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MECHANICAL PROPERTIES OF HYBRID FIBRE REINFORCED COMPOSITE CONCRETE (HYFRCC)

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Abstract: Introducing fibres into concrete not only enhances the requisite properties of reinforced concrete but also changes the material characteristic from brittle to ductile failure. Steel fibre (SF) is found to enhance the flexural and tensile strengths, and at the same time is able to resist the formation of macro cracking and concrete spalling. Meanwhile, polypropylene fibre (PPF) will contribute to the tensile strain capacity and compressive strength, and also delaying the formation of micro cracks. Therefore, the mechanical properties of concrete are discussed in this paper of which SF and PPF are combined and mixed together in concrete. For this purpose, hooked-end type deformed steel fibre and fibrillated type virgin polypropylene fibre are used in the experimental work where the concrete strength is maintained for grade C30. The specimens incorporated with SF and PPF are different in terms of its percentage proportions, however, the total volume fraction is fixed at 1.5%. The experimental result shows that the percentage proportion containing 75% SF and 25% PPF produced the highest flexural and tensile strengths with an increase of 45.89% and 25.93%, respectively than that of the plain concrete. For flexural toughness, specimen with 100% SF and 0% PPF produced the highest value of 66.6 Joule. Meanwhile, for compressive strength, there is not much contribution for both SF and PPF to the mechanical properties of the concrete.

Keywords: *Hybrid fibres, steel fibre, polypropylene fibre,*

1.0 Introduction

Concrete are the second most consumed construction materials after water with twice the amount used across the world than any other construction material. Concrete main characteristic is known to be strong in compression but weak in tension (Ahmed *et al,* 2006; Nordin *et al*., 2013*)* . Yet, concrete as a brittle material which is also associated with creep and drying shrinkage can also induced cracking problems and concrete deterioration (Ibrahim and Che Bakar, 2011; Ravasan, 2014). Concrete reinforced with short distributed fibres is known as fibre reinforced concrete (FRC) which can address some of the concerns on concrete brittleness and cracking growth (Balaguru and Shah, 1992; Awal *et al*., 2013). However, by hybridization with two or more different type of fibres, the mechanical and physical performances take benefits from each fibres and form a synergistic response (Banthia and Gupta, 2004). In this study, the hybridization is known as hybrid fibre reinforced composite concrete (HyFRCC). It is endeavoring to reduce shrinkage cracks and control the early thermal contraction of fresh concrete right after placing into the formwork. The combination of fresh concrete mixes with steel fibre (SF) and polypropylene fibrillated fibre (PPF) may improve the different mechanical properties of concrete as reported by Qian and Stroeven, (2000). HyFRCC has been applied in construction with an increasing rate such as in tunnel lining, tunnel segmental wall, sleepers for railways and many others. Looking into this possibility, therefore, the main objective of this study is to determine the mechanical properties of the combined SF and PPF in concrete as compared with the plain ones. The SF and PPF used is shown in Figure 1. This study focuses on the compressive strength, flexural strength, splitting tensile strength and flexural toughness of the HyFRCC.

(a) Fibrillated polypropylene fibre

(b) Hooked end steel fibre

Figure 1:Type of fibres used in this study

Tadepalli et al (2009) in his study on the effects of steel fibre reinforcement found that the most effective shape for energy absorption capacity is the hooked end type fibres. Steel fibre with higher modulus of elasticity should be used with volume fraction, V_f within 0.5% to 1.5% as the additional fibres may reduce the workability of mix and cause balling which will be extremely difficult to separate by vibration (ACI 544.5R-10, 2010). Polypropylene fibre (PPF), which is a synthetic fibre made through extrusion process has low modulus of elasticity, low fire resistance and low durability. PPF fibre cannot prevent the formation and propagation of high stress level and cannot prevent larger cracks (Dilip, 2014; Zhang and Zhao, 2012). In order to improve the potential crack control, it is necessary to mix steel fibre and polypropylene fibre in concrete to reduce crack growth on structural element in construction industry. Synthetic fibres were observed as effective for bridging micro crack whereas steel fibres were found good for arresting macro crack. Figure 2 shows the schematic diagram how the hybridization of fibres controls the cracks.

