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Hybrid Fiber Reinforced Concrete Containing Pumice and Metakaolin

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ABSTRACT: Fiber reinforced concrete (FRC) has been widely used due to its advantages over plain concrete such as high energy absorption, post cracking behaviour, flexural and impact strength and arresting shrinkage cracks. But there is a weak zone between fibers and paste in fiber reinforced concretes and this weak zone is full of porosity, especially in hybrid fiber reinforced concretes. So it is necessary to apply a material that reduces porosity and consolidates this transition zone. In this research first, the flexural and impact resistance tests were carried out on hybrid fiber reinforced concretes to choose the optimum percentage of steel and polypropylene fibers based on flexural toughness, modulus of rupture and impact resistance. Finally, compressive strength tests were conducted on selected hybrid fiber reinforced concretes containing pumice and metakaolin to choose the better pozzolan and replacement level based on compressive strength test. Results showed that, metakaolin with 15% substitution for cement had a significant role in increasing compressive strength. However, pumice did not act on the same basis.

Keywords: Compressive Strength, Fiber Reinforced Concrete, Flexural Toughness, Pumice and Metakaolin, Steel and Polypropylene Fibers.

INTRODUCTION

Concrete is a brittle material. Fiber reinforced concretes are commonly used to provide toughness and impact resistance. Concrete reinforcement with a single type of fiber improves the mentioned properties in a limited range. But in hybrid fiber reinforced concretes (HFRC) two or more different fibers are suitably applied to provide superior properties. In a well designed composite, there is a positive interaction between the fibers so the resulting hybrid has a better performance than the mono fiber composite. It is called “Synergy”. Though fiber reinforced concrete has the mentioned advantages, for monofilament fibers such as steel fiber, there is a 40μm-thick transition zone with a lot of porosity much more than paste. This weak zone contains three layers. The first, 1 μm-thick layer covering the fiber, is full of calcium hydroxide. The second, 1 μm-thick layer around the first layer, is full of C-S-H. A thick layer around the second layer is full of calcium hydroxide.

Because of the weak zone between fibers and the paste in fiber reinforced concretes

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and especially in hybrid fiber reinforced concretes, it is necessary to apply materials that reduce porosity and consolidate this transition zone.

Meddah and Bencheikh (2009) found the relation between porosity and compressive strength in fiber reinforced concretes and showed that the decrease of porosity causes an increase in compressive strength.

Substitution of a portion of the cement for pozzolans improves the mechanical properties of fiber reinforced concrete and hybrid fiber reinforced concretes and reduces porosity in transition zones. Moreover, it reduces the project costs.

In this research, the effect of two natural pozzolans namely, pumice and metakaolin, on the mechanical properties of fiber reinforced concretes is investigated.

First, flexural and impact resistance tests are carried out on steel-polypropylene fiber reinforced concretes and on steel fiber reinforced concrete to choose the optimum percent of steel and polypropylene fibers based on flexural toughness, modulus of rupture and impact resistance. Finally, compressive strength test is conducted on the selected hybrid fiber reinforced concretes containing pumice and metakaolin to choose the better pozzolan and replacement level based on compressive strength test results.

EXPERIMENTAL PROGRAM

Aggregates

In this study, fine and coarse aggregates were obtained from a local source. Aggregate grading is shown in Table 1.The bulk density of coarse and fine aggregates are 2570 (kg/m^3) and 2710 (kg/m^3), respectively.

Table 1. Aggregate grading.

Sieve size	Percent by Weight Passing Individual
¾ in. (19 mm)	100
½ in. (12mm)	100
3/8 in. (10mm)	96
No. 4 (4.75mm)	75
No. 8 (2.4mm)	55
No. 16 (1.2mm)	37
No. 30 (600µm)	25
No. 50 (300µm)	11

Cementitious Material

The cement used in this study is type Π Portland cement. Chemical properties and composition and mechanical properties of cement are given in Tables 2 and 3, respectively.

The chemical properties and composition of pumice used as supplementary cementitious material are given in Table 2.

Table 2. Physical and chemical characteristics of cement, Metakaolin and Pumice.

