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Effectiveness of high performance mortar reinforced with fibers as a repair material

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ABSTRACT

The present work deals with engineering properties of high performance mortar (HPM) to be used as a repair material. The experimental study was conducted on HPM reinforced with mono steel fibers and hybrid fibers consist of steel and polypropylene fibers. The economical efficiency of the designed mono and hybrid fibers reinforced mortar were presented. The results indicate that the hybridization of 1.8% steel fibers and 0.2% polypropylene fibers is very beneficial to decrease the production cost of fiber reinforced mortar for large scale construction project applications. The combined system of substrate concrete with different mixes of HPM was used to study its bond strength properties. The experimental tests are: two-part bond strength tests in additional to three part-bond strength tests. It was found that HPM reinforced by hybrid fibers has the best performance when two-part bond strength is required. On the other hand, in three parts bonding, the combined system of NC with epoxy has the best bond strength while HPM reinforced fibers show a better failure mode.

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1. Introduction

Increasing service loads, excessive loading events, and exposure to an ever-changing ambient environment are some reasons why civil structures, over the service periods, degrade and ultimately develop performance deficiencies due to Haber et al. (2012). In several cases, it is economically more possible to repair and rehabilitate the structure than full destruction and reconstruction. Traditional methods of strengthening may include steel plating, addition of concrete, and near surface mounting additional steel. However, these methods have been proven valuable; but they can be cumbersome, time inefficient, and susceptible to corrosion due to Haber et al. (2012).

Recently different repair methods and materials are used to overcome damaged structures. The choice of them is a function of both the physico-chemical and the mechanical properties of the substrate based on Mallat et al (2011). A good repair material may improve the function and performance of the concrete structure. On the other hand, poor repair fails early or deteriorates the adjoining sound concrete material in a relatively short time as reported by Pattnaik (2006).

The repair materials should be contributed to the mechanical strength of the concrete structure and a high fluidity is required to fill cracks and pores completely. Besides, a repair material is sensitive to minor displacements and must have an elastic modulus as close as possible to that of the concrete substrate. Hence, a repair material with a high fluidity and a relatively high compressive strength is required due to Liu and Huang (2008).

Cemenititious composite are assumed to be highly compatible with concrete structure in terms of physical, chemical and mechanical properties in order to assure the long term durability as stated by Schueremans et al. (2011). Cementitious composites are typically characterized as brittle, with a low tensile strength and strain capacity. Fibers are incorporated into cementitious matrices to overcome this weakness, producing materials with increased tensile strength, ductility and toughness

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with improved durability due to Balaguru and Shah (1992). The character and performance of fiber-reinforced composites (FRC) change, depending on the properties of cementitious composites and the fibers according to Mehta and Monteiro (2006), and Kuder and Shah (2010).

The use of a single type of fiber may enhance the properties of FRC to a limited level. However, the concept of hybridization, which is the process of adding two or more types of fiber into concrete, can offer more attractive engineering properties. This is related to the presence of one fiber enables the more efficient utilization of the potential properties of the other fiber as reported by Sahmaran et al. (2005). Hybrid fibers of different sizes and types may play vital roles in resisting cracking at different scales, and consequently to achieve high performance. It has been proven that the incorporation of fiber into cementitious materials can significantly improve their toughness and ability of resisting crack, and many research works have been carried out on fiber-reinforced cementitious composites due to previous researches prepared by Mehta and Monteiro (2006), Kuder and Shah (2010), Sahmaran et al. (2005) and Sun et al. (2001).

Steel fiber has a considerably larger length and higher Young's modulus as compared to the other fiber-types due to Bentur and Mindes (1990). However, the addition of steel fibers at higher dosages has some disadvantages in terms of poor workability and higher cost. In addition, the high stiffness of steel fibers in the matrix means that voids and honeycombs could be formed during placing as a result of improper compaction at low workability as reported by Yao et al. (2003). The addition of flexible fibers (such as polypropylene fibers) leads to good fresh mortar properties and a reduction in early age cracking. The beneficial effects of flexible fibers can be attributed to their high aspect ratios and increased fiber availability (because of their lower density compared to steel) at a given volume fraction. Having lower stiffness, these fibers are particularly effective in controlling the propagation of microcracks in the plastic stage of concrete and their contribution to post-cracking behaviour is known to be significant according to significant studies prepared by Sahmaran et al. (2005), Sivakumar and Santhanam (2007) and Dawood and Ramli (2010).

Therefore, the objectives of this study are to produce high performance mortar reinforced with hybrid fibers and then tested for mechanical tests. Besides, the economic efficiency using TOPSIS is considered for such evaluation. Furthermore, the repair tests are prepared for the evaluation of such HPM.

2. Materials and Mix Proportions

2.1. Material properties

Ordinary Portland cement type I, was used in different mortar mixes. Metakaolin used in this study was subject to a thermal treatment at 750°C for 60 minutes. The chemical compositions of ordinary Portland cement and metakaolin are shown in Table 1. Superplasticizer has been provided by Sika ViscoCrete-SF 18 and was used to establish the desired workability of mixes. The fine aggregate was natural sand, with fineness modulus of 2.18. The steel fiber was low carbon cold drawn steel wire and their characteristic are shown in Table 2. The polypropylene fiber was supplied by AYLA Company and their characteristics are shown in Table 3. Epoxy was used in this study as a repair material for the damaged concrete. This material was produced by KÖSTER KB Fix.

Table 1. Chemical composition of ordinary portland cement.

Metakaolin % by weight	Ordinary Portland Cement % by weight	Constituent
1.39	62.20	Lime (CaO)
54.62	21.31	Silica (SiO_2)
41.06	5.89	Alumina (Al_2O_3)
1.60	3.62	Magnesia (MgO)
1.06	2.67	Iron oxide (Fe_2O_3)
0.1	2.60	Sulfur trioxide (SO_3)
6.12	1.59	Loss of ignition
-	33.37	C_3S
-	35.92	C_2S
-	11.09	C_3A
-	8.12	C_4AF

Table 2. Characterization of steel fibers.

Fiber properties	Quantity
Average fiber length (mm)	12
Average fiber diameter (mm)	0.20
Aspect ratio (I/d)	60
Tensile strength (MPa)	>1100
Ultimate elongation (%)	4
Specific gravity	7.85

Table 3. Characterization of polypropylene fibers.

Fiber properties	Quantity
Average fiber length (mm)	12
Tensile strength (MPa)	137-689
Young's Modulus (GPa)	3.4-4.8
Toughness (GPa)	8.82
Elongation (%)	25-40
Specific gravity	0.9
Melting point (°C)	160

2.2. Mix proportions

The mortar compositions are given in Table 4. A total of eleven mortar mixes were prepared using water-binder (cement + metakaolin) in a ratio of 0.40 and the metakaolin was used in the porder of 10% as a partial replacement of cement. The amount of cement, metakaolin, sand and free water were kept constant. The amount of superplasticizer varied from 1.5% to 2.2% by weight of binder content to maintain flowability for all the mixes. The steel fibers were added to the mix according to the volumetric fraction of 1.0, 1.2, 1.4, 1.6, 1.8 and 2.0% of the mixes was used in preparing the M1-M6 mixes. However, the 2% hybrid mix of fibers was composed of different amounts of steel and polypropylene fibers in the preparation of mixes M7 to M10.

Table 4. High performance mortar mix proportions.

Index	Cement (kg/m^3)	MK (kg/m^3)	Sand (kg/m^3)	SP (%)	W/C	SF (%)	PPF (%)	Flow (%)
M0	585	65	1462	1.5	0.4	-	-	130
M1	585	65	1462	1.5	0.4	1.0	-	130
M2	585	65	1462	1.5	0.4	1.2	-	130
M3	585	65	1462	1.5	0.4	1.4	-	125
M4	585	65	1462	1.5	0.4	1.6	-	125
M5	585	65	1462	1.8	0.4	1.8	-	120
M6	585	65	1462	1.8	0.4	2.0	-	120
M7	585	65	1462	2.0	0.4	1.8	0.2	120
M8	585	65	1462	2.0	0.4	1.6	0.4	115
M9	585	65	1462	2.2	0.4	1.4	0.6	110
M10	585	65	1462	2.2	0.4	1.2	0.8	100

2.3. Test methods

Three cube 50×50×50 mm samples were used for each mix to test the compressive strength at various ages 7, 28 and 90 days according to ASTM C109. The flow test for mixes was performed according to ASTM C230 with a designed flow of 130%. The cube specimens were left in the molds for 24 hours at 20 °C after casting. After demolding, the specimens were kept in plain water until the time of the test. Compressive strength test was performed directly after the density test according to ASTM C642. Splitting tensile test was achieved using 150 × 300 mm cylinders according to ASTM C469. Bond strength test (slant shear) was tested using cylinder 76.2×152.4 mm according to ASTM C882. Besides, three 40×40×160 mm prismatic steel molds were used to prepare the specimens for the flexural strength test according to ASTM C348, and the toughness indices were determined according to ASTM C1018.

2.3.1. Two-Part bond strength tests

The design of normal concrete used as substrate, are given in Table 5. The normal concrete is proposed here as substrate concretes that it needs to be repaired using repair materials. NC substrate are cast at 28-day earlier than the repair material and the composite specimens were tested after curing period of 28-day. The specimens of that concrete were sawed and the interface surface prepared by sandblasting to connected by repair materials in one system. Also the failure modes were examined for all test specimens.

Table 5. Mix proportions of normal concrete used as substrate concrete.

Mix	W/C	Cement (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	M.A.S (mm)	Slump (mm)
NC substrate	0.5	320	640	1280	10	50

In the test of slant shear strength, the repair mortar is bonded to a substrate concrete specimen on a slant elliptical plane inclined at 30° angle from vertical to form a 75×150 mm composite cylinder as shown in Fig. 1. Before the repair mortar is bonded, the slant surface of the substrate concrete specimen is prepared by sandblasting as shown in Fig. 2(a).

The change in the water/binder ratio of the fresh repair mortar due to the water absorption of pre-cast NC halves might result in a decrease in its workability. Hence, all halves cylindrical specimens were cured in water for an additional 24 h before repair mortar was poured. The test is performed by determining the compressive load required to fail the composite cylinder and the bond strength is calculated as [*max load*] / [*area of elliptical surface*].