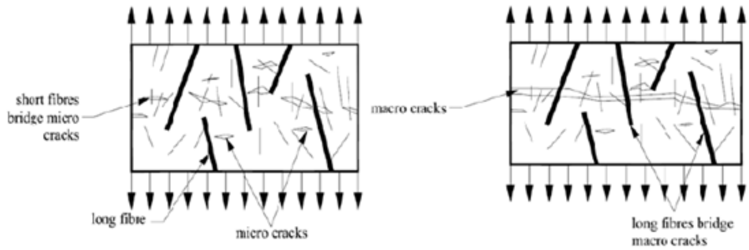


Figure 2: Actions of hybrid fibres in controlling cracks. Source (ACI 544 1.R-96, 2002)

2.0 Materials and Methods

2.1 Materials , Concrete Mix, Specimen Preparation & Testing

Six (6) concrete batches are produced and tested during fresh and hardened state. The first batch is the control batch with plain concrete where the fibre volume fraction, V_f = 0%. The other five (5) batches are HyFRCC with different proportion of SF and PPF. All concrete batches have the same amount of cement, fine aggregate, coarse aggregate, water, and superplasticizer. The water-to-cement ratio is also fixed at 0.55 for all concrete batches. The total amount of SF and PPF based on the different percentage proportion is shown in Table 1. The design mix is based on the method given by the Department of Environment (DoE). The concrete mix is designed to achieve compressive strength of 30 N/mm^2 at 28 days. The addition of fibre is known to affect the workability and flow ability of fresh concrete. Therefore, superplasticizer is added in the concrete mixture to improve the workability especially at higher volume fraction. The mixing of the materials is carried out in specific sequence as stated in BS EN 206:2013.

Table 1: Concrete mixture proportion

Concrete Batch	**Steel Fibre Hooked End (Kg)**	**Fibrillated Polypropylene Fibre (Kg)**	**Design at 28-days (N/mm^2)**	**w/c**	**Ordinary Portland Cement (Kg)**	**Fine Aggregate (Kg)**	**Coarse aggregate (max size of 10mm) (Kg)**	**Water (Kg)**	**Super-plasticizer (ml)**
PC	0.00	0.00	30	0.55	40.95	81.40	66.60	22.50	250
SF(100-0)	10.60	0.00							
HY(75-25)	7.95	0.15							
HY(50-50)	5.30	0.30							
HY(25-75)	2.65	0.45							
PP(0-100)	0.00	0.60							

The SF used in this study is also known as hooked end steel fibres. This type of SF has been used in the construction industry to improve the properties of hardened concrete. The introduction of hooked-end deformed type SF has been elaborated in detailed in ACI544.4R-88 1999. PPF is more effective in controlling drying shrinkage and durability as described by Dilip, (2014) and Zhang and Zhao, (2012). Table 2 and Table 3 summarised the properties of SF and PPF used in this study, respectively.

Table 2: Properties of Steel Fibre

Properties	**Steel Fibre**
Type	HE0.75/60
Shape	Hooked-End Deformed
Length (mm)	60
Diameter (mm)	0.75
Aspect Ratio , l/d	80
Tensile Strength	1100
Unit Weight (kg/m^3)	7850
Coating	None
Elastic Modulus ,E	205000 MPa

Table 3: Properties of Polypropylene Fibre

Properties	**Polypropylene Fibre**
Type	Virgin PPF
Shape	Fibrillated
Length (mm)	19
Thickness (mm)	0.2
Unit Weight (kg/m^3)	446
Tensile Strength	400 N/mm^2
Thermal Conductivity	Low
Elastic Modulus ,E	3500 MPa

The fibre mixing process in the concrete mixer is shown in Figure 3. Coarse and fine aggregates are first introduced into the mixer and mixed for a few minutes. This is then followed by cement and water. Then fibres are added in stages to avoid the “balling effect” phenomena to occur. This will also help to achieve uniform material consistency and produce good concrete workability. After both fibres are added, the concrete is mixed continuously with sufficient time between 3 to 5 minutes at high speed rotation in order to ensure uniform distribution of the fibres throughout the concrete.