Chemical Composition		Type 2 Cement	Metakaolin	Pumice
SiO_2	%	19.9	74.3	67.7
Al_2O_3	%	3.58	17.8	15.8
Fe_2O_3	%	3.94	0.82	3.39
CaO	%	59.9	3.38	3.90
MgO	%	3.08	0.22	0.99
SO_3	%	5.00	------	0.33
Na_2O	%	0.05	0	2.95
K_2O	%	0.84	0.39	2.00
TiO_2	%	0.35	------	0.33
MnO	%	------	------	0.04
P_2O_5	%	0.06	------	0.12
LOI	%	2.51	2.56	2.30
C_3S		48.68	------	------
C_2S		20.33	------	------
C_3A		2.82	------	------
C_4AF		11.99	------	------

Table 3. Mechanical properties of normal mortar.

Mechanical Properties	(MPA)
Compressive strength (28 days)	31.25
Flexural strength (28 days)	2.6

Table 4. Chemical and mineralogical analyses of kaolin.

	Chemical Analysis (%)								Mineralogical Analysis (%)			
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	LOI	Kaolinite	Quartz	Calcite	Other
Kaolin	74.97	17.8	0.81	2.22	0.13	0.05	0.55	7.18	50.73	39.27	6	4

Local kaolin with high kaolinite content (K) was thermally treated by the special furnace at 800°C and 60 minutes burning time to produce metakaolin. The chemical composition of MK used as the supplementary cementitious material and chemical and mineralogical analyses of kaolin are given in Table 2 and Table 4, respectively.

Fibers

Steel fibers used in this study are hooked ended and are obtained from BASF Company (see Figure 1). Physical and mechanical properties of steel fibers are given in Table 5.

Fig. 1. Steel fibers.

Table 5. Physical and mechanical properties of steel fibers.

Length (mm)	Diameter (mm)	L/D	Tensile Strength (MPA)	Density (kg/m^3)
36	0.80	45	>1200	7850

The type of polypropylene fibers used, is staple with a length of 12 mm (see Figure 2). Physical and mechanical properties of polypropylene fibers are given in Table 6.

Fig. 2. Polypropylene fibers.

Superplasticizer

The superplasticizer used in this study is Gelenium 50 which is a carboxylic-based super plasticizer.

MIXING AND CURING PROCEDURE

Steel - Polypropylene Hybrid Fiber Reinforced Concrete Specimens

The mixing procedure started with a dry mixing of coarse and fine aggregates with steel fibers for 30 seconds. Then, one third of the mixing water was added to the mixture and was mixed for 30 seconds. After that, cement and a half of pp fibers were added to the mixture and were mixed for 2 minutes. Finally, the rest of the water and polypropylene fibers were added to the mixture and were mixed for another 1.5 minutes. The fresh concrete was placed in 100*100*500 mm prismatic molds and 100*200 mm cylindrical molds. The former is used for the flexural test and the latter for the impact resistance test.

Table 6. Physical and Mechanical properties of Polypropylene fibers.

section	Length (mm)	Tensile Strength (MPA)	Elongation	Density (kg/m^3)
round	12	400	12%	910

All molds were removed after 24 hours and the specimens were cured in water containers for 28 days. Table 7 gives the detail of the mixture proportions for a cubic meter of concrete. As shown in Table 7, five mixtures were made. All the mixtures were prepared in pan mixer which has 0.06 m^3 capacity. Table 8 gives the details of the mixture proportions for a cubic meter of concrete.

Table 7. Fiber dosages in hybrid fiber reinforced none pozzolan concrete.

Mixture number	Fiber Type	Fiber Dosage (%)
SP0	-	0
SP1	steel	0.25
	polypropylene	0.75
SP2	steel	0.5
	polypropylene	0.5
SP3	steel	0.75
	polypropylene	0.25
SP4	steel	1
	polypropylene	0

Steel - Polypropylene Hybrid Fiber Reinforced Concrete Specimens Containing Pozzolan

In this step, with the optimum percentage of the steel and polypropylene fibers, a control mixture and five mixtures in which cement was substituted with various proportions of pumice and metakaolin were made. The mixing procedure started with dry mixing of coarse and fine aggregates with steel fiber for 30 seconds. Then, one third of the mixing water, one third of the polypropylene fiber and metakaolin were added to the mixture and were mixed for 1 minute. After that, cement, pumice and one third of pp fiber were added to the mixture and were mixed for 2 minutes. Finally, the rest of the water and polypropylene fibers were added to the mixture and were mixed for another 1.5 minutes. The fresh concrete was cast in 100*100*500mm prismatic molds and 100*100*100 mm cubic molds .The former is used for flexural test and the latter for compressive strength test.

