that mixed rubber into concrete is beneficial to the deformability and durability (Turatsinze, 2005). A recent study by Ho et al. (2008) confirmed that rubber aggregate incorporation improves the strain capacity of concrete before macro-crack localization.

Although the utilization of rubber powder in concrete has attracted attention in the field of building materials in the past decades, the research on Engineered cementitious composite (ECC) mixed rubber powder is limited. ECCis a uniqueclass of the new generation high-performance fiber-reinforcedcementitious composites (HPFRCC) featuring high ductilityand medium fiber content, which designed based on micromechanics theory by Victor Li at 1990s. Tensile strain capacity at a rangeof 3 to 5% has been demonstrated in ECC materials usingpolyethylene fibers and polyvinyl alcohol (PVA) fibers withfiber volume fraction no greater than 2% (Li, 1998; 2002). Fig.1 shows a typical tensile stress–straincurve of ECC and its tight crack width (Li, 1998). The large straincapacity in ECC is contributed by sequential development of multiple cracks, instead of continuous widening of one localized crack in concrete. Theassociated high fracture toughness and controlled crackwidth (typically below 100 μm) make ECCs anideal material to improve serviceability and durability of the civil infrastructures.

ECC is called green material because of the constituents includes high volume of fly ash which is a by-product of coal burning power plants and usually considered a waste material. In an effort to develop green ECC with local waste materials, Zhou et alhave developeda number of ECC mixtures with blast furnace slag (BFS) and limestone powder successfully(Zhou, 2009). In this study, it is attempted to use rubber powder to replace silica sand partially. On one hand, it consumes the waste rubber reasonably; on the other hand, it reduces the consuming of silica sand, which would improve the greenness of ECC further.

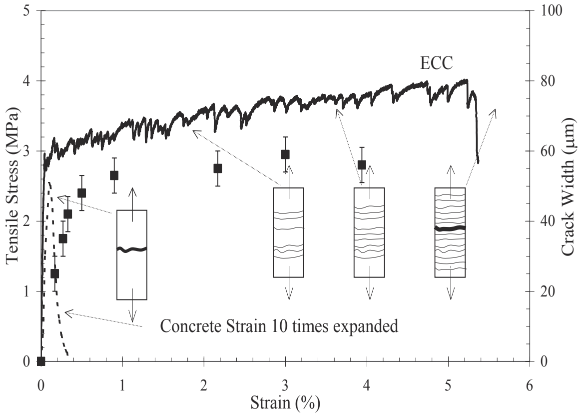


FIG .1. Tensile stress–strain curve and tight crack widthcontrol of ECC.

In this paper, it is attempted to do the researchbout the influence of rubber powder on ECC. Four-point bending and compressive tests were performed to investigate the effect of the addition of rubber powder on properties of ECC. Moreover, the influence on crack width and density were also highlighted.

EXPERIMENTAL PROGRAM

Materials

The mixtures are shown in Table 1, the ECC mixture includes Portland cement, fly ash, silica sand, rubber powder, and PVA fiber. Totally there are twoparticle sizes of rubber powder, including 450μm and 200μm in average. Thereare threemixtures which includedifferent dosages (0, 10%, 15% by volume replacing silica sand) for each rubber powder size.The properties of PVA fiber were revealed in Table 2.

Table 1. Mix proportion of ECC mixture (g/L)

Mix number	cement	Fly ash	Silica sand	Rubber powder/	Rubber particle size(μm)	water	Super-plasticizer	PVA fiber
Mix.1	395	868	459	0	--	312	8	216
Mix.2	395	868	413	21(10%)	200	312	8	216
Mix.3	395	868	390	31(15%)	200	312	8	216
Mix.4	395	868	413	21(10%)	450	312	8	216
Mix.5	395	868	390	31(15%)	450	312	8	216

Table 2. Properties of PVA fiber

Diameter (μm)	Length (mm)	Tensile strength (MPa)	Modulus (GPa)	Density (g/cm^3)
39	12	1620	42.8	1.2

Mixing and Testing

The matrix materials and rubber powder were first mixed with ahigh-shear mortar mixer for 1 min at low speed, followed by the addition of waterand superplasticizer. Mixing continued at low speed for 1 min and then athigh speed for 2 min. After fibers were added, the material was mixed at high speed for another 8 min.The fresh ECC was then cast into steel formwork and then demolded after 1 day curing. The specimens were then cured under standardcuring condition (20°C, 95% RH) until testing.All the specimens were cured for 14 days before testing. The bending specimens have dimensions of 400x70x16mm, while the compressive specimens with dimensions of 70x70x70mm.

