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Flexural Performance of Hybrid Fiber Reinforced Cement Composites Under Elevated Temperatures

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ABSTRACT

Historically, the flexural behavior of hybrid fiber cement composites is not completely understood using the traditional test methods. This research presents the results of an experimental investigations on a high performance cement composites (HPCC) containing both micro steel fibers (SF) and micro polypropylene fibers (PP) before and after elevated temperature exposure. The experimental program was developed to study the flexural performance (flexural strength, toughness and stiffness) under high temperature using mono and hybrid (SF) and (SF + PP) fibers. Mixtures were divided into eight different groups, with constant w/c of 0.28 and different fibers content.

Based on the results of this research, the replacing of micro (SF) in high performance cement composites by 15 % of micro (PP) fibers is recommended at high temperature exposure due to the fact that all hybrid fiber HPCC specimens show slight decreasing in flexural behavior compared to samples reinforced with 1% volume fraction of mono steel fibers after high temperature exposure.

أداء الانثناء للألواح الإسمنتية المسلحة بالألياف الهجينة تحت تأثير درجات الحرارة العالية

تاريخياً، يعد سلوك الانثناء للمركبات السمنتية المسلحة بالألياف الهجينة غير مفهوم بصورة متكاملة باستخدام الفحوصات التقليدية. بينت هذه الدراسة نتائج مختبرية اجريت على مركبات سمنتية عالية الاداء احتوت على الياف حديدية مع الياف البولي بروبيلين قبل وبعد التعرض لدرجات الحرارة العالية. طور البرنامج العملي من اجل دراسة اداء الانثناء (مقاومة الانثناء والصلابة والصلادة) تحت تاثير درجات الحرارة العالية باستخدام الياف الحديد الاحادية والياف الحديد–البولي بروبيلين الهجينة. قسمت الخلطات الى ثمان مجاميع مختلفة بنسبة ماء الى سمنت ٠,٢٨ ومحتوى الياف متغير بناءاً على نتائج هذه الدراسة فان من الضروري استبدال جزء من الياف الحديد المستخدمة في الالواح السمنتية المركبة بـ ١٥% من الياف البولي بروبيلين عند التعرض لدرجات الحرارة العالية. بصورة عامة، بالمقارنة مع نماذج احادية التسليح بـ ١% من الياف الحديد اظهرت جميع الالواح السمنتية المسلحة بالالياف الهجينة تحسناً في خواص الانثناء بعد التعرض الى درجات الحرارة العالية.

الكلمات المفتاحية

مقاومة الانثناء، المركبات السمنتية، الياف وحيدة وهجينة، درجات حرارة شديدة، الياف حديدية والياف بولي بروبيلين.

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Introduction

Over the past decades, researches showed that ductility and toughness can be increased by the addition of fibers into conventional concrete and/or mortar [1]. Geometry of the fiber, and the type of material of which the fiber is made are the most important factors to which the properties of the concrete are affected by [2]. These fibers open up new applications of cementitious composites such as exterior cladding for industrial building and warehouse, exterior sound and fire barrier wall, interior wall lining, interior sound insulation and fire resistant partitions, interior fire or weathering resistant floor, wall and ceiling linings, fire or moisture resistant furniture, etc. [3].

The mechanical behavior of cementitious composites can be significantly improved using fiber reinforcement, which is considered to be one of the most effective solutions for increasing flexural strength and toughness [4]. After the formation of cracks, it has been proven that the addition of fibers to concrete and/or mortar is an effective way to delay the widening and propagating of cracks due to bridging mechanisms provided by fiber reinforcement [5]. Numerous of researches has been carried out to investigate the performance of mono fiber reinforced cementitious composites [6], but little, if any, has been done on the addition of hybrid fibers specially under elevated temperatures.

Pizzol et al. [7] published an experimental study to evaluate the effectiveness of different fibers (steel and plastic) in evaluating reinforced concrete (RC) beams and to give a performance guide of concrete used in structural situations. They concluded that the inclusion of both steel and plastic fibers were better than stirrups in improving the load-bearing capacity and toughness of concrete. In other words, the replacing of conventional transverse ties by a combination of steel and plastic fibers is favorable for bearing quality enhancement.

