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The Effect of Polymers like SBR, PVDC and LLDPE on the Fracture Characteristics of High Performance Concrete (HPC)

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ABSTRACT

In this study, the strengthening and toughening effects of polymeric materials on the high performance concrete (HPC) were investigated. The HPC was produced using ordinary Class 52.5 N Portland cement, silica fume and superplasticiser. The selected polymers included styrene-butadiene-rubber (SBR) latex; polyvinylidene chloride (PVDC); and linear low density polyethylene (LLDPE) with additive of 1.5%, 3% and 5% by weight in the cement content. The measured mechanical and fracture properties included compressive and tensile strengths; the modulus of rupture; fracture energy; fracture toughness and dynamic elastic modulus. The results indicate that the polymers used increase the compressive and tensile strengths of the HPC, in particular for the 1.5% weight content, but did not enhance other properties.

1. INTRODUCTION

Compared with most construction materials, concrete is regarded as a brittle material. The brittleness of concrete increases with the compressive strength; for super-high-strength concrete, failure can be sudden, explosive and disastrous. Therefore, it is necessary to carry out research on the brittleness of concrete in order to establish parameters for assessing the brittleness, find ways to improve the brittleness, and design and manufacture concrete materials with high strength and low brittleness. Three-point bend tests on HPC notched beams are normally performed to obtain the fracture characteristics. There are two methods for determining the fracture energy. The first one was proposed by RILEM, known as the work-of-fracture method (RILEM,

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1985). The second method was proposed by Bažant and Pfeiffer (Einsfeld & Velasco, 2006), as a procedure known as the size effect method (SEM).This is used for analysing geometrically similar beams. Previous research shows that some polymers added to the concrete mix causes a reduction in the water cement ratio (w/c); an increase in porosity; delayed setting (for a high amount of polymer); and shrinkage reduction (Chmielewska, 2008). Polymers are widely used in structural concrete due to its high bonding strength with most aggregates; outstanding dimensions at stability from low creep/shrinkage during and after curing, low porosity and permeability, high thermal resistance; improved chemical resistance; outstanding fatigue resistance and good electrical insulation. Polymer concrete has become a significant group of concretes that use polymers to supplement or replace cement as a binder. However, this paper focuses on polymer modified concrete where additive polymers are used to modify the properties of the concrete. Styrene-butadiene rubber (SBR) is a polymer made from butadiene and styrene monomers. It has a good mechanical property and processing behaviour and can be used like natural rubber (Peng, 2011). The SBR has excellent bond strength in the concrete, higher flexural strength, and lower permeability (Bhutta & Ohama, 2010). Sinan Hinisliog and Emine Agar (2004) show that due to high stability of waste HDPE-modified bituminous binders provide better resistance against permanent deformations and contributes to recirculation of plastic wastes as well as to protection of the environment. The purpose of this research was to study the effects of polymers on the fracture performance of high performance concrete (HPC). In addition, the optimum quantities of polymers in the mix design for the HPC were also determined.

2. EXPERIMENTAL

2.1 Materials for Producing the HPC

The cement used was Procem Ordinary Portland cement, which is classified as Class 52.5 N CEM 1 cement according to BS EN 197-1 (BSI, 2011) and is available in 25 kg bags. The chemical compositions of the cement are given in Table 1, according to the manufacturer's specifications.

Table 1 Chemical compositions of the cement used

Sulphate (SO_3, %)	Chloride (Cl, %)	Alkali ($EqNa_2O$, %)	Tricalcium Silicate (C_3S, %)	Dicalcium Silicate (C_2S, %)	Tricalcium Aluminate (C_3A, %)	Tetracalcium Aluminoferrite (C_4AF, %)
2.5 to 3.5	<0.10%	< 1.0%	40.0 to 60.0	12.5 to 30.0	7.0 to 12.0	6.0 to 10.0

Dry granite aggregates were used with a maximum size d_{max} = 10 mm, a specific gravity G_{SSD} = 2.90, a water absorption W_{abs} = 0.66% and a total water content W_{tot} = 0%. Siliceous natural sand was used with G_{SSD} = 2.64, W_{abs} = 3.72% and W_{tot} = 3.5%. The silica fume used was the Elkem microsilica grade 940-D Densifiled silica fume powder, which replaced 10% of the total cementitious materials. The chemical compositions of the silica fume are given in Table 2.

Table 2 Compositions of the silica fume used

SiO_2 (%)	H_2O (%)	Loss on ignition (LOI, %)	Bulk density (kg/m^3)	Specific gravity
More than 90	Less than 1.0	Less than 3.0	500-700	2.20

The Structuro 11180 type superplasticizer, a new generation of polycarboxylate (PC) polymer superplasticizer (high range water reducer), was used for the mix with

- a total solid content of 40%, and
- a specific gravity of 1.10.

Three types of polymers were adopted for this study. The Styrene-Butadiene-Rubber (SBR) latex is in liquid form (Fig. 1). The physical and chemical properties of the SBR are given in Table 3.

Table 3 Physical and chemical properties of the SBR used

State	Colour	Odour	pH	Relative density	Water solubility	Viscosity
Liquid	White	Aromatic	9-11	0.9-1.1	Miscible in water	100-1000 mPa s

Fig. 1 The SBR latex

The polyvinylidene chloride (PVDC) is in powder (Fig. 2). The physical and chemical properties of the PVDC are given in Table 4.

