

MECHANICAL AND SHRINKAGE PROPERTIES OF HYBRID STEEL AND POLYPROPYLENE FIBRE REINFORCED CONCRETE COMPOSITE

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Article history

Received

17 March 2016

Received in revised form

23 May 2016

Accepted

15 August 2016

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Graphical abstract



Abstract

An experimental study had been carried out to investigate the mechanical properties, expansion and shrinkage of fibre reinforced concrete composite (FRC). However, instead of using single type fibre of either steel (SF) or polypropylene (PPF), this study also combined the two types in one mix. The mechanical properties investigated in this study include compressive strength, splitting tensile strength and flexural strength. Three different FRC mix proportions and one normal concrete (control) were casted which includes (a) 75% SF, (b) 75% SF + 25% PPF, (c) 25% PPF, and (d) 0% fibre for control (PC). Meanwhile, the volume fraction, V_f for the FRC was fixed at 1.5% and the concrete strength was designed to achieve grade C60 at 28 days. The results show that the use of fibres in concrete decreased the workability of concrete. In addition, concrete mix with both SF and PPF produced the highest splitting tensile and flexural strengths by an increase of 75.9% and 86.5%, respectively as compared with the control. Furthermore, expansion and shrinkage of FRC was found to be less than the control. It can be concluded that the combined SF and PPF in concrete gives the most appropriate combination as regards to the highest flexural and splitting tensile strengths, and also reduced the shrinkage strain.

Keywords: Shrinkage, mechanical properties, steel fibre, polypropylene fibre, fibre reinforced concrete

Abstrak

Satu kajian eksperimen telah dijalankan untuk menyiasat sifat-sifat mekanikal, pengembangan dan pengecutan konkrit komposit bertetulang gentian (FRC). Walau bagaimanapun, selain daripada menggunakan gentian tunggal jenis keluli (SF) atau polipropilena (PPF), kajian ini juga menggabungkan dua jenis gentian dalam satu campuran. Sifat-sifat mekanikal yang disiasat dalam kajian ini termasuk kekuatan mampatan, kekuatan tegangan dan kekuatan lenturan. FRC ini terbahagi tiga perkadaran campuran dan satu konkrit biasa (kawalan) yang meliputi (a) 75% SF, (b) 75% SF + 25% PPF, (c) 25% PPF, dan (d) 0% serat untuk kawalan (PC). Sementara itu, pecahan isipadu, V_f bagi FRC telah ditetapkan pada kadar 1.5% dan kekuatan konkrit direkabentuk supaya mencapai gred C60 pada 28 hari. Hasil kajian menunjukkan penambahan gentian dalam campuran konkrit akan mengurangkan tahap keboleherjaannya. Selain daripada itu, konkrit yang ditambah dengan gabungan gentian SF dan PPF telah menghasilkan kekuatan tegangan dan lenturan yang lebih tinggi, masing-masing sebanyak 75.9% dan

85.5% berbanding dengan konkrit kawalan dan konkrit lain. Tambahan lagi, pengembangan dan pengecutan konkrit yang mengandungi gentian didapati kurang berbanding konkrit kawalan. Maka dapatlah disimpulkan bahawa gabungan SF dan PPF dalam konkrit memberikan gabungan paling sesuai berhubung kekuatan tegangan dan lenturan yang tertinggi, dan juga mengurangkan terikan pengecutan.

Kata kunci: Pengecutan, sifat-sifat mekanikal, gentian keluli, gentian polipropelina, konkrit bertetulang gentian.

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1.0 INTRODUCTION

Concrete is known to be strong in compression but weak in tension [1]. This explained by its low resistance it exhibits to cracking which is caused by the concrete low tensile strength. Due to this setback, the inclusion of short discontinuous fibres such as synthetic, steel, natural or glass fibre in concrete is pertinent. Each type of fibre has its own properties, thus benefited in various ways when mixed in concrete. Fibre reinforced concrete (FRC) had been studied over the last few decades because it was found to improve the tensile resistance and the failure mode of normal concrete. Apart of being used as reinforcement, fibres are also effective in arresting cracks from forming and propagating at micro and macro levels [2, 3]. This is because fibres helps to reduce the widening of crack due to the available mechanical bond with the cement paste [4]. Fibres in concrete have also been found to be effective in controlling micro-cracks that can occur due to plastic shrinkage and drying shrinkage [5].

