Mechanical properties of hybrid fiber reinforced concrete

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The research reported herein studied the effect of adding Fibrillated Polypropylene (FPP), Glass Fiber (GF), and Carbon Fiber (CF) at relatively low volume fractions on the fresh and hardened properties of concrete. The research was also concerned with optimizing the combined use of two different fiber types in cementitious matrix. Two series of hybrid Fiber Reinforced Concrete (FRC) were examined. The first series contained FPP and GF, and the second series contained FPP and CF, with a volume fraction ranging between 0.1 and 0.5%. Hydrating characteristics were evaluated through the compressive strength, modulus of elasticity, splitting tensile strength, impact strength, drying shrinkage, modulus of rupture, and toughness indices. The inclusion of low-modulus fiber (FPP) in concrete led to a considerable improvement in toughness, and impact strength. Meanwhile, the high modulus fibers (i.e., GF and CF) led to a considerable improvement in modulus of rupture, and splitting tensile strength. Results revealed the effectiveness of adding FPP on improving the toughness, and impact strength of carbon and glass FRC, which are characterized by their improved strength properties. The fractured surface of FRC specimens was also examined through Scanning Electron Microscope, in order to assess the failure mechanism of different types of fiber.

تعتبر عملية دعم وتحسين خواص الخرسانة باستخدام الألياف أحد الطرق الفعالة لتحويل الخرسانة إلى مادة شبه مرنة ، هذا بالإضافة إلى تحسين خواصها الميكانيكية. وتعتمد عملية دعم الخرسانة بالألياف على عدة عوامل أهمها نوع وشكل وخواص الألياف المستخدمة. ويهتم هذا البحث بدراسة استخدام خليط من الألياف (ألياف البولىبروبلين – الألياف الزجاجية – ألياف الكربون) فى دعم الخرسانة وتأثيرها على خواص الخرسانة. حيث تم دراسة نوعين من الخلطات الخرسانية إحداهما مدعمة بألياف البولىبروبلين والألياف الزجاجية والأخرى مدعمة بألياف البولىبروبلين وألياف الكربون ، وتراوحت نسب الألياف المستخدمة بين ٠,١% إلى ٠,٥% بالحجم. ولقد تم دراسة خواص الخرسانة المدعمة بالألياف من خلال اختبار مقاومة الضغط و الانحناء والشد غير المباشر ومقاومة الصدم ومعاملات المتانة. وكذلك تم استخدام الميكروسكوب الإلكتروني فى دراسة شكل وأسلوب الانهيار للخرسانة المدعمة بالألياف. وقد ظهر من خلال نتائج الدراسة أن مقاومة الخرسانة للصدم ومعاملات المتانة تتحسن كثيراً عند إضافة ألياف البولىبروبلين ، أما مقاومة الخرسانة للضغط والانحناء والشد فتتحسن عند استخدام الألياف الزجاجية وألياف الكربون.

Keywords: Glass fiber, Carbon fiber, Mechanical properties, Load-deflection curves, Toughness indices

1. Introduction

Fiber reinforcement is an effective and economical way to convert brittle concrete into a pseudo ductile material suitable for many applications. The improvement in Fiber Reinforced Concrete (FRC) depends on the type, mechanical and geometrical properties of reinforcing fibers. The fibers used in FRC material are often divided into tow broad category as follows [1] ; (a) Low modulus, high elongation fibers such as nylon, polypropylene and polyethylene in which the fibers enhance primarily the energy absorption characteristics only; (b) High strength, high modulus fibers such as steel, glass, asbestos and carbon in which the fibers enhance (to some extent) the strength of the composites.

Based on the previous explanation, fiber reinforced concrete could be defined as a composite material consisting of a cement-based matrix containing ordered or randomly distributed fibers that are acting as crack arrestors. This eventually leads to restrict the growth of cracks in the matrix, hence, controlling them from enlarging under stress into cracks that eventually cause failure. So, it is logical to expect superior composite properties if more than one type of fibers are incorporated into the matrix to form a hybrid FRC. Hybriding offers more freedoms towards the optimization of the benefits derived from each individual type of fibers. For example, it is possible to obtain a material with an enhanced strength from brittle fibers, as well as improved toughness from ductile fibers [2]. Inherent differences in the properties of fibers make hybrid reinforcement a suitable variable in the design of FRC composites. To use a combination of different types successfully in cementitious matrixes, due consideration should be given to the mix proportioning and manufacturing procedures to achieve a uniform dispersion of different fiber types in the matrix [3]. Very limited work on hybrid FRC has been done so far, but nevertheless the advantage of hybridizing has been confirmed.

