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Fracture behavior of monotype and hybrid fiber reinforced self-compacting concrete at different temperatures

Moosa Mazloom*, Hemin Karimpanah[a] and Mohammad Karamloo[b]

Department of Civil Engineering, Shahid Rajaee Teacher Training University, Lavizan, Tehran, Iran

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Abstract. In the present study, the effect of basalt, glass, and hybrid glass-basalt fibers on mechanical properties and fracture behavior of self-compacting concrete (SCC) mixes have been assessed at room and elevated temperatures. To do so, twelve mix compositions have been prepared such that the proper workability, flowability, and passing ability have been achieved. Besides, to make comparison possible, water to binder ratio and the amount of solid contents were kept constant. Four fiber dosages of 0.5, 1, 1.5, and 2% (by concrete volume) were considered for monotype fiber reinforced mixes, while the total amount of fiber were kept 1% for hybrid fiber reinforced mixes. Three different portions of glass and basalt fiber were considered for hybridization of fibers to show the best cocktail for hybrid basalt-glass fiber. Test results indicated that the fracture energy of mix is highly dependent on both fiber dosage and temperature. Moreover, the hybrid fiber reinforced mixes showed the highest fracture energies in comparison with monotype fiber reinforced specimens with 1% fiber volume fraction. In general, hybridization has played a leading role in the improvement of mechanical properties and fracture behavior of mixes, while compared to monotype fiber reinforced specimens, hybridization has led to lower amounts of compressive strength.

Keywords: fracture energy; fiber reinforced SCC; temperature; hybridization of fibers

1. Introduction

Self-compacting concrete (SCC), is a powerful generation of concrete, with the high ability to fill complex formworks and flow through congested reinforcing without external vibration and under its own weight (Karamloo *et al*. 2019b). Besides, it could lead to a more sustainable construction, since it reduces the noises of vibration (Zarghami *et al*. 2017, Zarghami *et al*. 2018, Zarghami *et al*. 2019, Zarghami and Fatourehchi 2020). Therefore, these key features have turned this material to a good volunteer to be used in infrastructures as well as tall buildings. In fact, during a service life of a building or an infrastructure, fire could threaten the safety of the structures. Therefore, it would be necessary to study the behavior of the used material under elevated temperature. Although concrete, in general, is known for its inherited fire resistance, the recent evidence shows that the explosive spalling could occur due to the exposure of concrete at elevated temperatures. This circumstance is far more aggravated for high strength or high performance generations of concrete (Missemer *et al.* 2019). The reason behind this fact could stem from that these generations are achieved by tailoring their microstructures and therefore maximizing the packing density with ultra-fine particles (Missemer *et al*. 2019). SCC regardless to having superplasticizers, consisted of large amounts of ultra-fine particles such as limestone powder as a neutral filler, and in some cases other additives such as silica fume, fly ash, or colloidal nano silica. Hence, SCC could be sensitive to explosive spalling.

Fibers are a good solution to bridge the stresses along the faces of the crack. However, this performance highly depends on the type and volume of the fibers (Smarzewski 2019b). The use of fibers goes back to about 3500 years ago (Kabay 2014). However, the use of fibers in cement-based materials such as concrete has mainly occurred during the recent two decades. The reason behind this prevalence of using fibers in concrete stems from the fact that almost all of cement-based materials suffer from the drawback of having low tensile strength, which will lead to a cracking even in the absence of notable loads. Therefore, more attention has been paid to the use of fibers either natural or synthetic to improve the cracking behavior of cement-based materials. In this regard, many researches have been conducted all over the world to find the best solution. For instance, it is reported that the use of fibers reduces the abrasive wear of concrete (Grdic *et al*. 2012, Siddique *et al*. 2012). Felekoglu *et al*. (2007) concluded that the use of steel fibers could lead to a considerable increase in energy absorption and toughness of self-compacting repair mortars. Ding *et al*. (2009) observed that the use of steel and polypropylene fibers increases the ductility and flexural toughness of self-compacting high performance concrete. Nevertheless, they reported that compressive strength and flexural strength remained unchanged (Ding *et al*. 2009). Nataraja *et al*. (2000) reported that both the length and aspect ratio of steel fibers could affect the flexural

*Corresponding author, Professor
E-mail: mazloom@sru.ac.ir
[a]M.Sc.
E-mail: h.karimpanah1994@gmail.com
[b]Research Assistant
E-mail: m.karamloo@sru.ac.ir

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Table 1 Chemical properties of cement and silica fume

Chemical composition	Cement (%)	Silica fume
CaO	63.95	0.49
SiO_2	21.46	96.4
Al_2O_3	5.55	1.32
Fe_2O_3	3.46	0.87
MgO	1.86	0.97
SO_3	1.42	0.1
K_2O	0.54	1.01
Na_2O	0.26	0.31
SiC	-	0.5
Cl	-	0.04

Table 2 Mechanical properties of cement

Mechanical properties					
Blaine (m^2/kg)	Initial setting time (min)	Final setting time (min)	3-day compressive strength (MPa)	7-day compressive strength (MPa)	28-day compressive strength (MPa)
330	120	240	17	27	40

Table 3 Properties of fibers

Fiber type	Length (mm)	Diamater (mm)	Tensile strength (MPa)	Elastic modulus (GPa)	Specific gravity(g/cm^3)	Melting Point (°C)
Glass	10	0.02	3450	69	2.55	1400
Basalt	10	0.011	2950	90	2.67	600

