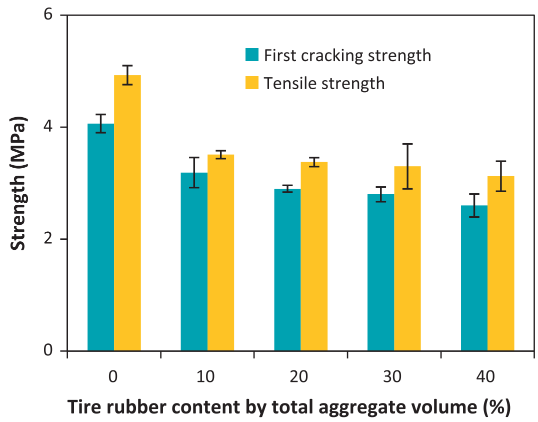

Fig. 3. Tensile first cracking and ultimate strength of ECC at 28 days.

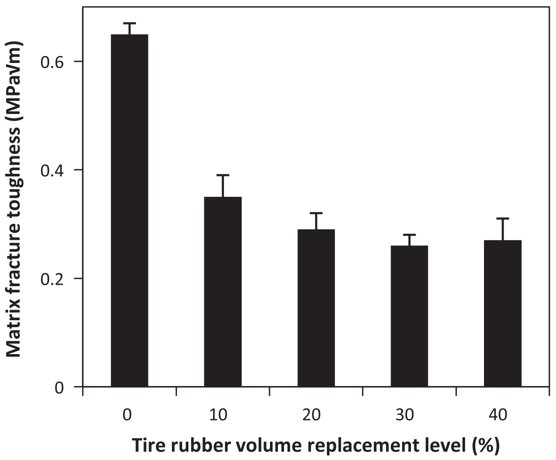

Fig. 4. Matrix fracture toughness of ECC at 28 days.

fracture toughness. First, the increasing porosity of ECC with tire rubber content weakens the matrix. As observed in Fig. 5a and b, the ECC mixture with tire rubber (R40) has a more porous structure than ECC with no tire rubber (R0). The dark circles represent pores in Fig. 5a and b. Second, the weak interfacial bond between tire rubber particles and surrounding cement paste allows a crack to easily develop around the tire rubber particles [20]. The fracture surface of dogbone specimen of mixture R40 after the uniaxial tension test was observed under ESEM (Fig. 5c). The tire rubber particle is identified in Fig. 5c through XEDS analysis (Fig. 5d). As shown in Fig. 5c with white dashed line, crack passes at the interface between tire rubber and cement paste. Additionally, only a few cement hydration products are observed on the surface of the tire rubber particle, indicating a poor bond at the tire rubber/cement paste interface which is consistent with previous studies [21,22]. In addition to first cracking strengths, the ultimate tensile strengths of ECC mixtures with tire rubber also show a downward trend (Fig. 3), which indicates a decrease in fiber bridging capacity [9] with increasing tire rubber content. This is likely due to the increase in porosity of the matrix that leads to reduced interfacial bond between fibers and matrix. Thus, the incorporation of tire rubber significantly reduces both first cracking strength and ultimate tensile strength of ECC.

The crack width is an important property for concrete repairs, as the magnitude of crack width determines the transport properties in cracked concrete and influences durability. Fig. 6 shows the crack pattern on the surface of tested ECC dogbone specimens of various mixtures after unloading. The unloaded crack width is approximately 30% of the crack width under load. As seen in Fig. 6 and Table 4, residual crack width decreases as the tire rubber content increases. The average residual crack width of ECC mixtures reduces from about 48 μm to 5 μm as the tire rubber volume replacement level increases from 0% to 40% (Table 4). It has been reported in the literature that water permeability of ECC scales with the third power of crack width [23] and chloride ion permeability scales exponentially with crack width [24]. Such small crack width in ECC containing tire rubber suggests that ECC with tire rubber will likely have lower permeability under cracked condition

