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Effects of fibre hybridization on multiple cracking potential of cement-based composites under flexural loading

Kamile Tosun-Felekoglu, Burak Felekoglu *

Dokuz Eylül University, Department of Civil Engineering, İzmir, Turkey

HIGHLIGHTS

- ▶ PP and PVA fibres affected the load–deflection curves in different manners.
- ▶ Increase in PP/PVA fibre ratio improved the ductility of composites.
- ▶ Hybrid fibre usage caused no synergistic flexural strength improvement.
- ▶ Matrix strength is the dominant factor determining flexural performance.

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ABSTRACT

The effects of individual and combined additions of polypropylene (PP) and polyvinyl-alcohol (PVA) fibres (PP/PVA fibre ratios: 3/0%, 2/1%, 1.5/1.5%, 1/2% and 0/3%) on the flexural behaviour of cement-based composites have been investigated. For this purpose, matrices at different strength grades have been used. The binder composition of high strength matrix (MI) was solely cement and 50% of cement was replaced with fly ash to prepare a comparatively low strength matrix (MII). Thirty prismatic samples are subjected to four-point flexural loading after 28 days of standard curing. The load–mid-span deflection curves have been plotted and simultaneously cracking patterns of composites have been photographed at definite deflection values. First cracking and flexural strength, deflection and relative toughness values have been determined for all samples.

Test results showed that the effects of PP and PVA fibres on load–deflection curves of cement-based composites are significantly different. Matrix strength is found as the dominant factor determining the flexural performance of fibre reinforced composites. Hybrid usage of PP and PVA fibres caused no significant improvement on flexural strength, relative toughness values and multiple cracking performances of composites.

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1. Introduction

Fibre reinforcement is the most effective way of improving the flexural strength and toughness capacity of cement-based composites. A combination of strain hardening and ductile behaviour is necessary for high flexural performance. For this purpose, microfibres are usually preferred to reinforce high performance composites. Micro-cracking control efficiency is the additional benefit of fibre reinforcement which improves the durability and service life of concrete structures. In order to provide such a combined load-carrying ability and ductile behaviour, a high fibre dosage is necessary. High fibre content usually causes workability problems if necessary precautions in matrix design are not taken into consideration [1]. Utilization of an effective superplasticizer and modification in matrix design may significantly improve the workability of composites incorporating high amounts of fibre.

Many types of fibres from different origin at variable strength and dimensions have been commercialized in the construction market. The effects of individual usages of these fibres in cement-based composites are well documented by fibre producers and some generalizations can also be made [2]. The selection of appropriate fibre type for a certain project may sometimes be confusing. Alternatively, the combined usage or hybridization of two or more fibres from different origin and/or fibres at different geometries may also be used to improve the composites' flexural performance. The intent is that the performance of these hybrid systems would exceed that induced by each fibre type alone. That is, there would be a synergy [3]. The concept of creating a synergy in terms of strength, ductility, crack control and workability is classified by Banthia and Gupta [4]. Recent studies focusing the effect of fibre hybridization on flexural performance and fibre combinations

* Corresponding author. Tel.: +90 232 3017041.
E-mail address: burak.felekoglu@deu.edu.tr (B. Felekoglu).

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employed in these studies can be listed as steel (ST)–polypropylene (PP) [5], polyvinyl-alcohol (PVA)–ST [1,6], ST–polyethylene (PE) [7,8], PVA–PE [9], ST–palm fibre [10], respectively. According to Ahmed et al. [7], the steel–PE hybrid composites exhibited lower flexural strength but higher deflection capacity than steel–PVA hybrid composites. They also concluded that, the rate of strength loss after peak load in steel–PE hybrid composites was low compared to steel–PVA hybrid system. Ahmed and Maalej [8] focused on the role of PE and ST fibres on flexural performance of hybrid fibre reinforced composites and concluded that PE fibres improve the tensile strain capacity of hybrid fibre composites whereas ST fibres contributed on the improvement of ultimate tensile strength.

In some cases, fibres from the same origin at different sizes (length and diameter) are also be used for hybridization. For example, Haim and Peled [11] used a combination of PVA fibres at different lengths and diameter for high performance repair mortar production and concluded that the amount of long fibres should be limited for a proper repair material. Akcay [12] also used a combination of ST fibres at different lengths to improve the tensile performance of concrete and concluded that, it was possible to increase the fibre dosage up to 5% by increasing the short fibre proportion and superplasticizer dosage.

In summary, different types of fibres can be used to improve the composite flexural performance and multiple cracking behaviours. As an alternative attempt, the effect of a combination of weak and strong fibres having completely different surface structure on flexural behaviour of cement-based composites was investigated. The multiple cracking behaviours of hybrid PP–PVA fibre composites under four-point loading have been characterized at constant fibre dosage (3% by volume). Two cement-based matrices at different strength grades have been employed for this purpose.