toughness of the concrete. Mazloom and Mirzamohammadi investigated the effect of elevated temperature on cementitious composite (Mazloom and Mirzamohammadi 2019a, Mazloom and Mirzamohammadi 2019b) and reported that mixes with polypropylene fiber which was tested at room temperature showed higher fracture energy than those tested at 100°C and 300°C. It should be noted that different fibers have different pros and cons. Therefore, the use of hybrid fibers has gathered a lot of attention (Afroughsabet *et al*. 2019, Bhosale *et al*. 2019, Hari and Mini 2019). For instance, Smarzewski (2019a) considered the effects of hybrid basalt-polypropylene fibers on fracture behavior of high-performance concrete. He tested fiber reinforced high performance concrete specimens with 1% and 2% of basalt and/or polypropylene fibers. According to the results of experiments conducted by Smarzewski (2019a), the use of the mentioned hybrid fibers has led to an extension of post-peak softening behavior while this is not in line with some reported results for basalt fiber reinforced concrete (High *et al*. 2015, Iyer *et al*. 2015). However, he reported that the shape of the softening curve is highly dependent to the properties and volume of the fibers (Smarzewski 2019a). He further claimed that not only the use of high modulus basalt and low modulus polypropylene fibers enhanced the fracture energy, but also it increased both the fracture energy and toughness and also hybrid fibers were more effective than using a single type of fiber (Smarzewski 2019a). In another experimental program conducted by Niu *et al*. (2019) it is reported that the use of basalt-polypropylene hybrid fibers could effectively lead to an increase of chloride ion resistance of concrete besides the increase of compressive strength. Barnat-Hunek and her co-workers (Barnat-Hunek *et al*. 2018) took further steps and used hybrid basalt-steel fibers in a self-compacting lightweight concrete with perlite aggregate. They reported that not only the use of these hybrid fibers enhanced the ductility of the cast self-compacting lightweight concrete, but also it led to the elimination of frost attack during a flexural tensile strength test. Wang *et al*. (2019) considered the mechanical properties of high performance concrete with hybrid basalt-polypropylene fiber. They reported that the compressive strength of single doped basalt or polypropylene fiber reinforced HPC increases with the increase of fiber volume fraction. However, hybridization showed both positive and negative synergy effects. Loh *et al*. (2019) investigated the mechanical properties of hybrid PVA-basalt fiber reinforced cementitious composites and reported that the use of the mentioned fibers improved the ductility of the specimens.

In the present study, glass and basalt fibers and a cocktail of them have been used to enhance the mechanical properties of SCC at normal and elevated temperatures. Therefore, in the next sections available literature about the use of glass, basalt, or hybrid fibers have been represented.

2. Materials and methods

2.1 Material properties and specimen preparation

In the present study, type I Portland cement have been used, whose physical and mechanical properties are tabulated in Tables 1 and 2, respectively. Silica fume, whose chemical properties are reflected in Table 1, is provided as a pozzolanic material and a partial replacement for cement. Natural river fine and coarse aggregate were provided, whose specific densities were about 2.65 and 2.75 gr/cm^3, respectively. Besides, the maximum nominal size of the coarse aggregate was 19 mm and the fineness modulus of the fine aggregate was about 2.72. In order to improve the workability and flowability of the mixtures, polycarboxylate based superplasticizer was used and to enhance the viscosity of the mix, limestone powder was chosen as a viscosity-modifying agent. Two types of fibers (glass and basalt fibers) have been used to enhance the mechanical properties of specimens at room and elevated temperatures. The properties of fibers have been reflected in Table 3.

Twelve mix compositions have been prepared, one of which was a control mix, four of which were basalt fiber-reinforced SCC, four of which were glass fiber reinforced SCC, and three remaining mixes were hybrid fiber reinforced SCC. In order to make comparison possible, the proportions of all contents, except for the fibers, were kept constant. To avoid agglomeration of fibers, the process of mixing was conducted such that at first, the mixture of fine and coarse aggregate along with the fibers were added to the mix and mixed for about 2-4 minutes. Then the mixture of cement, silica fume, and limestone powder was added along with the half of water contents and mixed for about 1-2 minutes. Afterwards, the remaining water, which was

Table 4 Mix compositions

Mix ID	Solid contents (kg/m^3)					Water (kg/m^3)	Superplasticizer (%wt. cement)	Fibers (% Vol.)	
	Cement	Fine aggregate	Coarse aggregate	Silica fume	Limestone powder			Basalt	Glass
NSCC	450	668	867	50	155	200	0.8	0	0
BFS-1	450	668	867	50	155	200	0.8	0.5	0
BFS-2	450	668	867	50	155	200	0.8	1	0
BFS-3	450	668	867	50	155	200	0.8	1.5	0
BFS-4	450	668	867	50	155	200	0.8	2	0
GFS-1	450	668	867	50	155	200	0.8	0	0.5
GFS-2	450	668	867	50	155	200	0.8	0	1
GFS-3	450	668	867	50	155	200	0.8	0	1.5
GFS-4	450	668	867	50	155	200	0.8	0	2
HYS-1	450	668	867	50	155	200	0.8	0.75	0.25
HYS-2	450	668	867	50	155	200	0.8	0.50	0.5
HYS-3	450	668	867	50	155	200	0.8	0.25	0.75

mixed with the superplasticizer, was added and mixed for about 2-3 minutes.

Table 4 shows the mix design parameters used in this study. As it can be seen, fiber reinforced SCC compositions were designed to assess the effect of fibers on mechanical properties and fracture behavior of the mixes at room and elevated temperatures. For each mix, nine 100×100×100 mm^3 cubic specimens according to (BS EN 12390 2000), nine 150×300 mm^2 cylindrical specimens according to ASTM C496 (ASTM C 496 2002), nine prismatic 100×100×350 mm^3 rupture modulus specimens according to ASTM C78 (ASTM C 78 2002), and nine prismatic 100×100×400×mm^3 specimens in accordance with ASTM C1609 (ASTM C1609 / C1609M-12 2012) were cast such that no external vibration was applied. Then all specimens were cured under water at temperature 20±2°C until the test date.

Table 5 Fresh state properties of the mixes

Mix ID	Slump flow test		J-ring test		V-funnel test
	Diameter (mm)	T_{50} (Sec)	Diameter (mm)	Height difference (mm)	V-time (Sec)
NSCC	730	3.3	720	3	4.6
BFS-1	700	4.2	650	5	5.2
BFS-2	670	5.3	600	9	6.7
BFS-3	630	6.4	530	15	8.1
BFS-4	600	7.1	500	17	9.3
GFS-1	710	3.9	700	4	4.9
GFS-2	680	4.6	650	8	5.6
GFS-3	650	5.7	600	13	6.8
GFS-4	630	5.9	570	14	7.2
HYS-1	640	5.8	570	12	7.2
HYS-2	650	5.6	590	11	7
HYS-3	660	5.4	600	10	6.8