The objectives of the present study are:

- Examining the effect of adding Fibrillated Polypropylene (FPP), Glass Fiber (GF), and Carbon Fiber (CF) at relatively low volume fractions on the fresh and hardened properties of concrete.
- Exploring the potentials of achieving balanced improvements in the performance characteristics of FRC through the combined use of different fiber types.

2. Experimental program

2.1. Materials

Three types of fiber were used namely, Fibrillated PolyPropylene (FPP), glass fiber (GF), and Carbon Fiber (CF). FPP fibers were fiber mesh type. The used glass fiber was chopped fiber, which is a new generation of alkali resistance glass fiber. Carbon fibers were produced by the Hercules Co. The fibers properties are listed in table 1. Ordinary Portland cement was used throughout the investigation. The coarse aggregate was crushed limestone, with a specific gravity, bulk density, and maximum aggregate size of 2.53, 1.4 ton/m^3, and 12.5mm, respectively. The fine aggregate was natural siliceous sand, which agrees with ASTM C-33 limits. The specific gravity, bulk density, and fineness modulus of sand were 2.65, 1.79 ton/m^3, and 2.3, respectively. Silica fume was used, as a partial replacement of cement in all mixtures (10% by weight), in order to facilitate the fiber dispersion. Superplasticizer, polymer type naphthalene formaldehyde sulphonate (sikament NN) complying with the type "F" of ASTM C-494, was used in all mixtures to insure adequate workability.

2.2. Mix proportions

The mix proportions of plain concrete was as follows: cement 360 kg/m^3; silica fume 40 kg/m^3; water 200 lit/m^3; sand 675 kg/m^3; coarse aggregate 1035 kg/m^3. The dosage of superplasticizer was chosen to keep the slump value mostly within the range of 6 to 10cm. Twenty two different mixes with single and hybrid fiber composites were prepared, nine mixes for single fiber, and twelve mixes for hybrid fibers. Details of mixtures are provided in table 2. The fine to coarse aggregate ratio was 0.4:0.6 by weight. Water/cement ratio of 0.5 and a cementitious content of 400 kg/m^3 were kept constant for all mixes.

Concrete was mixed in a horizontal rotating counter-flow mixer. Cement, silica fume, and aggregates were mixed alone for two minutes. Mixing was continued for further two minutes, while water (containing admixtures) was added. The fibers were then fed continuously to the mixer through a bar screen for an average period of 4 minutes. Fresh properties were measured, then concrete was cast in the molds. After a period of 24 hours, specimens were demoulded, and immerged in water till the testing date.

2.3. Testing procedure

Workability of fresh concrete was assessed by the slump test according to ASTM C-143. Air content was measured following ASTM C-138. Compressive strength was measured on cubes (10x10x10cm), at age of 7, and 28 days according to ASTM C–39. The splitting tensile test was conducted following ASTM C-496, on cylinders of 7.5 cm in diameter, and 15 cm in height. Static modulus of elasticity was determined according to ASTM C-469 at 28 days. The specimens used were cylinders of 15 cm in diameter, and 30 cm in height. Length

Table 1
Properties of fibrillated polypropylene, glass, and carbon fibers

Properties	Polypropylene	Glass	Carbon
Type	Fibrillated	Alkali resistance chopped strand	PAN
Trade name	Fiber mesh	CF – 140	As–4
Manufacturer	Synthetic industries	YINGPAL fibers	Hercules
Length, (mm)	14	12	12
Diameter, (μm)	396.5	17	10
Specific gravity	0.9	2.1	1.8
Modulus of elasticity, (ton/cm^2)	36	700	2340
Tensile strength, (ton/cm^2)	3.1	25.4	40
Aspect ratio	------	705.8	1200

Table 2
Type and volume fraction of fiber used in different concrete mixtures

Fiber type	Mix No.																					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
FPP	--	0.1	0.3	0.5	--	--	--	--	--	--	0.1	0.3	0.5	0.1	0.3	0.5	0.1	0.3	0.5	0.1	0.3	0.5
GF	--	--	--	--	0.1	0.2	0.4	--	--	--	0.1	0.1	0.1	0.2	0.2	0.2	--	--	--	--	--	--
CF	--	--	--	--	--	--	--	0.1	0.2	0.4	--	--	--	--	--	--	0.1	0.1	0.1	0.2	0.2	0.2

change measurements were conducted following ASTM C-440. The specimens used were 75x75x285mms. Measuring began 24 hours after casting without water curing.

The impact test was conducted at 28 days, following the procedure recommended by ACI Committee 544. Flexural strength and the load-deflection curves of specimens of dimension 10x10x50cm were determined by using a four point loading system. The flexural toughness indices were calculated according to ASTM C-1018. Scanning electron microscopy (SEM) was used to examine the fracture surfaces after flexural testing in order to identify the mechanism of failure of FRC.