2. Experimental study

An ordinary Portland cement (CEM I 42.5R) conforming TS EN 197 [13] standard and a type C fly ash conforming ASTM C618 [14] standard have been used. The specific gravity and Blaine fineness of cement and fly ash were 3.1, 336 kg/m^2 and 2.2, 290 kg/m^2, respectively. Fine grinded limestone powder (<100 μm) with a specific gravity of 2.67 was used as micro-aggregate phase of composites. In order to maintain appropriate workability a polycarboxylate-based superplasticizer is also employed in matrix compositions. The pH, specific gravity and solid content values of this admixture were 6.5, 1.18–1.20 and 35.7%, respectively. The physical and mechanical properties of PP and PVA fibres are presented in Table 1.

A hobart mixer with $\sim$1500 cm^3 capacity was used for mixture preparation. Standard ECC mixing procedure as described in Zhou et al. [15] was used. Dry ingredients (cement, limestone powder and fly ash) initially mixed for 30 s, then water and superplasticizer were gradually added and mixing was continued for 2 min until a homogeneous slurry is obtained. PP and PVA fibre combinations of 3–0%, 2–1%, 1.5–1.5%, 1–2% and 0–3% have been finally added to the mixtures and sample preparation sequence was finished after 2 min of high speed mixing. The workability of fibre reinforced mixtures has been measured by using a flow-table conforming the ASTM C1437 [16] standard requirements. Flow diameters of fibre reinforced fresh mixtures have been kept between 130 and 150 mm by using a polycarboxylate-based superplasticizers. The mixture proportions and required superplasticizer dosages are presented in Table 2. Three prismatic specimens have been prepared by casting fresh mixture into 25 × 60 × 305 mm molds for flexural testing. Additionally, the compressive strength values of hybrid fibre reinforced composites and fibre-free matrices have been determined according to ASTM C349 [17] standard. The broken portions of three 40 × 40 × 160 mm prismatic samples were used to determine the compressive strength values. Two level compaction was performed for all samples. After demolding, samples subjected to 20 °C water cured for 21 days and dried in laboratory condition for additional 7 days before testing.

Four-point flexural loading tests have been performed by using a deformation controlled testing machine. A loading configuration similar to described in ASTM C1609 [18] have been employed, with an exception of specimen size. Test setup is presented in Fig. 1. Mid-span deflection was measured and deflection rate kept constant (1 mm/min). The load vs. mid-span deflection curves has been plotted and bending ability of all specimens has been visualized by taking photographs at 2.5 mm deflection intervals during testing. The flexural strength and deflection capacity of composites have been determined according to ASTM C1609 [18]. The first sudden drop at load carrying capacity was accepted as the first cracking point. However, the determination of first cracking point was complicated for some samples when there is a continuous slope change at the initial linear portion of load displacement curves. In this case, two tangents were prolonged from the linear portions of curves and the vertical intersection point with the curve was accepted as the first cracking point.

The maximum load was higher than the first cracking load due to multiple cracking behaviour of composites incorporating high amounts of fibre. For this reason, calculation of toughness parameters at a definite deflection rate is not capable of reflecting the exact toughness capacity of composites and toughness parameters have been calculated in an alternative way. The relative toughness value of each composite has been determined by integrating the area under the load–deflection curve until the deflection capacity consumed at peak load. Finally, number of visible cracks formed throughout the testing period has been analyzed by using the final crack pattern photographs.

3. Results and discussion

The average load–deflection curves of hybrid fibre reinforced composites prepared by using MI and MII matrices are presented in Figs. 2 and 3, respectively. Note that, individual curves of each specimen and simultaneous photographs taken at 2.5 mm deflection intervals can be found in Supplementary Videos (Videos 1 and 2). In these videos, bold curve is the average of two or three specimens' load–deflection curves. Light coloured curve is the curve of actual test that photographs taken. Red arrows refer to the point of photograph captured on the actual curve. Unloaded photographs of specimens at the end of testing are also embedded to these videos. By this way, it is possible to observe and compare the bending capacity of composites at a given deflection value. It should be noted that in case of some specimens LVDT slip into the new formed crack. For this reason these curves are excluded from the average curve.

In general, the load carrying ability of PP fibre reinforced composites still maintained until a deflection value of 20 mm. However, PVA fibre addition decreased the load carrying ability of composites at higher deflection values. The complete failure of PVA fibre reinforced composites is observed at 10–15 mm deflection interval. This is due to the rupture of PVA fibres at high loads as a result of chemical bonding between rough and reactive PVA fibre surface and cementitious matrix [19]. After the peak load at deflection capacity is exceeded, the rupture of PVA fibres indirectly determined by hearing the numerous rupturing sounds of fibres from tested composites. This behaviour is observed almost all cases of PVA fibre reinforcement. The tensile strain capacity of 8 mm PVA fibres with 6% elongation capacity exceeded at this deflection levels and therefore rupture occurred. Employment of a weaker matrix retards this rupture phenomenon to higher deflection values. In low strength matrix, which contains more capillary pores and less hydration products, the crack initiation mechanisms are different since the micro cracking around pores increases deflections.

In case of PP fibre reinforcement, these fibres still bridge the cracks and transfer the load to the other sections of composite at

Table 1
The physical and mechanical properties of PP and PVA fibres.

Fibre type	Diameter (μm)	Length (mm)	Tensile strength (MPa)	Modulus of elasticity (GPa)	Elongation capacity (%)	Surface structure
PP	18–20	12	300	4	>30	Smooth
PVA	30–40	8	1600	42	6	Rough

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