In the test of splitting tensile strength, the composite specimen was constructed with one-half substrate concrete and other-half repair mortar as shown in Fig. 3. The interface surface of the substrate concrete specimen is prepared by sandblasting Fig. 2(b). The test is performed by determining the split tensile load required to fail the composite cylinder and the bond strength is calculated as [*max load*] / [*area of half cylinder*].

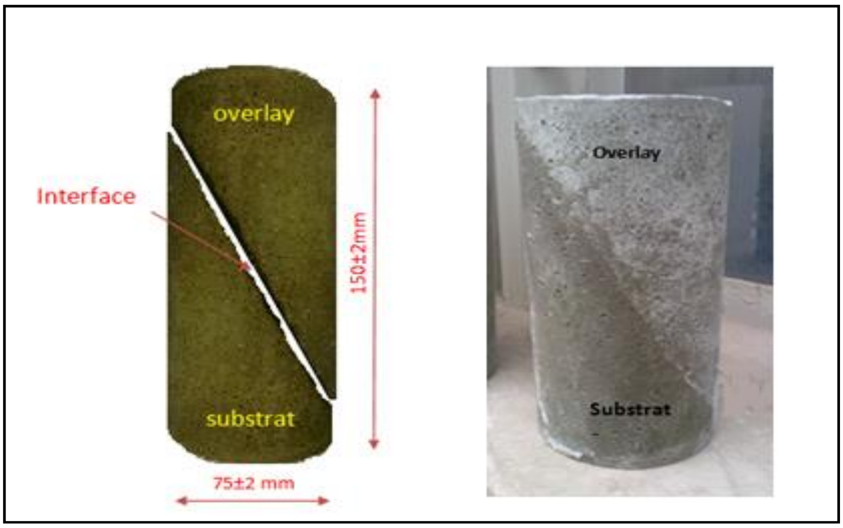

Fig. 1. Composite specimen for slant shear bond strength test.

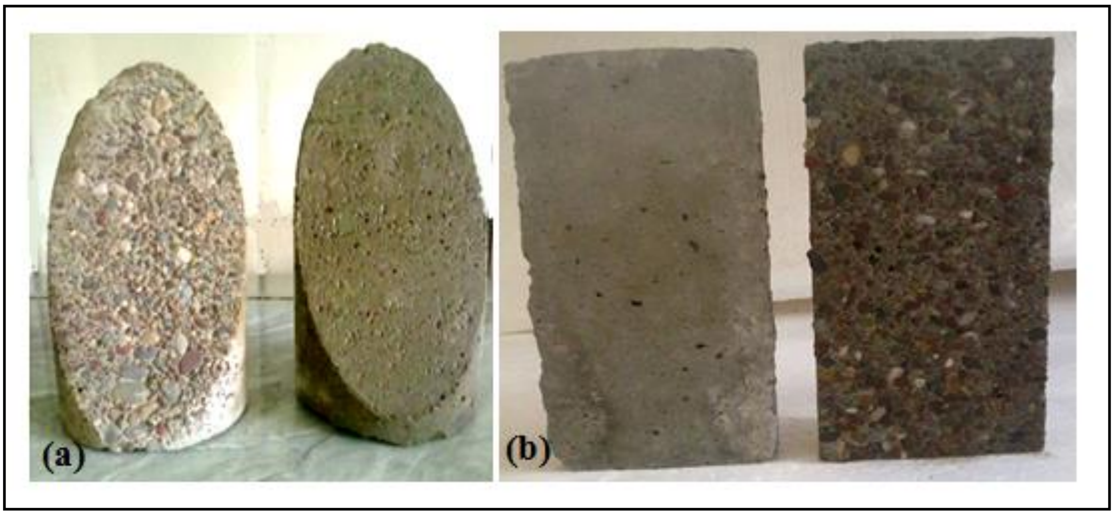

Fig. 2. Preparation of interface substrate concrete by sandblast.

Fig. 3. Composite specimen for splitting tensile strength.

2.3.2. Three-Part bond strength tests

In the test of slant shear, bond strength of the repair materials is determined using ASTM C882 as shown in Fig. 4. In this test procedure, a fresh mortar/epoxy layer with a thickness of 20 mm was placed on the diagonal bonding area between the two halves of NC substrate. Before the repair materials are bonded, the slant surface of the substrate concrete specimen is prepared by sand-blasting. At the same time, the interface surface prepared by dry brushing for epoxy bonding. The bond strength is calculated as [*max load*] / [*area of elliptical surface* × 2].

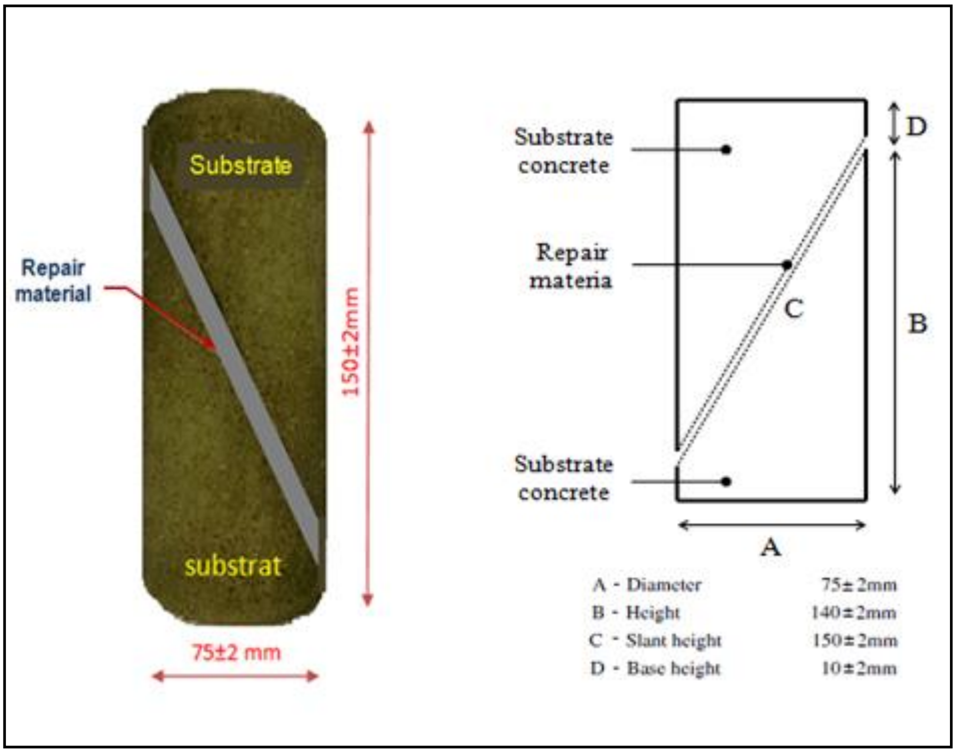

Fig. 4. Composite specimen for slant shear bond-strength test (three-part).

In the flexural strength test, concrete prisms 100×100×400 mm was cast as per standard ASTM C78 test procedure. The specimens of that concrete were sawed and the interface surface prepared by sandblasting shown in Fig. 5. The composite prism of repair material with substrates concrete was fabricated to the same dimensions as the control prism, with the exception that combining two substrate concrete portions by 20 mm mortar/epoxy materials at 45° as show in Fig. 6.

3. Test Results and Discussion

3.1. Pozzolanic activity index

The mean values of PAI for HPM replaced by 0, 5, 10 and 15% of MK after 7 and 28 days is obtained in Fig. 7. This figure indicates clearly that the highest compressive strength was obtained using 10% of total cementitious materials. This percentage of the metakaolin as a partial replacement of cement increases the compressive strength of the cement-mortar owing to the pozzolanic reaction between the amorphous silica in metakaolin and calcium hydroxide produced by the hydration of Portland cement due to Ramezanianpour and Jovein (2012). The use of more than 10% of metakaolin lessens the improvement in compressive strength and this may be due to the fact that C–S–H produced by metakaolin has a lower C: S ratio than the C–S–H resulting from the hydration of Portland cement alone as stated by the study prepared by Mustafa and Yaman (2007).

Fig. 5. Sandblast the two halves of NC substrate.

3.2. Flowability

Table 6 listed the flowability of HPM mixes reinforced with fibers. The inclusion of the fibers in HPM mixes reduces the flowability as fibers volume fraction increased due to Izaguirre et al. (2011). Thus; increasing the amounts of superplasticizer was needed to achieve the desired level of workability and to get a proper distribution of the fibers. The inclusion of 2% individual steel fiber "M6" reduced the value of the flow from 130 mm to 120 mm, despite increasing in SP dosage from 1.5% to 1.8%.

On the other hand, increasing of SP dosage up to 2.2% in the hybrid mix of 1.2% steel fiber plus 0.8% polypropylene fiber "M10", also conduct a reduction in flowability up to 100 mm. Therefore, it can be stated that individual steel fibers showed lesser effect on the flow capacity than that of steel plus polypropylene hybrid fibers relate to the inclusion of polypropylene fibers as reported by Bendjillalia et al. (2011).

Fig. 6. Composite prism of substrates concrete.

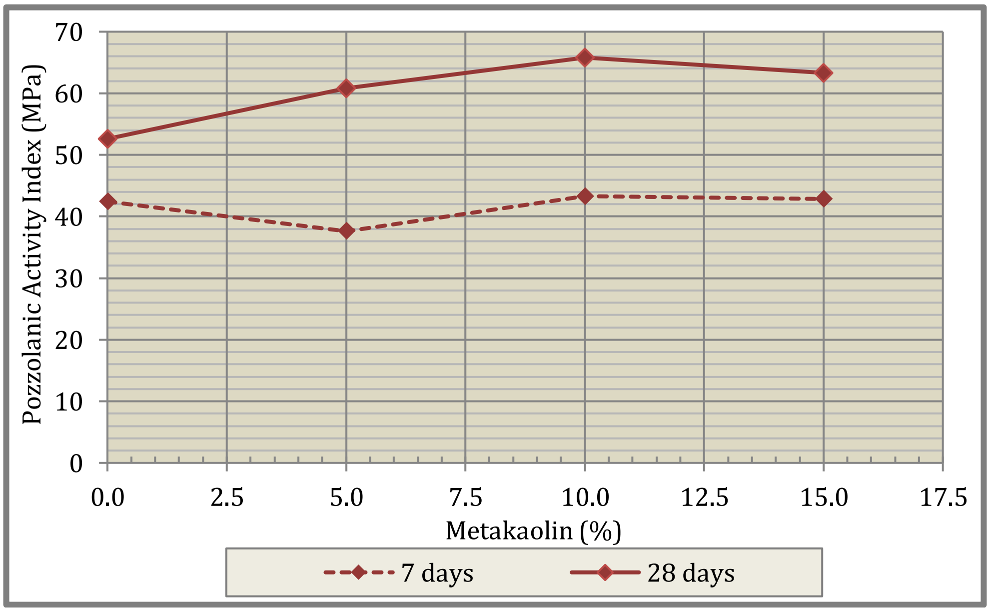

Fig. 7. Relationship between metakaolin percentage and PAI for HPM mixes.