3. Results and discussion

The air content of the fresh concrete mixtures with hardened properties (compressive strength, splitting tensile strength, modulus of elasticity, and impact test) are presented in table 3.

3.1. Air content

Based on the air content values presented in table 3, it is clear that the air content is inversely proportional to the fiber volume fraction, regardless of fiber type. Besides, the air content of all hybrid FRC mixtures showed an increase in its value, with the increase of GF and CF. The increase in air content may be attributed to the bridging effect of fibers when the mat of fibers is formed. The latter leads to forming more air bubbles, which could not find the way to move out by compaction. This phenomenon is mainly encountered with GF and CF, which are characterized by their high aspect ratio. The superplasticizer dosage may also be effective in increasing the air content, where mixes with high fiber volume fraction needs higher superplasticizer dosage in order to overcome the reduction in workability attributed to the increase in fiber content.

3.2. Cube compressive strength

The compressive strength of different FRC mixtures is presented in table 3. The cube compressive strength of polypropylene FRC shows a decrease in its value, with the increase of polypropylene fiber content. Meanwhile, the cube compressive strength of glass FRC and carbon FRC showed an increase in their values with the increase of

Table 3
Air content and hardened properties of different concrete mixtures

Mix No.	Fiber content (%by volume)			Air content (%)	Cube compressive strength (kg/cm²)		Splitting tensile strength (kg/cm²)	Modulus of elasticity (ton/cm²)	Impact resistance (No of blows)	
	FPP	GF	CF		7 days	28 days			N₁*	N₂**
1	--	--	--	2.0	266	403	46	306.7	480	485
2	01	--	--	2.1	260	395	46.5	305	482	562
3	0.3	--	--	2.3	253	387	47.2	298.5	487	657
4	0.5	--	--	2.7	249	379	47.9	294	490	760
5	--	0.1	--	2.3	268	407	48	307	485	492
6	--	0.2	--	2.9	272	412	48.9	308.5	492	512
7	--	0.4	--	3.4	279	422	49.8	309	500	530
8	--	--	0.1	2.3	270	410	50.3	308.7	488	503
9	--	--	0.2	3.0	278	422	51.4	312	497	535
10	--	--	0.4	3.9	287	431	52.5	316	505	560
11	0.1	0.1	--	2.4	261	396	48.2	305.5	489	569
12	0.3	0.1	--	2.6	253	385	49	299	493	673
13	0.5	0.1	--	2.9	250	381	49.4	294.5	496	771
14	0.1	0.2	--	3.0	267	405	49.3	306	495	593
15	0.3	0.2	--	3.2	255	386	50	299.5	501	689
16	0.5	0.2	--	3.6	253	383	50.4	295	505	797
17	0.1	--	0.1	2.5	264	400	50.5	306.5	492	588
18	0.3	--	0.1	2.6	259	393	51	300	496	679
19	0.5	--	0.1	3.0	255	386	51.8	296	497	777
20	0.1	--	0.2	3.2	272	411	51.7	308	498	611
21	0.3	--	0.2	3.5	267	406	52.1	301	505	710
22	0.5	--	0.2	3.8	260	395	52.8	297	508	808

* N₁: Number of blows to cause first crack.
** N₂:Number of blows to cause failure.

glass fiber and carbon fiber contents, respectively. The decrease in cube compressive strength of polypropylene FRC can be attributed to the low modulus of elasticity of FPP [4,5]. Besides, the increase in cube compressive strength of glass, and carbon FRC can be attributed to the high modulus, and high tensile strength of these fibers that bridge crack-like defects where compressive strength initiates [5]. However, the carbon FRC achieved higher compressive strength than glass FRC at different fiber content. This may be due to the relatively low mechanical properties of glass fiber compared to carbon fiber. Based on the previous discussion, the effect of glass, and carbon fibers on the hybrid FRC performance is obvious. Where the inclusion of the high modulus fibers (i.e., GF, and CF) overcome the negative effect of low modulus polypropylene fiber on the compressive strength of hybrid FRC.

Generally, test results showed that the inclusion of fibers exhibited a marginal effect on the compressive strength. This may be attributed to the low fiber volume fraction of fibers.

3.3. *Splitting tensile strength*

The splitting tensile test is usually carried out to determine only the first crack tensile strength, and not to be used for additional determinations, because of the unknown stress distribution after the first crack. For the previous reason, the inclusion of fibers didn't affect the splitting strength significantly. The strength before cracking depends mainly on three parameters, fiber modulus of elasticity, fiber volume fraction, and interfacial bond between fibers and the matrix [6]. The first tow parameters could be considered as one since the effect of modulus of elasticity is related to the fiber content.