Most of the results from previous studies show that the use of single type fibre can only improve the properties of FRC to a limited extent. Therefore, new approach is being considered by adding two or more fibres in normal concrete, known as hybrid fibre reinforced composite concrete (HyFRCC). This is because HyFRCC can offer better engineering properties. The presence of one fibre enables a more efficient utilization of the potential properties of the other fibre [6]. This improvement is due to the different properties, sizes and types of each fibre. Positive results were found in regards to the enhancement on the bearing load capacity of concrete by utilizing large size steel fibre (SF) and small size polypropylene fibre (PPF) [7].

There were currently 3000,000 metric tons of fibres used for concrete reinforcement [8]. Steel fibre remains the most used fibre in the construction industry (50% of total tonnage used) followed by polypropylene (20%), glass (5%) and other fibres (25%) [9]. SF is usually mechanically mixed in concrete without undergoing any chemical reaction. It shapes is normally deformed with hooked-end to provide better anchorage and to increase the bond strength between the fibres and concrete matrix [10-12]. SF also has high elastic modulus and stiffness to improve the tensile strength and concrete toughness

[13]. Aspect ratio (AR) is the ratio of fibre length against the diameter (l/d). Higher AR and volume concentration of fibre will increase the performance of the FRC. SFs considerably enhanced concrete durability, flexural toughness and strength [14]. In the other hand, controlling the concrete crack width and pattern are also important for durability and aesthetic appearance. Shrinkage cracks can occur when concrete members undergo restrained volumetric changes (shrinkage) as a result of drying, autogenous shrinkage or thermal effects. Once the tensile strength of concrete exceeded, cracks will start to develop [15]. The tensile strength of concrete increases with the addition of SFs, but in order to produce concrete with homogenous tensile properties, the formation of micro cracks must be eliminated. Hence, synthetic fibre such as PPF used in this study with the length of 19 mm can act as micro fibre to eliminate or reduce the formation of micro cracks. This is because PPF has good ductility, fineness, and dispersion properties, and therefore can restrain plastic cracks [16]. On the other hand, SFs can reduce the formation of macro cracks. Thus, it is expected that the combination of PPF and SF will produce superior structural element by enhancing the mechanical properties of the concrete.

There are many types of fibre in the market but the two commonly used in practice are steel and synthetic fibres. SFs are used in a wide range for structural applications such as industrial floors and pavements [17], precast element [18] and tunnel lining [19]. Meanwhile, synthetic fibre is also commonly used in construction especially to enhance the fresh state properties where plastic shrinkage occur and need to be controlled. Synthetic fibres are also added in low volume fractions to normal concrete to act as secondary reinforcement or to control inherent plastic shrinkage from occurring at the early ages [20]. Among the polymer fibres, PPF has attracted the attention among researcher because of its low cost, outstanding toughness and can enhance shrinkage cracking resistance in FRC. PPF is purely hydrocarbon with high crystallinity, chemical inertness and does not absorb water. It is usually made in the form of plastic film and therefore it can easily reach the mesh structure between the individual fibrils to create a mechanical bond between the matrix and fibre [5, 7, 21]. This study investigated the effect of the inclusion

of synthetic fibrillated type PPF and hooked-end type SF on the properties of FRC at fresh and hardened state. Experimental test at fresh state was carried out for its workability, while compressive strength, splitting tensile strength, flexural strength, expansion and shrinkage were determined at hardened state. Hooked-end type SF was chosen because of its sufficient anchorage bond with the cement matrix. Meanwhile, fibrillated type PPF was chosen based on its ability to reduce concrete shrinkage at fresh state. The amount of fibres included in the concrete mix for SF and PPF were 88.3 kg/m^3 and 1.67 kg/m^3 , respectively.