2.2 Methodology

In the present study, effect of basalt, glass, or a cocktail of basalt and glass fibers on the mechanical properties and fracture behavior of fiber reinforced self-compacting concrete has been evaluated. To do so, twelve mixes have been cast, eight of which have single type of fiber (basalt or glass) with volume fractions 0.5, 1, 1.5, and 2. In addition, three hybrid basalt-glass fiber reinforced mixes, whose portion of each fiber type are shown in Table 4, have been cast such that for each of which, the total volume fraction of fiber contents was kept constant and equal to 1%. The reason behind choosing this volume fraction stems from the fact that the maximum compressive strength of each monotype fiber reinforced concrete mix was achieved at 1% volume fraction. In order to evaluate the effect of elevated temperature, two temperatures of 100°C and 300°C were chosen and the specimens were exposed to the mentioned temperatures for one hour at the heating rate of 10°C /min. Afterwards, all specimens were tested in accordance with BS EN12390 (BS EN 12390 2000), ASTM C496 (ASTM C 496 2002), ASTM C78 (ASTM C 78 2002), and ASTM C1609 (ASTM C1609/C1609M-12 2012) to determine compressive strength, splitting tensile strength, rupture modulus, and flexural performance of each mix, respectively, at the room and elevated temperatures. It should be mentioned that all mixes at fresh state were tested in accordance with EFNARC guidelines (EFNARC 2002) to make sure the proper workability, flowability, and passing ability. To do so, slump flow diameter, flow time (T_{50}), J-ring diameter and height difference, and V-funnel time have been measured and compared with the recommended values reflected in EFNARC (EFNARC 2002).

3. Results and discussion

3.1 Fresh state properties

In order to assess the workability of the mixes, slump flow, J-ring, and V-funnel tests were conducted in accordance with EFNARC (EFNARC 2002). Table 4 shows the fresh state properties of each mix. As it can be seen, all mixes showed good workability, flowability, and passing ability.

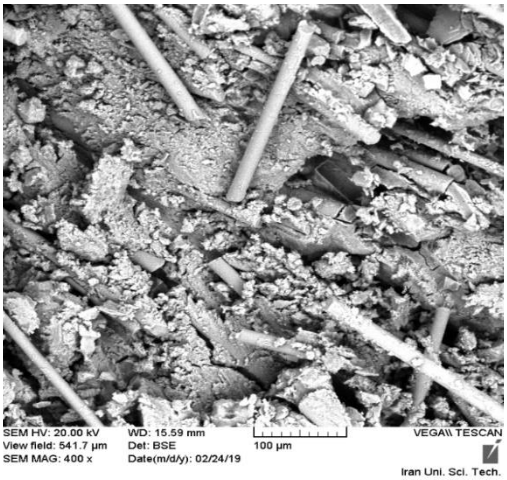

Fig. 1 Basalt fiber reinforced SCC exposed to 100C

3.2 Mechanical properties at room and elevated temperature

Mechanical properties of concrete are highly dependent on the temperature it was exposed to. The reason behind this originates from the behavior of the microstructure of concrete at elevated temperatures. In other words, at elevated temperatures, the water imprisoned at the pore structure of concrete evaporates and brings about some physiochemical reactions such as dehydration, di-hydroxylation, and decomposition (Mahapatra and Barai 2019). Therefore, the internal structure of concrete changes as it exposes to elevated temperature. To be more precise, the inter-structure water evaporates at temperature about 105°C and after the temperature reaches 110-170°C gypsum burns (Mahapatra and Barai 2019). The burning process for C-S-H compound starts within the temperatures 180-300°C followed by the dehydration of CH at 450-550°C, and melting of $CaCO_3$ at 700-900°C. The dehydration of $Ca(OH)_2$ and the conversion of it to CaO lead to a liberation of water and occurrence of shrinkage, as a result of which the reduction of compressive strength occurs (Düğenci *et al*. 2015). In other words, the reason behind the reduction of strength and resistance at elevated temperatures stems from dehydration and decomposition process, because of which the porosity and pore size increase (Chu *et al*. 2016, Li *et al*. 2017). In the present study, all specimens, after curing under water, were tested at room temperature, 100°C, and 300°C, to assess the behavior of glass fiber reinforced SCC, basalt fiber reinforced SCC, and hybrid fiber reinforced SCC. Table 6 shows the mechanical properties of each mix at room and elevated temperatures. As it can be observed from Table 6, the use of basalt fibers was not only efficient in enhancing the mechanical properties of SCC, but also it led to a better response in elevated temperatures. In other words, at the room temperature, the use of 0.5% basalt fiber has led to an increase of compressive strength by 3.94%. However, this amount of basalt fiber has led to a better result in higher temperatures. In other words, 10.05% and 21.03% improvement of compressive strength has been observed at 100 and 300°C, respectively in comparison with control mix. This shows that the basalt fibers are still able to bridge tensile stresses, even at temperatures 100 and 300°C. Figs. 2 and 3 show that in contrast to the polypropylene fibers which evaporate in high temperatures, as reported in (Li *et al*. 2019), basalt fibers still can resist without melting. The performance of glass fiber was even better than basalt fiber. The addition of 0.5% by volume of concrete has led to an increase of compressive strength by 5.97%. This originates from the fact that the tensile strength of glass fiber is higher than basalt fiber. Besides, due to higher melting point, a better resistance to elevated temperature was also observed in comparison with basalt fibers. In other words, the improvement of compressive strength at 100 and 300°C was about 15.69 and 29.45%, respectively. Indeed, due to the use of fibers, the improvement of compressive strength was not linear. Fig. 3 shows the effect of fiber volume fraction on compressive strength of fiber reinforced SCC. As it can be seen, the optimum fiber volume fraction with regards to compressive strength was 1%. Sun *et al*. (Sun *et al*. 2019) by means of conducting mechanical experiments and also developing a damage constitutive model in accordance with Mori-Tanaka homogenization theory along with progressive damage theory, have reported a similar trend in both experimental and numerical investigation on basalt reinforced concrete. Structural reliability by means of second order or first order methods (Roudak *et al*. 2017a, Roudak *et al*. 2017b, Roudak *et al*. 2018, Roudak and Karamloo 2019) could also be a proper tool to further assess the reliability of the fibers as they could include the probabilities contribute to fiber orientation.