The splitting tensile strength of different FRC mixtures is presented in table 3. In case of polypropylene FRC, since the used fibers have a modulus of elasticity lower than that of matrix, hence, a reduction should be expected for all mixes. On the other hand, the interfacial bond will help to sustain tensile stresses leading to increasing the tensile strength of polypropylene FRC. For carbon, and glass FRC, which are characterized by a modulus of elasticity higher than that of the matrix, hence, an increase in tensile strength should be expected for all mixes.

The two previous reasons are affecting the tensile strength at the same time, so, for low fiber volume fraction, the effect of the interfacial bond is more distinct than the effect of fiber modulus of elasticity. On the other hand, for higher volume fraction of fibers, the effect of fiber on modulus of elasticity is more pronounced than the interfacial bond. Based on the previous discussion, the effect of glass and carbon fibers on the hybrid FRC splitting tensile strength is distinct. Where the inclusion of GF, and CF within the hybrid FRC leads to a significant increase in its splitting tensile strength. Generally the splitting tensile strength of all concrete mixtures increases with the increase of fiber volume fraction.

3.4. Modulus of elasticity

The modulus of elasticity of different FRC mixtures is presented in table 3. Modulus of elasticity of polypropylene FRC decreases as the polypropylene fiber content increases. Modulus of elasticity of glass, and carbon FRC increases as the glass and carbon fibers content increases. The decrease in elastic modulus of polypropylene FRC may be due to the inclusion of low modulus of elasticity material (FPP), which in turn reduces the modulus of elasticity of the composite. The effect of fiber volume fraction is significant, so the higher the fiber volume fraction, the lower the modulus of elasticity.

The reduction in the modulus of elasticity will affect the design of the structures with respect to deformations. The structures cast with polypropylene FRC will exhibit more deformation than those structures cast with conventional concretes. Besides, the reduction in modulus of elasticity indicates higher ability for sustaining impact and dynamic loads as will be described in the impact test results.

The increase in the modulus of elasticity of glass FRC, and carbon FRC with the increase of glass, and carbon fibers content, respectively, may be attributed to the inclusion of high modulus fibers, which increase the modulus of elasticity of the composite.

The increase in modulus of elasticity in case of carbon fiber is higher than the increase in glass fiber. This observation may be due to the modulus of elasticity of carbon fiber (2340 ton/cm^2) that is higher than that of glass fiber (700 ton /cm^2).

Based on the pervious discussion, in case of hybrid FRC, it is thus logical that the higher the glass, and carbon fibers content the higher the modulus of elasticity of the hybrid FRC. As for compressive strength, test results showed that the inclusion of fibers exhibited only marginal effect on the values of the modulus of elasticity. This may be attributed to the low fiber volume fraction of fibers.

3.5. Impact strength

The impact resistance of different mixes, expressed as the number of blows required to cause the first visible crack in FRC specimens (N_1), and to continue opening that crack until failure, ultimate impact strength (N_2), is presented in table 3.

It is obvious that the first cracking impact strength increase as the fiber content increase regardless of fiber type. This may be due to the ability of fibers to work as crack arrestor. Simultaneously, the enhancement in (N_1) due to the inclusion of polypropylene fiber was insignificant. This observation may be attributed to the low modulus of elasticity and low tensile strength of this fiber. Carbon fiber reinforced concrete exhibited an increase in (N_1) higher than that obtained in case of FRC containing polypropylene, and glass fibers. This observation may be attributed to the ability of carbon fiber (high strength fiber) to bridge the microcracking [7]. Generally, the first cracking impact strength depends on the fiber characteristics (volume fraction, modulus of elasticity of fiber, and its tensile strength), and the matrix cracking properties.

After the first cracking, the enhancement of the ultimate impact strength (N_2) is dependent on the amount of energy absorbed during de-bond and pullout or yield and fracture of the fibers [8, 9]. Fig. 1 shows the ultimate impact strength (N2) of polypropylene FRC, glass FRC, and carbon FRC. It is clear that the ultimate impact strength of FRC increased with the increase of fiber content. Meanwhile, polypropylene fiber led to an increase in (N2) higher than that obtained in case of glass, carbon fibers. This observation may be attributed to the large amount of energy absorbed in debonding, stretching, and pulling out of polypropylene fiber (low modulus fiber) which occurs after matrix had cracked [10, 11]. Fig. 2 shows the ultimate impact strength (N_2) of different hybrid FRC mixes. The ultimate impact strength of all hybrids FRC mixes showed an increase in their values with the inclusion of glass and carbon fibers.