2.0 EXPERIMENTAL PROGRAM

2.1 Material and Mix Proportion

Cement used in this study was Ordinary Portland Cement (OPC) Type 1. Meanwhile, 10 mm well graded size crushed granite and locally available river sand were used for the coarse and fine aggregates, respectively. The concrete strength was designed based on the DoE method to achieve compressive strength of 60 N/mm^2 at 28 days. Meanwhile, the water-to-cement ratio, w/c was fixed at 0.38. Hooked-end type SF of 60 mm long and 0.75 mm diameter was used in this study as shown in Figure 1, giving an aspect ratio, l/d of 80. Meanwhile, the virgin fibrillated type PPF as shown in Figure 2 was 19 mm long. The properties of both SF and PPF are given in Table 1 and 2, respectively. The mixture is different in proportions and is based on the percentage of (i) 0% (control), (ii) 75% SF + 25% PPF, (iii) 75% SF and (iv) 25% PPF. Meanwhile, the total fibre volume fraction, V_f was fixed at 1.5% for each proportions for consistency. In order to improve concrete workability, superplasticizer was also added in the mixture at 3% of the cement content. The material proportions for 1 m^3 concrete are summarised in Table 3.



Figure 1 Hooked-end type SF



Figure 2 Fibrillated type PPF

Table 1 Details of Steel Fibre (SF)

No.	Parameters	Capability
1	Type	HE 0.75/60
2	Shape	Hooked-End Deformed
3	Length (mm)	60
4	Diameter (mm)	0.75
5	Aspect Ratio, l/d	80
6	Tensile Strength (N/mm^2)	1100
7	Unit Weight (kg/m^3)	7850
8	Coating	None
9	Elastic Modulus, E (MPa)	205 000

Table 2 Details of Fibrillated Polypropylene Fibre (PPF)

No.	Parameters	Capability
1	Type	Virgin PPF
2	Length (mm)	19
3	Thickness (mm)	0.2
4	Unit Weight (kg/m^3)	446
5	Tensile Strength (N/mm^2)	400
6	Thermal Conductivity	Low
7	Elastic Modulus, E (MPa)	3500

Table 3 Material proportions for 1 m^3 concret

Concrete Batch	SF (kg/m^3)	PPF (kg/m^3)	FA (kg/m^3)	CA (kg/m^3)	Water (kg/m^3)	Cement (kg/m^3)	w/c	SP (%)
Control	-	-	794	794	210	522	0.38	3
75% SF	88.3	-	794	794	210	522	0.38	3
75% SF + 25%PPF	88.3	1.67	794	794	210	522	0.38	3
25% PPF	-	1.67	794	794	210	522	0.38	3

SF – Steel Fibre, PPF – Polypropylene fibre, FA- Fine Aggregate, CA – Coarse Aggregate, w/c- Water-to-cement ratio, SP- Superplasticizer

2.2 Concrete Testing

The concrete mixture at fresh state was tested for its workability using slump cone test. The main purpose of the test is to determine the effect of adding fibre in concrete on its workability. In this study, concrete slump was designed between 60 mm and 180 mm and followed the method given in BS EN 12390-2: 2009 [22].

Cubes of 150 × 150 × 150 mm and cylinders of 100 mm diameter × 300 mm height were used to determine the compressive strength and splitting tensile strength, respectively. Meanwhile, prisms of 100 × 100 × 500 mm were used to determine the flexural strength and also for carrying out expansion and shrinkage test.

The compression, splitting tensile and flexural test was carried out using MATEST 2000 kN compression machine. The pace rate for the compression test was applied at 7.0 kN/s, while the flexural test at 0.5 kN/s. For the splitting tensile test, the pace rate was applied at 5.0 kN/s. The loading pace was constantly applied until the specimens failed.

The compressive strength for each proportion was determined at 7 and 28 days. Meanwhile, the tensile splitting and flexural strengths were determined at 28 days. In addition, expansion and shrinkage of the each proportion were also monitored. This was done by immersing the specimens in water for the expansion test, while the shrinkage was measured by exposing the specimens in air.

The procedures used in carrying out each test were in accordance to the related standard in BS EN 12390-3: 2009 [23] for compressive strength test, BS EN 12390-6: 2009 [24] for splitting tensile strength test, BS EN 12390-5: 2009 [25] for flexural strength test and BS ISO 1920-8: 2009 [26] for drying shrinkage test.

3.0 RESULTS AND DISCUSSION

3.1 Concrete Workability

The concrete slump relationship for all mixtures including the control (normal concrete) is shown in Figure 3. The relationship shows that the inclusion of fibres at $V_f = 1.5\%$ significantly altered the rheological behaviour of fresh concrete. It was found that adding short fibres in concrete mixture reduced its workability. In particular, the inclusion of SF increased the concrete resistance to flow. This can be seen from the figure where a descending pattern was observed when either SF or PPF were added into the concrete mixture. The combined SF and PPF in the mixture show the lowest slump at 62 mm due to higher amount of fibres in the mixture. This was found to be 33% less than the control mix suggesting that the mixture with the combined fibres was more congested as compared with the other single fibre mixture.

