Development of a Proper Mix-Design for Impact Loading of Deflection Hardening Hybrid Fiber Reinforced Concrete

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Abstract. This study aims to develop a low-cost Hybrid Fiber Reinforced Concrete (HyFRC) that exhibits deflection hardening behavior under bending and has high energy absorption capacity under impact loading by determining proper combination of steel and polyvinyl alcohol (PVA) fibers. More than forty mixtures were prepared including two mixtures of conventional concrete, six mixtures of Engineered Cementitious Composites (ECC), and thirty-six mixtures of HyFRC. The design parameters were chosen as fly ash to cement ratio (1.2, 1.7 and 2.2), steel fiber type and amount (0.5%, 0.75%, and 1.25% by volume), PVA fiber amount (0.25% and 0.50% by volume), and maximum aggregate size (D_{max}) of 8 mm and 16 mm. Several tests were carried out on fresh and hardened specimens such as bending, compression, and low-velocity flexural impact loading. Based on the results, it is found that the mixture with 0.75% steel fiber and 0.25% PVA showed the best performance for the aim of the study.

Keywords: Deflection hardening · Mix-design · Steel fiber · PVA · Low-velocity impact

1 Introduction

Hybrid fiber-reinforced concrete (HyFRC) contains two or more types of fibers with different materials, lengths, shapes, and aspect ratios. HyFRC consisting of steel macrofibers and PVA microfibers presents multiple cracking when subjected to static and dynamic loading (Blunt and Ostertag 2009). The proper hybridization of different types of fibers enhances the tensile strength, flexural strength, and toughness of the concrete, and may lead to present deflection-hardening behavior and high energy absorption capacity. HyFRC contains both fine and coarse aggregates, hybrid fibers (both steel and synthetic fibers), and industrial by-products, which makes the composite cheaper and more workable.

Blunt and Ostertag (2009) developed a deflection-hardening HyFRC mixture with steel and PVA fibers having a total fiber volume 1.5% and with D_{max} = 9.5 mm. In another study, Hey and Ostertag (2015) used similar D_{max} and type/amount of fibers in HyFRC and utilized mineral admixtures in the cement. In a study of Banyhussan et al. (2016), the total volume of hybrid fibers was 2%, D_{max} was 12 mm, and fly ash to portland cement ratio (FA/PC) was up to 0.7. Moreover, most of the studies on hybrid fiber reinforced composites without coarse aggregate utilize a fiber volume of more than 1.5%.

This study aims to find a proper mix-design for concrete which exhibits deflection-hardening. The novelty of this study is to employ lower fibers volumes (<1.5%), lower PVA amounts, a higher D_{max} (16 mm) and a higher FA/PC (1.2) than most of the studies in the literature. These features can enable to reduce the cost of the composite. The performance of the mixtures is tested under static and dynamic loading.

2   Experimental Program

Materials. Portland cement (PC) (named as CEM I 42.5R in TS EN 197-1), type F fly ash (FA), polycarboxylate-based superplasticizer, crushed limestone coarse aggregate (CA) with two different D_{max} (8 mm and 16 mm), river sand (RS), quartz sand (QS), three types of hooked-end steel fibers [ST1 (L = 30 mm, L/D = 40, 3D), ST2 (L = 60 mm, L/D = 65, 3D), and ST3 (L = 60 mm, L/D = 65, 5D)], and PVA fiber (L = 8 mm, L/D = 200) were used in the mixtures.

Mixture Proportions. Standard M45 ECC (Li 2008) mixtures with varying FA contents were prepared with the ratios given in Table 1. The proportions for HyFRC types are given in Table 2. For each HyFRC type given in Table 2, three types of steel fibers (ST1, ST2, or ST3), and two D_{max} values (8 mm and 16 mm) were used, which makes the total number of the mixtures thirty-six. One Normal Concrete (NC) without any fibers was also prepared with the same proportions with HyFRC. ECC mixtures were labeled according to FA/PC ratio as FA1.2, FA1.7, FA2.2. The HyFRC mixtures were labeled to show steel fiber type, steel fiber content, PVA content, and D_{max}, respectively. For example, ST2,1.25_P0.25_D8 mixture identifies that steel fiber type is ST2, steel fiber content is 1.25%, PVA amount is 0.25%, and D_{max} is 8 mm.

