Toughness Properties of Steel-Polypropylene Fibre Reinforced Concrete under Elevated Temperature

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Abstract. Application of fibres in concrete which is also known as fibre reinforced concrete (FRC) has been found to improve the energy absorption or toughness of the material. However, only little information on FRC toughness is found when it is exposed to high temperature such as under prolonged heat or fire. The main objective of the study is to evaluate the toughness behaviour of FRC by experimentation when exposed to elevated temperature. The fibre used in the experimental work is steel (ST) or polypropylene (PP), and also the combination of both fibres. The fibre dosage varied between the ST and PP summarised as (100-0), (75-25), (50-50), (25-75) and (0-100). Meanwhile, the total volume fraction, V_f is fixed at 1.5% and they are exposed to elevated temperature at the following degree; room temperature (27°C), 200°C, and 400°C. The research shows that the addition of fibres in concrete enhanced the FRC toughness, however, it reduces as the exposure temperature increases.

Introduction

Toughness is the ability of the materials to absorb energy during deformation. It is determined by calculating the area under the load-deflection graph. In order to improve the concrete toughness, fibres are usually added in the mixture also known as fibre reinforced concrete (FRC). At the same time, it will also increase the flexural strength of the concrete, improved ductility and cracking resistance [1-3]. The crack growth can also be delayed when the total volume fraction of the fibre increases. Previous study found that adding steel (ST) fibre more than the polypropylene (PP) fibre in the same mixture can enhance the FRC toughness [3].

FRC toughness can be affected when it exposed to heat. Heat can come from many sources such as fire and prolonged high temperature on the exposed surface. Explosive spalling has been observed by many researchers often resulting in serious concrete deterioration [4-7]. High temperature causes dramatic physical and chemical changes, resulting in concrete deterioration [8,9]. Therefore, to reduce deterioration and spalling, additional material such as ST or PP fibre is added in the mixture which has sufficient fire protection [10, 11]. However, minimal or even negative effects of PP fibre on the residual performance of the heated concrete may also occur [12].

Most literature reviews agree that the addition of single type of fibre in concrete can significantly improve concrete resistance. However, only a small amount of research work is found which combined two or more types of fibre in concrete. Even more, the findings from the FRC exposure to heat and tested for its mechanical properties are still limited. Combining two or more types of fibre in a single mixture has many advantages. However, it has to be balanced between the macro and micro fibres. This is because the micro fibres will inhibit the growth of early cracks that occur in the concrete by blocking the channel for bleeding process and therefore reduced the bleeding effects. While macro fibres, usually act as a tier for the concrete materials under applied load. Adding macro fibres will give stages of failure compared with plain concrete which is sudden and can easily breaks into two parts at failure [13]. In this study, ST and PP fibre is added in concrete mixture singularly and also by combining both fibres. This is because there is still little information on flexural toughness when both macro and micro fibres are combined in a concrete mixture. Furthermore, the main focus of the study is exposing the specimens to an elevated temperature of 200°C and 400°C of which most previous study only tested at room temperature i.e. 27°C.

Experimental Program

In order to achieve the objectives of the study, experimental works is carried out in the laboratory. Ordinary Portland Cement (OPC) is used in this study where the water-to-cement ratio is fixed at 0.53. This is to achieve concrete grade of C40 and at the same time to ensure that the mixture is not too dry when it is mixed with fibres. Meanwhile, fine aggregates of below 10 mm are used and coarse aggregates are between 10 mm and 20mm.

The total volume fraction of fibres, V_f are fixed at 1.5%from the total percentage of the concrete. The application of V_f = 1.5% is based on the findings by previous researcher which shows that the best proportion of the combined fibres for FRC is 75% ST fibres and 25% PP fibres [13]. The V_f = 1.5% is divided into five main batches to get the single and combined mixture: (i)100% ST fibres with 0% PP fibres (100-0), (ii) 75% ST fibres with 25% PP fibres (75-25), (iii) 50% ST fibres with 50% PP fibres (50-50), (iv) 25% ST fibres with 75% PP fibres (25-75), and (v) 0% ST fibres with 100% PP fibres (0-100).