Based on the published research results, Chen and Liu [8] have shown that the concrete performance can be improved by incorporating both steel and PVA fibers. They presented the benefits of fiber reinforced concrete (FRC) composite, such as increasing ultimate tensile strength, crack width control, ductile capacity in post-peak stage and fracture energy. The test data also showed that hybrid fiber reinforced concrete had better performance compared to plain concrete or concrete with only one type of fiber.

The mechanical properties of high strength light weight concrete (HSLWC) incorporating different types of mono and hybrid fibers were studied by Khalil and Mozan [9]. According to their finding, it is clear that the splitting tensile strength and flexural strength of all hybrid fiber HSLWC samples increased significantly in comparison to concrete samples incorporated 1% volume fraction of mono steel fiber.

Chuang [10] examined the performance of steel fiber reinforced RPC under laboratory temperature and after being heated in temperatures of 400 and 800 oC, respectively. He mentioned, “The peak stress and elastic modulus decreased obviously after higher temperature exposure, which significantly affected the failure mode of RPC”.

In consequence, the performance of various fiber reinforced cernent boards was evaluated in terrns of tensile stress-crack opening behavior by Sam et al [11]. The data collected from that study show that fibers with various geometrical and mechanical features can bridge cracks of various sizes from the micro to the macro scale and the tensile performance of the samples should not be improved using hybrid fiber reinforcements in the mix. This is in agreement with the finding of Jameran et al [12]. They also concluded that for single type of fiber in FRC, the best fiber mix proportion is the concrete batch of (100-0) % which is the one with ST fiber alone and for the combined ST-PP fibers in FRC, the concrete batch that can be adjudged as the most appropriate fiber mix proportion is the (75-25) %.

Objectives

The main objectives of this study is to determine the applicability of using thin sections of high performance cement composites containing both mono and hybrid fibers as an energy-absorbent material for potential structural and non-structural applications before and after high temperature exposure. Other objectives of such hybrid fiber concrete composite are listed as follow:

1. Improving concrete ultimate strength, for fiber that is stiffer, stronger and relatively smaller in size can bridge micro-cracks and to prevent bigger cracks and thus increase higher tensile strength of composite.
2. Increasing concrete composite ductile capacity, for fiber that is more flexible, ductile and relatively larger in size can bridge the macro-cracks and thus increases the toughness and ductile behavior in the post cracking stage.

Materials

The mono and hybrid fiber cement composite components consist of Portland cement, micro silica, fine aggregates, superplasticizer and tap water, in addition to fibers. Type I Portland cement was used to produce all of the investigated boards. According to Table 1, this cement is conformed to Iraqi Specification No. 5/1984. Densified micro silica produced by BASF Company, associated with 145 % accelerated pozzolanic strength activity index, was used as pozzolanic admixture. The chemical compositions of silica fume powder were also stated in Table 1. The results showed that micro silica used in this study conforms to the requirements of ASTM C-1240-05 and ASTM C-618 specifications. Natural sand with 2.36 mm maximum size was used as a fine aggregate in this research. Table 2 shows the grading of sand used in this work. The grading of sand is conformed to Iraqi Specification No.45/1984 (zone 1). The sulfate content, the bulk density, specific gravity and the absorption of the sand were 0.07 %, 1500 kg/m3, 2.65, and 1.2 % respectively.

Table 1: chemical composition of cementitious materials*.

Constituent	Cement (%)	Microsilica (%)
CaO	60.72	1.27
SiO_2	22.71	89.36
Al_2O_3	5.54	0.81
Fe_2O_3	2.35	0.52
MgO	2.27	---
SO_3	2.31	1.04
NaOH+KOH	0.49	1.33
Loss on Ignition	2.4	4.7

*Chemical tests were made by the National Center for Geological Survey and Mines.