All molds were removed after 36 hours and the specimens were cured in water containers during the test process. Table 8 gives the detail of the mixture proportions and the test time. As shown in Table 8, six mixtures were made.

As slump is not a suitable method for measuring the workability of fiber reinforced concrete, VeBe test was applied. To achieve VeBe time in the range of 3-10 seconds, Superplasticizer was added to the mixture.

Table 8. Proportions of hybrid fiber reinforced concrete mixtures containing pozzolan.

Mixture's Id	CTR	P10	P15	MK10	MK15	PMK
Steel fibers (kg/m^3)	58.50	58.50	58.50	58.50	58.50	58.50
Polypropylene fibers (kg/m^3)	2.28	2.28	2.28	2.28	2.28	2.28
Cement (kg/m^3)	450	405	382.5	405	382.5	382.5
Metakaolin (kg/m^3)	0	0	0	45	67.50	33.75
Pumice (kg/m^3)	0	45	67.50	0	0	33.75
Superplastisizer (kg/m^3)	1.346	1.480	1.596	1.730	1.923	1.558
VeBe time (sec)	4.0	4.9	5.1	5.9	6.0	5.3
Test time	7,28,90 and 180	7,28,90 and 180	7,28,90 and 180	7,28,90 and 180	7,28,90 and 180	7,28,90 and 180
The number of cubic molds	12	12	12	12	12	12

TEST METHOD

Flexural Toughness According To ASTM C 1609

Since there are a lot of difficulties in determining the first crack and measuring accurate deflection in ASTM C 1018 for evaluating flexural toughness, this standard was replaced with ASTM C 1609 (2010). Therefore, in this research ASTM C 1609 was applied to determine flexural toughness of fiber reinforced concrete.

Concrete beams of HFRC or FRC were tested in flexure using the four point loading arrangement specified in ASTM C 1609 test method As seen in Figure 3, toughness (T_{150}^{D}) defined as the area under the load-deflection curve, measured up to a specified deflection, L/150 .Therefore, the equivalent flexural strength ratio ($R_{T,150}^{D}$) is obtained according to Eq. (1), using the first-peak strength.

$$R_{T,150}^{D} = \frac{150\ T_{150}^{D}}{f_1 b d^2} \times 100\ \% \tag{1}$$

where $R_{T,150}^{D}$ is equivalent flexural strength ratio, L is span length (mm), T_{150}^{D} is toughness (J) up to deflection L/150, f_1 is modulus of rupture (kN.m), b is width of the specimen (mm) and d is height of the specimen (mm).

Impact Resistance

The impact resistance of the specimens was also determined in accordance with ACI committee 544 proposals (2001). For this purpose, 100*45 mm discs cut from 100*200 mm cylindrical specimens were used. The blows were introduced through a 4.45 kg hammer dropping frequently from a 45.7 cm height onto a 6.35 cm steel ball, which was located at the centre of the top surface of the disc. Since the method applied in this study was simulated with the standard one, the results are just used just to compare impact resistance of specimens.

The energy absorption up to specific deflection is obtained through the following Eq. (2):

$$U = n \times mgh \tag{2}$$

where U is energy absorption (N.m), n is number of blow, m is drop weight (N) and h is drop height (m).