Fig. 2 Basalt fiber reinforced SCC exposed to 300C

As it is apparent in Fig. 3 and Table 6, as the fiber volume fraction increased, at the first stage of the chart, the compressive strength increased while it followed by a decrease after reaching its peak at 1% fiber volume fraction. Although Sun *et al*. (2019) reported a similar trend, some studies reported the opposite. For instance, Dias and

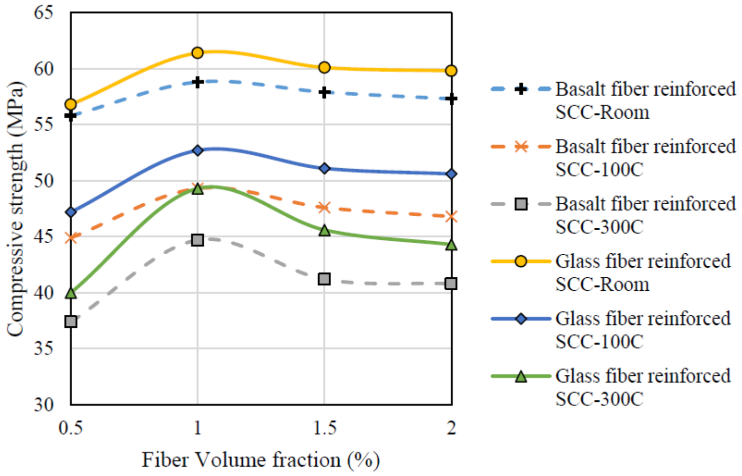

Fig. 3 Effect of fiber volume fraction on compressive strength of single type fiber reinforced SCC

Table 6 Mechanical properties of specimens at room and elevated Temperatures

Temperature (°C) / Mix ID	Compressive strength (MPa)			Splitting tensile strength (MPa)			Rupture modulus (MPa)		
	room	100	300	room	100	300	room	100	300
NSCC	53.6	40.8	30.9	5.19	3.89	2.08	8.10	6.00	3.66
BFS1	55.8	44.9	37.4	5.49	4.29	2.31	8.77	6.76	4.32
BFS2	58.8	49.3	44.7	6.18	5	2.88	9.98	7.94	5.28
BFS3	57.9	47.6	41.2	6.89	5.86	3.43	11.06	8.95	6.26
BFS4	57.3	46.8	40.8	6.2	5.34	3.42	10.86	8.89	6.45
GFS1	56.8	47.2	40	6.23	4.99	2.85	9.29	7.34	4.88
GFS2	61.4	52.7	49.3	6.96	5.69	3.40	10.56	8.50	5.95
GFS3	60.1	51.1	45.6	7.24	7.43	3.64	12.18	10.16	7.39
GFS4	59.8	50.6	44.3	7.33	5.91	3.43	12.49	11.02	7.92
HYS1	59.3	48.3	41.5	7.29	5.94	3.85	10.88	8.87	6.38
HYS2	61.8	50.3	44.6	8.02	6.78	4.51	12.26	10.31	7.73
HYS3	64.32	51.6	45	8.53	8.13	4.71	13.15	12.53	8.62

Thaumaturgo (Dias and Thaumaturgo 2005) claimed that the addition of 1.0% basalt fiber by volume to a geopolymeric concrete mixture has led to a decrease of compressive strength by 26.4%. However, they further claimed that the use of 0.5% basalt fiber has a negligible impact on compressive strength of geopolymeric concrete. These discrepancies between the reported results could be attributed to the differences in the constituents, as they play an important role in the global behavior of the mixture.

The use of hybrid basalt-glass fibers was also assessed. Since for both cases of basalt and glass fiber reinforced SCC, the maximum compressive strength was reached at 1% fiber volume fraction, the hybrid mixes were designed such that the total volume fraction of fibers is equal to 1%. HYS1, whose fiber included 0.75% basalt and 0.25% glass fiber, has shown 10.63% better compressive strength than SCC at room temperature. This superiority was even better at elevated temperatures. In other words, it showed 18.38% and 34.3% better compressive strength compared to normal SCC at 100 and 300°C, respectively. Moreover, the results showed that the effect of glass fibers was more dominant in hybrid fibers i.e., as the portion of glass fibers increased in the cocktail of fibers, the mix showed better compressive strength. Indeed, in comparison with glass fiber reinforced SCC mixes in the present study, the hybrid fiber mixes in almost all cases showed lower improvements either at the room temperature or at the elevated temperature. For instance, although the compressive strength of HYS3 was 4.76% higher than compressive strength of GFS2 at room temperature, this parameter was 2.09 and 8.72% lesser for those specimens tested at 100 and 300°C, respectively. With regard to compressive strength, the best mix composition among hybrid fiber reinforced SCC mixes was HYS3. The reason behind this finding could stem from the fact that the tensile strength of glass fiber is much higher than basalt fiber. Hence, the tension produced by compression could be better tolerated by the glass fibers than basalt fibers. Fig. 4 illustrates the effect of temperature on compressive strength of monotype fiber reinforced concrete as well as hybrid fiber reinforced concrete in comparison with normal SCC.

It is apparent in Fig. 4 that basalt fiber reinforced concrete at its optimum fiber volume fraction and room temperature showed higher compressive strength than glass fiber, while as the temperature increased, the glass fiber reinforced SCC showed better compressive strength. Besides, HYS3 showed the best compressive strength at room temperature. However, its strength decayed steeply as the temperature increased. Fig. 4 also infers that the decline in compressive strength in NSCC was faster than other mixes followed by HYS1.

Splitting tensile strength of concrete is one of the important mechanical properties of concrete. Fig. 5 illustrates the effect of fiber volume fraction on splitting tensile strength of self-compacting concrete. As it can be seen, the use of 0.5% by concrete volume basalt fiber has led to an increase of splitting tensile strength by 5.78%, 10.28%, and 11.06% at room, 100, and 300°C, respectively. The reason behind this finding could stem from the fact that the fibers, even after exposure to elevated temperatures, were able to bridge the stresses. Fig. 6 shows a microstructure of fractured specimen at 300°C and with 1% glass fiber