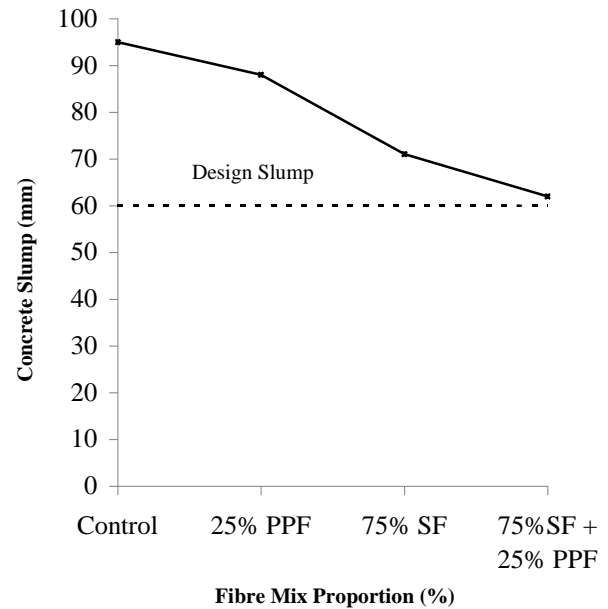


Figure 3 Relationship between concrete slump and fibre mix proportion

3.2 Concrete Strength

The results of the compressive strength, splitting tensile strength and flexural strength for all mixtures including the control are given in Table 4. In general, the compressive strength relationship shown in Figure 4 for all mixtures achieved the targeted design strength of 60 N/mm² at 28 days. The compressive strength of 75% SF mixture increased by 10.4% compared with the control. Similarly, the combined 75% SF + 25% PPF mixture increases by 10.0% from the control. However, when only 25% of PPF was added in concrete the compressive strength decreases by 0.30% as compared with the control. This finding suggested that the inclusion of fibre does not have significant effect on the improvement to the compressive strength, which was also verified by other researchers [17, 27, 28]. However, improvement can be observed by the failure pattern as shown in Figure 5. There was less cracking appeared at failure, which suggested an improvement to the failure mode as compared with normal concrete. This shows that the brittle failure observed in normal concrete can be improved to more ductile mode by adding fibres in the mixture.

The tensile strength for concrete with 75% SF was found to increase by 76.7% as compared with the control. Meanwhile, for the 75% SF + 25% PPF mixture, the tensile strength was increased by 86.6% compared with the control. However, the tensile strength for the 25% PPF mixture was only 5.9% higher than the control. This shows that PPF has less effect on the tensile strength as compared with SF due to the different in length and stiffness of the fibre. This was expected and previous studies showed that PPF only contributed in reducing micro-crack at fresh state of

the concrete mixture [29, 27]. The relationship between the tensile and flexural strengths as compared to the amount of fibre for all mixtures is shown in Figure 6. There was substantial increase of about 86.3% on the tensile strength by the fibre hybridization process of both SF and PPF. The failure mode of the cylindrical specimens was also improved as shown in Figure 7. It can be seen that the cracking pattern by the fibre hybridization process was less than the one with single fibre alone (either SF or PPF), while the control (normal concrete) splits into two parts. This shows that specimens with fibre hybridization process had higher ductility compared with normal concrete.

The flexural strength relationships in Figure 6 shows that the 75% SF mixture recorded an increase of 71.5% than the control, while the combined 75% SF + 25% PPF mixture increased by 75.9%. The increase in strength was attributed to the enhancement of tensile strength resulted from good bonding between the fibres and concrete matrix. However, for the mixture with PPF alone (25% PPF), a slight decreased of about 4.9% in strength was observed than the control. This was mainly due to the shorter PPF compared with SF which resulted in lower bonding mechanism between PPF and the concrete matrix. The experimental results show that the combined 75% SF + 25% PPF mixture produced better flexural resistance compared with the other mixtures. This pattern is similar to the finding from the tensile strength and also from other previous studies [30, 31, 32]. The failure mode of the prism specimens is shown in Figure 8. The FRC specimens did not break into two parts at failure compared with the control (normal concrete). From visual inspection, the combined 75% SF+ 25% PPF mixture had less cracking at failure compared with either the 25% PPF or the 75% SF mixture alone. The test results also indicate that the combined 75% SF + 25% PPF mixture enhanced both tensile and flexural strengths in terms of its ultimate loading capacity and failure mode.