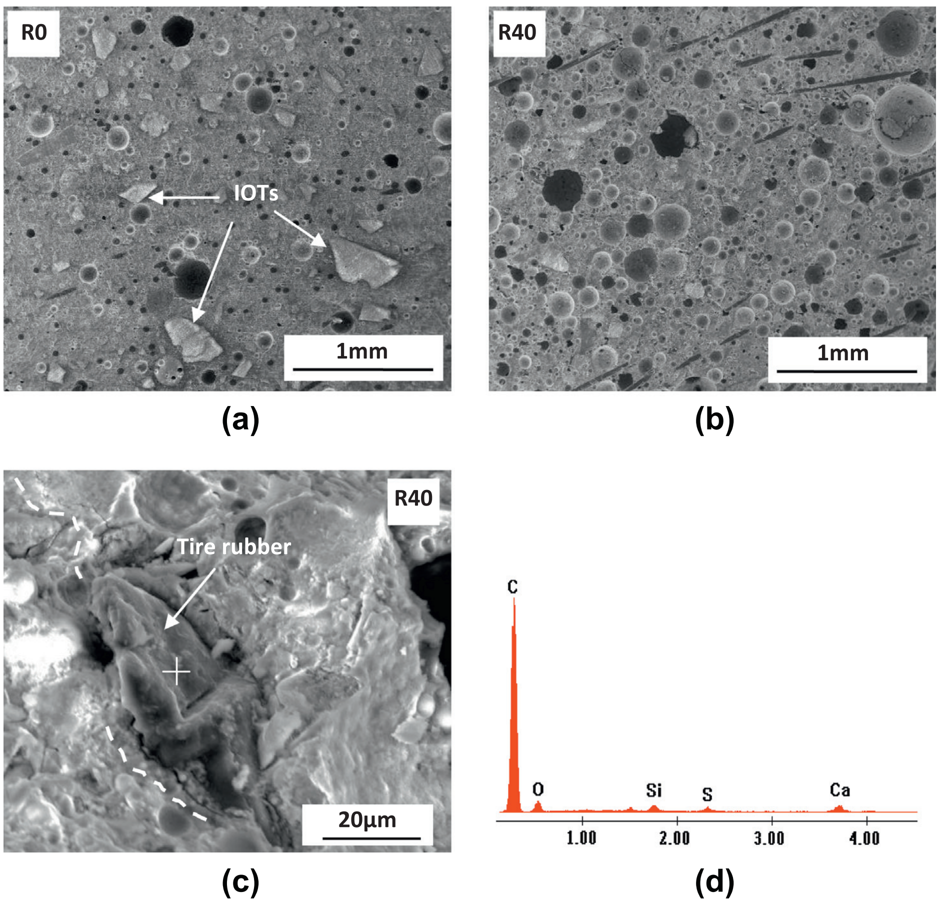

Fig. 5. ESEM images of ECC mixtures R0 and R40: ((a and b) polished composite samples of mixture R0 and R40, (c) fractured surface of R40 specimen after test, and (d) chemical composition of the particle under the cross cursor in (c)).

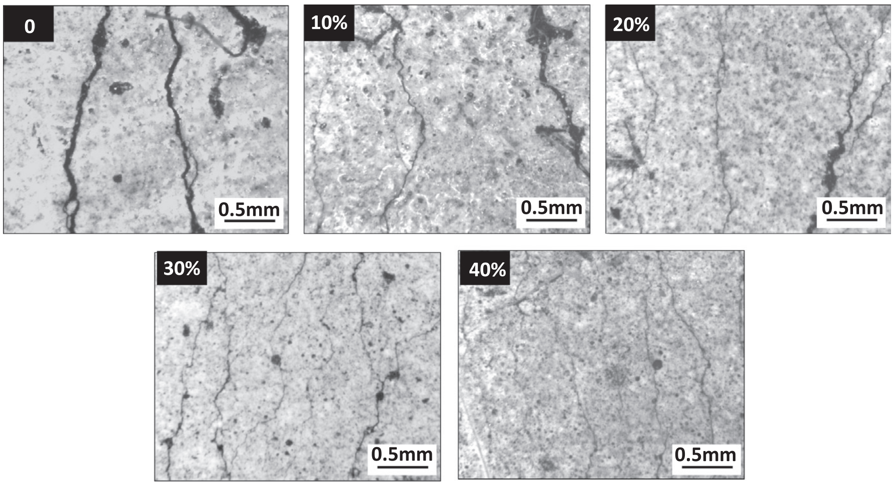

Fig. 6. Crack pattern of ECC mixtures with different tire rubber content (resolution = 1 μm).