Table 6. Flow of HPM mixes.

Index	M0	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
SP (%)	1.5	1.5	1.5	1.5	1.5	1.8	1.8	2.0	2.0	2.2	2.2
Flow (%)	130	130	130	125	125	120	120	120	115	110	100

3.3. Compressive strength

The results in Fig. 8 show the compressive strength of HPM mixes at 7 to 90 days. For HPM reinforced with different percentages of mono steel fibers (1, 1.2, 1.4, 1.6, 1.8 and 2%) as a volume fraction, the results in Table 7 indicate that the compressive strength increases with fibers content increase.

This enhancement in the compressive strength is most likely due to the fact of a reduction in the porosity of HPM and an enhancement in the mechanical bond strength due to Miloud (2005). These results are comparable with other researches in this regard who are Mohammadi et al. (2005). The increase in compressive strength of HPM incorporating with 2% steel fiber "M6" at 28-day was up to 14% compared to the reference mix "M0". This enhancement in the compressive strength may have resulted from the short length, high stiffness and high modulus of the steel fibers used in this study. As well as the ability of steel fiber to eliminate the microcrack of the cementitious matrix due to Steffen and Joost (2001) and Mustafa and Yaman (2007). The effect of steel fibers percentage on compressive strength of HPM is showed in Fig. 9.

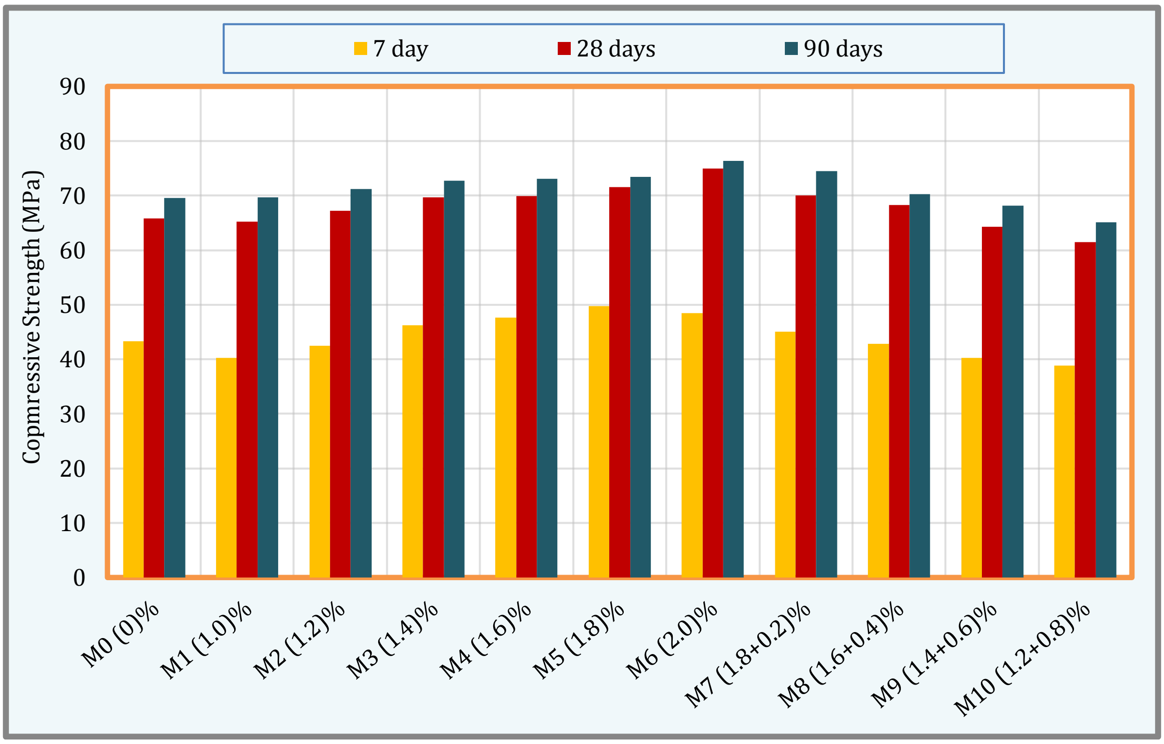

Fig. 8. Compressive strength of HPM reinforced different percentage of mono and hybrid fibers at different ages.

Table 7. Mechanical properties of HPM mixes.

Index	Steel fiber (%)	Polypro-pylene fibers (%)	Compressive strength (MPa) 7-day	Compressive strength (MPa) 28-day	Compressive strength (MPa) 90-day	Splitting tensile strength (MPa) 28-day	Flexural strength (MPa) 28-day
M0	-	-	43.30	65.80	69.50	3.10	9.14
M1	1.0	-	40.30	65.20	69.70	3.14	9.38
M2	1.2	-	42.50	67.20	71.20	3.16	9.27
M3	1.4	-	46.20	69.70	72.20	3.26	9.70
M4	1.6	-	47.60	69.90	73.10	3.45	9.75
M5	1.8	-	49.70	71.60	73.40	3.50	10.08
M6	2.0	-	48.50	74.90	76.30	3.65	10.50
M7	1.8	0.2	45.10	70.00	74.50	3.52	10.17
M8	1.6	0.4	42.80	68.30	70.30	3.35	10.10
M9	1.4	0.6	40.20	64.30	68.10	3.30	9.54
M10	1.2	0.8	38.80	61.50	65.10	2.90	8.86

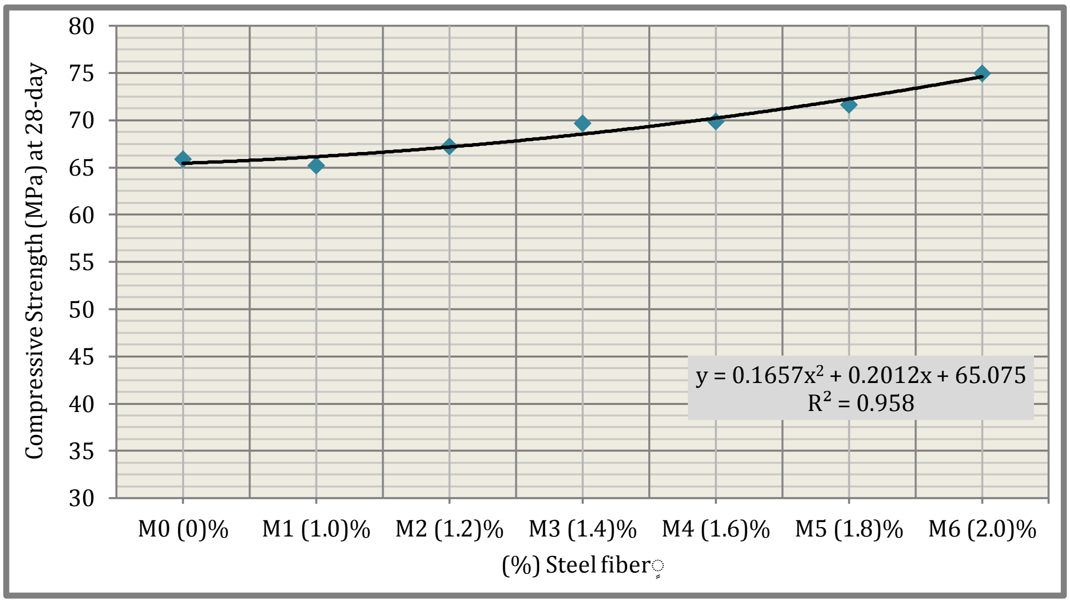

Fig. 9. Relationship between steel fibers content with compressive strength of HPM mixes.

On the other hand, for HPM reinforced with steel and polypropylene hybrid fiber, the comparison between reference mix "M0" with 1.8% steel fiber + 0.2% polypropylene fibers "M7" shows that this hybridization increase the compressive strength by about 7%. Furthermore, the use of 1.6% steel fiber + 0.4% polypropylene fibers "M8" shows increase in compressive strength by about 4%. On the other hand, the inclusions of 1.4% steel fiber + 0.6% polypropylene fibers "M9" and 1.2% steel fiber + 0.8% polypropylene fibers "M10" decrease the compressive strength of HPM by about 2.4% and 6.6%, respectively. This can be attributed to the low stiffness and also the ductility of the polypropylene fibers compared by steel fiber, as well as non-homogeneous distribution of polypropylene fibers generating a coherent matrix due to Markovic (2003). These observation is also supported by Qureshi et al. (2013) that also observed from their results that the increase of polypropylene fibers replacement shows a reduction in compressive strength, they showed the hybridization of (60 kg/m³ SF% + 1.5 kg/m³ PPF) decrease the compressive strength up to 13%. In the summary, the effects of steel-polypropylene hybrid fibers on the compressive strength depended on the percentage of steel fibers replaced by polypropylene fibers. The effect of hybrid fibers on compressive strength of HPM is illustrated in Fig. 10.