Figure 3: Concrete mixer

Slump test is used as a measurement tool to determine the concrete workability at fresh state. At 28 days, four (4) tests are carried out to determine the compression strength, tensile splitting strength, flexural strength and flexural toughness. For this purpose, cubes of 150 x 150 x 150 mm, cylinders of 150 mm diameter x 300 mm height, prisms of 100 x 100 x 500 mm and 100 mm x 100 mm x 350mm are prepared. The tests are carried out in accordance to BS EN 12390-2-2009 for slump test (BSI, 2009a), BS EN 12390-3:2009 for compressive strength (BSI, 2009b), BS EN 12390-6:2009 for splitting tensile strength (BSI, 2009d), BS EN 12390-5:2009 for flexural strength and ASTM C1609/C1609M-12 for flexural toughness (BSI, 2009c). The experimental setup for all tests is shown in Figure 4.

(a)Compression test | (b)Spliting tensile test | (c) Flexural test | (d) Toughness test

Figure 4: Experimental test setup

3.0 Results and Discussion

3.1 Experimental Results at Fresh State

Figure 5 shows the relationship between the concrete slump and the fibre percentage proportion at V_f = 1.5%. In this study, the concrete slump is designed between 60 and 180 mm. The relationship shows a descending pattern when fibres are added in the concrete mixture. SF with 60 mm long and PPF with 19 mm long when added in concrete affected the mixture by reducing the workability of the concrete. Furthermore, the higher the amount of fibres added, it also causes congestion in the concrete mix. The addition of both SF and PPF decrease the slump from 85 mm for plain concrete to only 40 mm.

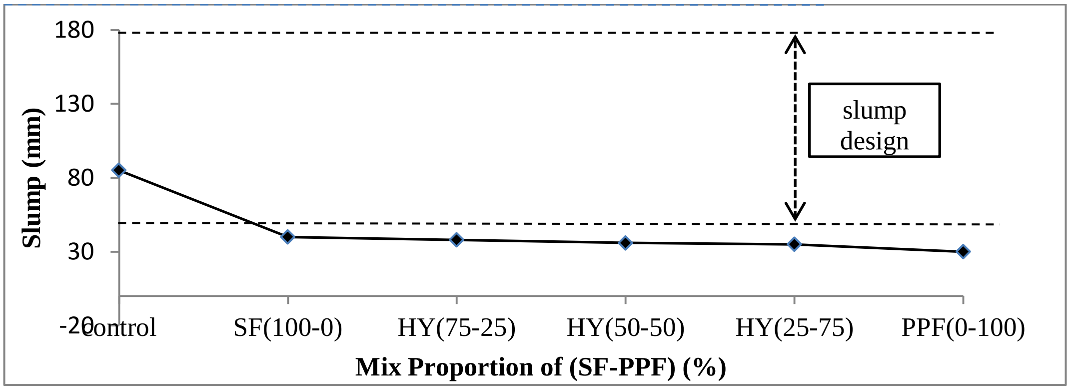


Figure 5: Relationship between concrete slump and fibre percentage proportion

3.2 Experimental Results at Hardened State

Table 4 summarizes the test results on the mechanical properties of plain concrete, FRC and HyFRCC including the compressive strength, flexural strength and splitting tensile strength. Figure 6 shows the relationship between the compressive strength and the percentage proportion of SF-PPF. The values in the table are based on the calculated average of three cubes. The compressive strength of SF(100-0) increases by 20.42% than plain concrete. For HyFRCC batches, Hy (75-25) increase by 8.56%, but Hy (50-50) and Hy (25-75) showed a decrease of 0.46% and 4.07%, respectively as compared with plain concrete. When only PPF is mixed in concrete, PPF(0-100), a further dropped in compressive strength by 6.65% is observed. The study found that HyFRCC does not have significant effect on the improvement of the compressive strength. The improvement can only be seen for FRC using SF as indicated by the results of SF(100-0) batch. However, improvement can be observed by the failure pattern of the cubes as shown in Figure 7. There are less cracking and at the same time improved the failure mode into a ductile manner.