than the control ECC mixture. In addition, crack width smaller than 50 μm, preferably below 10 μm was found to facilitate self-healing behavior in cracked ECC [25], which can further improve the transport properties and corresponding service life of ECC repairs.

3.2. Compressive strength

The average compressive strength test results of ECC mixtures at 28 days are shown in Fig. 7. As observed in Fig. 7, the incorporation of tire rubber in ECC mixture resulted in a significant decrease in compressive strength. The compressive strength of ECC mixtures decreased by about 63% (from 58 MPa to 22 MPa) when 10% volume of IOTs were replaced by tire rubber, while the decrease in compressive strength was only marginal with further increase in tire rubber replacement level from 10% to 40%. The compressive strengths of ECC mixtures containing tire rubber of 10–40% by total aggregate volume range from 15 to 22 MPa. Although the relatively low compressive strengths of ECC mixtures with tire rubber limits their applications in structural repairs such as beams and columns, these compressive strengths are considered adequate for non-structural repairs related to enhancing durability. ACI Committee 364 on rehabilitation states that there is no benefit of having repair materials with compressive strengths in excess of 4000 psi (28 MPa) [26]. In fact, high-strength concrete repairs are typically more brittle and, therefore, more prone to cracking than normal strength concrete. Furthermore, high tensile stresses are developed from restrained shrinkage and low stress relaxation due to typically high modulus and low creep of high-strength concretes [26]. Therefore, ECC containing tire rubber is expected to be particularly suitable for repairing non-structural concrete, such as catch basins, maintenance holes, valve chambers, pipe support, road base, sidewalk, curb, gutter, and similar applications [27].

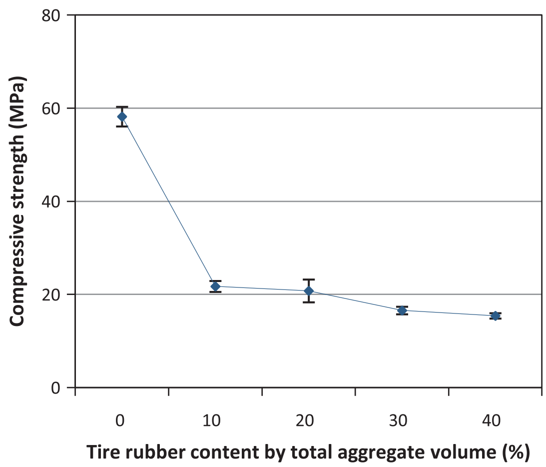

Fig. 7. Effect of tire rubber content on the compressive strength of ECC mixtures at 28 days.

The strength reduction of ECC mixture containing tire rubber can be partly attributed to the increase in porosity of ECC mixtures containing tire rubber. The porosity of ECC mixture was indirectly evaluated by the ratio of equilibrium density (ED) to computed density (CD) without considering water loss. Equilibrium density refers to the air dry density of ECC specimens after reaching a state of moisture equilibrium in the laboratory environment of 23 ± 3 °C and 25 ± 5% RH. Three cube specimens for each mixture was used for density measurements. Computed density refers to the density calculated according to mixture proportion. The equilibrium density and computed density of ECC mixtures together with ED/CD ratio are summarized in Table 5. It is an expected observation that the computed density of ECC mixtures decreases with increase in tire rubber replacement (by volume) as the specific gravity of tire rubber (1.14) is lower than that of IOTs aggregate (2.56). However, a more remarkable observation is the substantial decrease of ED/CD ratio with the incorporation of tire rubber in ECC mixtures, which points towards significantly higher porosity of ECC mixtures with tire rubber than that of ECC control mixture. The decreasing trend of ED/CD ratio (increasing trend of porosity) appears to correspond to that of compressive strength, suggesting a strong correlation between high porosity and low compressive strengths of ECC mixtures with tire rubber.