Table 4 Physical and chemical properties of the PVDC used

State	Colour	Density (g/cm^3)	Coefficient of friction	Water absorption – over 24 hours (%)	Hardness (Rockwell)
Powder	White	1.36	0.24	0.1	R98-106

Fig. 2 The PVDC powder

The linear low density polyethylene (LLDPE) is also in powder with green colour (Fig. 3). The physical and chemical properties of the LLDPE are given in Table 5.

Table 5 Physical and chemical properties of the LLDPE used

State	Colour	Density (g/cm^3)	Water absorption (%)	Surface hardness
Powder	Green	0.935	0.01	SD48

Fig. 3 The LLDPE powder

In general, the quality of water that is used in concrete is usually fit for human consumption, and the water containing large amounts of dissolved or solid impurities should be avoided because it may cause various negative effects on the properties of both fresh and hardened concrete. Therefore the water used for producing high performance concrete was high quality drinkable tap water.

2.2 The HPC Mix Designs

A high performance mix design was utilised according to the proposed method and followed the same approach as ACI 211–1 Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass (ACI, 2009). It is a combination of empirical results and mathematical calculations based on the absolute volume method (Aitcin, 2004). Twenty batches of concrete were produced for a total of ten mixes and for moulding forty beams. All the beams were 500 mm long, 100 mm wide and 100 mm deep and were tested at twenty-eight days. Three-point bend tests were performed on the notched polymer modified HPC beams to determine the fracture parameters. The experimental study was divided into ten mixes, whereby different amounts of the SBR, PVDC and LLDPE were used. Table 6 shows the detailed polymer modified HPC mixes used in this study. Along with the beam specimens, a total of one hundred and twenty cubes of 100 mm x 100 mm x 100 mm were cast for the ten concrete mixes. The cubes were tested at seven, twenty-eight and ninety days, and had an average compressive strength of 110 MPa. Before testing the beam specimens, notches of half depth were produced using a diamond sawn at the mid-sections of the specimens. The test set-up is shown in Fig. 4.

Fig. 4 The set-up in the testing machine

Table 6 Mix designs of polymer modified high performance concrete

Name and percentage of polymers in mix design (per 1 m^3)	Mix 1 0.0%	Mix 2 1.5% SBR	Mix 3 3.0% SBR	Mix 4 5.0% SBR	Mix 5 1.5% PVDC	Mix 6 3.0% PVDC	Mix 7 5.0% PVDC	Mix 8 1.5% LLDPE	Mix 9 3.0% LLDPE	Mix 10 5.0% LLDPE
Cement (kg)	505	505	505	505	505	505	505	505	505	505
Coarse aggregate (kg)	996	996	996	996	996	996	996	996	996	996
Sand (kg)	830	809	786	756	770	757	739	770	757	739
Water (l)	134	114	99.5	80	134	144	163.8	134	144	163.8
Silica fume (kg)	55	55	55	55	55	55	55	55	55	55
Superplasticizer (l)	20	20	20	20	20	20	20	20	20	20
Polymers (l or kg)	0	17.5 l	35 l	58.3 l	8.4 kg	16.8 kg	28 kg	8.4 kg	16.8 kg	28 kg
Water–cementitious materials ratio (w/cm)	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25

3. RESULTS AND DISCUSSIONS

3.1 Unit Weight (Density)

The unit weight or density of the hardened concrete ρ_c was measured at 28 days and calculated from

$$\rho_c\ (\text{kg/m}^3) = W_{air} / (L_c B_c H_c) = W_{air} / (W_{air} - W_{water}) \quad (1)$$

where
W_{air} is the mass of concrete in the air (g),
W_{water} is the mass of concrete under the water (g),
L_c is the length of the cube specimen (mm),
B_c is the width of the cube specimen (mm),
H_c is the depth of the cube specimen(mm) .

The test results of the density for the HPC with different polymers at 28 days are shown in Fig. 5. For the SBR modified concrete, the density slightly varied for different contents but the trend was inconclusive, with an average density of 2450 kg/m^3 which was slightly higher than the density of the reference concrete with ρ_c = 2438 kg/m^3. The PVDC modified concrete had a slightly higher average density of 2457 kg/m^3. The density for the HPC with the LLDPE slowly decreased with the increasing polymer weight content, down by 0.4%, 1.0% and 2.2% for the contents of 1.5%, 3% and 5%, respectively.