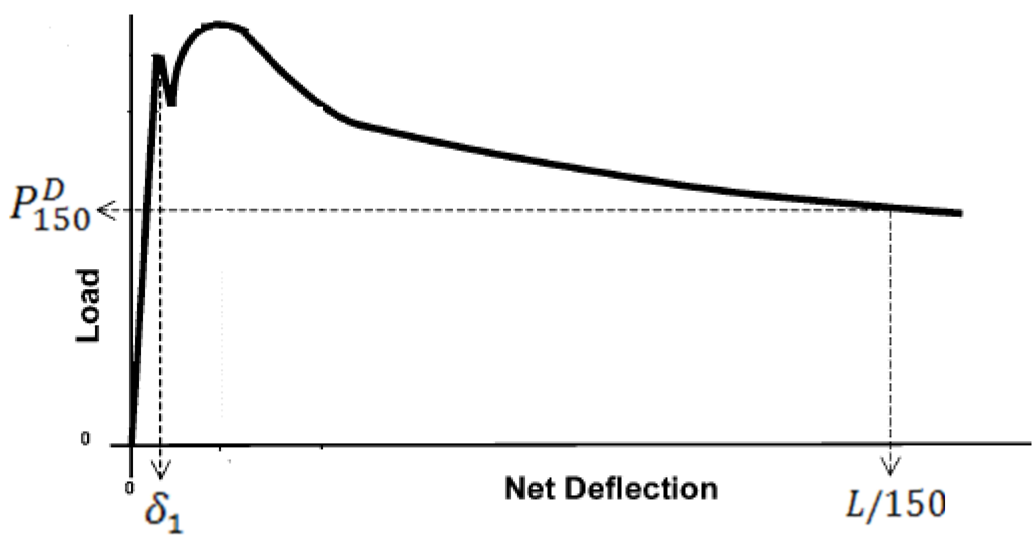

Fig. 3. Definition of Toughness according to ASTM C 1609

Compressive Strength Tests

This test was carried out to evaluate the specimens containing pozzolans.

RESULTS AND DISCUSSIONS

Hybrid Fiber Reinforced Concrete Test Results

Flexural Test

Load-deflection curves are shown in Figure 4. As shown in Figure 4, for all specimens, the load_deflection curve is gradually strain softening. After first crack, a sudden increase in flexural strength is due to bridging and arresting steel fibers on macro crack. This performance of steel fibers is due to its high length and tensile strength.

Modulus of rupture

Modulus of rupture results are presented in Table 9 and Figure 5. As shown in Table 9 and Figure 5, the results indicate that the substitution of the polypropylene fiber with steel fiber in HFRC has affected the MOR of the polypropylene - steel hybrid fiber reinforced concrete. The highest flexural strength provided by the composite with higher percentage of steel fibers (mixture SP4) is due to their high tensile strength and elastic modulus. Although polypropylene fibers are short and capable of bridging micro crack, they do not have significant influence on MOR due to their low tensile strength and elastic modulus.

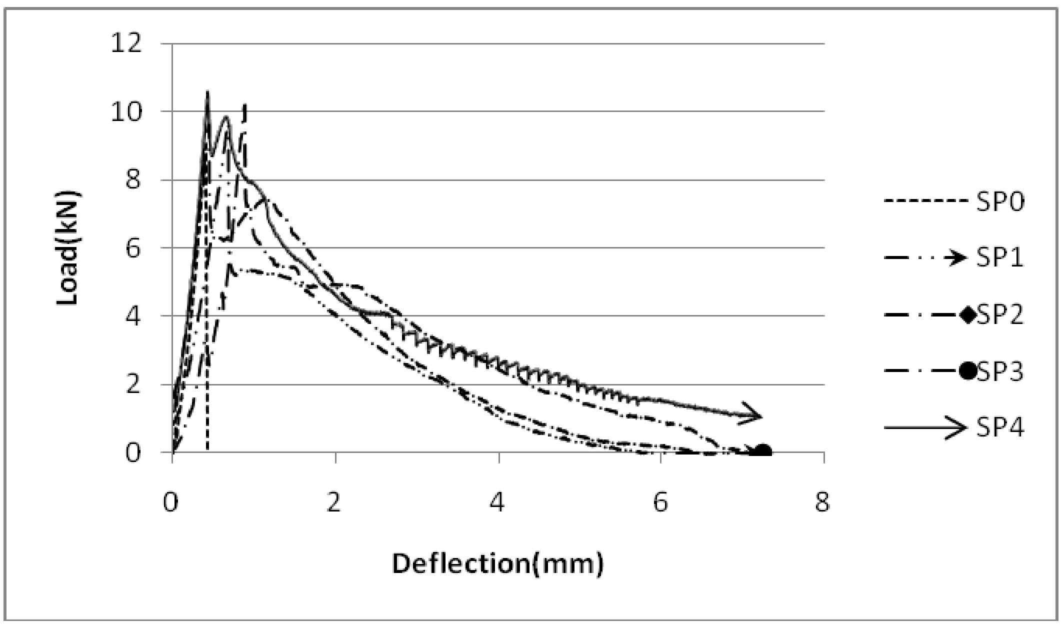

Fig. 4. Load-deflection curve of concrete mixtures.

Table 9. Toughness, modulus of rupture and equivalent flexural strength ratio according ASTM C 1609.