The strength reduction of ECC mixtures with tire rubber may also be partly related to the mechanical flexibility and non-polar nature of tire rubber. The elastic modulus for tire rubber ranges from 1.2 MPa to 5.2 MPa [11], which is far less than that of cement paste [28]. Due to the elastic incompatibility (stiffness contrast) between tire rubber particles and cement paste under applied

Table 5
Density of ECC mixtures (kg/m^3).

Mix ID	R0	R10	R20	R30	R40
Computed density (CD)	2035.3	2013.5	1990.9	1969.1	1946.3
Equilibrium density (ED)	1974.3	1368.3	1330.2	1317.4	1252.6
ED/CD	0.97	0.68	0.67	0.67	0.64

loading, stress concentrations may occur around the soft tire rubber particles [29]. By observing the fracture surface of ECC with tire rubber after compression test, similar scenarios of crack propagating along the tire rubber particles as shown in Fig. 5c were observed under ESEM. In addition, the non-polar nature of tire rubber makes its interface with the cement paste weaker as discussed in Section 3.1. Both these factors may cause crack initiation and propagation at low applied loads, causing a reduction in compressive strength.

3.3. Elastic modulus

The elastic modulus of various ECC mixtures was determined by the slopes of the elastic portion of the uniaxial tensile stress–strain curves. The representative pre-peak portions of the uniaxial stress–strain curves of ECCs are shown in Fig. 8, which clearly shows that the elastic modulus (slope) decreases with increase in tire rubber replacement level. The average elastic modulus test results of ECC mixtures at 28 days are shown with the solid line in Fig. 9. Elastic modulus of ECC containing tire rubber ranges from 7 to 11 GPa; in comparison, elastic modulus of the control mixture is 23 GPa. The replacement of 10% volume of IOTs aggregate with tire rubber leads to over 50% reduction in elastic modulus, while further increasing the amount of tire rubber in ECC mixtures results in a less significant reduction. The reduction in elastic modulus can be partly attributed to the incorporation of flexible tire rubber with significantly lower elastic modulus compared to IOTs aggregate. However, the increase in porosity with increasing tire rubber content may have a more dominant role in the reduction of elastic modulus, similar to its effect on compressive strength as explained above.

The tensile elastic modulus of ECC mixtures was also numerically estimated using the following empirical relation (Eq. (3)) in ACI 318 building code [30]. This formula relates the compressive elastic modulus of concrete with the compressive strength and density and is applicable for concretes with densities in the range of 1440–2560 kg/m^3. The density of ECC mixtures in this study ranges from 1253 to 1974 kg/m^3, which is close to the specified density range. Assuming that the tensile and compressive elastic modulus of ECC are almost equal, the tensile elastic modulus values were calculated using the empirical relation and are shown with the dashed line in Fig.9. It can be seen that the calculated values of elastic modulus are in good agreement with the test results. This supports the reliability of test results and verifies the strong dependence of elastic modulus of these ECC mixtures on compressive strength and density, similar to other concretes.

$$EM = 0.043d^{1.5}f^{0.5} \tag{3}$$

EM is the elastic modulus (MPa), d is density (kg/m^3), and f is compressive strength (MPa) at 28 days.

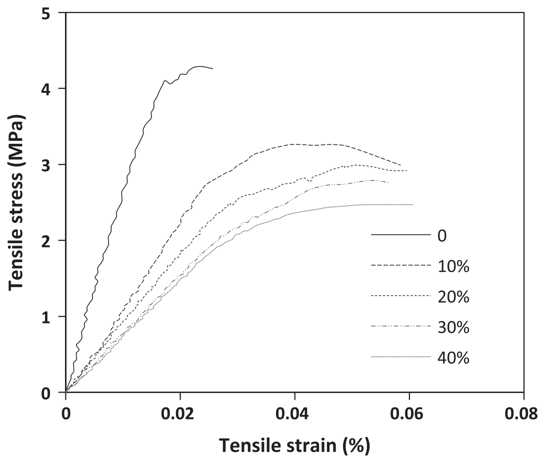

Fig. 8. The representative pre-peak portion of tensile stress–strain curves of ECCs at 28 days.