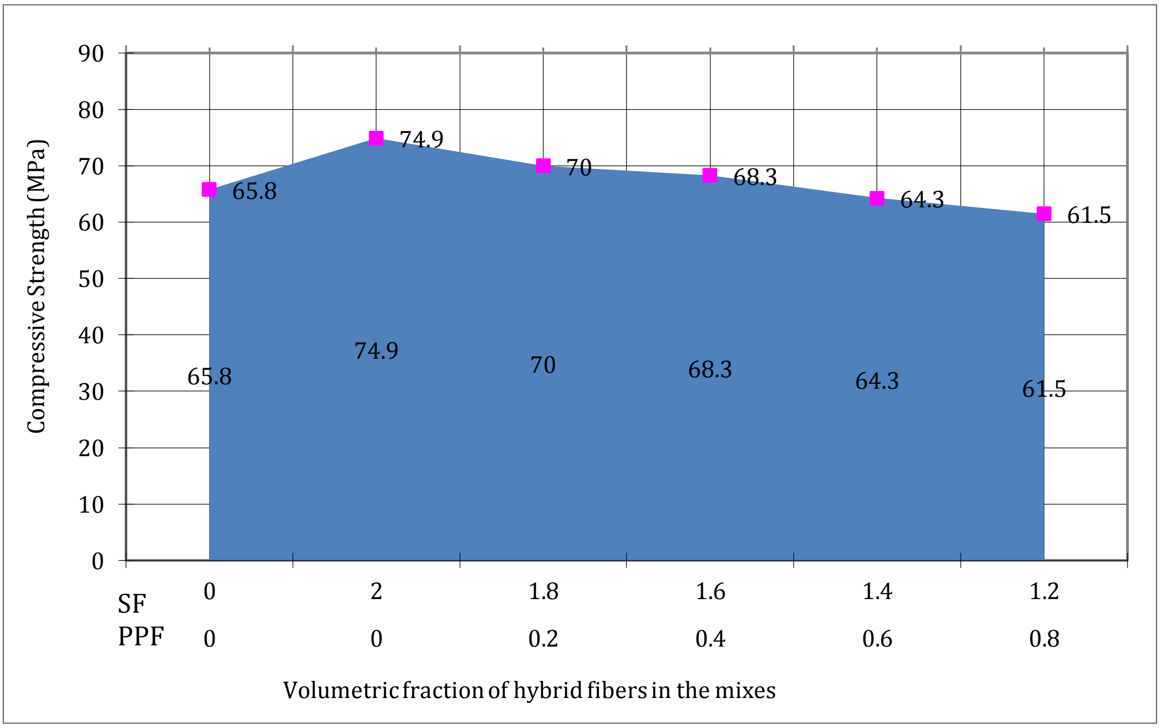

Fig. 10. Relationship between hybrid fibers content (steel+polypropylene) with compressive strength of HPM mixes.

3.4. Splitting tensile strength

For HPM reinforced with steel fibers, the splitting tensile strength increased with an increase of steel fibers content as show in Table 7. HPM reinforced with 2.0% steel fiber as a volume fraction has splitting tensile strength higher than control mix at 28-day by about 18%. This increment may attribute to the high tensile strength of the fibers which bridge the cracks and enhance the splitting tensile of HPM as also supported by other researchers; Aydin (2007), and Dawood and Ramli (2012). The relationship between steel fibers content with splitting tensile strength of HPM mixes are shown in Fig. 11.

On the other hand, for HPM reinforced with steel and polypropylene hybrid fibers, the splitting tensile strength of the HPM at 28 days was up to 13.5% for mortar mix reinforced with 1.8% steel fibers + 0.2% polypropylene fibers "M7" compared with the reference mix "M0". The splitting tensile strength increased by about 8.0% and 6.5% for mixes with 1.6% steel fibers + 0.4% polypropylene fiber "M8" and 1.4% steel fibers + 0.6% polypropylene "M9", respectively. The hybridization of 1.2% steel fibers + 0.8% polypropylene fiber "M10" shows a decrease in splitting tensile strength by about 6.8%. The effect of hybrid fibers content on splitting tensile strength of HPM is illustrated in Fig. 12.

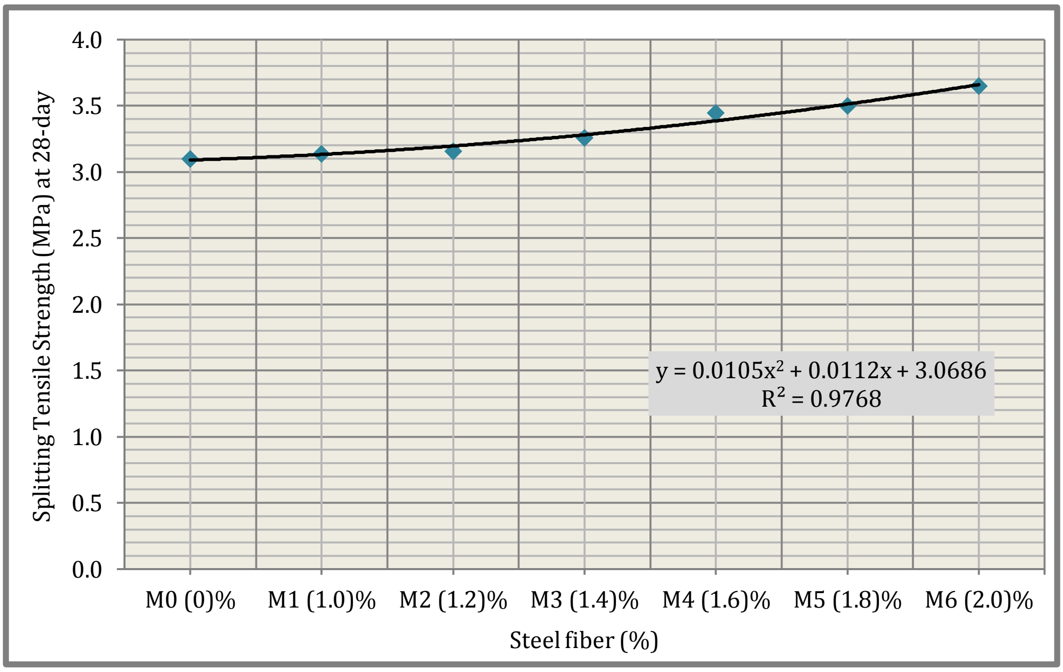

Fig. 11. Relationship between steel fibers content with splitting tensile strength of HPM mixes.

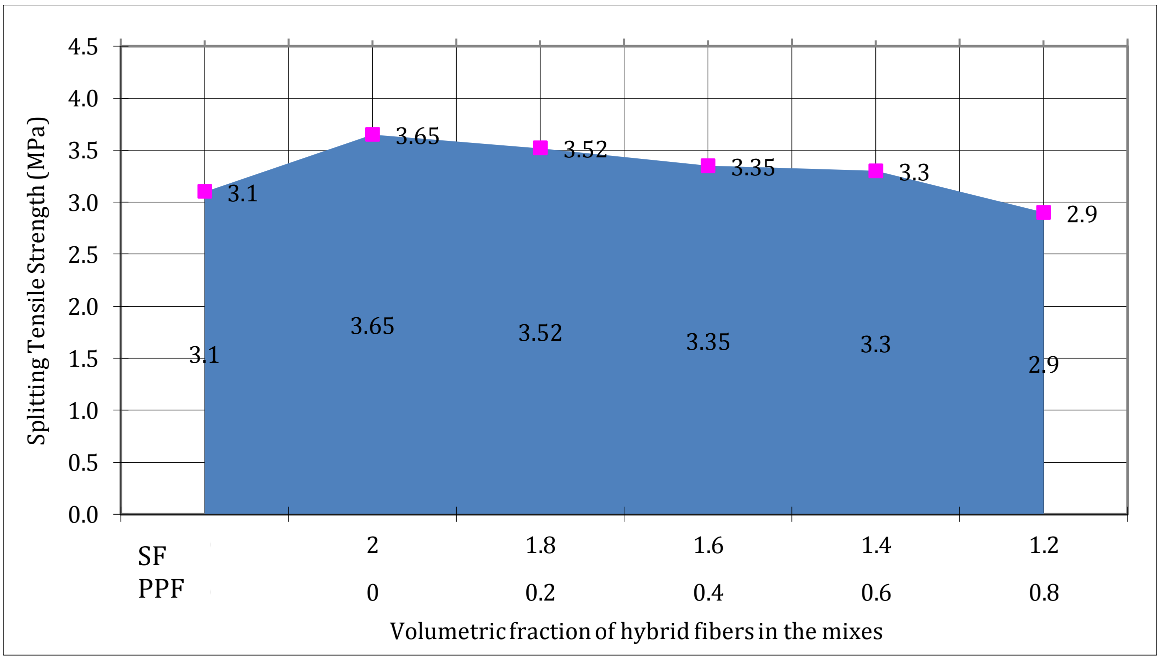

Fig. 12. Relationship between hybrid fibers (steel+polypropylene) with splitting tensile strength of HPM mixes.

As a result it can be stated that the effect of hybrid fiber in splitting tensile strength is expected since the plane of the failure is well defined diametric 'splitting'. The higher the number of fibers is bridging the diametric crack, the higher would be the split tensile strength due to Sivakumar and Santhanam (2007). However, fiber availability is not the only parameter governing the strength; the stiffness of the fiber is also a major parameter affecting the strength. The increased fiber availability of polypropylene fiber with the high stiffness of steel fiber resulted in a significant enhancement of the split tensile strength for these combinations up to a specific limit.

3.5. Flexural tensile strength

The results of flexural strength of HPM are illustrate in Table 7. For HPM mixes reinforced with individual steel fiber, flexural strength demonstrated an appreciable increase in flexural strength with a percentage increase of steel fibers. HPM mix containing steel fiber up to 2% "M6" has a flexural strength up to 15% higher than that of the control mix "M0". It was observed that, the formations of cracks were extended in the specimens without steel fibers "reference mix" in greater numbers. Whereas, they were the least in the specimens reinforced with the highest steel fibers content used in this study such observation are comparable by other researches in this regard; Dawood and Ramli (2010) and Koksal et al. (2008) .The effect of steel fibers percentage on flexural strength of HPM is illustrated in Fig. 13.

As a result, the increase in flexural strength, increase the resistance against crack propagation due to the loads effects and decrease the possible crack propagation due to internal stresses occurring in the matrix, since the use of steel fibers makes mortar stronger and thus durable against the cracks due to Mohammadi et al. (2005), and Sevil et al. (2011).