Mixture's ID	MOR (MPA)	T_{150}^{100} (N.m)	Equivalent Flexural Strength Ratio
SP0	4.53	0	0
SP1	4.73	13.70	0.42
SP2	4.77	16.83	0.51
SP3	5.03	17.43	0.53
SP4	5.05	19.31	0.57

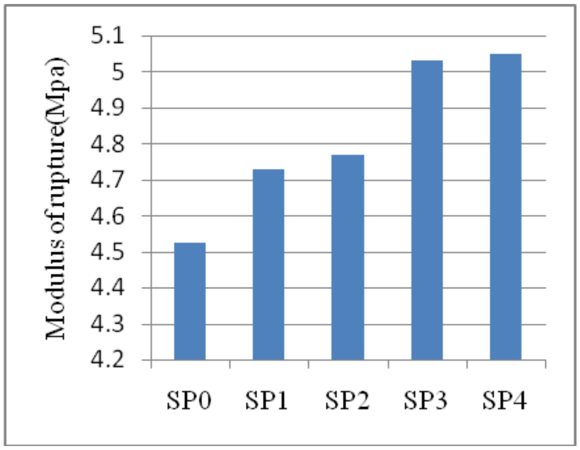

Fig. 5. Modulus of Rupture (MOR) of concrete mixtures.

Flexural toughness according to ASTM C 1609

Flexural toughness and equivalent flexural strength ratio are presented in Table 9. From Table 9, it can be seen that the toughness for the HFRC with higher steel fibers content is relatively higher than those containing less steel fibers. Moreover, equivalent flexural strength ratios of all specimens are relatively near 0.5. It can be seen that polypropylene fibers have no effect on toughness index due to their short lengths, low tensile strength and elastic modulus (see Figure 6). Indeed, the most important factors affecting toughness index are the fiber type, length and fiber dosage. Moreover, Table 9 shows that in composites having more steel fibers, the amount of energy absorption after the first crack increases due to its high elastic modulus, length and tensile strength.

Fig. 6. Bridging of steel fibers on macro cracks.

Therefore, mixture SP3 has higher amount of MOR and toughness compared to other hybrid fiber reinforced concretes.

Impact Resistance

Table 10 shows the number of blows for the first crack and the final failure. As shown in Table 10, the number of blows for the first crack doesn't differ between all mixtures. Indeed, fibers had significant effect on the number of blows for final failure and on average it is 4-5.5 times more compared to plain concrete due to bridging of fibers on macro cracks. There is a significant difference between failure mechanism of plain concrete and FRCs. Under impact load, plain specimens are divided completely into three discrete pieces but fibers arrested cracks and caused cohesion in specimens. In plain concrete, there is no significant difference between the number of blows for the first crack and the final failure, but in FRCs, the ratio between the numbers of blows for the first crack to the number of blows for the final failure is about 5 due to bridging of fiber on macro cracks.

Results showed that by increasing the amount of steel fiber in hybrid fiber reinforced concrete, the number of blows for the first crack and the number of blows for the final failure increased due to its high length and elastic modulus. In fact, Polypropylene fibers didn't have significant effect on impact resistance. This is attributed to their short length and low elastic modulus. It seems that after emerging the first crack, polypropylene fiber could not bridge on macro cracks due to their short length. On the other hand, steel fibers bridged on macro crack and arrested them. Therefore, two key factors that affected the amount of impact resistance of FRCs are fibers characteristic (tensile strength, elastic modulus, etc.) and fiber length (aspect ratio).

Table 10. Impact resistance test results.

Mixture's ID	Number of Blows for First Crack	Number of Blows for Final Failure
Sp0	6	8
SP2	8	35
SP3	9	39
SP4	11	44

Relation between Energy Absorption for the First Crack in Flexural and Impact Test

Table 11 and Figure 7 show the energy absorption for the first crack in impact resistance and flexural tests. From Table 11 it can be seen that with a correlation coefficient that is 0.91, there is a good correlation between flexural and impact test results. There is also a linear relationship between energy absorption for the first crack in impact resistance and flexural tests.

Table 11. Energy absorption for first crack in flexural and impact test.