The splitting tensile strength of SF (100-0) increases by 19.70% as compared with plain concrete. This can be seen from the relationship in Figure 8. For Hy (75-25), Hy (50-50) and Hy(25-75) batches, there is an increase of tensile strength by 25.93%, 18.11% and 18.97%, respectively. However, for PPF (100-0) batch, which is PPF alone, the increase in percentage is only 5.51%. There is also a substantial increase in the splitting tensile strength by hybridization process. This is shown by the result obtained for Hy(75-25) batch with 25.93% increase. The finding shows that HyFRCC improves the splitting tensile strength as compared with FRC or single fibre mixture and plain concrete. The failure pattern of the cylinder specimens is as shown in Figure 9. It is observed that the cracking on the specimens with hybrid fibres are less than concrete with mono fibres while the plain concrete specimen was split into two havles. This indicates that concrete specimens with hybrid fibre have higher ductility compared to plain concrete.

The flexural strength relationship in Figure 10 shows that SF (100-0) batch increases the strength by 36.58%. This mixture uses only single SF. The Hy (75-25), Hy (50-50) and Hy (25-75) batches show an increase of 45.89%, 10.59% and 13.98%, respectively. However, as the PPF proportion is increased, there is a slight drop in strength as compared with plain concrete. As for the FRC with PPF alone, PPF (0-100), the result suddenly shows a descending pattern with a decrease of 4.57%. The study suggested that HyFRCC of Hy(75–25) batch with flexural strength increase of 45.89% produced better flexural resistance as compared with the other batches. This is similar to that of the splitting tensile strength result. The sudden decrease in flexural strength for PPF(0-100) batch is probably due to the non-uniform fibre distribution in the specimen. The failure mode of prism specimens can be seen in Figure 11. The concrete specimens except the plain concrete did not break into two parts at failure. Therefore, the test results show that hybridization process improved both the splitting tensile and flexural strengths as compared with single fibre mixture or FRC and plain concrete.

Table 4: Result of compressive strength, flexural strength test and splitting tensile test

Concrete Batch (SF-PPF)	**Compressive Strength, f_{cu}**		**Splitting Tensile Strength, f_t**		**Flexural Strength, f_{ct}**	
	N/mm^2	**Difference than PC (%)**	**N/mm^2**	**Difference than PC (%)**	**N/mm^2**	**Difference than PC (%)**
PC (Control)	38.78	0.00	4.284	0.00	6.013	0.00
SF (100-0)	46.70	20.42	5.128	19.70	8.213	36.58
HY (75-25)	42.10	8.56	5.395	25.93	8.774	45.89
HY (50-50)	38.66	-0.46	5.061	18.11	6.651	10.59
HY (25-75)	37.20	-4.07	5.101	18.97	6.854	13.98
PPF (0-100)	36.20	-6.65	4.520	5.51	5.738	-4.57

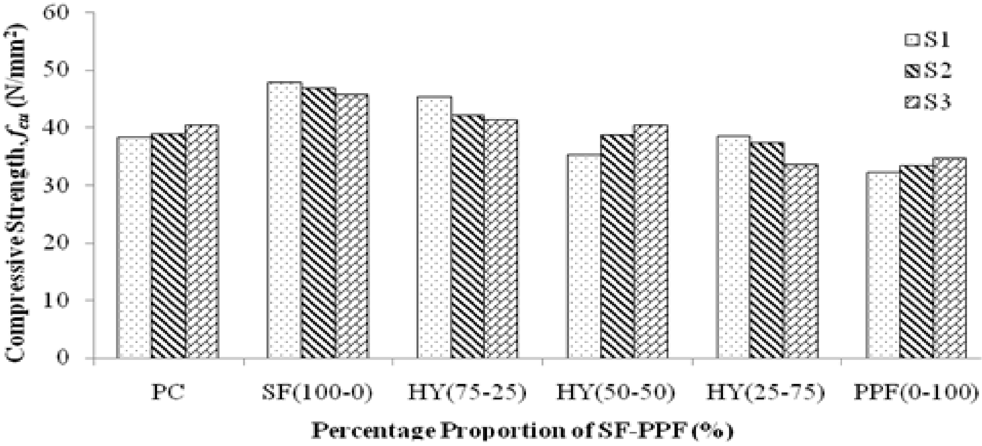
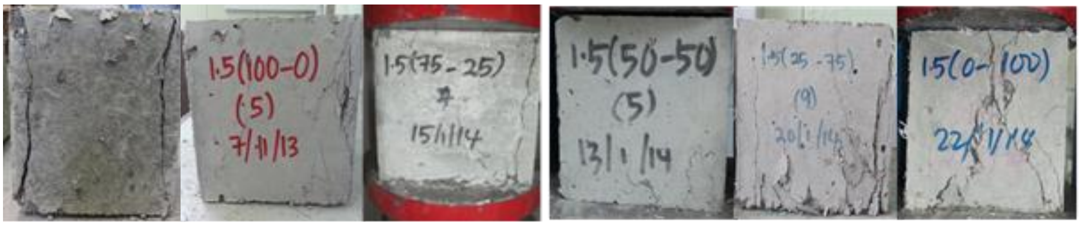


