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Effects of fibre type and matrix structure on the mechanical performance of self-compacting micro-concrete composites

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ABSTRACT

The compatibility of matrix and fibre properties is one of the key parameters in the successful design of fibre reinforced cementitious composites. In order to achieve the desired performance, the properties of each constituent of composite should be properly configured. The aim of this study was to investigate the performance of two polymer based micro-fibres (polypropylene and polyvinyl alcohol) in different matrices (high strength and comparatively low strength with fly ash incorporation) which were designed to contain considerably high amounts of fibres (1% by volume) while maintaining their self-compactability. The fresh state thixotropic behaviour of fibre reinforced matrices was minimised by proper adjustment of water/cementitious material ratio and admixture dosage. The mechanical properties (first crack strength and displacement, flexural strength and relative toughness) of prismatic composite samples were compared by three point flexural loading test. The typical behaviours of selected composites and collapse mechanisms of PP and PVA fibres in these matrices were characterised by microstructural studies. It was concluded that, a high strength matrix with a high strength fibre give the best performance from the view point of flexural strength and toughness performance. However, incorporation of fly ash did not cause a significant reduction in composite performance possibly due to its enhancing effect on matrix–fibre interface adhesion. The possibilities and suggestions to further improve the performance of the composites were also discussed.

1. Introduction

The use of fibre reinforced cementitious composites for various structural applications are gaining popularity throughout the world. The flexural strength and toughness properties of these composites may be significantly improved by incorporation of different types of fibres. The success of the composite mainly depends on the fibre and matrix compatibility from the view point of strength, elasticity and load transfer related to the surface adhesion properties. Steel, glass, carbon and polymer based fibres are commonly employed in many fibre reinforced composite applications. Polymer based fibres are very versatile and their performances in composites are quite different from one to another [1–3]. For example, the performance of a cement based fibre reinforced composites of polyolefin based fibres with low strength (polypropylene — PP and low density polyethylene — LDPE) and high strength (high density polyethylene — HDPE) one performs very differently [4]. In addition to their mechanical and elastic properties, the surface structure of these fibres is very effective on their performance. Their highly hydrophobic and smooth surfaces usually reduce the composite performance [4]. On the other hand, polyvinyl alcohol (PVA) based fibres perform extremely different in a cement based matrix due to their surface formation and high strength [5]. In recent years, PVA fibres are gaining importance in fibre reinforced composite applications [6–8]. By proper adjustment of surface properties of PVA fibres and employment of a suitable matrix, Li et al. [9] improved the performance of cementitious composites which are known as engineered cementitious composites (ECC). These high performance cementitious composites demonstrate a multiple cracking and strain hardening behaviour. Due to their crack resisting and crack width minimising performance, they have been accepted as extraordinary high performance materials against durability related problems [10–12].

The homogeneous dispersion of fibres and application easiness of fresh mixtures are other important aspects of composite success when reinforced with fibres [13]. These targets can only be obtained by using a self-compactable mixture without any signs of fresh state unstability. The optimisation of water/cementitious materials ratio and superplasticiser dosage will bring the best solution for a particular fibre type and dosage [14]. In recent years, the thixotropy related pseudo-workability loss has also been realised in particular in low water/cement and low $D_{\max}$ mixtures [15–18]. For this reason, the thixotrophy of mixtures should also be minimised.

In this study, a comparative test programme has been programmed to evaluate the performance of a high strength and a relatively low strength matrix reinforced with polymer based fibres.

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These matrices were specially designed to sustain high amount of fibres (1% by total volume) without losing their self-compactable structure and their thixotropy related instant workability loss was minimised by employment of longer mixing times. The strength–toughness properties were compared on prismatic samples. Results were discussed with the aid of microstructural investigations and further improvement possibilities were presented.

2. Experimental study

2.1. Materials

An ordinary Portland cement (CEM I 42.5R) and a C type of fly ash were used as the binder phase of micro-concretes. The chemical, physical and mechanical properties of binders are listed in Tables 1 and 2 respectively. The activity index of fly ash was determined according to TS EN 450 [19] procedure. Limestone powder was employed as micro-aggregate. The specific gravity and Blaine value of this material were 2.58 and 443 m^2/kg respectively. The maximum aggregate size of micro-concrete mixtures was in the order of 100 µm. This reduced aggregate size results in a composite of high fibre holding capacity. In order to improve the flowability of micro-concretes a polycarboxylate based superplasticiser with a solid content of 35.7% was used. In standard cement mortars a CEN standard sand conforming the EN 196-1 [20] requirements was used.