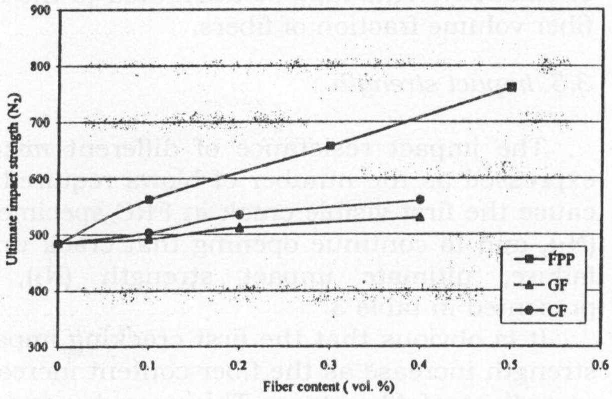

Fig. 1.Relation between ultimate impact strength (N2), and fiber volume fraction.

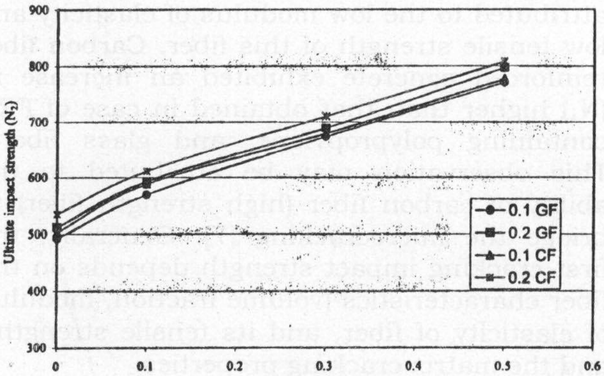

Fig. 2. Ultimate impact strength of different hybrid FRC.

3.6. *Length change measurement*

As expected, all FRC mixes revealed lower free shrinkage strains compared to plain concrete. Besides, the free shrinkage of all FRC mixes proved to be dependent on the fiber content, the higher the fiber content the lower the free shrinkage of the FRC composite. Polypropylene FRC introduced lower shrinkage compared to glass, and carbon FRC. Meanwhile, the free shrinkage exhibited by the carbon FRC was lower than that of glass FRC. Hybrid composites reinforced with polypropylene, and carbon fibers exhibited the lowest free shrinkage among other hybrid FRC. The inclusion of fibers within the matrix may restrain the free contraction of the composite, also sustains such tensile stresses and reduces or prevents, macrocracks in FRC, so reduce the shrinkage [12].

3.7. *Flexural strength and toughness indices*

First cracking load (p_{cr}) is defined as the load at which the load–deflection response starts to deviate from linearity. Maximum load (p_m) is the largest load at which the deflection continues to increase without any increase in applied force. Transition load (p_t) is defined as the small load, which is located between the first cracking load and the maximum load. First peak load (p_p) is defined as the largest load that is located between the first cracking load and the transition load. Final load (p_f) is the load at a deflection of 4 mm (the deflection at which the test was stopped). The first cracking strength (σ_{cr}) and flexural strength (σ_f) were calculated, corresponding to first cracking load and first peak load, respectively.

The load deflection curves of polypropylene FRC, glass FRC, and carbon FRC are shown in figs. 3-5. Loads and flexural strength of all mixes is presented in table 4.

The plain concrete beam failed in a brittle manner after the occurrence of the first crack, thus the first peak load of the plain concrete mix is equal to the first cracking load, while for polypropylene FRC, glass FRC, and carbon FRC, the first peak load predominate.

For FRC containing large amount of fibers, both strength (i.e., first cracking strength and

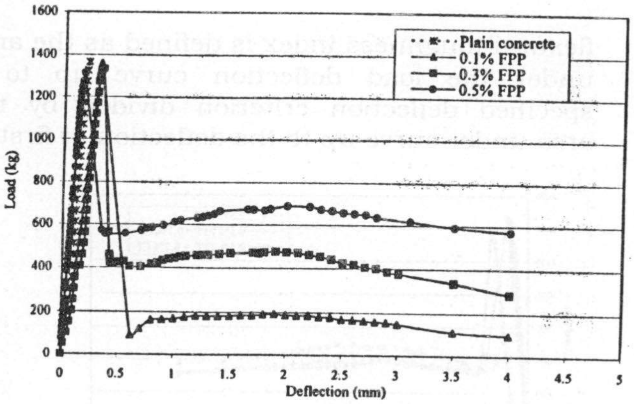

Fig. 3. Load-deflection curves of polypropylene FRC with different fiber volume fraction.

ultimate flexural strength) were quite distinct, but for smaller amount they were the same. Both first cracking strength (σ_{cr}) and flexural strength (σ_f) decreased with the increase of FPP content. This observation may be attributed to the inclusion of low modulus fiber (polypropylene fiber). The increase in transition and maximum load of polypropylene FRC may be due to the ability of polypropylene fiber to bridge the macrocracks in the post peak region also indicates the ability of such type of fibers (brittle fibers) in transferring load across the face of the pre-critical crack [2,13].