It is apparent that the cement past cracking occurred due

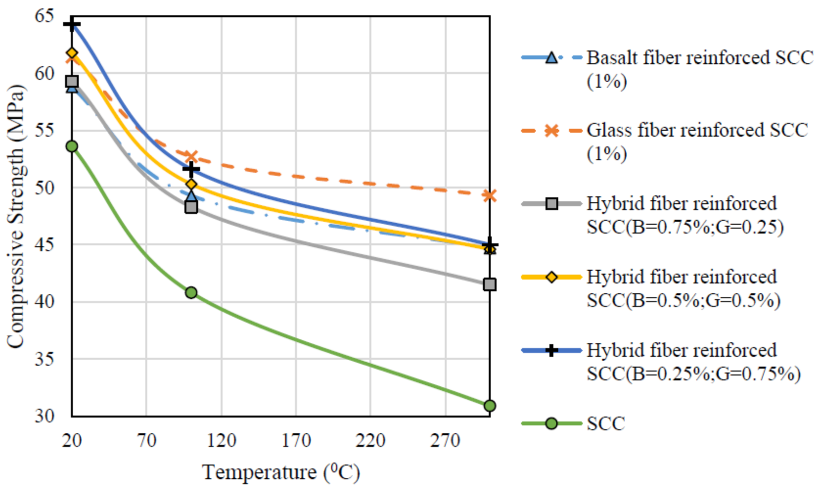

Fig. 4 Effect of elevated temperatures on compressive strength of fiber reinforced SCC as well as normal SCC

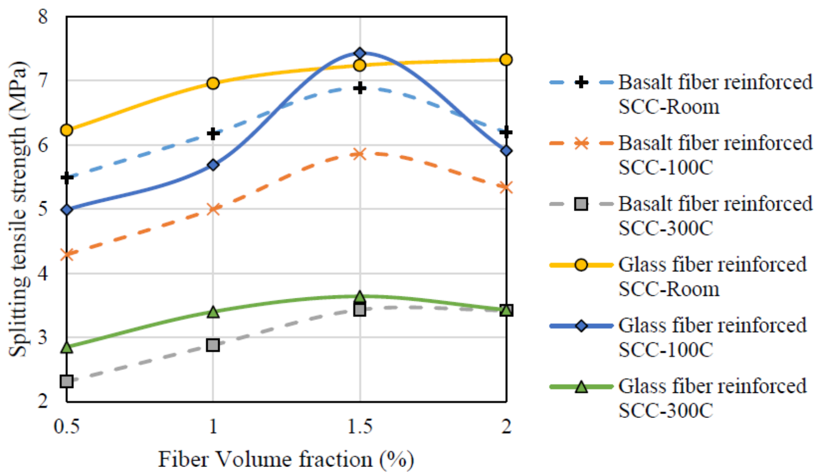

Fig. 5 Effect of fiber volume fraction on splitting tensile strength of monotype fiber reinforced SCC

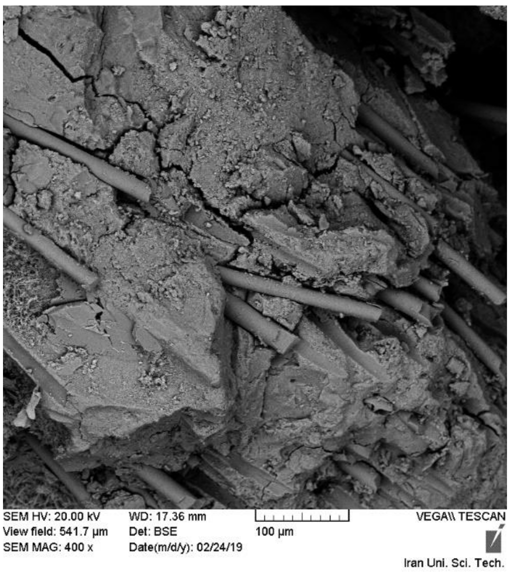

Fig. 6 Glass fiber reinforced SCC at 300°C

to elevated temperature, while the glass fibers are still healthy. It is worth mentioning that when the cracks reached fibers, either the crack stopped or it continued its way along the surface of fiber. Although this will enhance the absorbed fracture energy of the specimen, the bonding behavior of these fibers should be investigated in a separate in depth study. From splitting tensile strength point of view, the glass fiber reinforced SCC specimen showed, generally, higher strength than the basalt reinforced SCC specimens, especially at elevated temperatures. For example, 0.5% glass fiber by concrete volume enhanced the splitting tensile strength of self-compacting concrete by 20.04, 28.28, and 37.02%, at room, 100, and 300°C, respectively. These improvements were approximately two times more than the improvements of those specimens by the same dosage of basalt fiber. In contrast to the performance of mixes with regards to the compressive strength, Hybrid fiber reinforced mix compositions showed higher splitting tensile strength than both the basalt and glass fiber reinforced concrete. For instance, HYS3 showed 38.53% higher splitting tensile strength than GFS2 at 300°C. Sadrinejad and his co-workers (Sadrinejad *et al*. 2018) reported a similar trend for splitting tensile strength in hybridization of polypropylene and polyolefin fibers. However, they mentioned that those fibers did not show a positive effect on post cracking behavior of concrete. It is worth noting that according to Fig. 8, the optimum amount of fiber volume fraction for