Table 1. ECC mixture proportions (by weight).

| Mixtures	PC	Water/binder	FA/PC	QS/Binder	PVA (Vol%)
FA 1.2	1	0.27	1.2	0.36	2
FA 1.7	1	0.27	1.7	0.36	2
FA 2.2	1	0.27	2.2	0.36	2

Table 2. HyFRC mixture proportions (by weight) (binder content = 600 kg/m^3).

Mix	PC	FA/PC	Water/binder	RS	CA	Steel fiber (Vol%)	PVA (Vol%)
1	1	1.2	0.40	2.3	2.5	0.50	0.25
2	1	1.2	0.40	2.3	2.5	0.50	0.50
3	1	1.2	0.40	2.3	2.5	0.75	0.25
4	1	1.2	0.40	2.3	2.5	0.75	0.50
5	1	1.2	0.40	2.3	2.5	1.25	0.25
6	1	1.2	0.40	2.3	2.5	1.25	0.50

Mixing, Casting, and Curing. ECC mixtures were prepared using a 20-liter capacity planetary mixer, and HyFRC mixtures were prepared by a 100-liter capacity rotatory mixer. Almost all mixtures were self-consolidating and no mechanical vibration was required. However, manual vibration such as formwork shaking by hand was required for the mixtures with higher amounts of PVA and steel fibers.

For compressive strength tests, three 50-mm cube specimens for each ECC mixture and three 150-mm cube specimens for each HyFRC mixture were casted. For static bending tests, three 360 × 75 × 50 mm prismatic specimens and three 600 × 150 × 150 mm prismatic specimens were cast for each ECC and HyFRC mixtures, respectively. For impact loading test, six 600 × 100 × 100 mm notched specimens with 30 mm notch depth were prepared. All specimens were stored in isolated plastic bags for 7 days followed by 21 days of dry curing at laboratory conditions.

Test Methods. Compressive strength, four-point bending test (ASTM C1609) made by a deformation controlled universal testing machine (Fig. 1a), and impact loading test made by a drop-weight test machine (Fig. 1b) were performed on the specimens.

1a   1b
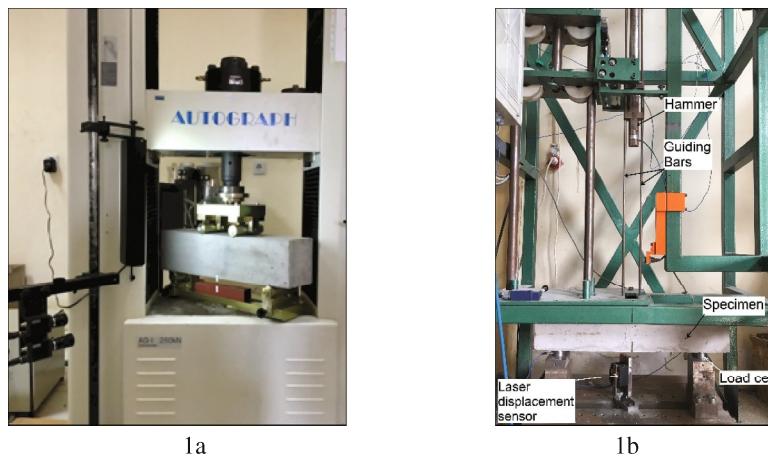
Fig. 1. (a) Static test setup, (b) Low-velocity impact test setup.