The load carrying capacity of FRC containing brittle fibers (GF and CF) decreased with the increase of the corresponding deflection. This phenomenon may be attributed to the inability of brittle fibers to

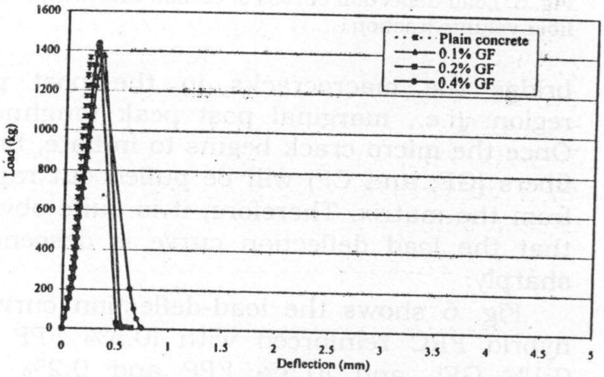

Fig. 4. Load-deflection curves of glass FRC with different fiber volume fraction.

Table 4
Flexural properties, and toughness indices

Mix No.	Fiber content (% by volume)			Properties							Toughness indices		
	FPP	GF	CF	P_{cr} [a] (kg)	P_p [b] (kg)	P_t [c] (kg)	P_m [d] (kg)	P_f [e] (kg)	σ_{cr} [f] (kg/cm²)	σ_f [g] (kg/cm²)	I_5	I_{10}	I_{20}
1	--	--	--	1365	1365	--	--	--	61.5	61.5	1.0	1.0	1.0
2	01	--	--	1355	1360	90	190	100	61	61.2	2.4	3.1	4.4
3	0.3	--	--	1295	1335	425	475	285	58	60	2.8	4.7	8.5
4	0.5	--	--	1250	1315	555	690	570	56	59	4.2	5.6	9.1
5	--	0.1	--	1375	1375	--	--	--	62	62	1.6	1.6	1.6
6	--	0.2	--	1385	1405	--	--	--	62.5	63.5	1.8	1.8	1.8
7	--	0.4	--	1425	1440	--	--	--	64	65	2.8	2.8	2.8
8	--	--	0.1	1450	1450	--	--	--	65	65	2.1	2.3	2.3
9	--	--	0.2	1500	1520	--	--	--	67.5	68.5	2.6	2.7	2.7
10	--	--	0.4	1530	1570	--	--	--	69	70.5	3.0	3.8	4.5
11	0.1	0.1	--	1365	1375	110	210	80	61.5	62	2.1	2.9	3.9
12	0.3	0.1	--	1325	1335	410	490	340	59.5	60	3.2	4.4	7.4
13	0.5	0.1	--	1295	1335	570	695	620	58	60	4.0	5.5	12
14	0.1	0.2	--	1375	1395	190	210	80	62	63	2.1	2.8	3.8
15	0.3	0.2	--	1345	1375	325	395	290	60.5	62	3	4.8	8.5
16	0.5	0.2	--	1325	1345	540	625	530	59.5	60.5	4.1	5.1	9.4
17	0.1	--	0.1	1415	1450	105	190	105	63.5	65	2.3	2.9	3.9
18	0.3	--	0.1	1395	1415	300	330	240	63	63.5	2.7	3.8	5.6
19	0.5	--	0.1	1355	1385	510	605	520	61	62.5	4.0	5.0	8.7
20	0.1	--	0.2	1490	1510	150	185	80	67	68	2.7	3.3	4.2
21	0.3	--	0.2	1460	1480	400	425	245	65.5	66.5	3.7	5.2	8.3
22	0.5	--	0.2	1440	1460	520	590	510	64.5	65.5	4.2	5.3	8.9
Values for elasto-plastic materials											5.0	10	20

[a] P_{cr} : First cracking load [b] P_p : First peak load [c] P_t : Transition load
[d] P_m : Maximum load [e] P_f : Final load [f] σ_{cr} : First cracking strength [g] σ_f : Flexural strength

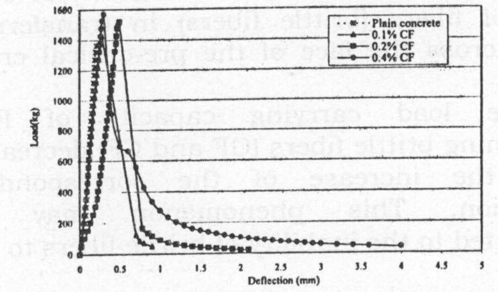

Fig. 5. Load deflection curves of carbon FRC with different fiber volume fraction.

bridge the macrocracks in the post peak region. (i.e., marginal post peak toughness). Once the micro crack begins to initiate, brittle fibers (GF, and CF) will be pulled out rapidly from the matrix. Therefore, it is quite obvious that the load deflection curve is descending sharply.