Two polymer based fibres with distinct properties were selected. As can be seen from Table 3, the mechanical, elastic and surface structure properties of polypropylene (PP) and polyvinyl alcohol (PVA) fibres are considerably different. To illustrate the surface roughness differences between fibres, SEM images captured at the same magnification are also presented in Fig. 1. The polyolefin based polypropylene fibres are highly hydrophobic with a very smooth surface structure. Their tensile strength and modulus of elasticity are comparatively lower than PVA fibres. On the other hand, the elongation capacity of polypropylene fibres is considerably higher than PVA fibres. The rough surface of PVA fibres improves the mechanical interlocking related adhesion capacity of this fibre in a matrix; however, in some cases the low elongation capacity of this fibre may negatively affect their toughness improving performance.

2.2. Preparation of composites and flow rate measurements

Initial trial mixtures showed that, the optimum PP or PVA fibre content is about 1% for maintaining self-compactability. Two groups of matrices "high strength" and "relatively low strength" were prepared. The binder phase of the first matrix solely composed of cement, while 50% of cement was substituted with fly ash in the second matrix. The second matrix can be accepted as a high volume fly ash mixture, which has similar matrix mixture proportions like "green ECC" [21,22]. The 56 days average compressive strengths of plain matrices were 70 and 45 MPa respectively.

As mentioned before, previous studies revealed that, micro-concretes are susceptible to thixotropy related pseudo-workability loss and related pseudo-cold joint behaviour [17,18, 23]. In order to minimise the thixotropy related pseudo-cold joint behaviour, special matrices with adjusted Water/Cementitious Materials ratio (W/CM) and superplasticizer dosages are employed. By this way the negative effects of fibre inclusion on composite homogeneity was minimised. Mixture ingredients of two main matrices are listed in Table 4. For comparison purpose a standard mortar mixture was also prepared.

Another attempt to reduce the thixotropy was changing the mixing procedure of plain and fibre reinforced composites. The mixing sequence of plain and fibre reinforced mixtures were different. Cement and in the case of second matrix fly ash, were dry mixed for 30 s in a Hobart mixer. After addition of water and superplasticizer mixing was continued for a period of 2 min. In case of fibre reinforcement, fibres were added to the fresh mixture at this period and mixing was prolonged to 4 min. This additional mixing activated the polycarboxylate molecules and improved their orientation through the shear direction which results in a reduced thixotropy related initial workability loss.

Flow rate measurements were conducted by using a double mould system equipped with a video camera (Fig. 2). A classical spread cone as a practical indicator of yield value of mixtures was used [24,25]. Details of the setup are explained in detail elsewhere [26]. The two cone moulds were filled with flowable mixtures. The mould at the left was lifted up and flowing rate was recorded. The relative flow value–time relations of various micro-concrete mixtures are presented in Fig. 3. After a five minute of waiting period, the mould at the right was lifted up and delayed flowing rate was recorded. The relative flow values were calculated by using the $\Gamma = \frac{(d_1 * d_2) - d_o^2}{d_o^2}$ formula for 5, 10, 15 and 30 s after lifting. Where Γ is the relative flow value at any time, d_o is the initial flow diameter (100 mm), d_1 and d_2 are the perpendicular measurements of maximum and minimum diameters of spread if the flow area is not circular. The differences between initial and delayed flowing rates and final relative flow values can be attributed to the thixotropy related pseudo-workability loss of mixtures. An example of a highly thixotropic mixture is also illustrated in Fig. 2. If this difference is low, mixture can be effectively used in practice. Any delay in casting will not negatively affect the fresh composite's filling efficiency. However, if this difference is high, possible problems related to the formation of pseudo-cold joints between individual casting results in joining problems. This time may be as small as minutes as illustrated in this test procedure. In some cases, remixing is advised to reduce this effect. However, this method can only be effective to a certain extent in case of highly thixotropic mixtures. A total of seven mixtures (SH, MI, MII, MI-PP, MI-PVA, MII-PP, MII-PVA) were tested by using this procedure. The relative flow value (Γ) − time relations of various micro-concrete mixtures are presented in Fig. 3.