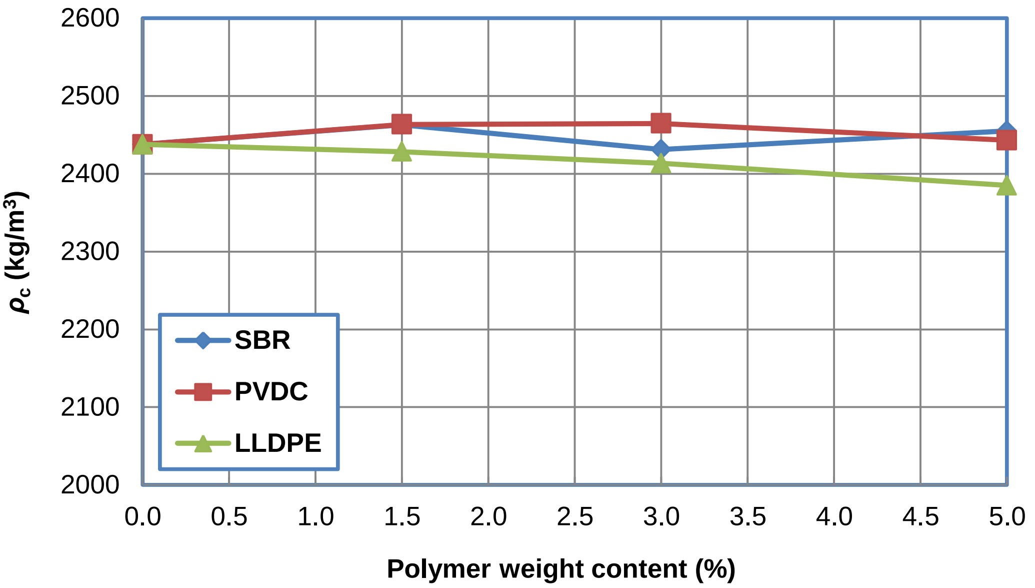

Fig. 5 Densities of the HPC with different contents of polymers at 28 days

3.2 Compressive Strength

Standard cube specimens of 100×100×100 mm were cast and tested for obtaining the compressive strength at 7, 28 and 90 days. After obtaining the certain strength for nominal high performance concrete through trial mixes and fixing the dosages of the polymer proportion, modified high performance concrete specimens were produced by adding different types and contents of polymers. The cube specimens were demoulded 24 hours after casting and kept in the water in the curing room for 90 days. However, a further 24-hour cure in the air was needed for polymer based composites to complete the polymerisation process. The developments of the compressive strength f_{cu} for the polymer modified high performance concrete for different dosages of polymers and at different ages say 7, 28 and 90 days are presented in Figs. 6 to 8, respectively.

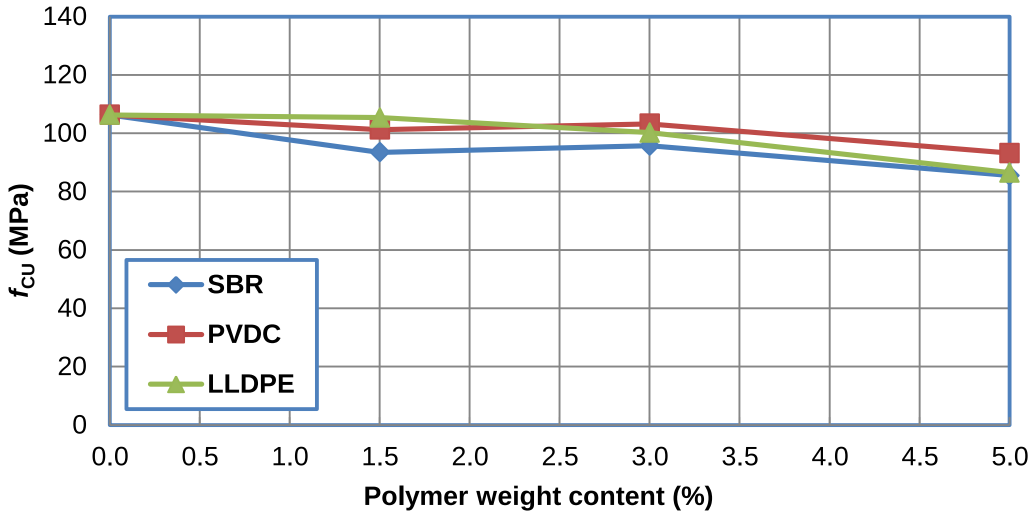

Fig. 6 Compressive strength of the HPC with different contents of polymers at 7 days

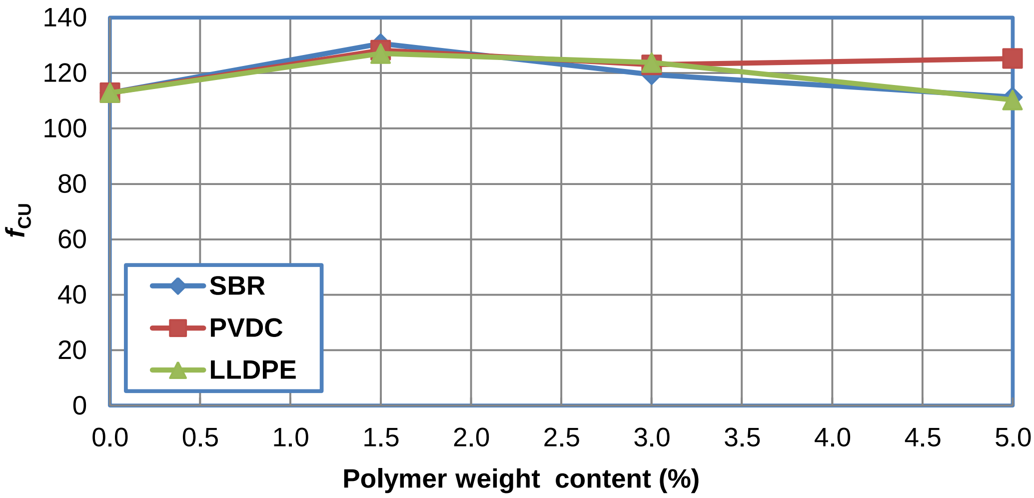

Fig. 7 Compressive strength of the HPC with different contents of polymers at 28 days