Table 4 Summary of the concrete strength test results

Concrete Batch	Compressive Strength, f_{cu}	Splitting Tensile Strength, f_{ct}	Flexural Strength, f_l
(SF-PPF)	N/mm ²	N/mm ²	N/mm ²
Control	6.01	37.29	0.00
25%PPF	6.56	40.69	6.31
75%SF +25%PPF	11.08	58.05	10.58
75%SF	17.44	57.67	10.32

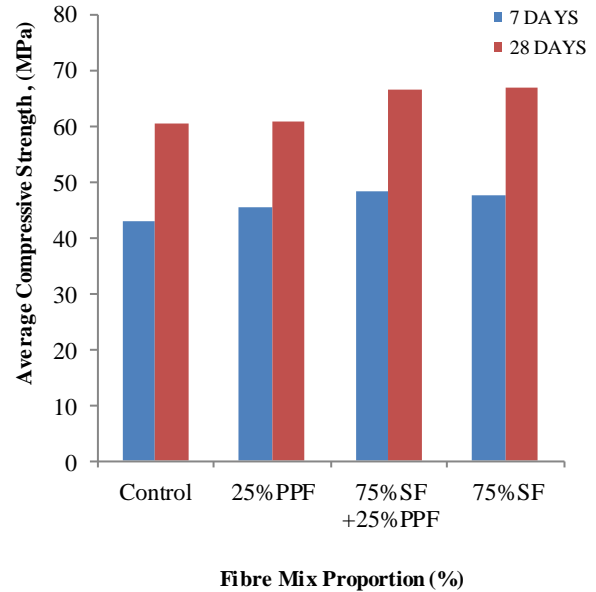


Figure 4 Relationship between the average compressive strength and fibre mix proportion

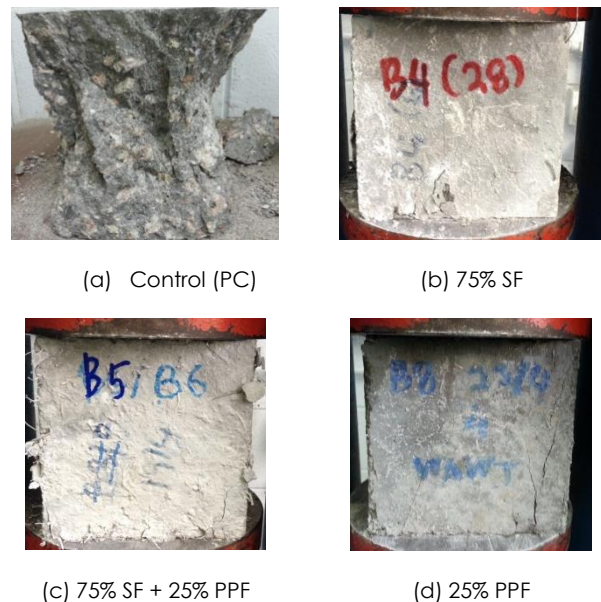


Figure 5 Failure mode of the cube specimens

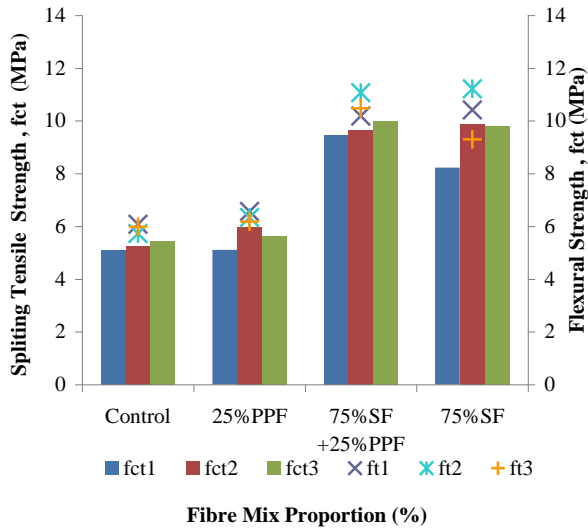
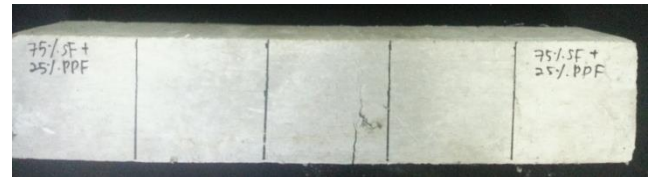