Drop-weight test is an instrumented machine (Yardımcı et al. 2017) allowing the free-fall of a cylindrical hammer with changeable weight from an adjustable height onto the mid-span of the specimen. For this study, the weight and height were adjusted as 4.26 kg and 2 m, respectively. The drop of the hammer provided a hammer tip velocity of 6.264 m/s. Two piezoelectric load cells were attached to the supports for obtaining the reaction forces vs. time history. The sum of the reaction forces is considered as the true bending force in strength, toughness and fracture energy calculations (Banthia et al. 1989; Dancygier et al. 2012). Mid-span deflection vs. time history was obtained by a noncontact laser displacement sensor which is placed under the notched specimen (Fig. 1b). This system provides complete load-deflection curves of the beam samples subjected to low-velocity flexural impact loading.

3   Results and Discussions

ECC. Compressive strength, flexural strength, and toughness under static bending Results (the average values) of the ECC mixtures at 28 days are presented in Fig. 2a. Figure 2b shows the typical load-deflection curves of the ECC mixtures tested under static bending.
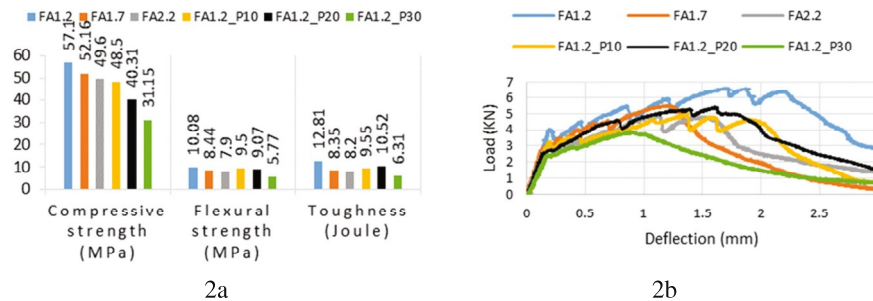

Fig. 2. (a) Mechanical Properties of ECC, (b) Load-deflection curves for ECC.

Results indicate that the compressive strength, flexural strength, and toughness decrease as the FA/PC increases. This can be explained by the relatively lower PC contents which can slow down the rate of strength gain. Moreover, more fibers are probably pulled out instead of ruptured, due to reaching the maximum bridging stress which fibers can reach.

Since perlite can act like a flaw causing more cracking at smaller stresses and more deflection, effects of using perlite were also studied. The FA1.2 mixture was reproduced by replacing the 10%, 20% or 30% of the QS with presoaked expanded perlite (D_{max} = 4 mm). These mixtures were labeled as FA1.2_P10, FA1.2_P20, and FA1.2_P30 in Fig. 2. The results for ECC mixtures with saturated perlite show that the compressive strength and flexural strength decreases when the perlite content increases. According to Keskin et al. (2013), large aggregate size and lower strength of expanded

perlite act as stress concentrator and can prevent the uniform distribution of the fibers. Larger perlite particles may also cause balling of PVA fibers which act as voids and cause greater local water-to-cement ratio in the interfacial transition zone. Regarding the toughness, the 20% perlite replacement exhibited the highest toughness among the ECC mixtures with 10, 20, and 30% perlite. However, the toughness for ECC mixture without perlite (FA 1.2) is still slightly higher than the mixture with 20% perlite.