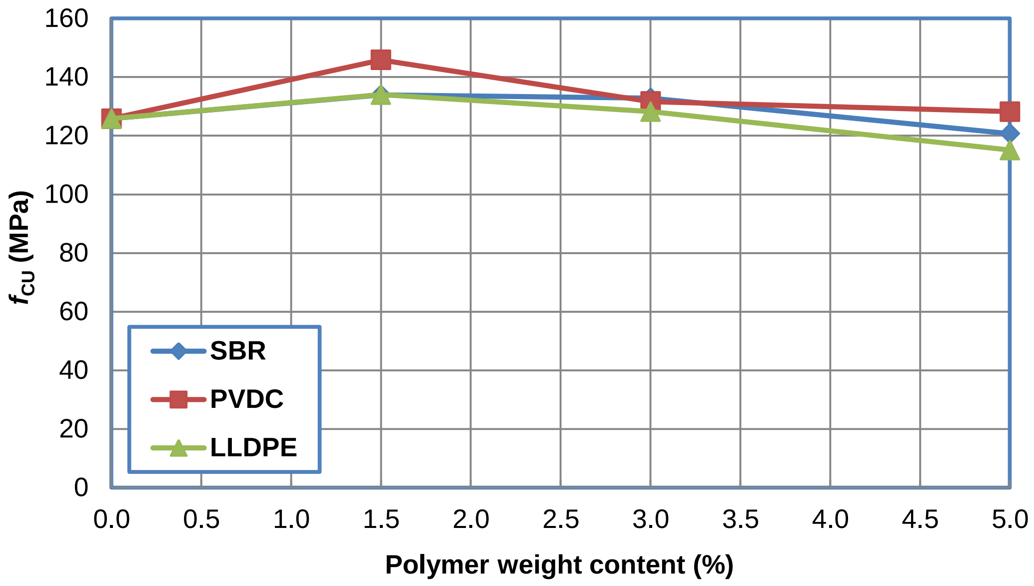

Fig. 8 Compressive strength of the HPC with different contents of polymers at 90 days

The test results of the compressive strength at 28 days indicate that the additions of 1.5% and 3% of the SBR resulted in an increase of approximately 16% and 6% in the compressive strength, respectively, while the content of 5% SBR led to a slight decrease of approximately 1.35%. Additions of 1.5%, 3% and 5% of the PVDC to the mixes increased the compressive strength by 13.6%, 9% and 11%, respectively. Additions of 1.5% and 3% of the LLDPE increased the compressive strength by approximately 12.5% and 9%, respectively, while the addition of 5% LLDPE led to a slight decrease of approximately 2% in f_{cu}.

3.3 Splitting Tensile Strengths

The splitting tensile strengths of the conventional concrete and polymer modified concrete were only determined at 28 days on the cubes of 100×100×100 mm, which had been cured in water until the date of testing. Three cube specimens for each mix were tested and the mean values were obtained. The results are presented in Fig. 9.

The splitting tensile strength f_t' was calculated based on the following equation

$$f_t' = 2F_t/(\pi a^2) \qquad (2)$$

where

f_t' is the splitting tensile strength (MPa),
F_t is maximum splitting load (N),
a is the length of the cube specimen (m).

It can be seen from Fig. 9 that the tensile strength increased when the SBR latex, PVDC powder and LLDPE powder were added. For the contents of 1.5%, 3% and 5% SBR, the tensile strength increased by 23%, 72% and 23%, respectively. For the same contents of the PVDC, the tensile strength increased by 35%, 41% and 40%, respectively. Finally for the LLDPE modified HPC, the corresponding tensile strength increased by as high as 83%, 57% and 50%, respectively.

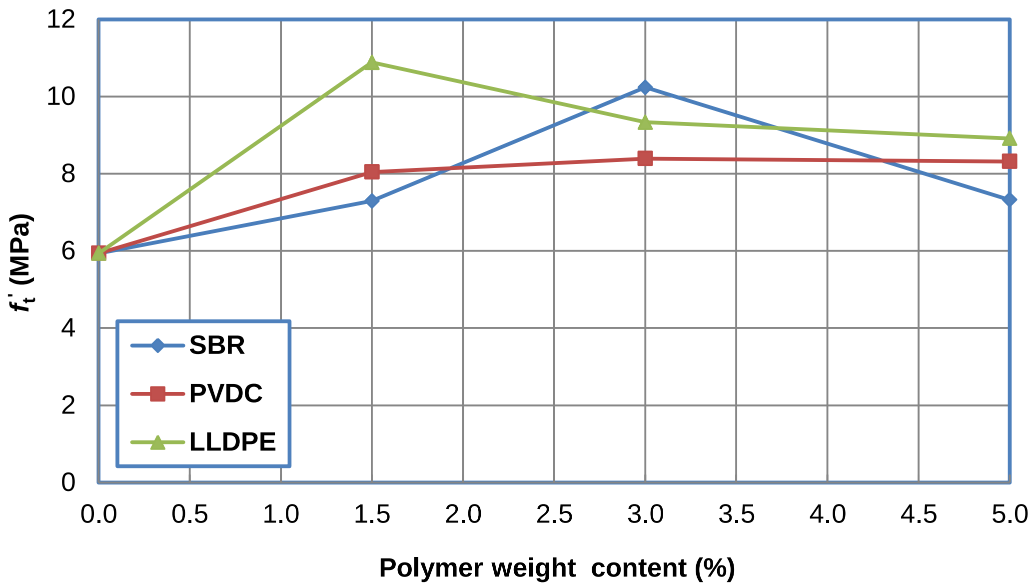

Fig. 9 Splitting tensile strength of the HPC with different contents of polymers at 28 days

3.4 The Modulus of Rupture

The modulus of rupture of the HPC was obtained at 28 days on the concrete beams of 100 x 100 x 500 mm (see Fig. 10), cured in water until the date of testing. Four beam specimens for each mix were tested and the mean values are presented in Fig. 11.