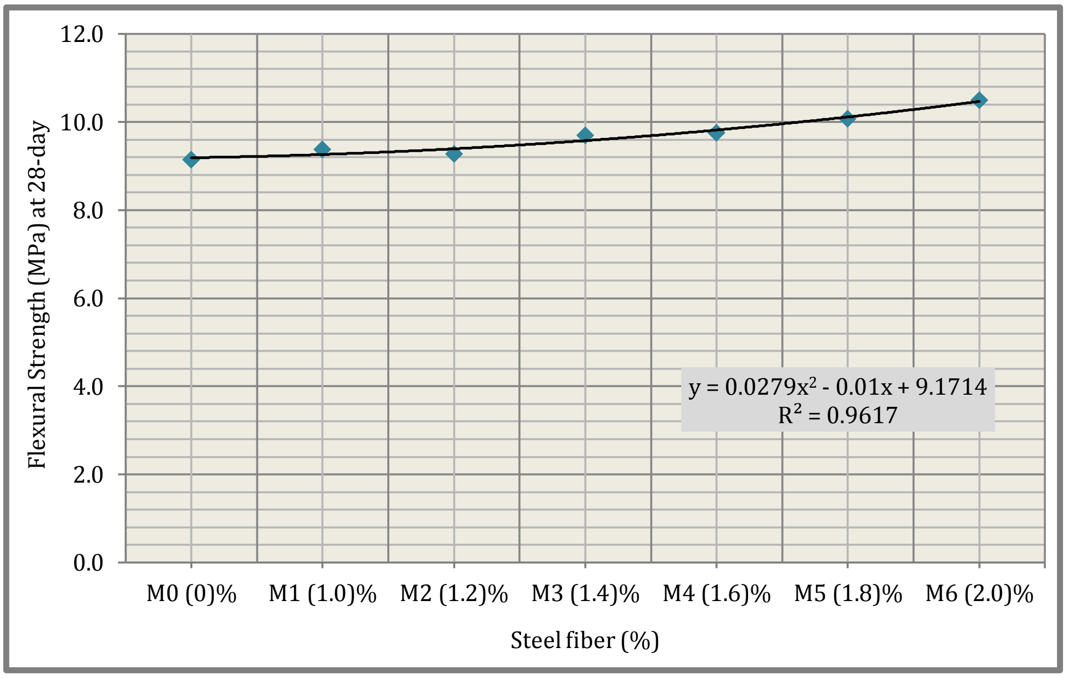

Fig. 13. Relationship between steel fibers content with flexural strength of HPM mixes.

On the other hand, for HPM mix reinforced with hybrid fiber, the hybridization of two fiber types and the aspect ratio showed noticeable enhancement in peak load as supported by other researchers; Hsie et al. (2008). The use of 1.8% steel fiber + 0.2% polypropylene hybrid fibers "M7" increased the flexural strength of HPM at 28 days by about 11.3% compared with the reference mix "M0". In addition, the flexural strength increased by 10.5% and 4.4% for M8 and M9 respectively, then the flexural strength decrease at hybridization of 1.2% steel fiber + 0.8% polypropylene fibers mix "M10" by about 3%.The effect of hybrid fibers content on flexural strength of HPM is illustrated in Fig. 14. It can be stated that the flexural strength of hybridization fibers mixes depends on the volume fraction of steel fiber, related to the high stiffness as compared to polypropylene fiber due to Campello et al. (2014). The latter fibers are more efficient in delaying the growth and propagation of micro- and meso-cracks before peak load due to Qureshia et al. (2013). Whereas polypropylene fiber at high content level led to an obvious decrease in strength, likely due to poor dispersion and agglomeration of the fibers in the matrix as also supported by Bendjillalia et al. (2011).

3.6. Flexural toughness

The results of flexural toughness at 28 days were evaluated using the ASTM C1018 test method. The toughness indices results of HPM mixes with different percentages of individual and hybrid fiber are discussed in this section. In essence, toughness is defined as the ability of fiber reinforced concrete to absorb energy before failure due to its post cracking performance, where the included fibers serves to prevent concrete failure and separation due to Natali et al. (2011). The toughness indices I5, I10 and I30 for different mixes in three-point bending are given in Table 8. For an elastic-brittle material, all indices should be 1. But for an elastic-ideal plastic material, I5, I10 and I30 should be closer to 5, 10 and 30, respectively due to Balendran et al. (2002). Fig. 15 shows toughness indices of HPM mixes, for the reference mix (without fibers) toughness indices is taken equal to 1.0 because the reference mix specimens in flexural test fail immediately after formation of the first crack.

For perusal of the result, HPM mixes reinforced with individual steel fibers, there is evident that the indices I5, I10 and I30 increase with increasing of fiber content in HPM mix. It can be clearly observed that the indices I30 are relatively higher susceptibility to the fiber content compared with I5 and I10 indices. This observation can be attributed based on the stiffness property and the mechanical performance of steel fibers which make them more efficient in this stage according to Lawler et al. (2003). However, the use of 2% of steel fiber boosts the toughness indices I5, I10 and I30 at 28-day by about 4.52, 8.46 and 19.0, respectively.

This enhancement can be attributed to the ability of steel fibers in the arresting cracks at both micro-and macro-levels. At the micro-level, fibers inhibit the initiation of cracks, while at the macro-level, fibers provide effective bridging and impart sources of toughness and ductility as supported by other researchers; Banthia and Sappakittipakorn (2007), and Dawood and Ramli (2011).

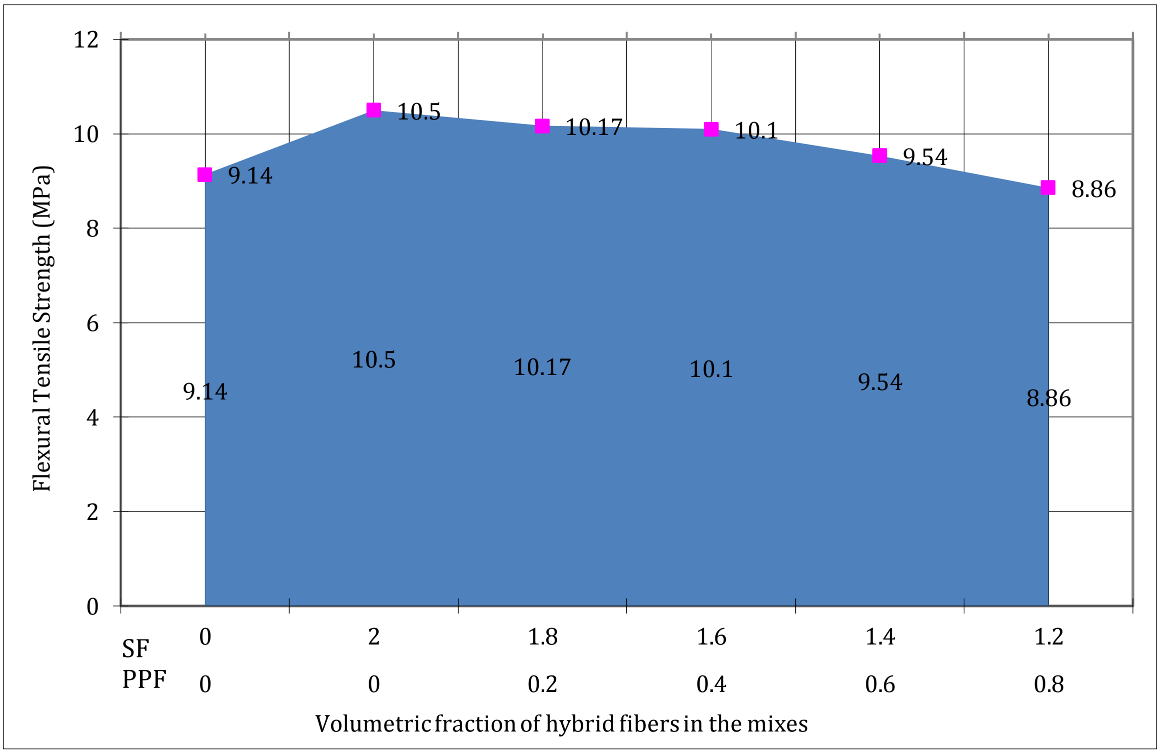

Fig. 14. Relationship between hybrid fibers content (steel+polypropylene) with Flexural strength of HPM mixes.

Table 8. Toughness indices of HPM mixes.

Index	Steel fiber (%)	Polypropylene fiber (%)	Toughness Indices I5 28-day	Toughness Indices I10 28-day	Toughness Indices I30 28-day
M0	–	–	1.00	1.00	1.00
M1	1.0	–	4.16	7.8	15.04
M2	1.2	–	4.44	8.15	15.59
M3	1.4	–	4.01	7.18	15.62
M4	1.6	–	4.46	8.43	17.59
M5	1.8	–	4.31	7.95	17.63
M6	2.0	–	4.52	8.46	19.00
M7	1.8	0.2	4.11	7.52	17.20
M8	1.6	0.4	4.83	8.80	16.65
M9	1.4	0.6	4.59	8.21	14.30
M10	1.2	0.8	4.53	7.69	9.72

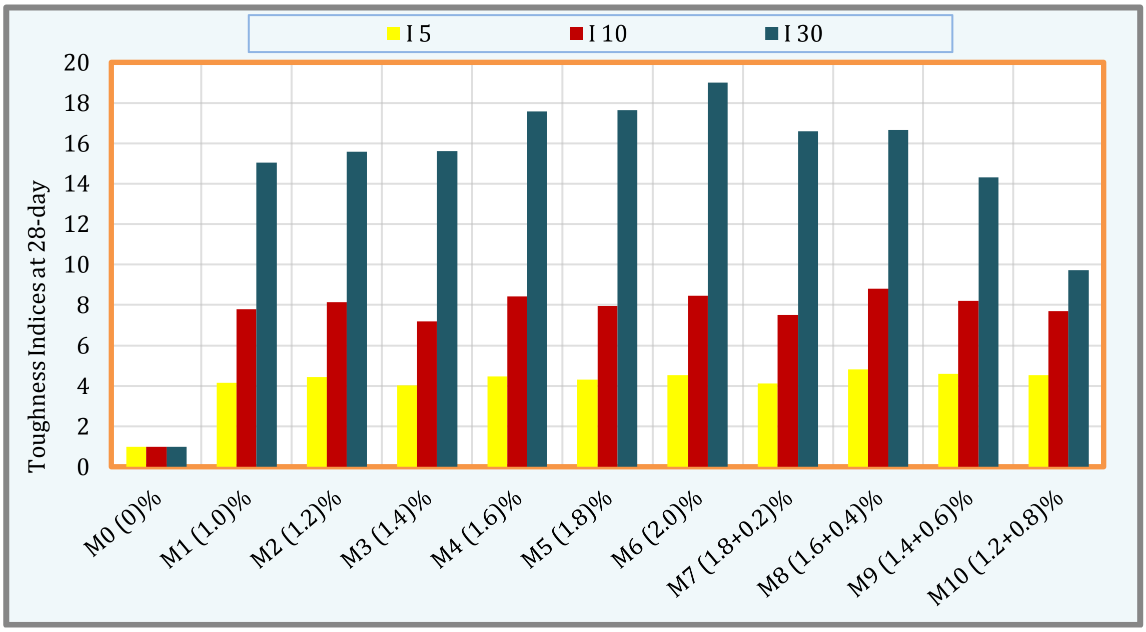

Fig. 15. Toughness indices of HPM mixes at 28-day.