HyFRC. This study is a part of a large scientific project involving both ECC and HyFRC. To make a link between these different types of composites, the results of ECC mixtures were used to select the FA/PC ratio (1.2) and perlite amount (20%) in HyFRC mixtures. Compressive strength, flexural strength, and toughness under static bending Results (average values) of the HyFRC mixtures at 28 days are given in Fig. 3a–c. Toughness is calculated as the area under the curve up to 3 mm deflection. Typical load-deflection curves for four selected HyFRC mixtures and a normal concrete with 16 mm D_{max} are shown in Fig. 3d.
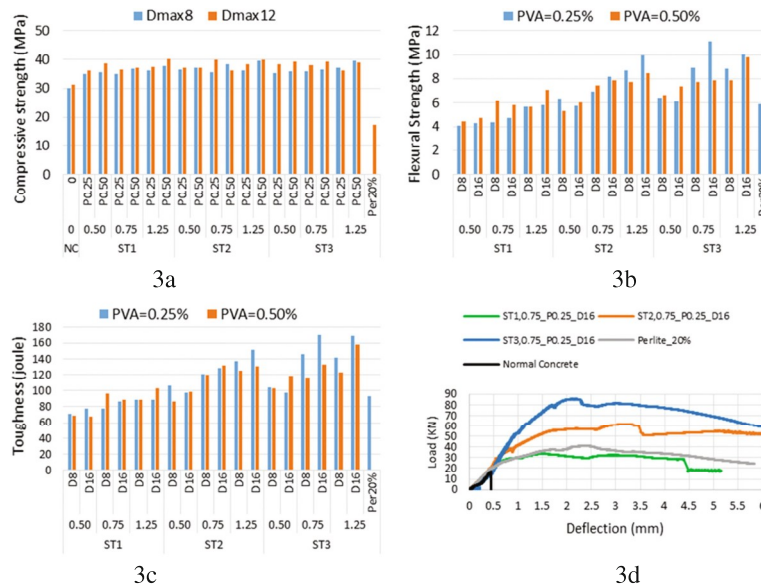

Fig. 3. (a) Compressive strength of HyFRC, (b) Flexural strength of HyFRC, (c) Toughness of HyFRC, (d) Load-deflection curves for HyFRC.

Compressive strength of HyFRC was higher than of that normal concrete (NC) as shown in Fig. 1a due to the ability of fibers to delay and bridge crack formation (Şahmaran and Yaman 2007). There is no significant difference in compressive strength between HyFRC mixtures. Compressive strength, flexural strength, and toughness generally increased when aggregate D_{max} increased from 8 mm to 16 mm (Fig. 3a–c). These observations can be explained by the fact that larger aggregate size shows more tortuous crack path, providing a rougher fracture surface, and cracks prefer to

propagate along the weaker interfacial zone or larger pores in the matrix under loading as the crack reaches an aggregate particle where it is forced to propagate either through the aggregate or travel around the aggregate-mortar interface which increase the mechanical behavior of the matrix (Banyhussan et al. 2016).

Flexural strength and toughness of HyFRC mixtures generally decreased when the PVA content increased from 0.25% to 0.50% (Fig. 3b, c). This was probably due to the significant decrease in workability of the mixture and high demand of superplasticizer which can cause bleeding and balling of steel fibers. On the other hand, an increasing trend was observed in flexural strength and toughness with an increase in steel fiber content. The effects of steel fiber type are also shown in Fig. 3b, c. The mixtures with ST2 and ST3 had considerably higher flexural strength and toughness when compared to the mixtures with ST1 probably due to the longer length and higher aspect ratio of both ST2 and ST3 providing greater interfacial bond strength by larger contact area between the fiber and matrix (Yang 2011). The length and aspect ratio of ST2 and ST3 were the same but ST3 results were higher than those of ST2 due an extra hook in ST3 type (5D) which was not present in ST2 type (3D). Moreover, tensile strength of ST3 type fiber was significantly higher than ST1 and ST2 (Tensile strength of ST1, ST2 and ST3 are 1225 MPa, 1160 MPa and 2300 MPa, respectively.)

The mixture with 20% perlite aggregate replacement caused a significant decrease in compressive strength, flexural strength, and toughness as compared with HyFRC mixtures without perlite because of the lower strength of expanded perlite and the greater local water-to-cement ratio in interfacial transition zone.

Impact loading. The ST3,0.75_P0.25_D16 mixture, which exhibited the highest flexural strength and toughness, was selected for low-velocity impact loading tests. To see the effect of steel fiber types for impact loading, the same mixture with three types of steel fibers and also the mixture with perlite were tested under impact loading. The load-deflection curves from static bending test of these four mixtures are given in Fig. 3d. As discussed earlier, the PVA fiber volume of 0.5% and coarse aggregate D_{max} of 8 mm generally decreased the performance of HyFRC, therefore, the mixtures with these parameters were not tested under impact loading.