The modulus of rupture, f_r, was calculated based on the following equation

$$f_r = 6\,M/[B\,(H - a_0)^2] \tag{3}$$

where

M is the maximum bending moment at mid-span of the beam and $M = F_r\,S/4$,
F_r is the maximum external load at mid-span of the beam specimen,
L is the length of the beam specimen = 500 mm,
B is the width of the beam specimen = 100 mm,
H is the overall depth of the beam specimen = 100 mm,
S is the effective span of the beam specimen = 400 mm,
a_0 is the notch depth of the beam specimen = 50 mm.

The modulus of rupture increased slightly by approximately 2% for the addition of 1.5% SBR in the HPC at twenty-eight days, while with additions of 3% and 5% SBR, f_r decreased by 1.7% and 4.5%, respectively. For the PVDC contents of 1.5%, 3% and 5% in the HPC mixes, the modulus of rupture decreased by 2.3%, 6.8% and 19%, respectively. For the LLDPE, the modulus of rupture decreased by 8%, 16% and 7.5%, respectively, for the contents of 1.5%, 3% and 5%, as shown in Fig. 11. This may be due to the slight increase of the brittleness of the polymer modified concrete.

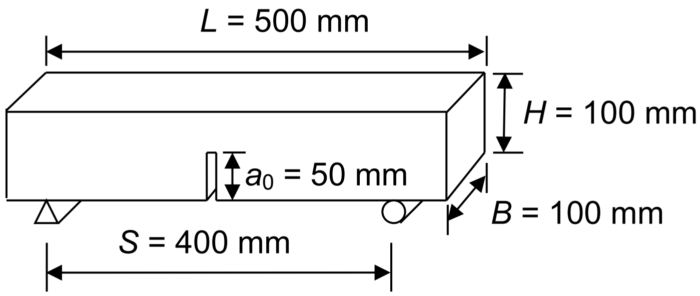

Fig. 10 Notched concrete beam under three-point-bending

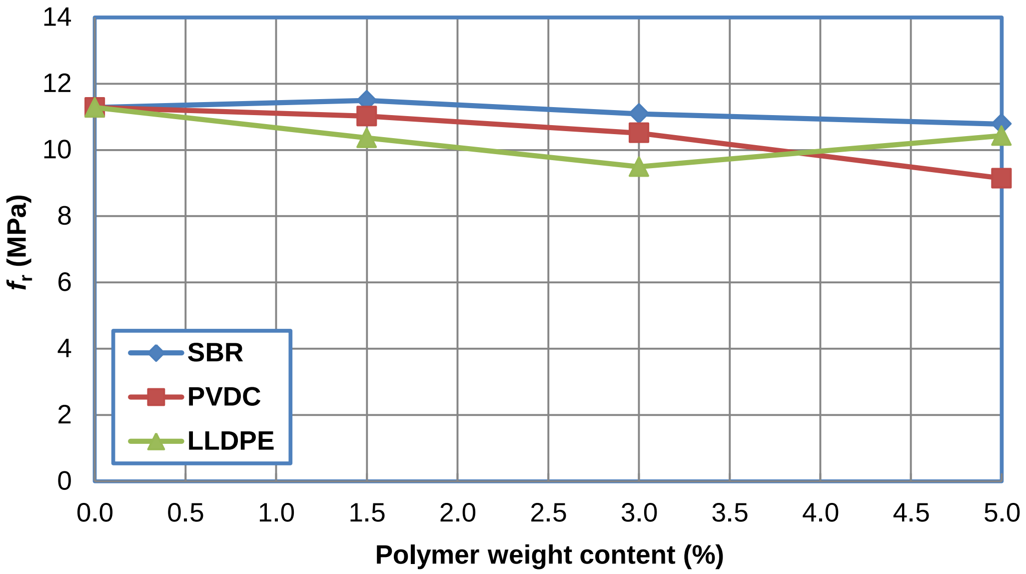

Fig. 11 The modulus of rapture of the HPC with different contents of polymers at 28 days

3.5 Fracture Energy

The fracture energy, G_F, defined as the total energy dissipated over a unit area of the cracked ligament, was obtained on the basis of the work done by the force (the area under a load-displacement curve from three-point bending testing on a centrally notched beam) associated with the gravitational work done by the self-weight of the beam. The fracture energy was calculated based on the following equation

$$G_F = (W_P + W_G)/A_{lig} \tag{4}$$

$$W_P = \int_0^{\Delta_{max}} P(\Delta)\,d\Delta \tag{5}$$

$$W_G = m\,g\,(L/S)\,(2 - L/S)\,\Delta_{max} \tag{6}$$

$$A_{lig} = B\,(H - a_0) \tag{7}$$

where

W_P is the work done by the externally applied force $P(\Delta)$,

W_G is the work done by the self-weight of the beam specimen,

$P(\Delta)$ is the externally applied force on the specimen and is a function of Δ,
Δ_{max} is the ultimate mid-span displacement when the beam is broken,
Δ is the mid-span displacement of the beam specimen,
A_{lig} is the area of the ligament of the beam specimen,
m is the mass of the beam specimen,
g is the acceleration due to gravity and g = 9.81 m/s^2.