Figure 6: Relationship between compressive strength (f cu) and volume proportion (%)



(a)PC(Control) (b)SF(100-0) (c)Hy(75-25) (d) Hy(50-50) (e)Hy(25-75) (f)PPF(0-100)

Figure 7: Failure mode of the cube specimens

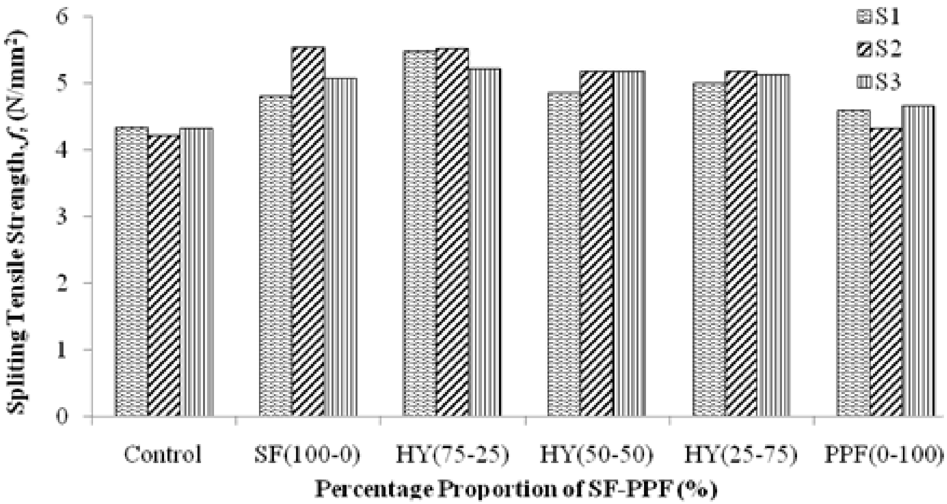


Figure 8: Relationship between splitting tensile strength (f_t) and volume proportion (%)

(a)PC(Control) (b)SF(100-0) (c)Hy(75-25) (d) Hy(50-50) (e)Hy(25-75) (f)PPF(0-100)

Figure 9: Failure mode of the cylinder specimens

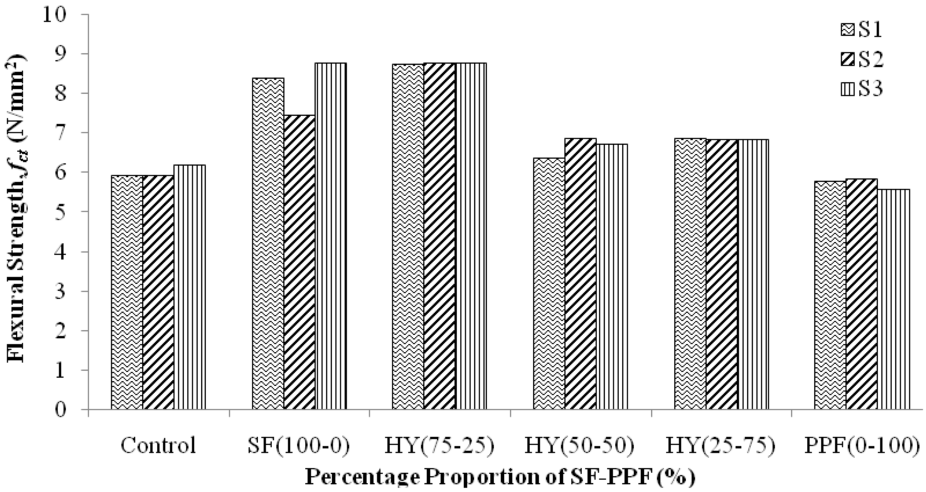


Figure 10: Relationship between flexural strength (f_{ct})and volume proportion (%)