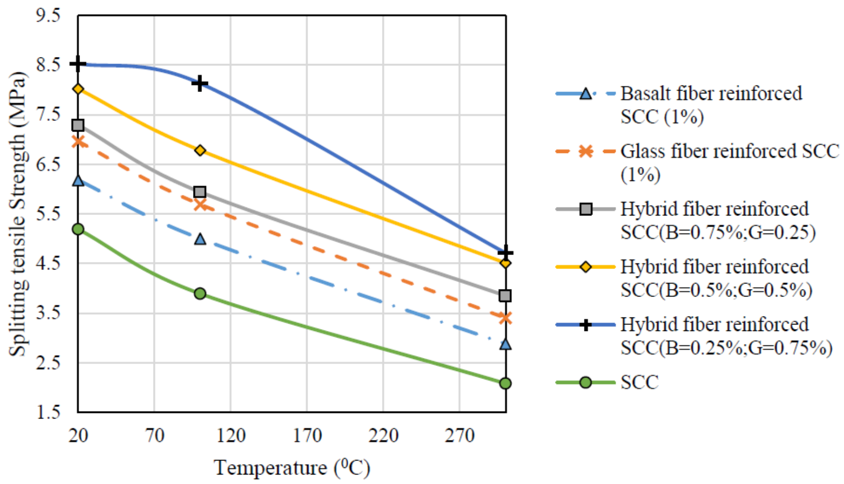

Fig. 7 Variation of tensile splitting strength versus temperature

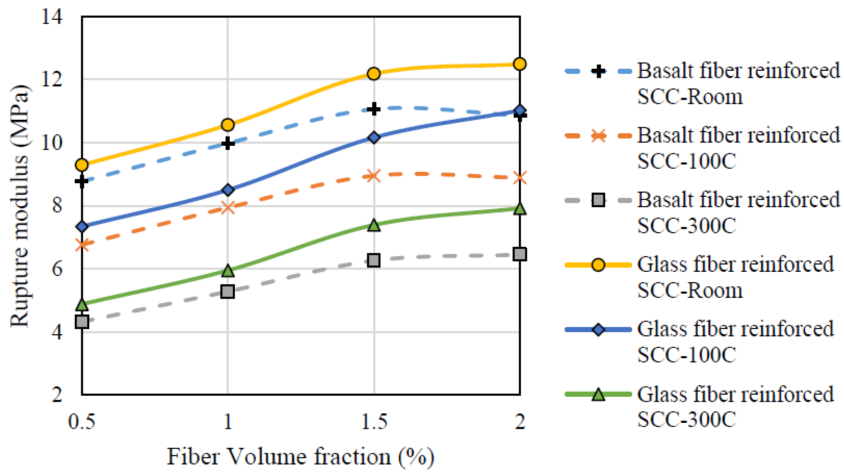

Fig. 8 Variation of rupture modulus versus fiber volume fraction

monotype fiber reinforced SCC was 1.5% by concrete volume. Fig. 7 shows the variation of splitting tensile strength versus temperature for mixes with 1% fiber volume fraction. It is apparent that mixes with hybrid fibers performed better that those with monotype fiber. Besides, it should be mentioned that although HYS3 had the best response at room and elevated temperatures, the trend of its decay was faster in comparison with other mixes. To be more clear, test results regarding splitting tensile strength of HYS3 showed 63.35, 109, and 126.44% higher strength compared to NSCC at room, 100°C, and 300°C, respectively.

Rupture modulus is another mechanical property, which was considered in the present study. Fig. 8 depicts the effect of fiber volume fraction on modulus of rupture of monotype fiber reinforced SCC. It is clear that the increase of fiber volume fraction increased the modulus of rupture of self-compacting concrete. However, the increase of volume fraction over 1.5% by concrete volume showed detrimental effect on rupture modulus of some cases. For instance, rupture modulus of BFS4 at room temperature was about 1.04% lower than that observed for BFS3. It is also apparent in Fig. 8 that the glass fiber reinforced mixes performed better than basalt fiber reinforced mixes. By comparing the performance of monotype fiber reinforced mixes to NSCC, one can conclude that the efficiency of the fibers was even better when they are exposed to elevated temperatures. To be more precise, the improvement of rupture modulus were achieved by means of adding 0.5% by concrete volume was about 14.69% compared to NSCC, while this improvement increased to 22.33, and 33.33% at 100°C and 300°C, respectively. It should be mentioned that the use of fiber dosages higher than 1.5% by concrete volume showed a detrimental effect on rupture modulus of basalt fiber reinforced mixes. Besides, this has led to a marginal improvement of rupture modulus of glass fiber reinforced mixes.

Fig. 9 shows the behavior of fiber reinforced mixes (with 1% fiber volume fraction) after exposure to elevated temperatures in comparison with NSCC. As it can be seen, similar to the results of splitting tensile strength tests, hybrid fiber reinforced mixes showed far better results, especially after exposure to elevated temperatures. In other words, HYS1 showed 9.02% higher modulus of rupture compared to BFS2, at room temperature. However, this mix showed 20.83% higher modulus of rupture compared to BFS2, at 300°C room temperature. Indeed, HYS3 showed the best performance at the test of modulus of rupture. This

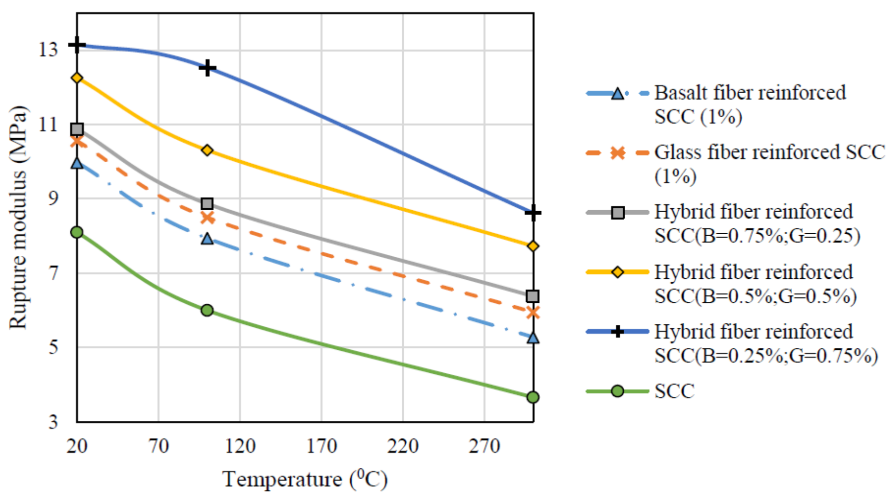

Fig. 9 Variation of rupture mudulus versus temperature for hybrid and monotype fiber reinforced SCC mixes with 1% fiber by concrete volume

mixture showed 135.52% higher rupture modulus compared to NSCC at 300°C.

Rupture modulus is another mechanical property, which was considered in the present study. Fig. 8 depicts the effect of fiber volume fraction on modulus of rupture of monotype fiber reinforced SCC. It is clear that the increase of fiber volume fraction increased the modulus of rupture of self-compacting concrete. However, the increase of volume fraction over 1.5% by concrete volume showed detrimental effect on rupture modulus of some cases. For instance, rupture modulus of BFS4 at room temperature was about 1.04% lower than that observed for BFS3. It is also apparent in Fig. 8 that the glass fiber reinforced mixes performed better than basalt fiber reinforced mixes. By comparing the performance of monotype fiber reinforced mixes to NSCC, one can conclude that the efficiency of the fibers was even better when they are exposed to elevated temperatures. To be more precise, the improvement of rupture modulus were achieved by means of adding 0.5% by concrete volume was about 14.69% compared to NSCC, while this improvement increased to 22.33, and 33.33% at 100°C and 300°C, respectively. It should be mentioned that the use of fiber dosages higher than 1.5% by concrete volume showed a detrimental effect on rupture modulus of basalt fiber reinforced mixes. Besides, this has led to a marginal improvement of rupture modulus of glass fiber reinforced mixes.