Fig. 12 shows the variations in the fracture energy G_F of the HPC with different contents of SBR, PVDC and LLDPE. It can be seen that G_F slightly increased by 3.5% for the 1.5% SBR content but decreased by 4.3% for the 3% SBR content. For the SBR content of 5%, G_F had a net increase of 7%. For the concrete with the 1.5% PVDC content, G_F was slightly enhanced by only 0.7%, but for the 3% and 5% contents, G_F largely decreased by 15.5% and 23.5%, respectively. For the concrete with the 1.5% and 5% LLDPE contents, G_F increased by 24% and 8%, respectively, while for the 3% LLDPE content, G_F slightly decreased with a net drop 4.5%.

Fig. 13 illustrates the relationships between the fracture energy and compressive strength for the high performance concrete with different types of polymers and the test results were inconclusive. For the compressive strength below 125 MPa, G_F monotonically decreased with the increasing f_{cu} but thereafter the reverse trends were observed.

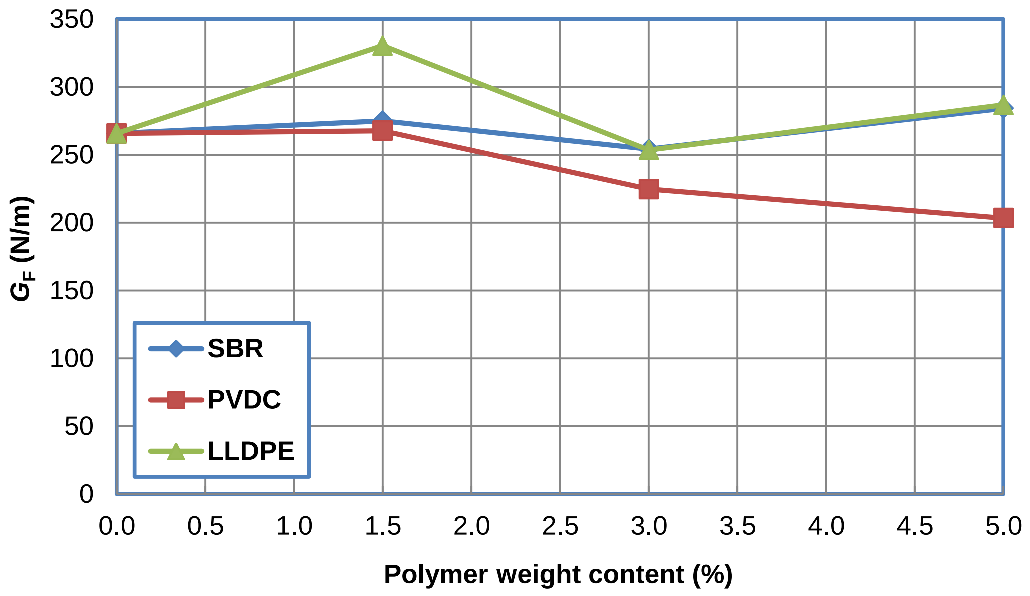

Fig. 12 Fracture energy of the HPC with different contents of polymers

3.6 Fracture Toughness

The fracture toughness K_{IC} was calculated using the effective crack model, based on the ASTM formula (Karihaloo & Nallathambi, 1989), as

$$K_{IC} = \sigma_n \, \alpha_e^{1/2} \, Y(a_e/H) \tag{8}$$

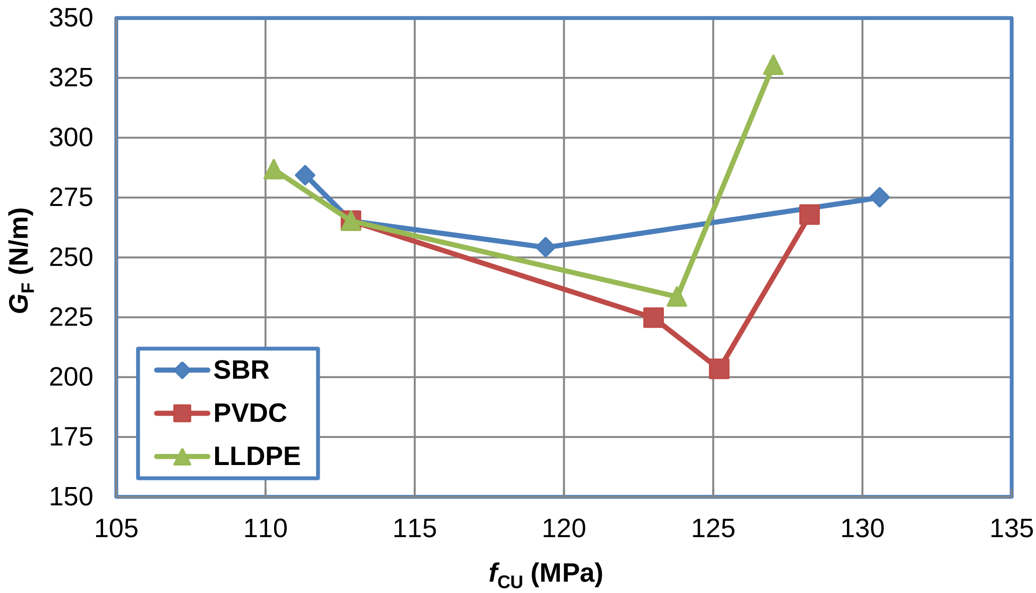

Fig. 13 Relationships between G_F and f_{cu} for the HPC with different polymers

where

σ_n is the nominal bending stress, given by

$$\sigma_n = 6\,M/(B\,H^2) \tag{9}$$

P_{max} is the peak load,

a_e is the effective crack length, determined from the regression equation as

$$\frac{a_e}{H} = C_1 \left(\frac{\sigma_n}{E}\right)^{C_2} \left(\frac{a_0}{H}\right)^{C_3} \left(1 + \frac{d_{max}}{H}\right)^{C_4} \tag{10}$$