Table 2: Properties of fine aggregates *.

Sieve size (mm)	Cumulative passing (%)	Limits of Iraqi Specification No. 45/1984	Cumulative retained (%)
4.75	95.2	90-100	4.8
2.36	78.6	60-95	21.4
1.18	52.0	30-70	48.0
0.60	24.3	15-34	75.7
0.30	10.9	5-20	89.1
0.15	3.8	0-10	96.2
Finesse Modules			3.352
SO_3 content = 0.175 %		< 0.5 %	limits of I.Q.S No.45/1984

*Tests were made by the Concrete Laboratory in Karbala Technical Institute.

A highly efficient third generation of polycarboxylic based High-range Water Reducer Admixture (HRWRA) having a density of 1.095 g/cm^3 was used in the mixtures (Sika ViscoCrete 5930). According to ASTM C494-03, this superplasticizer is classified as type F and G.

Steel fibers with a diameter of 0.2 mm and length of 13 mm and aspect ratio of 65 were provided by Sika Company with a tensile strength of 1180 MPa, relative density of 7840 kg/m^3. Polypropylene fibers with a diameter of 15 µm and length of 12 mm were used in the mixtures with a tensile strength of 300 MPa and relative density of 0.9 kg/m^3.

Mix Proportions and Casting Methodology

In order to assess the strength of high performance cement composites, different factors such as: fiber type, fiber dose and heating temperature were considered. The heating process was performed at different ambient temperatures (400 ºC, 500 ºC and 600 ºC) for 2 hours duration time. A comparison has to be made in the flexural performance for the heated specimens with control specimens (unheated specimens).

A total number of ٨ mixes were used for board production with subsequent different fiber type and volume fraction. Four mono (single) fiber reinforced cement composite (with 0.5, 0.75, 1.0, and 1.25 % volume fraction of steel fiber and four double hybrid fiber reinforced cement composites (including the dose that maximize the flexural strengths for steel fiber of 1.0, 0.90, 0.85 and 0.80 volume fraction + four doses of PP of 0.0, 0.10, 0.15 and 0.20 % volume fraction respectively). Then, all samples were subjected to three different ambient temperatures; (400, 500 and 600 ºC) associated with a comparison with those of control. The proportions of concrete mixes are summarized in Table 3.

Table 3: Mix proportions.

Mix type	Mono SF (%)	Hybrid (SF+PP) (%)
Fiber vol. fraction, V_f	0.50 0.75 1.00 1.25	1.00+0.00 0.90+0.10 0.85+0.15 0.80+0.20
Microsilica / cement by w.t.	50	50
SP / cement By w.t.	1.0	1.0
Sand / cement by w.t.	75	75
Water / cement by w.t.	28	28

Many trial mixes were carried out to find the suitable mix that having the desirable properties in the fresh state, as measured by the flow test according to ASTM C-1437-07, to satisfy the ASTM C-1185-12 requirements of 20 mm thickness composite boards in the hardened state. All the samples, which have dimensions of (305*152*20) mm, were kept inside their molds underneath wet burlap covered with a plastic sheet for 24 hrs. Then, they were demolded, and cured for the testing age (28 days).

Testing Procedures

Flexural tests were performed at 28-day according to ASTM C1185-12 and ASTM C1186-12 specifications. All samples having dimensions of (305 mm) in length and (152 mm) in width with 20 mm thickness. The specimens were simply supported over a span of (255 mm) and loaded at a displacement rate of 2.5 mm/min (which was conducted in a displacement-controlled mode). A computer controlled data acquisition system, (Plate 1), is used to record the test data. The load-deflection curves are characterized by the flexural strength, toughness (total area under the load deflection curve) and stiffness. Each value of the flexural strength was the average of the test results for three specimens.