(a) PC Control (b) SF(100-0) (c) Hy(75-25)

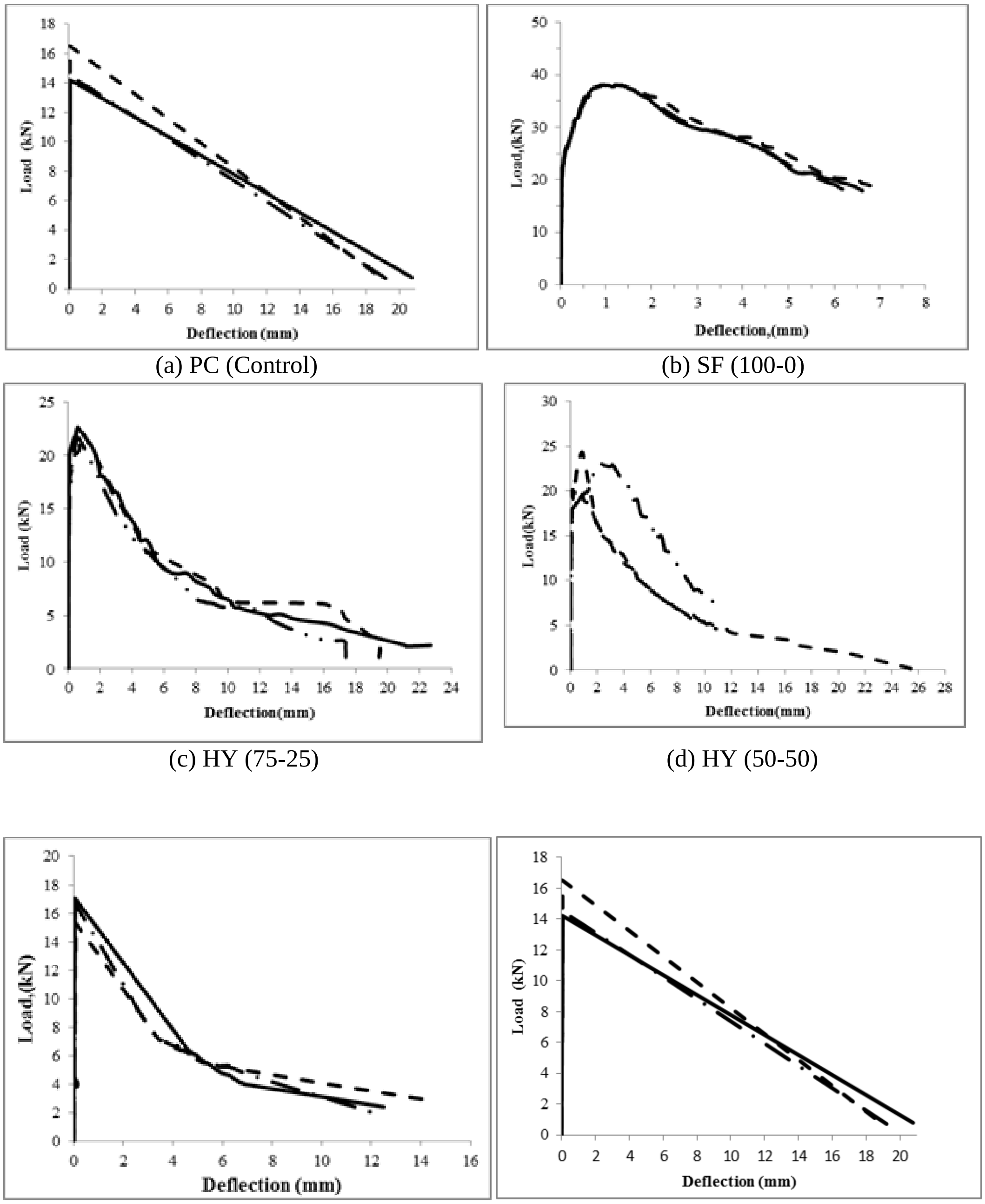
Figure 11: Failure mode of the prism specimens