3.4. Free drying shrinkage

The results of free drying shrinkage tests of ECC mixtures are shown in Fig. 10. Each data point in Fig.10 represents an average measurement of three specimens. As expected, free drying shrinkage of ECCs increases with the increase in the replacement of IOTs by tire rubber. At 28 days, the drying shrinkage of ECC steadily increases from 1000 με to over 1500 με as the replacement of IOTs with tire rubber increases from 0% to 40%. The increase in drying shrinkage with increasing tire rubber content can be attributed to the reduction in the amount of rigid IOTs particles, which act as internal restraints to shrinkage deformation. Moreover, the increase in porosity may also contribute to the higher shrinkage of ECC with tire rubber particles. Nonetheless, the free shrinkage strain of ECC with tire rubber is still one order of magnitude lower than the tensile strain capacity of ECC, suggesting that ECC with tire rubber can accommodate the shrinkage deformation without localized fracture failure.

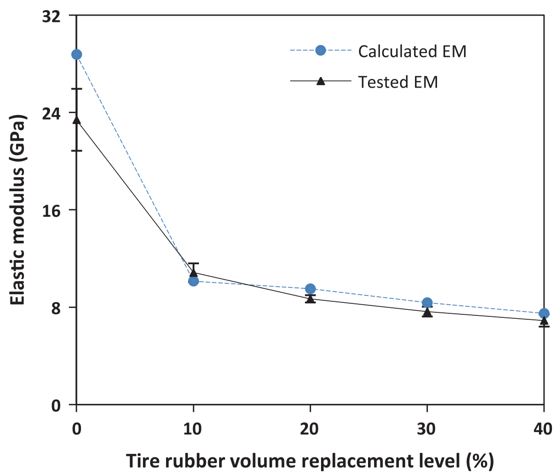

Fig. 9. Elastic modulus of ECC at 28 days.

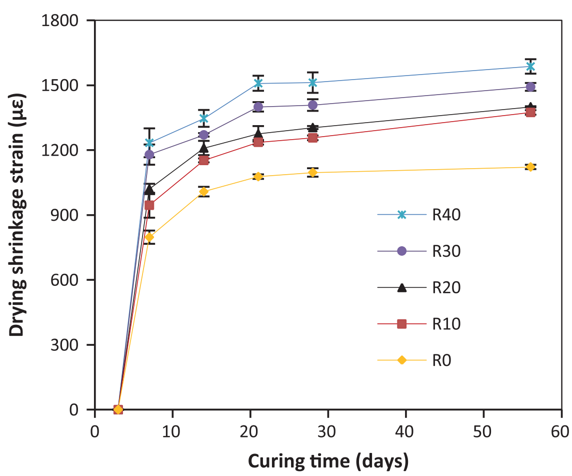

Fig. 10. Free drying shrinkage of ECC as a function of time.

3.5. Cracking resistance

Normalized cracking resistances R of ECC mixtures as a function of tire rubber content at 28 days are shown in Fig. 11. The cracking resistances (computed using Eq. (2)) of all ECC mixtures are normalized by the cracking resistance of the control mixture R0. ECC mixtures containing tire rubber exhibit higher cracking resistance than the control mixture, implying that ECC with tire rubber has a lower cracking tendency under restrained drying shrinkage. In the previous section, it is noted that the incorporation of tire rubber reduces first cracking strength and increases drying shrinkage strain of ECC. Both these factors lower the R value (Eq. (2)). In spite of this, ECC with tire rubber still shows improvement in normalized cracking resistance, which is attributed to the substantial reduction in elastic modulus with increasing tire rubber content, at least up to 30% IOT replacement by tire rubber. Therefore, the effectiveness of improving cracking resistance of ECC under restrained drying shrinkage by incorporating tire rubber is demonstrated.