E is the modulus of elasticity, determined from separate tests,

C_1 to C_4 are the empirical coefficients and

$C_1 = 0.249 \pm 0.029$, $C_2 = -\,0.120 \pm 0.015$, $C_3 = 0.643 \pm 0.015$, $C_4 = 0.217 \pm 0.073$

$Y(\alpha)$ is the correction function, given by

$$Y(\alpha) = \frac{1.99 - \alpha\,(1-\alpha)\,(2.15 - 3.93\,\alpha + 2.70\,\alpha^2)}{(1+2\,\alpha)\,(1-\alpha)^{3/2}} \tag{11}$$

α is the effective crack width and $\alpha = a_0/H$.

Fig. 14 shows the variations in the fracture toughness K_{IC} of the HPC with different contents of SBR, PVDC and LLDPE. In general, K_{IC} decreased with the additions of all three types of polymers. It can be seen that K_{IC} slightly increased by 1.5% for the 1.5% SBR content but sustained a net decrease of 1.5% and 4.2% for the 3% and 5% SBR contents, respectively. For the HPC with the PVDC, K_{IC} decreased continuously but slowly with the increasing PVDC content, down by 0.3%, 6.6% and 18.0% for the 1.5%, 3% and 5% PVDC contents, respectively. For the HPC with the LLDPE, K_{IC} decreased continuously with the increasing content, down by 7.8% and 15.0% for the 1.5% and 3% contents, respectively, while for the 5% content, K_{IC} slightly recovered and had a net drop of 7.2%.

Fig. 15 illustrates the relationships between the fracture toughness and compressive strength for the high performance concrete with different types of polymers and similar to the test results for G_F, the test results for K_{IC} were also inconclusive and did not show clear trends with the compressive strength.

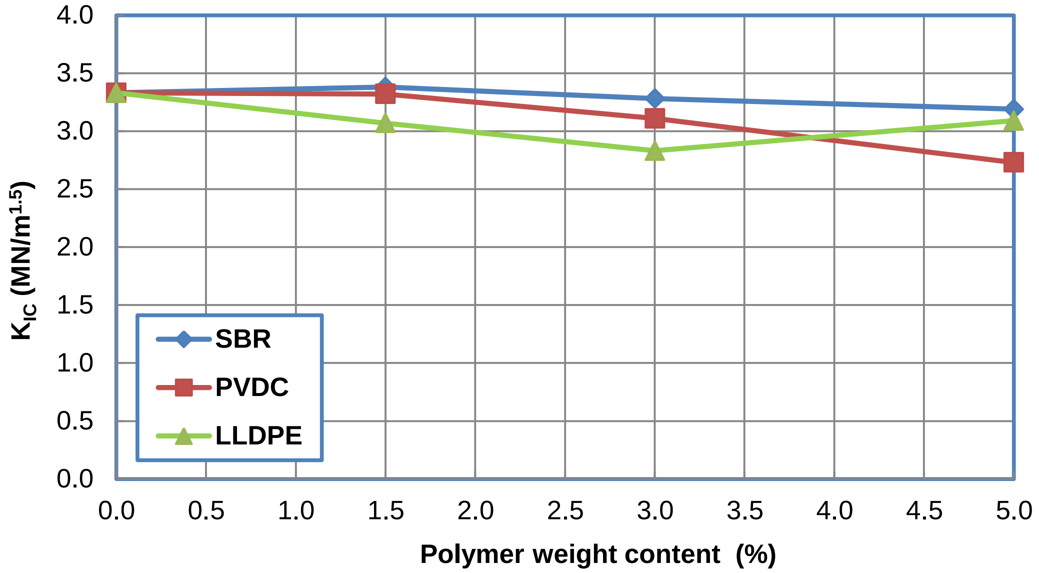

Fig 14 Fracture toughness of the HPC with different contents of polymers

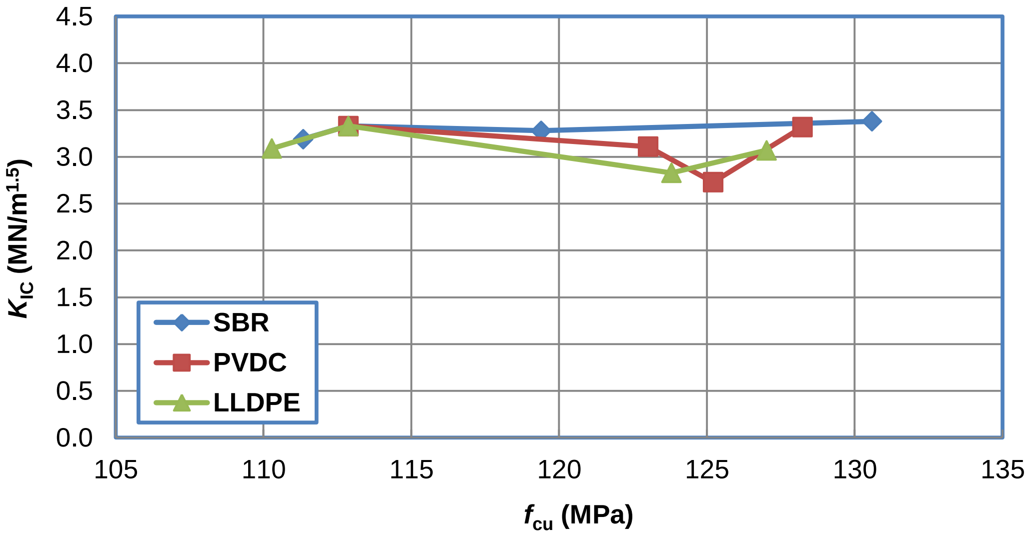

Fig. 15 Relationships between K_{IC} and f_{cu} for the HPC with different polymers