Toughness is an important characteristic for FRC. Flexural toughness can be defined as the area under the load-deflection curve under static load, which is the total energy absorbed prior to complete separation of the specimen (ACI 544 1.R-96, 2002). Based on the load-deflection relationship shown in Figure 12, apparent toughness indices are calculated and summarized in Table 5. The calculation follows the requirement in ASTM C1609/C1609M-12. The highest toughness indices are given by the FRC with SF (100-0) batch. The increase in toughness indices, T_{600} and T_{150} shows that FRC and HyFRCC are tougher than plain concrete. SF will resist the load when the prism is under loading and will absorb more energy before it fails. The result shows the ductile characteristic when the highest value of T_{150} is obtained by SF (100-0) batch with 66.5 Joule, while Hy (75-25) and Hy (50-50) batches obtained 38.6 Joule and 34.6 Joule, respectively. The values are higher than plain concrete with only 30 Joule. Meanwhile, for PPF (0-100) and Hy (25-75) batches, T_{150} is lower than plain concrete with 24.5 Joule and 25 Joule, respectively. This shows that when the proportion of PPF is higher than SF in the concrete mixture, it will intersect tiny macro crack to prevent from further growth and remains in its initial micro crack

As shown in Figure 12, the relationship shows a more ductile behavior for both FRC and HyFRCC batches. This is also can be seen by the failure mode where the samples did not break into two parts at failure as compared with plain concrete. At the same time, deflection continues to increase after the first crack occurred. As compared with plain concrete, the pattern shows steeper slope after the first crack with sudden drop in deflection

Table 5: Toughness indices

Concrete Batch (SF-PPF)	**P_{600} (kN)**	**P_{150} (kN)**	**f_{600} (N/mm^2)**	**f_{150} (N/mm^2)**	**T_{600} (J)**	**T_{150} (J)**
PC	16.2	15.0	4.86	4.50	8.0	30.0
SF(100-0)	34.9	35.0	10.47	10.50	14.2	66.5
HY(75-25)	22.4	18.5	6.72	5.55	11.1	38.6
HY(50-50)	21.5	16.7	6.45	5.01	9.5	34.6
HY(25-75)	16.2	12.5	4.86	3.75	8.1	25.0
PPF(0-100)	14.0	13.0	4.20	3.90	5.4	24.5



(a) PC (Control) (b) SF (100-0)

(c) HY (75-25) (d) HY (50-50)

(e) HY (25-75) (f) PPF (0-100)

Figure 12 : Load-deflection relationship for all concrete batches

4.0 Conclusions

Experimental tests have been carried out using different percentage proportion of fibre in concrete to investigate the mechanical properties of HyFRCC. Based on the test results obtained in this study, the conclusions that can be drawn are as follows:

(i) The workability of fresh concrete is found to decrease when the percentage proportion of fibre increases. Too much fibre in concrete will produce low workability due to congestion.

(ii) Fibres in concrete help to bridge crack, thus, reduce the crack growth. The combination of 75% SF and 25% PPF gives the highest value in flexural strength and tensile splitting strength with an increase of 25.93% and 45.89%, respectively from plain concrete. Meanwhile, SF (100-0) contributes more in compressive strength and flexural toughness. This shows that the effects of HyFRCC are less significant in compression strength even though they enhance splitting tensile and flexural strengths.

(iii) From the experimental results, the failure mode of FRC and HyFRCC changed from brittle into a more ductile manner. For flexural strength, splitting tensile strength and flexural toughness, the plain concrete specimens splits into two at failure, while for HyFRCC the failure is not sudden and can still carry load even though the ultimate load is reached.

5.0 Acknowledgements

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