After curing, the coupon specimens were used in four-pointbending test. The full span of the four-pointbending test was 300 mm with the middle span of 100 mm. The test was conducted under deformation control of 0.75 mm/min.Typically it takes about 20-30 minutes before the sample exhausts its deflection capacity and fails.

RESULTS AND DISCUSSION

Compressive strength

The material compressive properties for different mixtures can be found in Table 3.The compressive strength of mixtures which mix larger rubber powder particle is lower than that mix smaller rubber powder particle. That's because the larger particle increase the contact area between rubber powder and matrix. The compressive strength has a largely decrease after replacing silica sand by rubber powder with the ratio of 15% for Mix1, 3 and5 due to rubber powder reduce the toughness of matrix. However, it has negligible influence on compressive strength between Mix1, 2 and 4 with the ratio of 10%, which is not the same as literature referenced. It can be explained by the mechanism that compressive strength of ECC is controlled not only by toughness of matrix but also the fiber bridging restrain the horizontal deformation of specimen, consequently, increasing compressive strength. It demonstrates that the ratio of replacement by rubber powder with 10% cannot change the property of compressive strength.

Table 3. Compressive strength

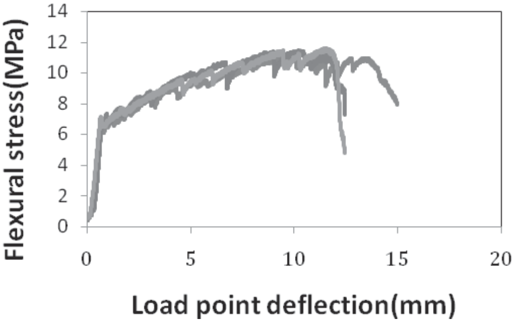
Mix No.	Mix1	Mix2	Mix3	Mix4	Mix5
fc' (MPa)	43.43	43.50	31.33	38.10	28.35

Flexural performance

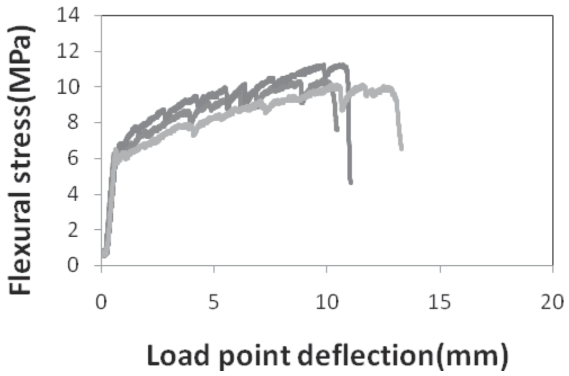
The flexural stress-load point deflection curves forall mixtureswere shown in Fig. 2. In theflexural stress–deflection curves, it defines the point of end of the linear stage as the first cracking strength, while the maximum flexuralstress is defined as the flexural strength, and thecorresponding deflection is defined as the flexuraldeflection capacity. The flexural specimen was first manually pre-loaded to make sure four loading points were in full contact with the specimen, which explainsthat the flexural stress is not zero at the beginning of the curve.

Fig.2 (a), (b) and(c) show the curves for A case which mixed smaller rubber particle size. It can be seen from A case that the first cracking strength gets lower as the ratio of replacement of rubber powder increase, denoting that it lower the toughness of ECC for using rubber powder replace silica sand. It can be explained by the mechanism that the bonding between the matrix and rubber powder is much weaker than silica sand. In addition, the flexural stress between Mix1 and Mix2 shows negligible influence, while it decreases obviously between Mix1 and Mix3. The phenomenon can be reflected by that the influence on compressive strength is negligible after replacing silica sand by rubber powder with the ratio of 10%.