Fig. 9 shows the behavior of fiber reinforced mixes (with 1% fiber volume fraction) after exposure to elevated temperatures in comparison with NSCC. As it can be seen, similar to the results of splitting tensile strength tests, hybrid fiber reinforced mixes showed far better results, especially after exposure to elevated temperatures. In other words, HYS1 showed 9.02% higher modulus of rupture compared to BFS2, at room temperature. However, this mix showed 20.83% higher modulus of rupture compared to BFS2, at 300°C room temperature. Indeed, HYS3 showed the best performance at the test of modulus of rupture. This mixture showed 135.52% higher rupture modulus compared to NSCC at 300°C.

Table 7 Fracture energy of each mix composition

	Fracture energy (N/mm)		
	Room	100°C	300°C
NSCC	2.28	Not tested	Not tested
BFS-1	4.28	2.66	1.82
BFS-2	5.12	3.64	3.38
BFS-3	7.78	4.71	2.90
BFS-4	8.92	4.75	3.14
GFS-1	5.67	3.85	2.31
GFS-2	7.99	5.45	2.94
GFS-3	14.92	7.36	3.80
GFS-4	9.83	8.45	4.16
HYS-1	7.87	5.75	3.70
HYS-2	10.09	7.83	4.93
HYS-3	18.37	9.98	4.69

3.3 Flexural and fracture behavior of mixes

As a quasi-brittle material, concrete fracture behavior is of great importance, since it could play a leading role either in design or in the behavior. In recent years, some studies investigated the effect of mix design parameters on fracture behavior of self-compacting normal or lightweight concrete without fibers (Karamloo *et al.* 2016a, Karamloo *et al.* 2016b, Karamloo *et al.* 2017, Mazloom *et al.* 2017, Karamloo and Mazloom 2018, Mazloom *et al.* 2018, Karamloo *et al.* 2019a, Karamloo *et al.* 2019b, Mazloom and Karamloo 2019). On the other hand, the use of fibers could affect the fracture behavior of concrete. Apart from fiber effect on fracture behavior, exposure of concrete to elevated temperature could affect the cracking pattern, as a result of which fracture energy and fracture toughness could be changed. In the present study, ASTM C1609 (ASTM C1609/C1609M-12 2012) was used to assess the flexural and fracture behavior of each mix at room and elevated temperatures. Based on the definition of Hillerborg (Hillerborg 1985), fracture energy can be defined as the area under load-deflection curve divided by cross section area. In this regard, total fracture energy of each specimen

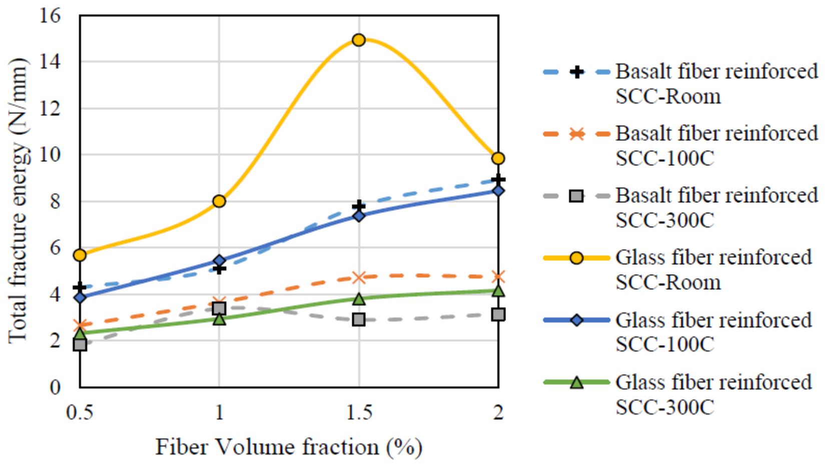

Fig. 10 Variation of fracture energy versus fiber volume fraction

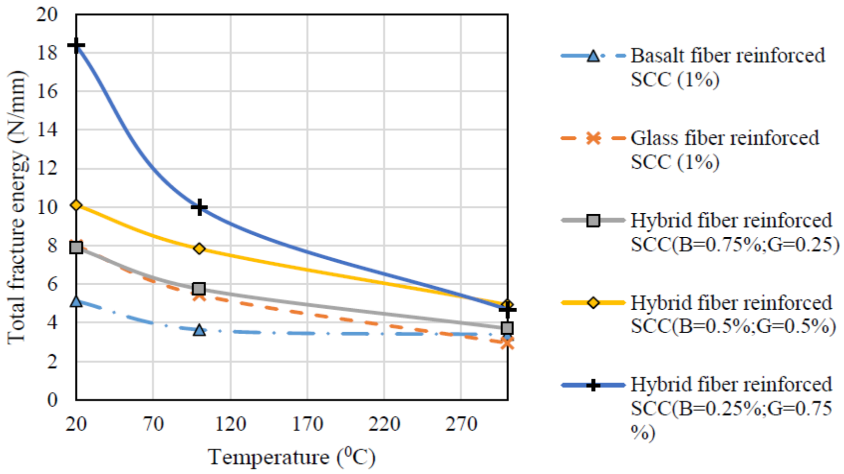

Fig. 11 The variation of fracture energy versus temperature

has been calculated and reflected in Table 7. It should be mentioned that the fracture energies of normal self-compacting concrete specimens at elevated temperature were not calculated, due to failure and cracking because of spalling phenomenon. It is worth mentioning that neither the use of different types of fibers nor the hybridization of fibers changed the failure mode of concrete mixes. In other words, all fiber reinforced mixes, showed identical cracking patterns with no obvious spalling.

In order to scrutinize the effect of fiber volume fraction on fracture energy of fiber reinforced SCC mix compositions, Fig. 10 has been prepared. As it can be seen, the fracture energy varied with the variation of fiber volume fraction. However, these variations did not always follow a same trend. Indeed, in almost all cases, except for basalt fiber reinforced SCC at 300°C and glass fiber reinforced SCC at room temperature, the increase of fiber volume fraction, increased the fracture energy of mixes. It is worth noting that the direction of fibers in mixes as well as their distributions could affect the results. Nevertheless, in the present study, since the casting procedure for all specimens have been kept the same, it is assumed that the effects regarding fiber orientation and distribution are negligible.