3.6. Cracking potential

The cracking potential parameter P for all ECC mixtures are calculated and summarized in Table 6. The creep strain, ε_{cp}, is adopted from previous research [31] and conservatively assumed the same for all ECC mixtures. It can be seen from Table 6, the P value decreases with increase in tire rubber replacement level, which is largely due to the increase in tensile strain capacity. All ECC mixtures exhibit highly negative P value, implying a large margin for suppressing fracture failure due to restrained drying shrinkage.

3.7. Restrained ring test

For comparison, restrained ring tests of the control mixture R0 with no tire rubber and mixture R40 with maximum tire rubber content were conducted. Crack width, crack length, and crack number of ring specimens were measured at 7, 14, 21, 30, 45, and 60 days after casting. The test results of average crack width, average crack length, and crack number at different ages are summarized in Table 7. As seen in Table 7, the average crack width of R40 is slightly lowered than those of R0 at all ages. However, both mixtures show crack widths well below 100 μm, which is typical for ECC material [13]. The measured crack width from the restrained ring specimen is larger than the residual crack width reported in Table 4 since the cracks in the ring specimens are in a loaded state. For concrete with crack width less than 100 μm, the water permeability coefficient [6] and chloride diffusion [32] were found to be nearly the same as that of uncracked concrete. From this perspective, the crack formation of ECC with or without tire rubber due to restrained drying shrinkage is expected to have little influence on the transport property and durability of concrete repairs.

The incorporation of tire rubber exhibits benefits in delaying crack initiation time and reducing crack formation (Table 7). For the control mixture R0, cracks initiated between 7 and 14 days, whereas for R40, cracks initiated between 21 and 30 days. Additionally, lesser number of cracks were observed on the ring surface of mixture R40 than that of R0 at all ages. These results can be attributed to the fact that mixture R40 has higher crack resistance R than mixture R0 as previously discussed. In both cases, the cracking potential is negative, so that no fracture failure (with tension-softening) occurs in these restrained ring specimens. The restrained ring tests clearly demonstrate the reduction in cracking tendency of ECC with tire rubber as partial replacements for aggregates, which suggests potential advantages in improving durability of concrete repairs under restrained drying shrinkage.

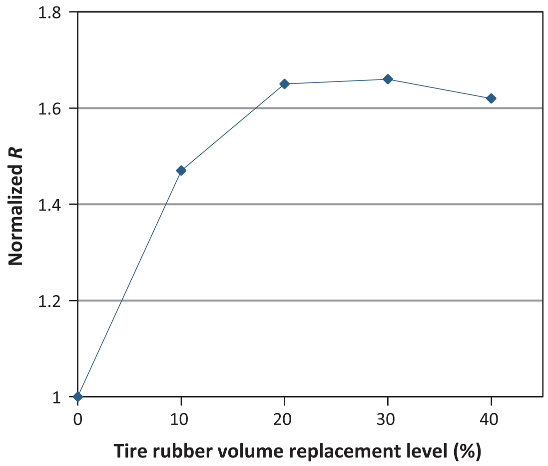

Fig. 11. Normalized cracking resistance R of ECC mixtures.

Table 6
Cracking potential for ECC mixtures.

Properties	R0	R10	R20	R30	R40
ε_{sh} (%)	0.11	0.13	0.13	0.14	0.15
ε_{e} (%)	0.017	0.023	0.027	0.031	0.033
ε_{i} (%)	1.77	1.99	2.12	2.56	2.97
ε_{cp} (%)	0.07	0.07	0.07	0.07	0.07
P	−1.75	−1.95	−2.08	−2.52	−2.92

Table 7
Restrained drying shrinkage behavior of ECC.