Drop-weight test results (flexural strength and toughness) of four selected HyFRC mixtures at 28 days are given in Fig. 4a, b. Toughness was considered as the area under the load-deflection curves up to a deflection of 3 mm. Typical load-deflection curves obtained from low-velocity impact loading tests are shown in Fig. 4c.

As the specimen sizes were different for the static bending and impact tests due to the setup limitations, Fig. 4b presents the toughness values for impact test without correlation with static bending test. The mixture with the best performance from static bending test (ST3,0.75_P0.25_D16) showed again the highest toughness and flexural strength under dynamic test. Figure 4a, b show that ST2 and ST3 results were higher than ST1, due to their longer length and larger aspect ratio. ST3 results were higher than ST2 due to the extra hook of the former one. Flexural strength and toughness of the mixtures with perlite were about 24% lower than those of the mixtures without perlite in dynamic loading. On the other hand, the decrease due to perlite was about 50% in the case of static bending test.
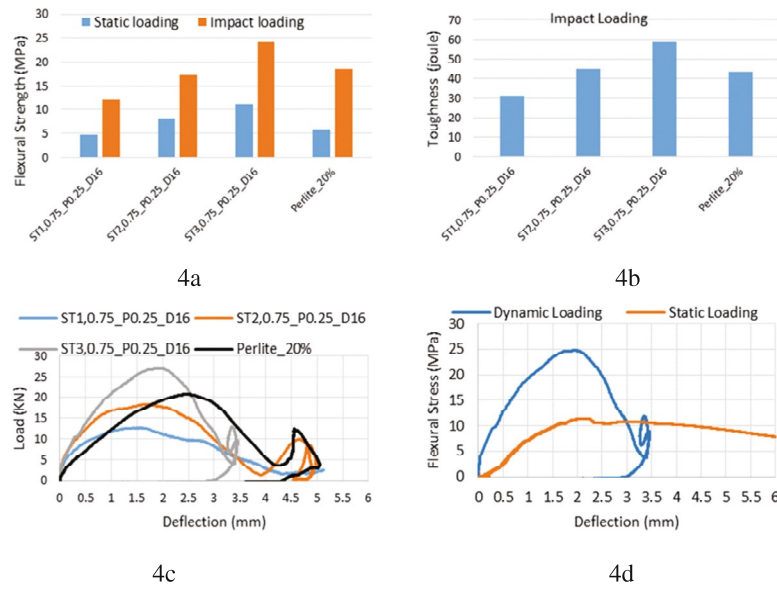
4a

4b

4c

4d

Fig. 4. (a) Flexural strength under static and impact loading, (b) Toughness under impact loading, (c) Load-deflection curves of impact loading, (d) Comparison of the best mixture under static and impact loading.

Figure 4a compares flexural strength results of dynamic and static tests. The dynamic increase factor (ratio of dynamic to static test results) for ST1,0.75_ P0.25_D16, ST2,0.75_P0.25_D16, ST3,0.75_P0.25_D16, and Perlite 20% mixtures are 2.57, 2.10, 2.19, and 3.17. The mixture with perlite shows the highest dynamic increase factor. Figure 4d matches the flexural stress-deflection curves of the best mixture (ST3,0.75_P0.25_D16) tested under static and dynamic bending.

4   Conclusions

Based on the results, it is found that the mixture with binder content = 600 kg, FA/PC = 1.2, w/b = 0.4, fine aggregate/coarse aggregate = 48/52, D_{max} = 16 mm, steel fiber type = ST3, steel fiber volume = 0.75%, and PVA volume = 0.25% is a proper combination that exhibits deflection hardening behavior with highest flexural toughness under both static and impact bending loads. It is also noticed that use of perlite reduced flexural strength and toughness of the mixtures, however the decrease was less for impact loading when compared to static bending.

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