Figure 6 Relationship between the average flexural strength, tensile strength and the fibre mix proportion



(c) 75% SF + 25% PPF



(d) 25% PPF

Figure 8 Failure mode of the prism specimens



(a) Control (PC)

(b) 75% SF

(c) 75% SF + 25% PPF

(d) 25% PPF

Figure 7 Failure mode of the cylindrical specimens



(a) Control (PC)



(b) 75% SF

3.3 Expansion and Shrinkage

Figure 9 shows the specimens used to determine the expansion and shrinkage for all mixtures. The expansion and shrinkage upon exposure to tropical climate condition were recorded up to 240 days.



(a) Specimens for expansion



(b) Specimens for shrinkage

Figure 9 Specimens exposed to tropical climate condition

The results of expansion and shrinkage for all mixtures are shown in Figure 10. Shrinkage can occur from the same source such as hydrated cement paste, exposed to humidity below saturation and absorbed water from C-S-H resulted in shrinkage strain [33]. Therefore, temperature and relative humidity (RH) are important parameters to be considered in the study. Figure 11(a) and Figure 11(b) shows the recorded temperature and relative humidity throughout the 240 days exposure, showing relatively constant value. The recorded average day-time RH and temperature were 82% and 28.8°C, respectively. Referring to the Malaysia Meteorological Department, the recorded daily average temperature and RH at Senai station is 26°C and 86.7%, respectively [34]. The data obtained from the meteorological station in Senai can best reflect the condition of the surrounding as it is the nearest location with the laboratory where the experimental test was carried out [35]. Meanwhile, the recorded monthly mean of RH was between 70% and 90% with an average daily maximum temperature between 31°C and 33°C. On the other hand, the average daily minimum temperature ranging between 22°C and 23.5°C. The shrinkage strain shown in Figure 10 is referred to drying shrinkage as autogenous shrinkage was not considered in this study. This is because the initial reading was taken after the specimen cured, where most of the hydration process which causes autogenous shrinkage would have taken place. The shrinkage was recorded up to 8 months. Strain for normal concrete is usually ranged between 400×10^{-6} and 1000×10^{-6} [36]. Meanwhile, the recorded drying shrinkage for all mixtures shown in Figure 10 ranged between 130×10^{-6} and 330×10^{-6} . This shows that for concrete grade C60 (high strength concrete), the relationships follow the normal trend with lower strain. Even though the cement content is higher for high strength concrete, but the low water content in the mixture restricted the shrinkage through less water losses into the surrounding. However, the lowest shrinkage strain for expansion in Figure 10 was recorded for 75% SF mixture and also the combined 75% SF + 25% PPF mixture. This is because the fibres have strong bonding properties with the concrete matrix which provided sufficient restraint to the mixture and therefore, reduced expansion and shrinkage. The higher shrinkage strain was recorded for normal concrete. This is due to the loss of moisture which resulted to the constant increase in shrinkage strain. Meanwhile, expansion with 25% PPF mixture was found to be moderate between the control and the combined 75% SF + 25% PPF mixture.