Fig. 16 shows the load–deflection relationship of HPM containing individual steel fiber, it was clearly observed the linearly behave from start loading up to first crack. Then; the majority of additional of steel fiber volume fraction is localized at the crack after the peak load, where the drop in load are accurse. The noticed drops in load seem to be higher for mixes containing lower fiber content and smaller for mixes containing higher ones due to Abd ElAty (2013).

For HPM reinforced with steel and polypropylene hybridization fibers, the highest improvement of toughness indices was found at the combining of 1.8% steel fiber + 0.2% polypropylene fiber "M7" as shown in Table 8. However, flexural toughness indices I5, I10 and I30 of such mix were found as 4.11, 7.52 and 17.2, respectively. It was clearly noticeable that the indices I30 were decreased with the increase of partial replacement of steel fibers by non-metallic fiber (polypropylene fibers). This behavior is related to insufficient steel fiber in this system for bridging the wider cracks as supported by Sivakumar and Santhanam (2007). From the results, it is evident that the ductility of HPM reinforced fiber depends primarily on the fiber's ability to bridge the cracks at high level of strain. Thus, stiffer fibers would be providing better crack bridging; this explains the good performance of steel fiber compared to polypropylene fibers due to Campello et al. (2014).

The load–deflection relationship for steel and polypropylene hybrid fiber mixes is shown in Fig. 17. It was being noticed that the fracture tends to reduce the drop of the load values after the peak load and also with increasing in polypropylene fiber replacement. However the steel fibers have more effect on the post crack strength and the polypropylene fibers has more effect on first crack zone. This observation can be attributed to the fact that the steel fibers which are much stiffer than polypropylene in the hybrid fiber system provide reasonable first crack strength and ultimate strength, whereas polypropylene fibers are relatively flexible and lead to improved toughness and strain capacity in the post-crack zone due to Qureshi et al. (2013).

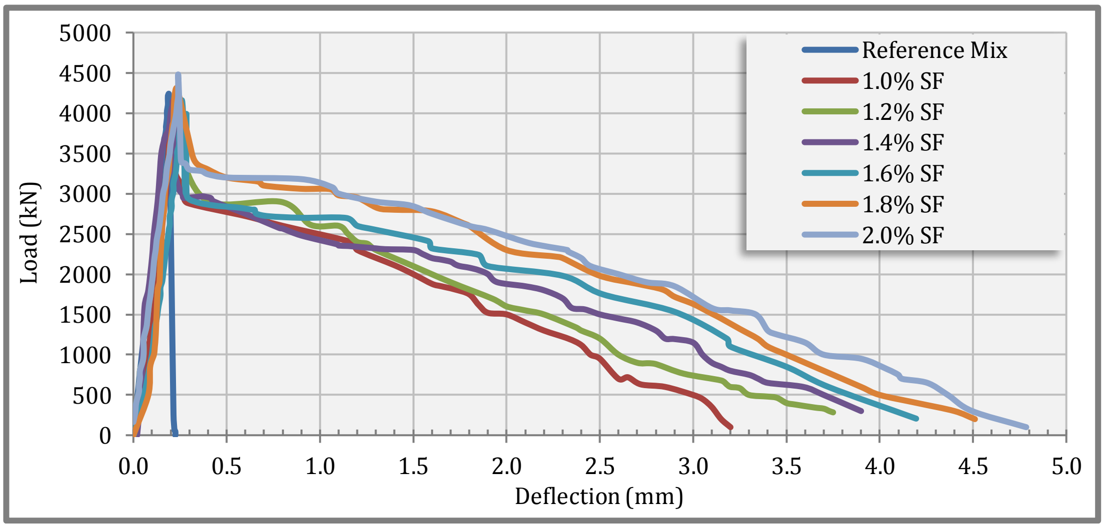

Fig. 16. Effect of steel fibers on flexural toughness of HPM mixes.

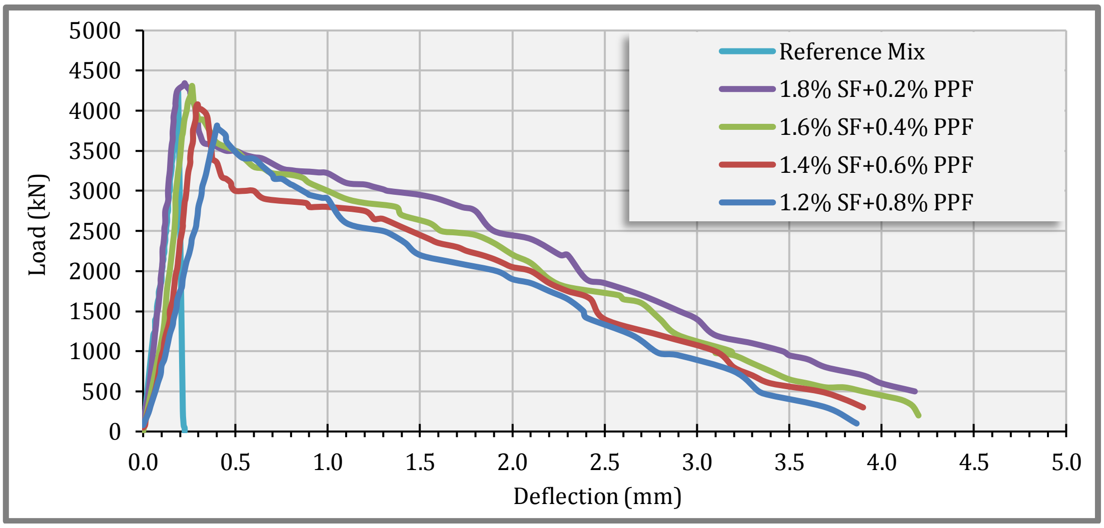

Fig. 17. Effect of hybrid fibers on flexural toughness of HPM mixes.

3.7. Bond strength

Slant shear test as per the specification of ASTM C882 was used to investigate the bond strength between NC substrate and HPM. The HPM was cast and bonded to the NC substrate specimens on a slant plane inclined angle of 30° from the vertical axis to form 75×150 mm composite cylinder specimens. The NC substrate specimens cast 28 days earlier than the overlay mortar, slant surface of the substrate concrete specimen was prepared by sandblasting. Where the interface was subjected to a combination of shear stress and compression forces, the slant shear test is the most appropriate test for such bond assessments.

The experimental results slant shear test presented in Fig. 18. Slant shear strength of composite cylindrical specimens of "M0" mix at 28-day was 10.5 MPa and this strength was increased with an increase of mono steel fiber reinforcement. This observation provided a means to the influence of the disparity of the mechanical properties of the HPM mixes due to Tayeha et al. (2013). The use of 2% volumetric fraction of steel fiber "M6" increased the slant shear strength by about 31% compared to reference mix "M0". On the hand, for HPM mixes reinforced with hybrid fibers, the HPM mix reinforced with 1.8% steel fibers + 0.2% polypropylene fiber mix "M7" exhibited the highest performance in this regard. Such increment was up to 58% compared with the reference mix. As well as bond strength was increased by about 39%, 25% and 14% for mixes M8, M9 and M10, respectively.

ACI Concrete Repair Guide as stated by Chynoweth et al. (1996) specifies the acceptable bond strength for repair work shall within the ranges of 13.8-20.7 MPa for slant shear strength at test ages of 28 days. This guideline is particularly useful for the selection of mortar mixes; M6, M7 and M8 to be used in a repair work.

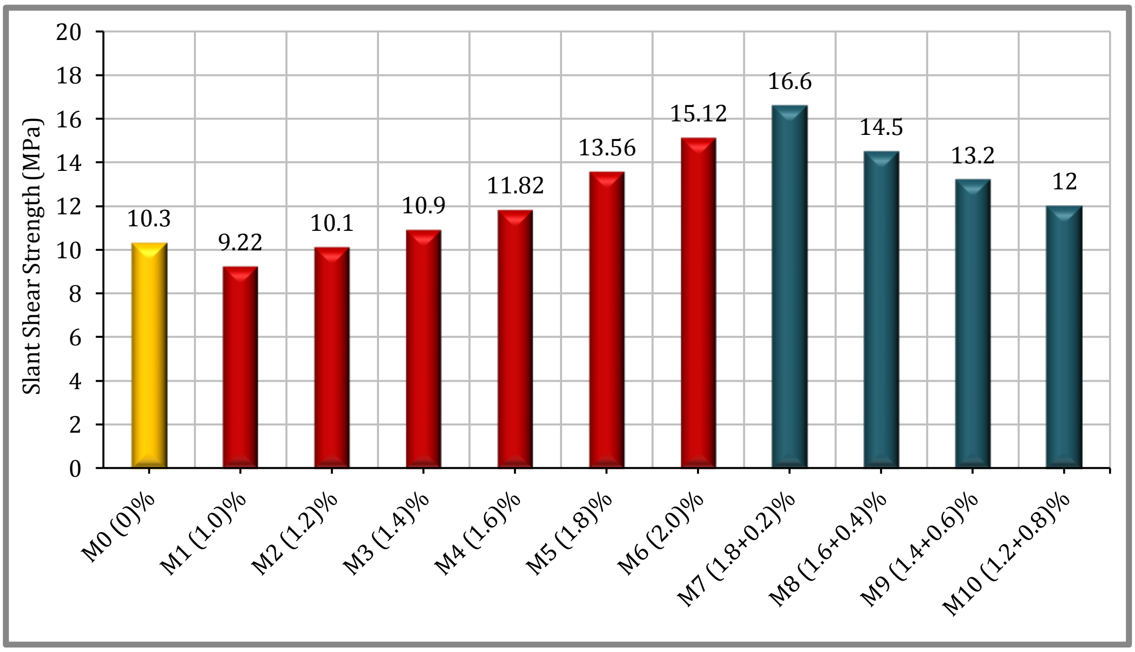

Fig. 18. Relationship between mono and hybrid fibers content with slant shear strength of HPM.

3.8. Dry density

The oven dry density of hardened HPM was determined according to ASTM C642. The results of the dry density test are listed in Table 9. The results at 28 days indicated that the use of steel fibers in HPM mixes increased the overall density of the mortar. The density value increased from 2170 kg/m^3 to 2230 kg/m^3 by the inclusion of 2% steel fibers. By contrast, it can be observed that increasing the amount of polypropylene replaced by steel fiber in the hybridization system reduced the density of the mortar. Therefore, the use of 0.8% of polypropylene fibers with 1.2% of steel fibers reduced the density to 2170 kg/m^3. As anticipated, the specific gravity of polypropylene fiber and the displacement of the mortar matrix during the mixing process reduce the density of the mixes as also supported by other study prepared by Momtazi and Zanoosh (2011).