Age (days)	R0			R40		
	Crack width (μm)	Crack length (mm)	Crack number	Crack width (μm)	Crack length (mm)	Crack number
7	0	0	0	0	0	0
14	31	51	10	0	0	0
21	39	59	21	0	0	0
30	46	66	22	35	52	5
45	50	69	22	43	73	9
60	53	72	22	46	77	9

4. Conclusions and future work

Based on the results in this experimental study, the following conclusions can be drawn:

(1) Incorporating tire rubber in ECC mixtures reduces elastic modulus significantly (by over 50%) which enhances the cracking resistance by lowering the tensile stress induced by restrained shrinkage, even when accompanied by an increase in free shrinkage strain and a decrease in first cracking strength.
(2) The tire rubber addition in ECC mixture is an effective solution to reduce the crack tendency in terms of crack initiation time and crack number, which is demonstrated by the restrained ring tests. Therefore, ECC with tire rubber has a significant potential to improve the durability of repairs that inevitably undergo restrained drying shrinkage when bonded to old concrete substrates.
(3) The replacement of IOTs aggregate by tire rubber improves the material tensile ductility. The tensile strain capacity of ECC mixture containing tire rubber in the range of 10–40% by total aggregate volume ranges from 2% to 3%. However,

the compressive and tensile strengths of ECC with tire rubber are significantly reduced, which limits its wide applications for structural repairs. In spite of this, the mechanical properties of ECC with tire rubber are adequate for non-structural repairs.

(4) High tire rubber content tends to reduce the crack width in ECC material. The residual crack width of ECC with tire rubber can be reduced to about 5 μm. Even in the restrained ring test, the long term crack width can be reduced to less than 50 μm. Such tight crack width is expected to promote self-healing in cracked ECC and thus further enhance the durability of ECC repairs.

(5) Increasing the amount of tire rubber in ECC mixtures increases free shrinkage strain. However, the shrinkage strain is an order of magnitude lower than tensile ductility, implying that ECC with tire rubber can accommodate the shrinkage deformation without localized fracture failure.

While the cracking tendency of ECC containing tire rubber is experimentally demonstrated unequivocally, the durability of concrete repair with such material requires additional research. These include permeability tests of ECC with tire rubber and lab-scale layered repair system investigations, research ongoing at the University of Michigan. The layered repair study specifically addresses potential delamination failure of repair layer. Although the lower stress buildup caused by restrained shrinkage due to a reduced elastic modulus should lead to a reduced interfacial stress between the repair layer and the concrete substrate, it is not clear whether the introduction of tire rubber could also lead to reduced interfacial bond strength. The results of permeability tests and layered repair system demonstration of ECC mixtures will be combined with the cracking tendency study reported here in future to comprehensively assess the durability performance of ECC repairs containing tire rubber.