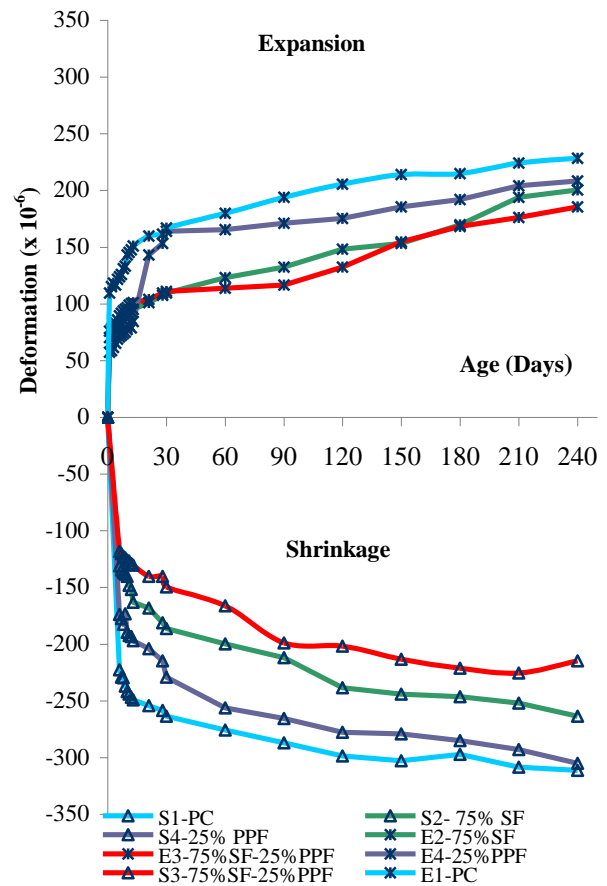


Figure 10 Expansion and drying shrinkage relationships for all concrete mixes

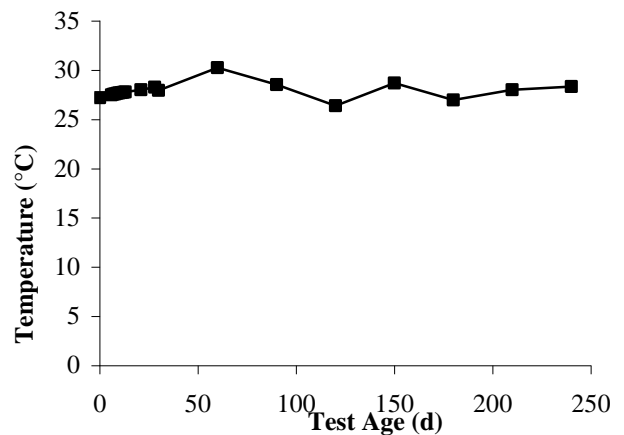


Figure 11(a) Temperature of test condition

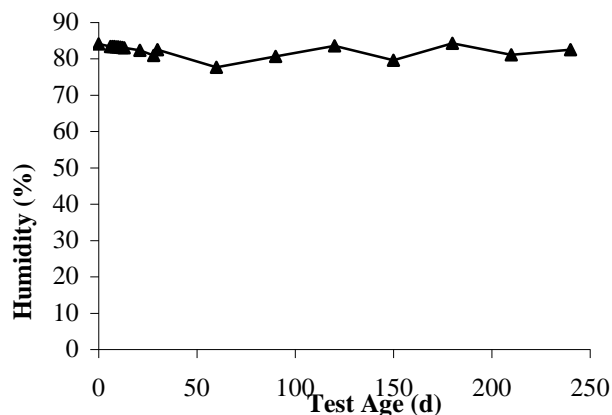


Figure 12(b) Relative Humidity of test condition

4.0 CONCLUSIONS

Based on the experimental test results, the conclusions that can be drawn as follows:

- (i) The workability of fresh concrete was found to be affected by the amount of fibre in the mixture. Higher amount of fibres in the concrete mixture resulted in low workability. The mixture with the combined 75% SF + 25% PPF was stiffer, less workable and difficult to compact as compared with the single fibre mixture alone of either 75% SF or 25% PPF.
- (ii) The combined 75% SF + 25% PPF mixture produced the highest flexural and tensile strengths showing an increase of 86.5% and 75.9%, respectively compared with normal concrete. The results also show that the effect from the combined fibres was less significant in compression even though they enhance the tensile and flexural strengths.
- (iii) The addition of fibres in the concrete mixture can reduce shrinkage and expansion strain. Experimental results show that the combined 75% SF + 25% PPF mixture resulted in less drying shrinkage and expansion compared with the other mixtures of 75% SF, 25% PPF and normal concrete.

Acknowledgement

This research was funded by the Research University Grant (RUG) No. 09H36. Invaluable appreciation goes to all staffs and Assistant Engineers in the Structures and Materials Laboratory, Faculty of Civil Engineering and Faculty of Chemical, Universiti Teknologi Malaysia (UTM). Special acknowledgment also goes to the Ministry of Higher Education Malaysia (MoHE) and Universiti Tun Hussein Onn Malaysia (UTHM) for the scholarship sponsored throughout the study.

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