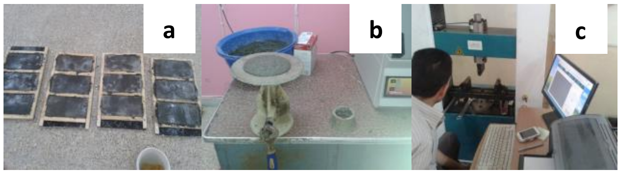


Plate 1: experimental setup: (a) specimen preparation, (b) flow and (c) flexural testing apparatus in the University of Technology.

Scanning Electron Microscopy (SEM)

The scanning electron microscope (SEM) has revolutionized research of cementitious composites. Often, cement and concrete research incorporates the use of the scanning electron microscope (SEM) to perform image analyses of cement-based materials according to ASTM C-856-04 (Plate 2). Although the results from the SEM only provide qualitative data regarding cement hydration products, the results are being used in this study to confirm the results of other techniques such as strength and toughness.

Plate 2: SEM apparatus (Model: TESCAN-VEGA/USA) in the Nanotechnology and Advanced Materials Center / University of Technology.

Results and Discussion

During the mixing stage, it was clearly noticed that the mixes containing mono steel fiber were more flowable compared to that containing hybrid fibers. This is due to the different properties of PP fibers, which make the mixing and dispersion more difficult.

The results of the flexural tests obtained in this research are presented in Figures (1-4) for mono fiber cement composites and Figures (5-7) for hybrid fiber cement composites. In order to reach the optimum fiber volume fraction (vf) that maximize the flexural strength, different proportions of steel fibers were used in the preliminary investigation, (0.5, 0.75, 1.0 and 1.25) %. The results from these tests were as expected and in agreement with previously conducted research on mono fiber reinforced cementitious composites [7, 10].

Figures 1, 2 and 3 present the flexural strength, toughness and stiffness for the used mix of varying steel fiber contents. As shown in these figures, boards that contained (vf = 1.0 % steel fibers) withstood higher loads than other boards of (0.5, 0.75 and 1.25) % vf. The reason for this can be attributed to the bridging mechanism of fibers in tension area. Moreover, these fibers confined the concrete during loading which allowed the boards to experience higher ultimate loads when compared to boards of lower content of same fibers [14]. In addition, the maximum flexural strength recorded was 6.44 MPa which corresponds to the mixture of 1.0 % steel fiber, while the minimum recorded was 4.12 MPa which corresponds to the mixture of 0.5 % steel fiber. Consequently, increasing the fiber content more than 1.0 % reduces the flexural strength and toughness due to balling of fibers.

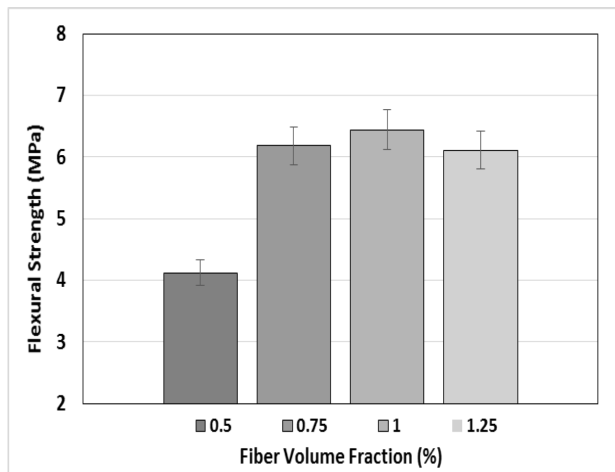


Figure 1: Flexural strength of cement boards of varying steel fiber volume fractions at laboratory temperature.

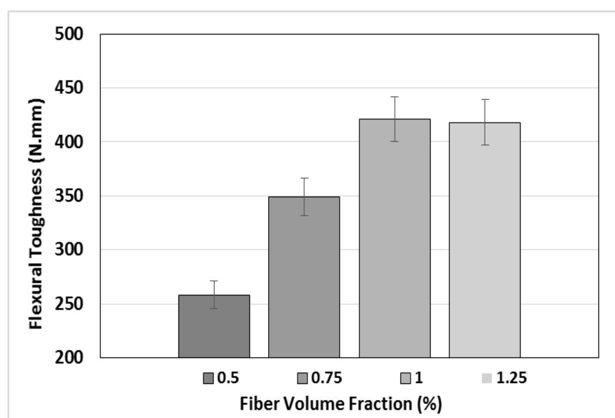


Figure 2: Flexural toughness of cement boards of varying steel fiber volume fractions at laboratory temperature.