For the deformability, it has a slight decrease after using rubber powder replace silica sand for Mix1 and Mix2, but the deformability of Mix2 is within the range of variation of Mix1 due tothe variation for ECC is large. So the slight decrease can be negligible. On the other hand, the deformability of Mix3 gets larger than Mix1. And the curve for Mix3 is quite gentle which can be explained that the existing rubber powder act the inert filler filling well the flaw that is inevitable in concrete micro-structure, thus improved the inner structure which is beneficial to the multi-cracking behavior. Another alternative mechanism can explain the deformability gets larger for Mix3 is that the number of rubber powder for Mix3 offer the sufficientartificial flaws in matrix which is beneficial to achieve the saturated multiple cracking, thus improve the deformability of ECC(Wang, 2004).



(a)


Flexural stress(MPa)
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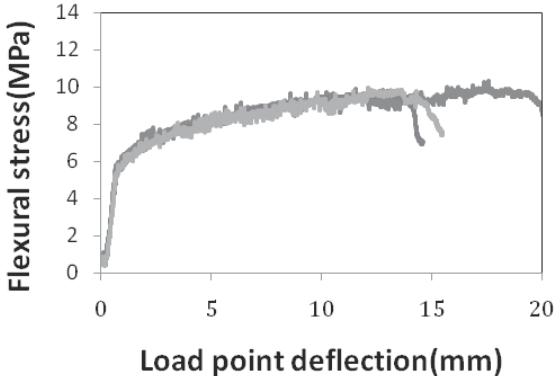
15
20
Load point deflection(mm)

(b)


Flexural stress(MPa)
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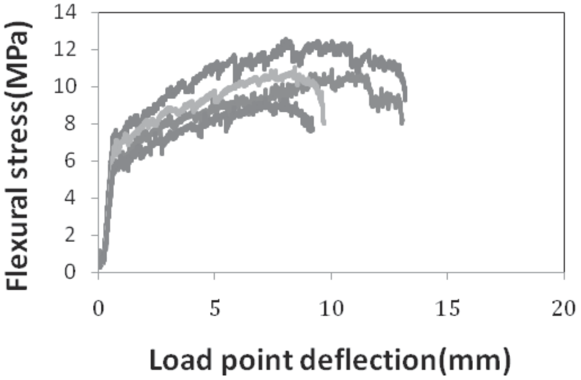
Load point deflection(mm)

(c)


Flexural stress(MPa)
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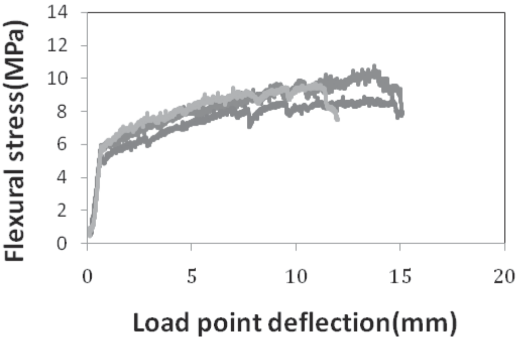
Load point deflection(mm)

(d)



(e)

FIG. 2. Flexural stress – load point deflection relation from FPBT test for (a) Mix1,(b) Mix2, (c) Mix3, (d) Mix4, (e) Mix5.

Fig.2 (a), (d) and (e) show the curvesfor B case which mixed larger rubber particle size. Similar to A case, it shows the same change trend for B case.However, the variation for Mix 4 is larger than the other mixtures. And the deformability of Mix5 is lower than Mix3, although the ratios of replacement of rubber powder are both 15%. This can be explained that the size of rubber powder for 200μm is more suitable to act artificial flaw than 450μm. Wang and Li reported that controlling the size of the artificial flaw is essential to effectiveness of improving the ductility of ECC (Wang, 2004).