Each concrete batch is then left to cure and tested at room temperature (27°C), and also exposed to 200°C and 400°C for one hour or 60 minutes. This means that in every concrete batch there will be 3 sub-batches. For each concrete batch, 3 prisms of 150 mm × 150 mm × 550 mm are used.

The volume of ST fibres is calculated using the following expression:

$$\text{Volume} = \frac{x_{st}}{100} \cdot \frac{1.5}{100} \cdot (steel\ density).(volume\ of\ mix\ design) \quad (1)$$

where x_{st} is the percentage of ST fibres and the steel density is taken as 7850 kg/m^3. Meanwhile, the volume of PP fibres is calculated using the following expression:

$$\text{Volume} = \frac{x_{pp}}{100} \cdot \frac{1.5}{100} \cdot (PP\ density).(volume\ of\ mix\ design) \quad (2)$$

where x_{pp} is the percentage of PP fibres and the polypropylene density is taken as 869.14 kg/m^3.

The toughness test carried out on prisms is to determine the flexural toughness. The test follows BS EN14651:2005+A1:2007 [14] and the test setup is shown in Figure 1.

Figure 1: Toughness test

After the casting process of the prisms, they were cured for 28 days. After the prisms are taken out from the curing tank, they are first dried for a few hours. The prisms which are used for comparison is left at room temperature (27°C) before the toughness test is carried out. Meanwhile, the other prisms are exposed to temperature of 200°C and 400°C for one hour. The process is carried out by heating the prisms in an oven at the desired temperature as shown in Figure 2.

Figure 2: Firing furnace oven

After the heating process, the prisms are cooled down at room temperature. This process takes about 24 hours (1 day) which is then followed by the flexural toughness test. Before the test, a slot is made under the prism following the BS EN14651:2005+A1:2007 requirements. The slot is used to ensure that the prism started to fail exactly at mid-span. The size of the slot is 5 mm width and 25 mm depth. The slot is sawn through the width of the prism at mid-span. The finished slot is shown in the Figure 3(a) and 3(b). The prism is then setup in the testing frame as shown in Figure 1. Vertical deflection is measured using LVDT which is positioned under the prism at mid-span. The load is then applied in increment of 0.5 kN. After the first crack is observed, the test is continued using deflection control. The test continued until the vertical deflection reached 10 mm.

Figure 3(a): Slot along the depth

Figure 3(b): Slot along the width

Results and Discussion

Table 1 shows the results of the flexural toughness test for the prisms left at room (27^{o}C) and also the one exposed to temperature of 200^{o}C, and 400^{o}C. The toughness indices are calculated based on the recommendation in ASTM C1018 [15]. From Table 1, for the single fibre of FRC at room temperature (27°C), the best fibre mix proportion is the concrete batch of (100-0) which is the ST fibres only, while the combined fibres of ST-PP is the (75-25). At 200°C, the best fibre mix proportion is the concrete batch of (100-0) which is also the ST fibres only, while the combined ST-PP is the (50-50). For the prisms exposed at 400°C, the best fibre mix proportion is the concrete batch of (100-0) which is the ST fibres only, while for the combined ST-PP is the (75-25).

Table 1: Flexural toughness indices results

Fibre Mix Proportion by Volume (%)		**Temperature (°C)**	**Toughness Indices**					
ST	**PP**		P_5 **(kN)**	P_{10} **(kN)**	f_5 **(MPa)**	f_{10} **(MPa)**	T_5 **(Joules)**	T_{10} **(Joules)**
Plain (Control)		27	15.1	5.5	3.69	1.34	13.83	20.17
100	0		34	26.1	8.31	6.38	31.14	95.71
75	25		31.6	25.3	7.72	6.18	28.95	92.78
50	50		24.5	18.1	5.99	4.42	22.44	66.37
25	75		23.8	20.2	5.82	4.94	21.80	74.07
0	100		22.5	19.9	5.50	4.86	20.61	72.97
100	0	200	30.1	21.8	7.36	5.33	27.57	79.94
75	25		28.1	20.3	6.87	4.96	25.74	74.44
50	50		24.3	21.9	5.94	5.35	22.26	80.31
25	75		17.1	11.9	4.18	2.91	15.66	43.64
0	100		9	4.5	2.20	1.10	8.24	16.50
100	0	400	27.1	24.6	6.62	6.01	24.82	90.21
75	25		28.4	23.5	6.94	5.74	26.01	86.17
50	50		17.2	14.2	4.20	3.47	15.76	52.07
25	75		9.9	8	2.42	1.96	9.07	29.34
0	100		7.3	4.3	1.78	1.05	6.69	15.77