Fig. 6 shows the load-deflection curve of hybrid FRC reinforced with (0.5% FPP and 0.1% GF), and (0.5% FPP and 0.2% GF). Besides, fig. 7 shows the load-deflection curve of hybrid FRC reinforced with (0.5% FPP, 0.1% CF), and (0.5% FPP, 0.2% CF). Through the aforementioned figures it may be concluded that GF and CF maintained their ability to increase the strength, and FPP retained its toughening mechanism in hybrid FRC.

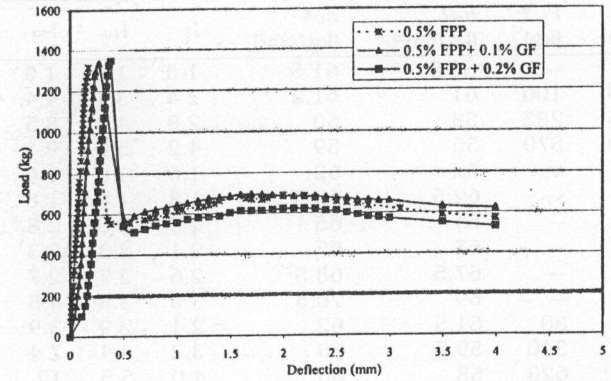

Fig. 6. Load-deflection curves of hybrid FRC reinforced with (0.5% FPP, 0.1% GF), and (0.5% FPP, 0.2% GF).

Flexural toughness is defined as the area under the flexural load- deflection curve, and it is an indication of the energy absorption capability of a material [11,14]. The flexural toughness indices used in the data analysis presented in this study were measured according to ASTM standard C-1018. A flexural toughness index is defined as the area under the load deflection curve up to a specified deflection criterion divided by the area under curve up to the deflection at first cracking. Flexural toughness indices have been determined for specific deflection criteria. These criteria are the deflection up to the first cracking (δ), the deflection up to three times the first cracking deflection (3δ), the deflection up to 5.5 times the first cracking deflection (5.5δ), and the deflection up to 10.5 times the first cracking deflection (10.5δ). Toughness indices I_5, I_{10}, and I_{20} were then calculated by taking the ratios of the energy absorbed to a deflection of 3δ, 5.5δ, and 10.5δ, respectively. The determination of the previous flexural toughness indices is based on the load deflection curves of all mixes. Toughness indices of all mixes are given in table 4.

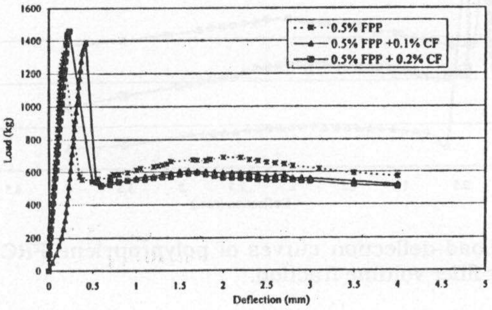

Fig. 7. Load-deflection curves of hybrid FRC reinforced with (0.5% FPP, 0.1% GF), and (0.5% FPP, 0.2% GF).

Generally, the flexural toughness indices of polypropylene, glass, and carbon fibers exhibited an increase on their values with the increase of fiber volume percent. This observation may be attributed to the fact that toughness significantly increases with the addition of fibers. FRC reinforced with 0.5 % FPP, and hybrid FRC reinforced with (0.5% FPP + 0.2% GF), and (0.5% FPP + 0.2% CF) behaved in a fully ductile fashion up to a deflection of 3 times the first crack, since the toughness index I_5 is approximately equal to 5.0 at that deflection. However, when dealing with higher deflections, a semi-ductile behavior is noticed, since the values of I_{10} and I_{20} are extremely lower than that recorded for elasto-plastic materials.

3.8. Scanning electron microscopy

Fig. 8 shows the fractured surface of FRC reinforced with 0.5% FPP, fig. 9 shows the fractured surface of FRC reinforced with 0.4% GF, and fig. 10 shows the fractured surface of FRC reinforced with 0.4% CF. All photomicrography were taken at the failure surface of specimens tested in bending.