Table 9. Dry density of HPM mixes.

Index	M0	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
Steel fiber (%)	–	1	1.2	1.4	1.6	1.8	2	1.8	1.6	1.4	1.2
Polypropylene fiber (%)	–	–	–	–	–	–	–	0,2	0.4	0.6	0.8
Dry Density (kg/m^3) (28-day)	2170	2170	2180	2190	2200	2220	2230	2215	2185	2180	2170

3.9. Economical efficiency

In order to give a clearer picture about the real benefits of using the designed mono and hybrid fibers, a classical method called TOPSIS (Technique for Order Performance by Similarity to Ideal Solution) is used to consider the compressive strength, flexural strength, toughness indices and bond strength in combination with the fiber cost as also adopted by other studies prepared by Hshiung and Jih-Jeng (2011) and, Tien-Chin and Tsung-Han (2007).

Table 10 illustrates the data of the reinforcement mixes with their mechanical properties and cost in I.D. used in this mathematical method.

Table 10. Properties of HPM mixes used in TOPSIS method.

Index	Steel fiber (%)	Polypro-pylene fiber (%)	Compressive strength (MPa)	Flextural strength (MPa)	Toughness indices I 30	Bond strength (MPa)	Cost
M1	1.0	–	65.20	9.38	15.04	9.22	785.00
M2	1.2	–	67.20	9.27	15.59	10.10	942.00
M3	1.4	–	69.70	9.70	15.62	10.90	1099.00
M4	1.6	–	69.90	9.75	17.59	11.82	1256.00
M5	1.8	–	71.60	10.08	17.63	13.10	1413.00
M6	2.0	–	74.90	10.50	19.00	13.80	1570.00
M7	1.8	0.2	70.00	10.17	17.20	16.61	1425.60
M8	1.6	0.4	68.30	10.10	16.65	14.50	1281.20
M9	1.4	0.6	64.30	9.54	14.30	13.16	1136.80
M10	1.2	0.8	61.50	8.86	9.72	11.96	992.40

-Cost per 1 kg of steel fibers = 10000 I.D
-Cost per 1 kg of polypropylene fibers = 7000 I.D
-Cost per 1 kg of Epoxy = 18000 I.D

Step 1: Construct the decision matrix M: In this study, there are 10 alternatives (M1 to M10) and 5 criteria (Compressive Strength R1, Bond Strength R2, Flexural Strength R3, Toughness Indices R4, and Fiber Cost R5). Therefore, the common decision matrix can be expressed as:

$$M = \begin{bmatrix} m11 & m12 & m13 & m14 & m15 \\ m21 & m22 & m23 & m24 & m25 \\ \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots \\ m111 & m112 & m113 & m114 & m115 \end{bmatrix}. \quad (1)$$

In this study, decision-making problem can be expressed in matrix format as:

$$M = \begin{bmatrix} 65.2 & 9.38 & 15.04 & 9.22 & 785 \\ 67.2 & 9.27 & 15.59 & 10.10 & 942 \\ 69.7 & 9.70 & 15.62 & 10.90 & 1099 \\ 69.9 & 9.75 & 17.59 & 11.82 & 1256 \\ 71.6 & 10.08 & 17.63 & 13.10 & 1413 \\ 74.9 & 10.50 & 19.00 & 13.80 & 1570 \\ 70.0 & 10.17 & 17.20 & 16.61 & 1425.6 \\ 68.3 & 10.10 & 16.65 & 14.50 & 1281.2 \\ 64.3 & 9.56 & 14.30 & 13.16 & 1136.8 \\ 61.5 & 8.86 & 9.72 & 11.96 & 992.4 \end{bmatrix}. \quad (2)$$

Step 2: Establish the weighted normalized decision matrix N: The raw data need to be normalized using the following equation to eliminate anomalies with different measurement units and scales in several multi-criteria decision-making problems.

$$v_{ij} = \frac{m_{ij}}{\sqrt{\sum_{i=1}^{10} m_{ij}^2}}, \quad (i = 1, 2 \ldots 5, \; j = 1, 2 \ldots 10) \tag{3}$$

Then the weighted normalized decision matrix can be computed by multiplying the importance weights of evaluation criteria and the normalized decision matrix.

$$n_{ij} = w_j \cdot v_{ij}, \tag{4}$$

where w_j is the importance weight of R_j and $\sum_{j=1}^{5} w_j = 1$.

In this study, the importance weights of evaluation criteria w_j for $R1$, $R2$, $R3$, $R4$, $R5$, are 0.2. Then the weighted normalized decision matrix N can be expressed as:

$$N = \begin{bmatrix} 0.0602 & 0.0609 & 0.0594 & 0.0460 & 0.0409 \\ 0.0621 & 0.0601 & 0.0615 & 0.0503 & 0.0491 \\ 0.0644 & 0.0629 & 0.0617 & 0.0543 & 0.0573 \\ 0.0646 & 0.0633 & 0.0694 & 0.0589 & 0.0655 \\ 0.0662 & 0.0654 & 0.0696 & 0.0653 & 0.0737 \\ 0.0692 & 0.0681 & 0.0750 & 0.0688 & 0.0819 \\ 0.0647 & 0.0660 & 0.0679 & 0.0828 & 0.0744 \\ 0.0631 & 0.0655 & 0.0657 & 0.0723 & 0.0668 \\ 0.0603 & 0.0620 & 0.0565 & 0.0656 & 0.0593 \\ 0.0568 & 0.0575 & 0.0384 & 0.0596 & 0.0518 \end{bmatrix}. \tag{5}$$

Step 3: Determine the positive and negative ideal reference points (A+ and A-): In this study, $R1$, $R2$, $R3$ and $R4$ are the benefit-type attributes I (the higher the better), while $R5$ is the cost-type attribute J (the lower the better). The positive ideal reference points A+ and negative ideal reference points A- can be expressed as:

$$A^+ = \{a1^+, a2^+, \ldots a5^+\} = \{(\max n_{ij} \mid j \in I), (\max n_{ij} \mid j \in J)\}, \tag{6}$$

$$A^+ = \{a1^-, a2^-, \ldots a5^-\} = \{(\max n_{ij} \mid j \in I), (\max n_{ij} \mid j \in J)\}. \tag{7}$$

Therefore, in this study, the positive ideal reference points A+ and negative ideal reference points A- can be calculated as:

$$A^+ = (0.0692, 0.0681, 0.0750, 0.0828, 0.0409), \tag{8}$$

$$A^- = (0.0568, 0.0575, 0.0384, 0.0460, 0.0819). \tag{9}$$

Step 4: Calculate the distance to positive and negative ideal reference point (d+ and d-): The distance of each value in the weighted normalized decision matrix to the positive ideal reference point and negative ideal reference point can be derived respectively as:

$$d + i = \sqrt{\sum_{j=1}^{5} (n_{ij} - a_j^+)^2}, \tag{10}$$

$$d - i = \sqrt{\sum_{j=1}^{5} (n_{ij} - a_j^-)^2}. \tag{11}$$

Therefore, in this study, the distance to positive ideal reference point d+ and the distance to negative ideal reference point d- can be calculated as:

$$d+= \begin{bmatrix} 0.0416 \\ 0.0376 \\ 0.0361 \\ 0.0353 \\ 0.0378 \\ 0.0433 \\ 0.0345 \\ 0.0302 \\ 0.0330 \\ 0.0476 \end{bmatrix}, \quad d-= \begin{bmatrix} 0.0463 \\ 0.0408 \\ 0.0361 \\ 0.0387 \\ 0.0396 \\ 0.0461 \\ 0.0492 \\ 0.0421 \\ 0.0355 \\ 0.0331 \end{bmatrix}. \tag{12}$$

Step 5: Obtain the closeness coefficient r^*: Once the distances to positive ideal reference point and the distance to negative ideal reference point are determined, the closeness coefficient r^* can be obtained as:

$$r_i^* = \frac{(d_i^-)}{(d_i^+) + (d_i^-)}. \tag{13}$$

Therefore, in this study, the closeness coefficient r* can be calculated as:

$$r^* = \begin{bmatrix} 0.5263 \\ 0.5202 \\ 0.4999 \\ 0.5224 \\ 0.5117 \\ 0.5160 \\ 0.5876 \\ 0.5825 \\ 0.5176 \\ 0.4102 \end{bmatrix}. \tag{14}$$

A candidate fiber hybridization with an r^* close to 1 has the shortest distance from the positive ideal reference point, and the largest distance from the negative ideal reference point. In other words, a large r^* indicates good performance. The ascending rank of all the groups in this study is substituted as follows:

M7 > M8 > M1 > M4 > M2 >M9 > M6 > M5 > M3 > M10

The HPM reinforced by 1.8% steel fiber +0.2% polypropylene fiber "M7" having the largest closeness coefficient value, is the best among the ten mixes.

3.10. Bond strength results of the combined system

In this section, the evaluations of the selected mix in section 4.9 are presented. NC substrate are cast at 28-day earlier than the overlay mortar and the composite specimens were tested after curing period of 28-day. The results are presented in Figs. 19 and 20 with their details in Tables 11 and 12 for the two parts and three parts bond strength.

3.10.1. Effect of HPM on two-part bond strength

Table 11 contains the distinctive values for composite specimens involved: NC substrate bonded to reference mix "R+M0", HPM reinforced by 2% mono steel fiber "R+M6" and HPM reinforced by 1.8% steel fiber + 0.2% polypropylene fiber "R+M7", with a sand blasting interfacial surface. The failure modes generally can be categorized into three types that is: 'Type A' is pure interfacial failure; 'Type B' is interfacial failure with partially substrate failure and 'Type C' is substratum failure as also supported by other study prepared by Tayeha et al. (2013).

The results present in Fig. 19 indicate a significant increase in slant shear strength and splitting tensile of HPM reinforced by 1.8% steel fiber + 0.2% polypropylene fiber "R + M7". This can be attributed to the efforts of steel fibers as well as polypropylene fibers to bridging the cracks and prevent the composite specimens from taking apart as reported by Chan and Chu (2004). On the other hand, the enhancement in bond strengths was less effective by using HPM reinforced by 2% steel fiber "R + M6" even though the fiber reinforcement prevents the composite specimens from separation. Consequently, the results show that the enhancement was less effective using reference mix "R + M0" and with the worse failure mode 'Type A' to use it as a repair material.