Figure 4(a) and 4(b) show the samples before and after the exposure to high temperature. Further observation found that the addition of fibres in the concrete mixture inhibits the crack growth that occurred on the prisms during the loading increment. Compared this to plain concrete the result shows that the concrete mixture without adding any fibres has very low toughness indices and energy absorption. Furthermore, plain concrete breaks into two parts at failure, while FRC experienced stages of crack propagation, which the FRC absorbed energy after the ultimate load. Both ST and PP fibres hold the prisms from breaking into two parts and only produced flexural cracks at failure.

(a) Before exposure (b) After exposure

Figure 4: Prism condition before and after exposure to high temperature

From Figure 2 and 3, the exposure of FRC to elevated temperature shows that the toughness indices decrease as the temperature increases. This is due to spalling and deterioration of the prisms after the heating process as shown in Figure 4(b). When this occurred, the prisms become more brittle as compared with the one left at room temperature (27°C).

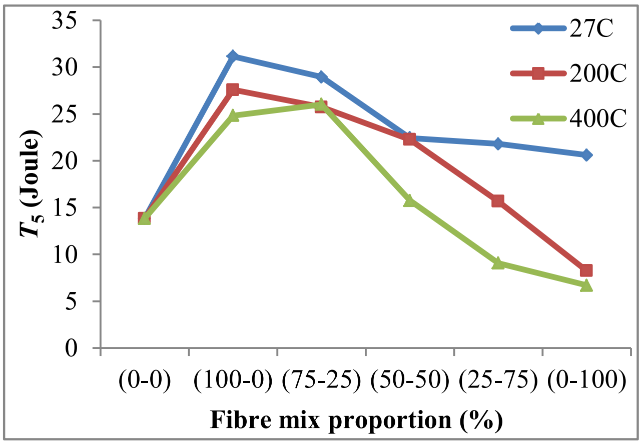

Figure 2: Toughness indices T_5

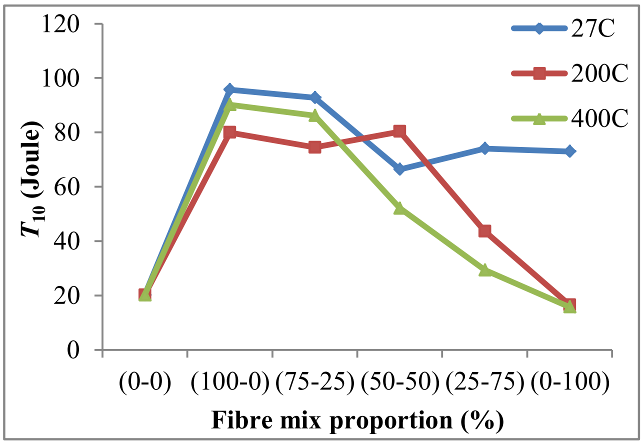

Figure 3: Toughness indices T_{10}

Conclusion

From the experimental work on flexural toughness, conclusions can be drawn as follows:

(a) When the prisms are exposed to an increase in temperature, the toughness indices and energy absorption is reduced.

(b) The concrete experienced spalling and deterioration after the heating process. At the same time, the prisms become more brittle.

(c) Addition of fibres in concrete enhanced the toughness. Adding ST and PP fibres in concrete inhibits cracking growth.

(d) For single type of fibre in FRC, the best fibre mix proportion is the concrete batch of (100-0) which is the one with ST fibre alone.

(e) For the combined ST-PP fibres in FRC, the concrete batch that can be adjudged as the most appropriate fibre mix proportion is the (75-25).

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