The comparison for the fracture energy of specimens with total of 1% fiber contents has been illustrated in Fig. 11. As it can be seen, fracture energy of mixes decreased as temperature increased. Indeed, the rate of the decline of fracture energy was higher before 100°C. Besides, it is apparent that HYS-3 showed the best fracture energy followed by HYS-2, HYS-1, GFS-2, and BFS-2. This shows that the energy absorption by the hybrid fiber reinforced SCC mixes was higher than that for monotype

Table 8 Ductility factor of each mix at different temperatures

	Ductility factor		
	Room	100°C	300°C
NSCC	1.9	Not tested	Not tested
BFS-1	7.72	8.043	5.31
BFS-2	17.81	12.13	5.98
BFS-3	18.39	17.84	6.77
BFS-4	35.18	18.51	8.06
GFS-1	19.27	13.64	14.40
GFS-2	40.12	20.87	15.94
GFS-3	41.17	26.62	17.52
GFS-4	20.41	29.73	18.34
HYS-1	28.04	25.14	9.60
HYS-2	47.57	35.86	11.99
HYS-3	54.83	40.05	8.30

fiber reinforced SCC mixes. In order to decompose the total fracture energy needed for rupture of specimens and initial fracture energy, defined as an energy needed to reach deflection equal to $\frac{\text{Span}}{150}$, and to investigate the effect of fibers on the ductility of the mixes, a ductility factor is defined as

$$\mu = \frac{G_F}{G_f} \quad (1)$$

where G_F is total fracture energy and G_f is initial fracture energy. Table 8 shows the amount of μ for each mix at different temperatures.

It is clear that the ductility factors at room temperature are higher than those was measured at elevated temperatures. The reason behind this could be attributed to the fact that not only the compressive portion of cross section under bending test acts better, due to higher compressive strength, but also the bonding strength of the tensile part is higher. Therefore, the specimens at room temperature could endure higher amounts of displacement as well as dissipating higher amounts of energy. It is worth noting that effect of the used fibers, either monotype fibers or hybrid fibers, on post peak behavior of the specimens was too negligible. Although a similar trend was observed by Sadrinejad and his co-workers (Sadrinejad *et al*. 2018) when they were investigating the effect of hybrid polypropylene-polyolefin fibers on concrete, this could be a negative feature of using basalt or glass fiber in concrete. Indeed, more experiments are needed to reach such a conclusion.

4. Conclusions

From the result of presented experimental study, following conclusions could be drawn:

1. The use of 0.5%, 1%, 1.5%, and 2% by concrete volume basalt fiber in self-compacting concrete mixes has led to the increase of compressive strength by 3.94%, 9.7%, 8.02%, and 6.9%, respectively, at room temperature. This shows that in order to improve the compressive strength of self-compacting concrete, the optimum amount of basalt fiber was about 1% by concrete volume.
2. The results also shows that the optimum basalt fiber volume fraction was 1% for specimens exposed to 100°C and 300°C. In other words, the use of 1% basalt fiber by concrete volume has led to an increase of compressive strength by 20.83% and 44.66% compared to normal SCC mixes exposed to 100°C and 300°C, respectively.
3. Regarding the compressive strength, the results of the mixes indicates that the use of glass fiber in self-compacting concrete mixes was more efficient than the use of basalt fiber i.e., the addition of 1% glass fiber by concrete volume the compressive strength of specimens at room, 100°C, and 300°C increased by 14.55%, 29.17%, and 59.55%, respectively. It is worth noting that the results of the compressive strength tests indicate that the optimum fiber volume fraction for glass fiber is 1%.
4. Compared to the compressive strength of monotype fiber reinforced mixes, hybridization has not led to good results and in some cases, has led to a decrease of compressive strength in comparison with the monotype fiber reinforced mixes. For instance, HYS1 with 0.75% basalt fiber and 0.25% glass fiber showed 2.02% and 7.16% lower compressive strength than BFS2 at 100°C and 300°C, respectively.
5. As the amount of fiber volume fraction increased from 0.5% to 1.5% by concrete volume fraction, the splitting tensile strength of basalt fiber reinforced SCC and glass fiber reinforced SCC increased. However, in both type of mixes, the efficiency of fibers decreased after adding higher dosages of fibers. For instance, the addition of 0.5%, 1%, and 1.5% glass fiber by concrete volume has led to the increased of splitting tensile strength by 28.28%, 46.27%, and 91%, respectively, for specimens exposed to 100°C. However, this improvement was about 51.93% for a mix with 2% glass fiber by concrete volume.
6. In contrast to the results regarding compressive strength, the test results regarding the splitting tensile strength of specimens, show that hybridization of fibers was beneficial at both room and elevated temperatures, compared to monotype fiber reinforced mixes. To be clearer, the performance of hybrid fiber reinforced SCC mixes were from 4.74% to 38.53% better that glass fiber reinforced mixes with 1% fiber volume fraction either at room or at elevated temperatures.
7. In almost all cases, the increase of fiber volume fraction has led to an increase of rupture modulus. However, this increase was negligible for fiber dosages higher than 1.5% by concrete volume. Besides, by the increase of temperature, the effect of fibers was more notable. For instance, the use of 1.5% glass fiber in SCC has led to an increase of rupture modulus by 50.37% compared to normal SCC mix at room temperature. However, this improvement for specimens tested after exposing to 300°C be reached 101.91%. This shows the leading role of fibers, especially after exposure to elevated temperatures.
8. Test results indicated that the cocktail of 0.25% basalt fiber and 0.75% glass fiber showed 31.76%, 57.81%, and 63.26% higher modulus of rupture at room, 100°C, and 300°C, respectively, than the BFS-2.
9. The results indicates that as the temperature increased the fracture energy decreased. Indeed, the fiber volume fraction as well as the fiber type affected the results regarding the fracture energy. In other words, at room temperature, glass fiber reinforced SCC with 1.5% fiber showed the most fracture energy in monotype fiber reinforced mixes, which was 14.92 N/mm and HYS3 showed the most fracture energy amongst all mixes. In general, the fracture energies of hybrid fiber reinforced mixes were higher than monotype fiber mixes with equivalent amount of fiber. Moreover, the glass fiber reinforced mixes showed higher fracture energies than basalt fiber reinforced compositions.

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