Table 1
The chemical, physical and mechanical properties of CEM I 42.5R type Portland cement.

Oxide composition (wt.%)		Mixed compounds (Bogue %)			
CaO	63.70	C_3S	63.01	C_3A	10.16
SiO_2	19.14	C_2S	3.89	C_4AF	9.13
Al_2O_3	5.75	*Compressive strength (MPa)*			
Fe_2O_3	3.00	2 days			20.4
MgO	0.90	7 days			41.1
Na_2O	0.65	28 days			50.6
K_2O	0.83	*Physical properties*			
SO_3	2.78	Specific gravity			3.12
Cl	0.001	Blaine SSA (m^2/kg)			336
Loss on ignition	2.84	Volume expansion (mm)			1
Free CaO	0.55	Consistency water (%)			28.8
Insoluble residue	0.70	Initial setting time (min)			135
		Final setting time(min)			245

Table 2
The chemical and physical properties of C type fly ash.

Oxide composition (wt.%)		Physical properties	
SiO_2	42.14	Specific gravity	2.20
Al_2O_3	19.38	Blaine SSA (m^2/kg)	290
Fe_2O_3	4.64	Pozzolanic activity index (%) TS EN 450	93.8
CaO	26.96		
MgO	1.78		
K_2O	1.13		
Na_2O	–		
SO_3	2.43		
Cl	0.0010		

Table 3
The physical and mechanical properties of fibres.

Fibre type	Density (g/cm^3)	Diameter (micron)	Length (mm)	*L*/*D* ratio	Tensile strength (MPa)	Elongation at break (%)	Modulus of elasticity (GPa)	Cross-section form	Surface structure
Polipropylene (PP)	0,95	40	12	300	400–550	>30	5,6	Circular	Smooth
Polivinyl alcohol (PVA)	1,3	30	8	267	1600	6	42	Circular	Rough

2.3. Mechanical testing

After the flow rate measurements, mixtures were poured into 40*40*160 mm prismatic moulds without any compaction. Six samples were prepared for each mixture. Prismatic samples were remoulded one day after casting and standard cured for a period of two months. This long curing period was selected to give enough time for the pozzolanic reaction to take place in case of fly ash incorporated composites. Two months old samples were subjected to three points loading flexural test by using a close loop displacement controlled machine. In case of plain samples the displacement rate was adjusted to 0.02 mm/min, while this rate was 0.2 mm/min for fibre reinforced samples. Data collection was continued till the load on samples reduced to 100 N. Testing also ended if the displacement values at midspan exceed 3 mm while the load is over 100 N. As can be observed from Fig. 4a–g, load–displacement curves of all samples were plotted at the same scale (*y*-axis: 6000 N, *x*-axis: 3 mm). However, for plain samples, it is hard to observe the initial load–displacement behaviour of samples at this scale. For this reason partial graphs with a smaller scale (*y*-axis: 3000 N, *x*-axis: 0.25 mm) were also plotted and illustrated in the same figure.

From the load–displacement curves, first cracking strength and displacement at this strength were determined. The first cracking loads and maximum loads were approximately similar for plain mixtures. However, the maximum load was higher than the first cracking load in case of fibre reinforced composites. 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 first cracking strengths and displacements of all composites are plotted in Fig. 5. Another important parameter which can be derived from load–displacement curves is the flexural strength and the displacement at maximum load. These parameters are useful as the indicators of load carrying capacity of composites even at high displacement rates. These properties are also plotted in Fig. 6. The most important advantage of fibre incorporation is the improvement of toughness. In this study, toughness of composites was determined as the area under the load–displacement curves at the displacement of 1.5 mm which is approximately 1/90 of loading span. These values are presented in Fig. 7. The average of six samples was used in the figures. The standard deviation of strength and toughness values were also plotted in Figs. 5–7 as bar charts with one standard deviation plus and one minus.

3. Test results and discussion

3.1. Characterisation of fresh micro-concretes

Relative flow value–time relations of micro-concrete mixtures prepared by using MI and MII matrices are illustrated in Fig. 3a and b respectively. As can be seen from Fig. 3a, the initial relative flow values of plain and fibre reinforced MI mixtures are in the order of 2.3 and 3.2.