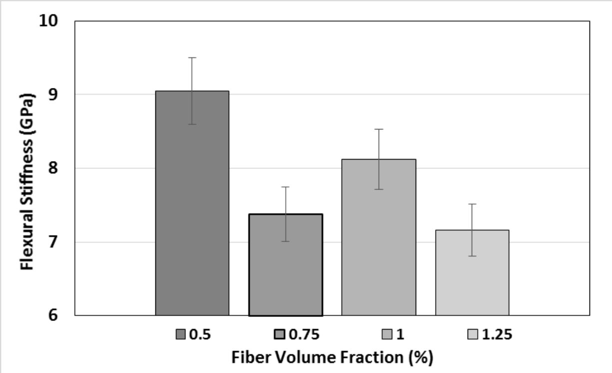


Figure 3: Flexural stiffness of cement boards of varying steel fiber volume fractions at laboratory temperature.

The toughness index characterizes a materials post-cracking behavior and can be used to estimate a materials energy absorbing capabilities. As expected, the toughness values increased with increasing percentages of steel fiber in the mix as shown in Figure 4. One of the main benefits which the addition of fibers to concrete results in a more ductile behavior of a brittle material like concrete and/or mortar. The fact that the overall toughness increased with the addition of fiber demonstrates a degree of success in that increasing the ductility of a fiber cement composite was an overall goal. So, it became evident that 1.0 % is the optimum volume fraction that maximize the flexural strength and would be used later in heat evaluations purposes.

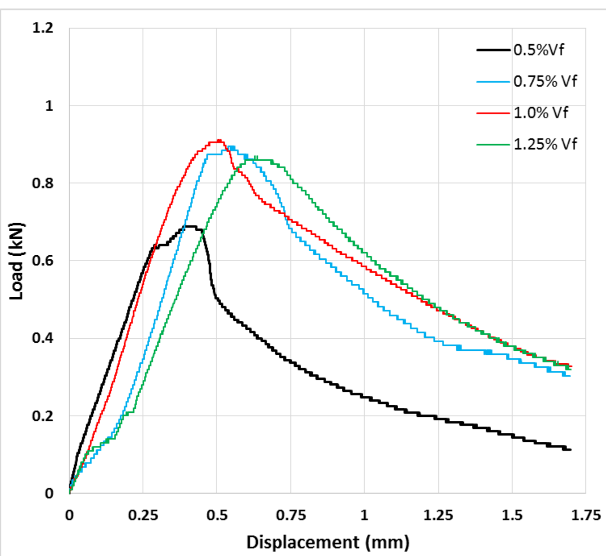


Figure 4: Load-deflection curves of cement boards of varying steel fiber volume fractions at laboratory temperature.

The load-deflection curves obtained experimentally for the fiber reinforced boards are shown in Figure 4, which shows that the boards exhibited a linear elastic response up to a load level of about 0.85 kN, indicating that the stiffness of the boards was high up to this point. The maximum load of the board was able to sustain experimentally 0.9 kN, at a displacement of 0.5 mm. The post-peak response up to ultimate failure was 0.36 kN at a displacement of 1.7 mm, (the solid red line).