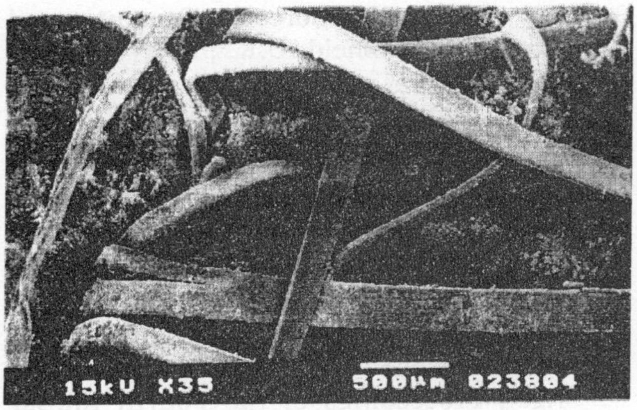

Fig. 8. SEM micrograph of fractured surface for 0.5 % polypropylene FRC.

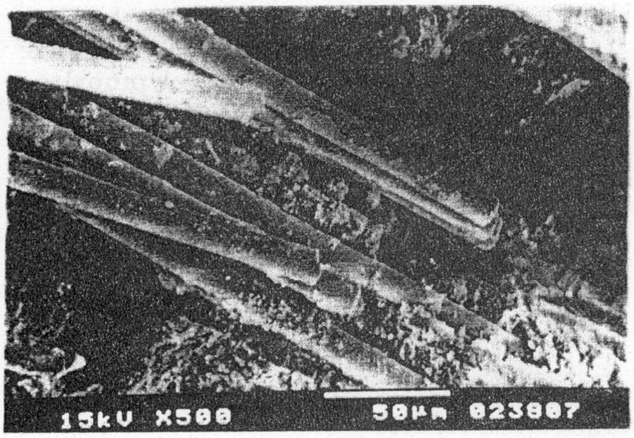

Fig. 9. SEM micrograph of fractured surface for 0.4% glass fiber reinforced concrete.

Scanning electron microscopy (SEM) micrographs denote that fiber pullout is the predominating failure mechanism (i.e., fiber pullout mechanism is a major component of strengthening for these composites). In the case of glass and carbon FRC, the previous discussion of impact strength and load–deflection curves indicated that the extent of fiber pullout was significantly lower than the polypropylene FRC. Therefore, the polypropylene FRC achieved a higher toughness performance than that exhibited by glass, and carbon FRC.

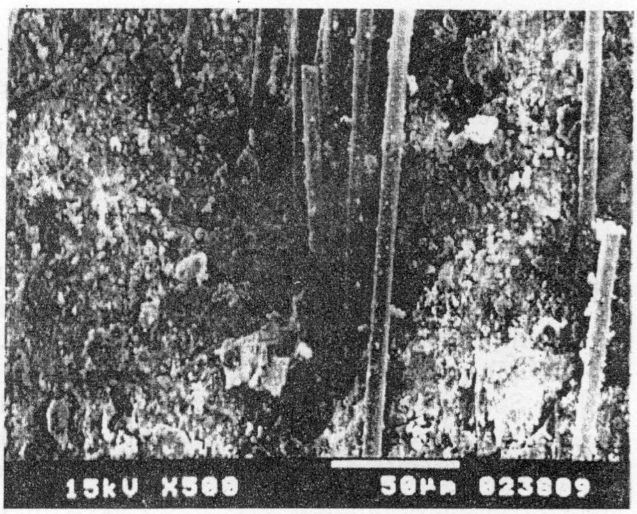

Fig. 10. SEM micrograph of fractured surface for 0.4% carbon fiber reinforced concrete.

4. Conclusions

The inclusion of low-modulus fiber (FPP) in concrete led to a considerable improvement in toughness, and impact strength. Meanwhile, the high-modulus fibers (i.e., GF, and CF) lead to a considerable improvement in modulus of rupture, and splitting tensile strength. Generally, all FRC mixes reveal a less free shrinkage strains compared to plain concrete.

Results also revealed the effectiveness of adding FPP on improving the toughness, and impact strength of carbon and glass FRC, which are characterized by their improved strength properties. Finally, it can be concluded that carbon, and glass fibers maintain their ability to increase the strength, and polypropylene fiber maintains its toughness mechanism in hybrid FRC.

The potentials for achieving balanced improvements in the performance of concrete through the combined use of hybrid FRC at low Volume fraction were explored. Besides, the positive effect of hybridizing has been demonstrated, leading to the development of cementitious composite with superior performance at reasonable costs.

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