Crack width

It is observed that specimens of all mixtures exhibit multiple micro-cracking behaviors under bending test, as is shown in Fig.3. Crack width control many transport properties in cracked concrete material and has a direct impact on durability (Lepech, 2005).So it is necessary to investigate the crack width. The crack width in this paper is measured by optical microscope. The average of crack width for each mixture is shown in Table 4. It is seen obviously that the crack width get smaller with the increasing volume of rubber powder.The explained mechanism is that the rubber powder embeds in the matrix, and the surface of rubber powder is very rough; consequently, increase the interface frictional bond restrains the slippage of fiberwhich is responsible for the tight crack width.

The crack width of B case mix with lager rubber powder particle is tighter than that of A case. It demonstrates that it is beneficial to increase the interface frictional bond for the larger rubber powder particle.

FIG. 3. Multiple cracking along the length of the specimen.

Table 4. Average crack width

Mix No.	Mix1	Mix2	Mix3	Mix4	Mix5
Average crack width(μm)	63	57	51	49	41

CONCLUSIONS

In this paper, it is attempted to develop ECC using rubber powder partially replace silica in order to improve the greenness of ECC and expects to enhance the deformation capacity of ECC.The influences of rubber powder on the mechanical behavior of ECC were studied. The following specific conclusions can be drawnfrom this study:

1. The influence on compressive strength of ECC is negligible when the dosage rubber powder is 10% which due to the fiber bridging restrain the horizontal deformation of specimen. While the compressive strength reduce greatly when the dosage rubber powder is 15% because of large the volume of rubber powder.
2. The deformation capacity gets improved when the dosage rubber powder is 15%, while it does not change when the dosage rubber powder is 10%. And, the first cracking strength decreases as the dosage of rubber powder increase, denoting the toughness of ECC decreases.To some degree, the rubber powder act as the artificial flaw making matrix easier to crack.

3. The addition of rubber powder increases the interface frictional bond restrains the slippage of fiber which contributes to tight crack width which is contributed to the increasing the interface frictional bond, consequently, improve its durability.

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Effect of Limestone Powder on Microstructure of Ternary Cementitious System

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ABSTRACT: The pressure to reach sustainability favours the development of ternary composite cement. The synergistic effect on mechanical behaviour at 28 days between limestone powder (LP) and pozzolanic additives, i.e. fly ash (FA) and blast furnace slag (BFS), has been documented. In order to better understand the synergistic effect, this article investigated the effect of LP on the microstructure ofPC-FA and PC-BFScementitious system. The mineralogy and pore structure were determined after 28 days of curing at 20°C and 95% relative humidity. The mineralogy in pastes was identified by means of X-Ray diffraction (XRD) and thermogravimetry (TG). The pore structure was evaluated by Mercury intrusion porosimetry(MIP). The results showed that neither monosulfoaluminate nor ettringite was found in any of the XRD patterns,instead carboaluminate was observed.Hemicarboaluminate produced in FA-PC or BFS-PC system transformed into monocarboaluminate with the addition of LP. The porosity was enlarged compared with LP-free paste system. It seems that both the physical and chemical effect of LP contribute to the synergistic effect on mechanical behaviourof cementitious system hydrated up to 28 days.

INTRODUCTION

CO_2 emissions from concrete production accounts for around 8% man-made CO_2(Karen, 2012). The blending of cement clinker with supplementary cementitious materials (SCMs), such as blast furnace slag (BFS), fly ash (FA) and limestone powder (LP), has been the most promising route to increase the sustainability of construction engineering. Nowadays, Portland cement (PC) is still the essential component in cementitious system and blended cements are most often binary, e.g. FA-PC and BFS-PC. While at high replacement levels, the early age mechanical behaviour of binary cementitious system becomes an issue. An possible approach to improve early age mechanical behaviour is to develop ternary cement system, in which different SCMs can interact with each other and may enhance the performance of concrete. LP is a particularly interesting SCM, it can decrease the cost due to the less demand of gypsum content (Weerdt, 2011a) and produce almost zero associated