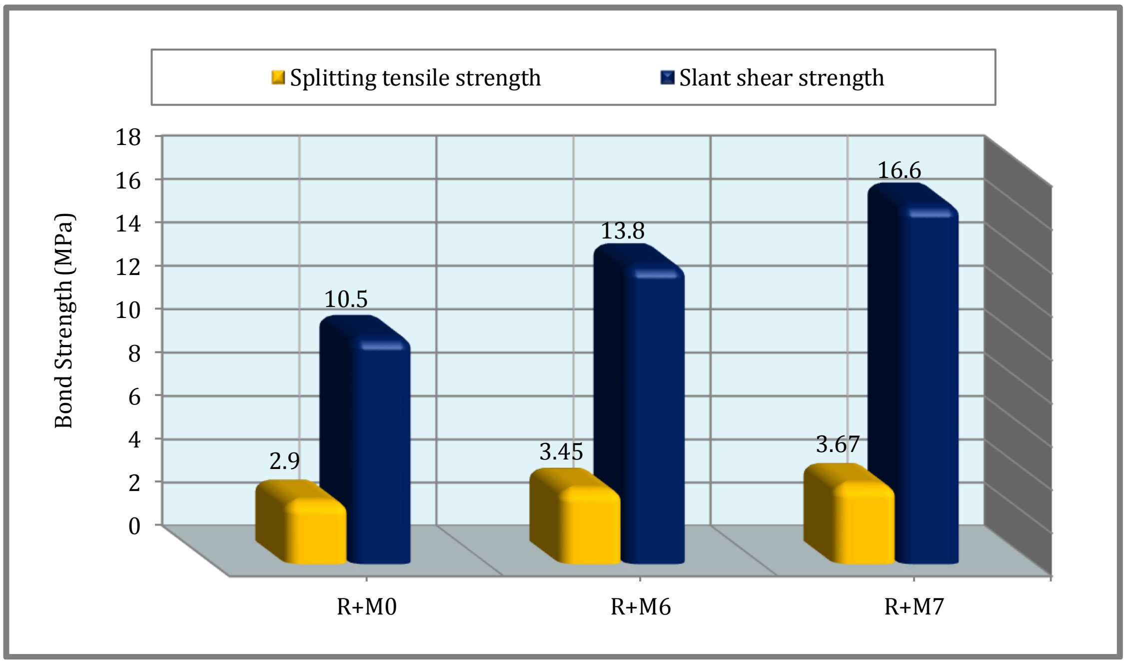

Fig. 19. Two parts bond strength.

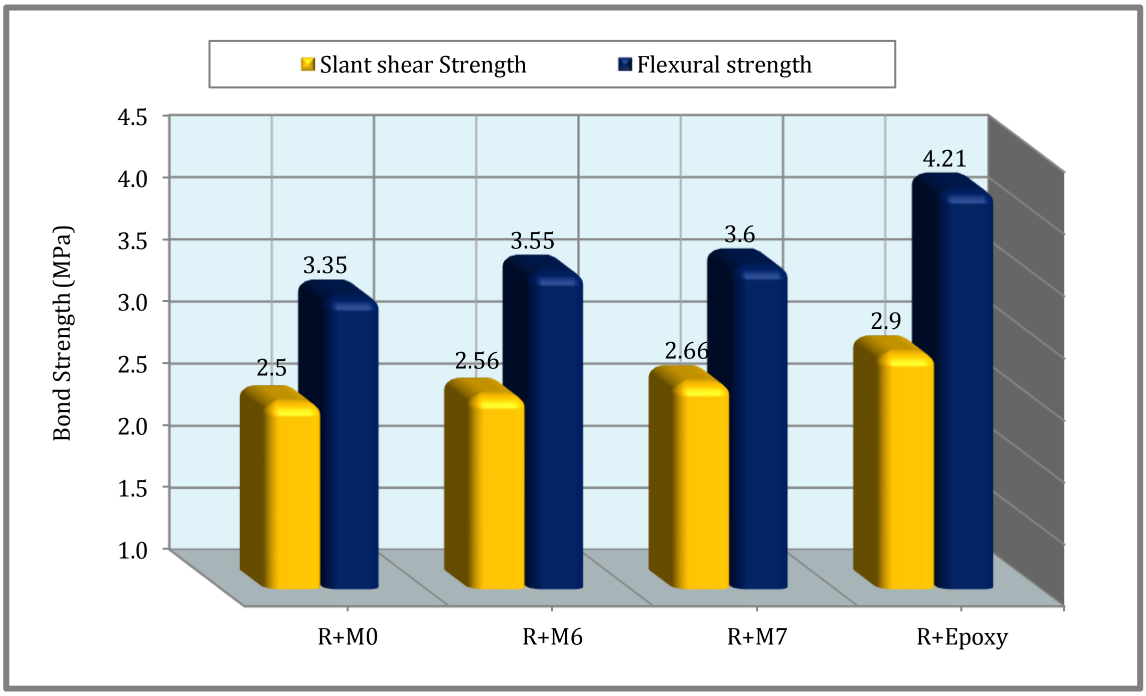

Fig. 20. Three parts bond strength.

Table 11. Properties of combined system [normal concrete + HPM mixes].

Index		Bond strength (Two-part)					
		Slant Shear Strength			Splitting Tensile Strength		
		Force (kN)	Strength (MPa)	Failure Mode*	Force (kN)	Strength (MPa)	Failure Mode*
R+M0	Sample 1	92.5	10.5	A	58.1	2.9	A
	Sample 2			B			A
R+M6	Sample 1	122.0	13.8	C	69.3	3.45	B
	Sample 2			C			B
R+M7	Sample 1	146.6	16.6	C	73.4	3.67	B
	Sample 2			C			B

*Failure mode:
Type A is pure interfacial failure; Type B is interfacial failure with partially substrate failure and Type C is substratum failure.

Table 12. Properties of combined system [normal concrete + HPM/epoxy].

Index		Bond strength (Three-part)					
		Slant Shear Strength			Flexural Strength		
		Force (kN)	Strength (MPa)	Failure Mode*	Force (kN)	Strength (MPa)	Failure Mode*
R+M0	Sample 1	44.9	2.5	A	12.1	3.35	A
	Sample 2			B			A
R+M6	Sample 1	45.4	2.56	C	12.7	3.5	B
	Sample 2			C			B
R+M7	Sample 1	47.1	2.66	C	13.1	3.60	B
	Sample 2			C			B
R+Epoxy	Sample 1	52.3	2.9	B	15.3	4.21	A
	Sample 2			B			A

*Failure mode:
Type A is pure interfacial failure; Type B is interfacial failure with partially substrate failure and Type C is substratum failure.

3.10.2. Effect of HPM on three-part bond strength

The results of slant shear strength and the flexural strength are very important in the evaluation of repair materials. Slant shear of full cylinder in addition to composite beam are measured after connecting two parts of NC substrate with the overlay layer of M0, M6 and M7 as well as the epoxy material. As the results illustrated in Table 12, the best value of slant shear strength is the value of 2.9 MPa from the combination of NC with epoxy and the interface failure occurred after the damage in the NC substrate 'Type B failure mode'. Slant shear strength was found 3.5 MPa and 3.6 MPa for "R+M6" and "R+M7" respectively and the failure occurred only in the NC substrate 'Type C' and there is no separation between the NC substrate and the HPM which indicates that superior bond behavior due to the presence of fibers. The least value was obtaining in the combination system with reference mix "R+M0" with 'Type A' failure mode.

For the flexural strength, Figure 20 shows the combination of NC substrate with epoxy boasts the best value of 4.21 MPa compare to other connect system although it shows 'Type A' failure mode. The performance of HPM reinforced with fiber was found to be lesser effective in improving than epoxy, although the presences of the fibers prevent the combined specimen from separation and be evidence for 'Type B' failure mode. The least value of composite beam strength was obtained by combinations with reference mix "R+M0".

In general, it can be concluded that HPM reinforced by hybrid fibers has the best performance when two-part bond strength is required. On the other hand, in three parts bonding, the connection of NC with epoxy has the best bond strength value while HPM reinforced fibers show a superior failure mode in view of the fact that there is no separation in the composite specimen.

4. Conclusions

Depending on the testing program of this investigation, the following conclusions can be drawn:

- Incorporation of metakaolin in HPM mixes at 10% as a partial replacement of cement gives the highest increase in compressive strength compared with other ratios of replacement.
- The inclusion of mono steel fibers has a lesser effect on the flowability of HPM compared with hybrid fibers (steel + polypropylene).
- The use of 2% steel fibers increases the compressive strength of HPM by about 14%. Whereas, the hybridization of 1.8% steel fibers + 0.2% polypropylene fibers gives the highest increment of 7% compared with the other hybridization mixes.
- The splitting tensile strengths of HPM are significantly improved by incorporating 2% of steel fiber. Thus, the splitting tensile strength of HPM has increased by about 18% higher than that of the control mix. However the inclusion of the hybrid fibers of 1.8% steel fiber plus 0.2% polypropylene fibers increase the splitting tensile strength by about 14%.
- The use of fibers increases the flexural strength of HPM. However, steel fibers show best performance compared with hybrid fibers. The highest increment of the flexural strength of HPM is 15% by the incorporation of 2.0% steel fibers.
- The toughness indices results show that the use of 2% of mono steel fiber boasts the highest performance compared with other mixes. On the other hand in the hybridization fiber, steel fibers provide reasonable first crack strength, while the polypropylene fibers improve toughness strength in the post-crack zone.
- Hybridization of 1.8% steel fiber + 0.2% polypropylene fiber performs the best result according to the TOPSIS method, which is very beneficial to decrease the production cost.
- The combined strength of two-part shows the use of HPM reinforced by 1.8% steel fibers + 0.2% polypropylene fibers exhibits better performance than that of other composite systems.
- Most of the failure mode in two-part bond tests was through the NC substrate specimen which indicated the bond strength between HPM and NC substrate is stronger than the cracking strength of the NC.
- The best value of three-part bond test was obtained by combination of NC substrate with epoxy as a repair material, while the least values was obtained from repair material using HPM.
- HPM reinforced with fibers show a superior failure mode in three-part bond test in view of the fact there is no separation in the composite specimens in contrast to epoxy combined system.

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