Figure 5 shows the relationship between flexural strength and temperature of exposure of mono and hybrid cement composites of different fiber contents. A trend toward decreasing the flexural strength with increasing temperature of exposure and PP fiber content is noted in all cases. This is due to the lower tensile strength of polypropylene fibers and also the weaker bonding between fibers and the cernent matrix after heating [15]. As can be seen from inspection of the results from Figure 5, the exposure to 400, 500 and 600 °C produces little difference in strength. Meanwhile, these differences became very high as compared to control mix. Also, it was observed during testing that the failure mode for heated specimens was very rapid with little warning prior to complete failure as compared to unheated specimens. Furthermore, the comparison between flexural strength values for specimens containing 1 % volume fraction of steel fiber (100-0) and hybrid fiber specimens (90-10), (85-15) and (80-20) shows that the maximum percentages of decrease in flexural strength for hybrid fiber specimens are 65%, 61% and 67% as compared to control mix respectively. It can be observed that specimens containing a combination of steel to PP fibers of (85-15) shows the lowest percentage decrease in flexural strength values relative to mono steel fiber mix in all exposure temperatures.

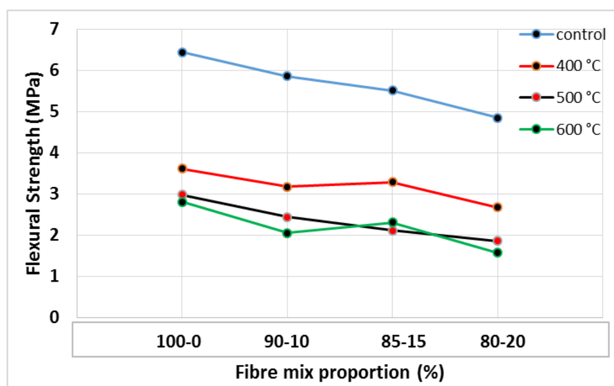


Figure 5: Flexural strength indices for different fiber proportions and ambient temperatures.

Similar to the development of flexural strength degree, the toughness (Figure 6) of the mono and hybrid fiber reinforced samples decreased as the applied temperature increased. After that, it kept decreasing at an increasing rate even when some of steel fibers are replaced by PP fibers. This is due to both degradation of cementitious matrix and polymerization of PP fibers (as it shown in Plate 3-b) that fills the empty spaces and micro pores which make the ITZ denser. This phenomena remediate the structure of matrix after heating and thus, increasing the ultimate flexural strength but reduced toughness because of the lower bridging mechanisms of fibers. It appears that in thin sections (2 cm here), the flexural behavior of hybrid fiber cement composites is the same in flexural strength for thick samples but, it diverse in toughness.

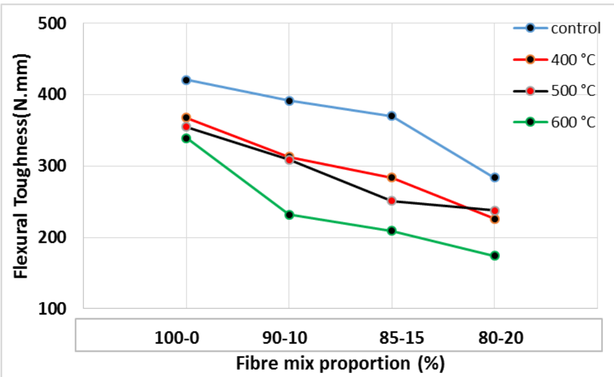


Figure 6: Flexural toughness indices for different fiber proportions and ambient temperatures.

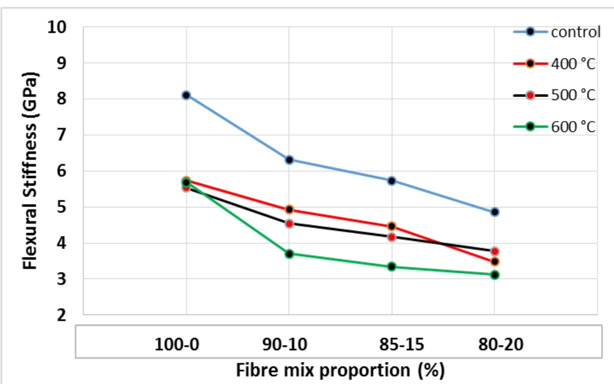
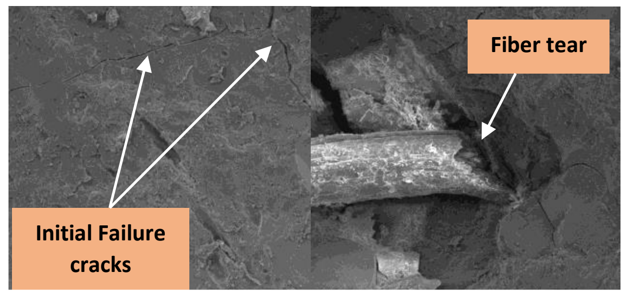