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References

[1] Mather B, Warner J. Why do concrete repairs fail. Interview held at Univ. of Wisconsin. <http://aec.engr.wisc.edu/resources/rsrc07.html>; 2003.
[2] Li VC. High performance fiber reinforced cementitious composites as durable material for concrete structure repair. Int J Restor 2004;10:163–80.
[3] Kabele P. Assessment of structural performance of engineered cementitious composites by computer simulation. CTU Reports 5(4), Czech Technical University in Prague; 2001.
[4] Wittmann FH, Martinola G. Decisive properties of durable cement-based coatings for reinforced concrete structures. Int J Restor Build Monument 2003;9:235–64.
[5] Li M, Li VC. Behavior of ECC/concrete layer repair system under drying shrinkage conditions. Int J Restor Build Monument 2006;12:143–60.
[6] Lepech MD, Li VC. Water permeability of engineered cementitious composites. J Cem Concr Compos 2009;31:744–53.
[7] Li VC, Henrik S. Elevating FRC material ductility to infrastructure durability. In: Proceedings of BEFIB; 2004, p. 171–86.
[8] Huang X, Ranade R, Ni W, Li VC, et al. Development of green engineered cementitious composites by using iron ore tailings as aggregate. Constr Build Mater 2013;44:757–64.
[9] Li VC, Tailoring ECC. For special attributes: a review. Int J Concr Struct Mater 2012;6:135–44.
[10] Zhou J, Qian S, Ye G, Copuroglu O, Breugel KV, Li VC, et al. **Improved fiber distribution and mechanical properties of engineered cementitious composites by adjusting the mixing sequence**. **Cem Concr Compos** 2012;34:342–8.
[11] Beatty JR. Physical properties of rubber compounds. In: Clark SK, editor. Mechanics of pneumatic tires. Washington (DC): United States Department of Transportation, National Highway Traffic Administration; 1981.
[12] Li M. Multi-scale design for durable repair of concrete structures. Doctoral dissertation: The University of Michigan; 2009.
[13] Yang E, Yang Y, Li VC. Use of high volumes of fly ash to improve ECC mechanical properties and material greenness. ACI Mater J 2007;401:303–11.
[14] Ranade R, Stults MD, Li VC, Rushing TS, Roth J, Heard WF, et al. Development of high strength high ductility concrete. Proc 2nd Int'l RILEM Conference on Strain Hardening Cementitious Composites (SHCC2), Rio de Janeiro, Brazil, 2011. p. 1–8.
[15] JSCE. Recommendations for design and construction of high performance fiber reinforced cement composites with multiple fine cracks. Tokyo: Japan Soc. of Civil Engineers; 2008.
[16] ASTM E399-12. Standard test method for linear-elastic plane-strain fracture toughness KIc of metallic materials.
[17] Li VC, Mishra DK, Wu HC. Matrix design for pseudo strain-hardening fiber reinforced cementitious composites. RILEM J Mater Struct 1995;28(183):586–95.
[18] AASHTO PP 34-99. Standard practice for estimating the cracking tendency of concrete. American Association of State Highway and Transportation Officials, Washington, DC; 1999.
[19] Li M, Li VC. High-early-strength engineered cementitious composites for fast, durable concrete repair – material properties. ACI Mater J 2011;108:3–12.
[20] Ganjian E, Khorami M, Maghsoudi AA. Scrap-tyre-rubber replacement for aggregate and filler in concrete. Constr Build Mater 2009;23(5):1828–36.
[21] Pelisser F, Zavarise N. Longo, T A, Bernardin AM, et al. Concrete made with recycled tire rubber: effect of alkaline activation and silica fume addition.. J Clean Prod 2011;19(6):757–63.
[22] Ling TC. Effects of compaction method and rubber content on the properties of concrete paving blocks. Constr Build Mater 2012;28(1):164–75.
[23] Wang K, Jansen DC, Shah PS, Karr AF, et al. Permeability study of cracked concrete. Cem Concr Res 1997;27:381–93.
[24] Tsukamoto M. Tightness of fiber concrete. Darmstadt Concr 1990:215–25.
[25] Yang Y, Lepech MD, et al. Autogenous healing of engineered cementitious composites under wet–dry cycles. Cem Concr Res 2009;39:382–90.
[26] ACI Committee 364. Cement-based repair materials. <http://www.concrete.org/FAQ /afmviewfaq.asp?faqid=52>; 2006.
[27] City of Toronto specifications TS13.00. Specification for non-structural concrete. <http://www.toronto.ca/techservices/pdf/conspecs/Standards_for_Roads_2010/Records_Archived_Standard_Specifications/TS_13.00-Jun2001.pdf>; 2011.
[28] Valenza JJ, Jeffrey JT. Permeability and elastic modulus of cement paste as a function of curing temperature. Cem Concr Res 2012;42:440–6.
[29] Khatib ZK, Fouad MB. Rubberized portland cement concrete. J Mater Civ Eng 1999;11(3):206–13.
[30] ACI Committee 318. ACI 38-11 building code requirements for structural concrete and, commentary; 2011.
[31] Billington S, Rouse JM. Time-dependent response of highly ductile fiber-reinforced cement based composites. In: Brandt AM, Li VC, Marshall IH, editors. Proc BMC-7, Warsaw Poland; 2009. p. 47–56.
[32] Sahmaran M, Li M, Li VC. Transport properties of engineered cementitious composites under chloride exposure. ACI Mater J 2007;104:604–11.