3.7 Dynamic Elastic Modulus

The dynamic modulus of elasticity, E_d, was indirectly determined by using the ultrasonic testing method. The dynamic modulus of elasticity of the HPC was measured on three 100 mm cubes at 7, 28 and 90 days for each concrete mix, respectively, and calculated from

$$E_d = \rho_c V^2 \tag{12}$$

where

V is the velocity of the ultrasonic wave in m/s, and $V = L_0/t$,
L_0 is the length of specimen in m,
t is the time for the ultrasonic wave to travel through the specimen length in s.

The test results for the dynamic elastic modulus at 28 days are shown in Fig. 16. In general, E_d did not vary largely with the polymer content for each type of polymer. Because of different states, densities, volume contents of the polymers used in this study, the measured dynamic elastic moduli were slightly different. The dynamic elastic modulus did not show significant changes with the increasing SBR content. The average value of E_d for the HPC with the SBR was 72.10 GPa which was slightly larger than the one for the reference concrete with E_d = 68.01 GPa. This is because the addition of SBR improved the interface between the aggregates and cement paste. The dynamic elastic moduli for the HPC with the PVDC and LLDPE slowly decreased with the increasing polymer content. On average, the corresponding values of E_d were 66.70 GPa and 68.13 GPa, either slightly smaller than or approximately the same as the value of the reference concrete.

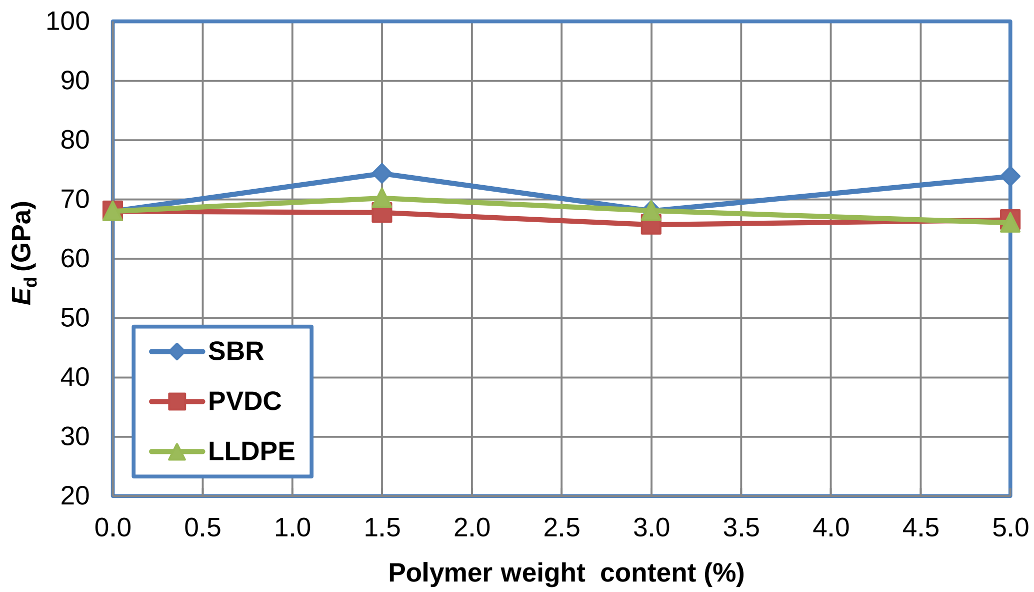

Fig. 16 Dynamic elastic modulus of the HPC with different polymers at 28 days

4. CONCLUSIONS

In this study, the strengthening and toughening effects of polymer materials on the high performance concrete (HPC) were investigated. The HPC was manufactured using ordinary Class 52.5 N Portland cement, silica fume and superplasticiser. The adopted polymers were the styrene-butadiene-rubber (SBR) latex, the polyvinylidene chloride (PVDC) and the linear low density polyethylene (LLDPE) with contents of 1.5%, 3% and 5% in weight of cement content. The measured fracture properties included compressive strength, tensile strength, the modulus of rupture, fracture energy, fracture toughness and dynamic Young’s modulus.

The test results at 28 days indicate that the additions of 1.5% and 3% SBR, PVDC and LLDPE into the HPC could largely improve the compressive strength by up to 15.7%, while the addition of 5% SBR and LLDPE did not show any enhancement except for the addition of 5% PVDC which enhanced the compressive strength by 10.9%.

The results for the tensile strength were more encouraging than those on the compressive strength, depending on different dosages of polymers. For the HPC with the SBR, the tensile strength could be increased by up to 72%. For the HPC with the PVDC, the tensile strength could be increased by about 40% on average. For the HPC with the LLDPE, the tensile strength could be increased by as much as 83%.

The modulus of rupture, fracture toughness and dynamic Young’s modulus obtained from the tests on the notched HPC beams were not enhanced for lower dosages of polymers and slightly decreased for higher dosages. This could be due to the slight increase in the brittleness of the HPC with these polymers.

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