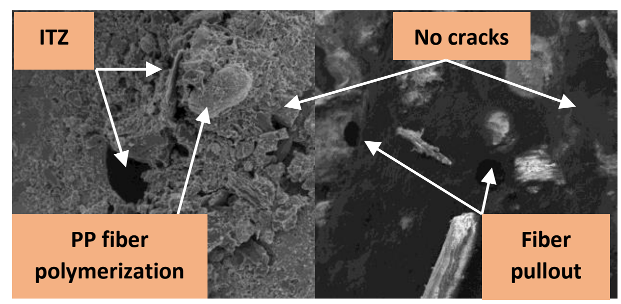
Figure 7: Flexural stiffness indices for different fiber proportions and ambient temperatures.

From results shown in Figure 7, fiber type and heating temperature had significant effects on the bending stiffness of mono and hybrid cementitious composites. Higher ambient temperature and the combination of steel and PP fibers all resulting in lower bending stiffness. The higher the heating temperature, the lower the modulus of elasticity MOE (Figure 7). As for flexural strength, for all three ambient temperatures, the max stiffness decreases by (32, 41, 42 and 36 %) for (100-0), (90-10), (85-15), and (80-20) % vf compared to control specimens.

After carefully observing the broken surfaces of specimens made from steel and/or PP fibers, the pictures of several representative locations were taken and shown in Plate 3. It is clearly seen in Photograph (a) / Plate 3 the formation of initial micro cracks in hydrated cement paste, meanwhile at 600 °C the polymerization of PP fiber fill the empty spaces which reducing the number of cracks as shown in Photograph (b). Besides the deterioration of paste, this reason that make the boards fail quickly after elevated temperature exposure. Since contribution from the PP fiber debonding stage is small compared to pull-out due to the small volume fraction, fracture energy from the debonding stage is negligible. In addition, contribution from steel fiber debonding can also be neglected because the energy is too small compared to steel fiber pull-out. However, energy contributed from an aggregate bridging action and PP fiber pull-out are still small compared to steel fiber pull-out (plate 3-a). This proves again that PP fibers only control strength and early age micro-cracks and does not contribute much to later ductile behavior (plate 3-b). However, steel fibers would contribute the most fracture energy and greatly increase overall ductile capacity.



a : unheated specimens.



b : heated specimens at 600 °C.

Plate 3: Fractured surface SEM images of the (85-15) % vf cementitious composites: (a) non-he
(b) heated at 600 °C.

Conclusions

Accomplishments and findings described in the present research can be summarized as follows:-

- The flexural performance of fiber reinforced cementitious composites can be improved by blending two different fibers together in a matrix under elevated temperatures, because these different fibers play a role at two various levels, material and structural, according to the type, length and diameter of fibers.
- After the high temperature exposure, the combination of steel and PP fibers (mix 85-15) shows the highest percentage increase in flexural strength with respect to mono SF mix.
- In thin sections (2 cm here), the flexural behavior of hybrid fiber cement composites is

the same in flexural strength for thick samples but, it diverse in toughness.

- According to SEM photographs, polymerization of PP fibers (after heating) fills the empty spaces and micro pores which make the ITZ denser. This phenomena remediate the structure of matrix and thus, enhance the ultimate flexural strength but reduced toughness because of the lower bridging mechanisms of fibers.
- All the investigated boards show higher flexural strength than that mentioned in ASTM C-1186-12 even after high temperature exposure. So, these mixes can be used for both structural and non-structural situations.

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