Mixture's ID	Energy Absorption for First Crack in Flexural Test (kN.m)	Energy Absorption for First Crack in Impact Test (kN.m)
SP0	1.42	12.30
SP2	2.32	16.40
SP3	2.61	18.45
SP4	2.84	22.55

Hybrid Fiber Reinforced Concrete Containing Pozzolans Test Results

Compressive Strength Test Results

The Compressive strength test was applied to cubic specimens with five cement substitutions. Table 12 shows test results in 7, 28, 90 and 180 days. As shown in Table 12, it can be seen that the substitution of cement for 10 and 15 percent metakaolin caused an increase in the compressive strength. On the other hand, the substitution of cement for pumice reduced the compressive strength. The negative performance of pumice is because of its low pozzolanic activity and the reduction of cement is due to substitution of cement for pumice. So the amount of CSH which is the result of cement hydration and the amount of $Ca(OH)_2$ which is needed for pozzolanic reaction decreased. Therefore, not only didn't the substitution of cement with pumice improved the transition zones (transition zones between fibers and paste and aggregate and paste), but it also weakened this zone due to increased porosity due to reduction of CSH. This behaviour of pumice is the same at all ages.

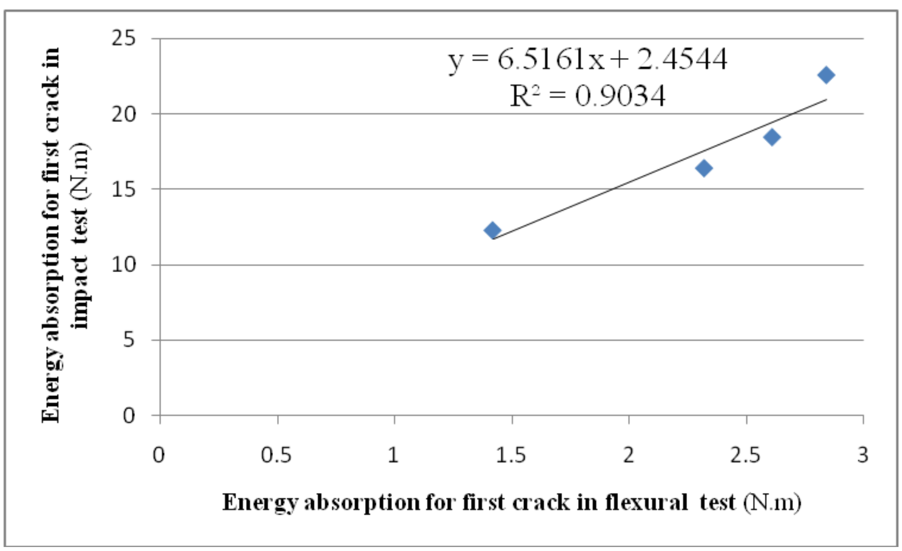

Fig. 7. Relation between energy absorption for first crack in flexural and impact test.

Table 12. Compressive strength test results (MPA).

Mixture's ID	Substitution Percentage of Cement for Pozzolan	Age of Testing (day)			
		7	28	90	180
CTR	0%	18	29	41	44
P10	10% Pumice	17	29.5	34.5	37.6
P15	15% Pumice	16.7	26.5	32.5	37
MK10	10% Metakaolin	18.7	32.5	38	44.5
MK15	15% Metakaolin	19	36	44.5	46.5
PMK	7.5% Pumice +7.5% Metakaolin	16	27.5	34	39.4

However, metakaolin increased the compressive strength. This performance is due to its high pozzolanic reaction, particle fineness and high amount of kaolinite mineral. So, substitution of cement for metakaolin increased the amount of CSH which is the result of pozzolanic reaction. Moreover, metakaolin accelerated cement hydration reaction, that increased the amount of CSH at early ages (7 and 28 days) so increasing compressive strength. The specimens in which 15% metakaolin was replaced with cement showed higher amount of compressive strength.

CONCLUSIONS

Due to limited obtained results in this investigation, the following conclusions can be drawn:

1. Hybrid fiber reinforced concrete with 0.75% steel fibers and 0.25% polypropylene fibers had higher toughness indexes, modulus of rupture and impact resistance than other hybrid mixtures.
2. With a great regression coefficient that is 0.91, there is a linear relationship between energy absorption for the first crack in impact resistance and flexural test.
3. Substitution of cement for 15% metakaolin caused a maximum increase in compressive strength.
4. Pumice didn't show a good performance and caused increasing in the amount of porosity in the weak transition zone.

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