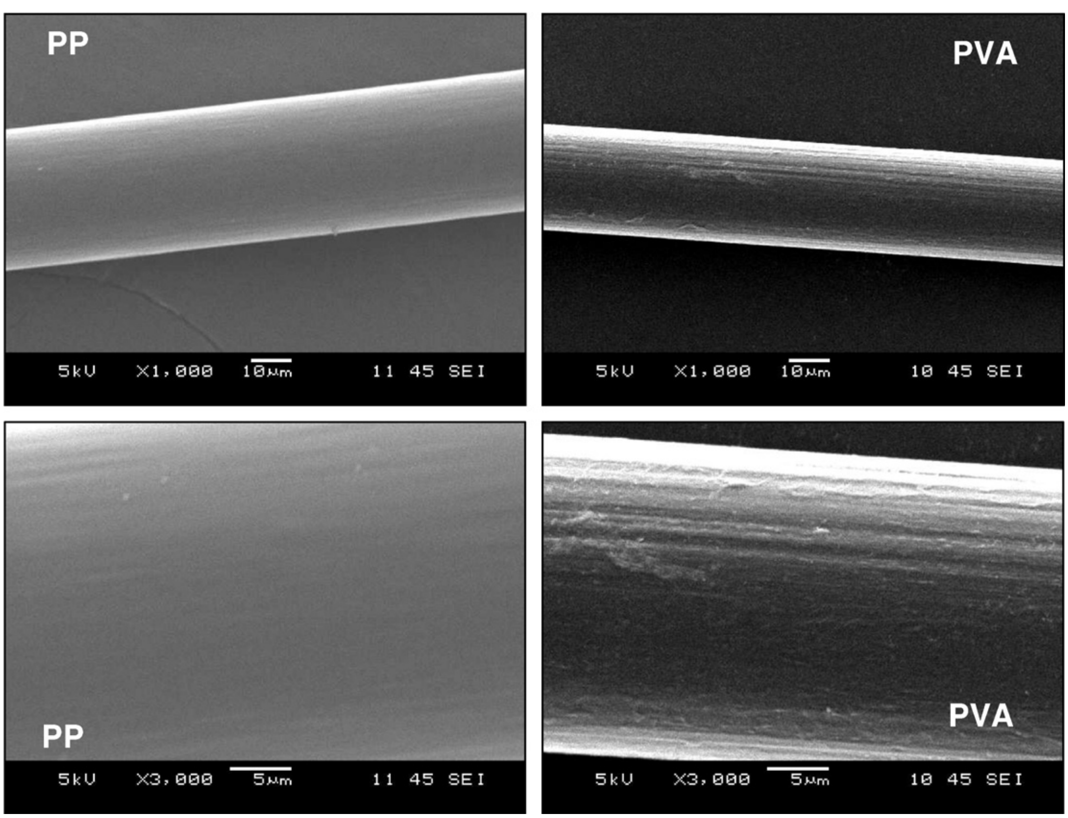


Fig. 1. Scanning electron microscope images of polypropylene and polyvinyl alcohol based fibres at 1000× and 3000× magnifications.

Table 4
Mixture ingredients (kg/m^3).

Mixture ingredients (kg/m^3)	Micro-concrete I (MI)	Micro-concrete II (MII)	Standard mortar (SH)
Cement	854	378	506
Limestone powder	854	757	0
C type fly ash	0	378	0
Water	380	399	273
Standard sand	0	0	1519
Superplasticizer	8.6	5.1	0

After a waiting period of 5 min, the relative flow values decreased at different orders. Plain mixture lost approximately half of its initial flow value after this waiting period. However, the loss of relative flow value was very low in case of fibre reinforced samples. This difference may be attributed to the initial mixing procedure of plain mixtures. In case of fibre incorporation possibly additional mixing activated the polycarboxylate molecules and improved their thixotropy reducing behaviour [27,28]. Similar performance was also observed in fly ash incorporated MII mixtures (Fig. 3b). The initial relative flow values of plain and fibre reinforced MII mixtures are in the order of 2.5–3.5. The 5 min delayed relative flow value of plain mixture was four times lower than that of its initial value. However, fibre incorporation and additional mixing time reduced the thixotropy related flow value loss of other mixtures.

It should be noted that the above mentioned mixing technique is not a unique and universal procedure. Depending on the properties of local ingredients procedures may be revised to enhance fresh state performance. Different mixing procedures were successfully applied in the development stage of self-compacting polymer fibre reinforced composites by various researchers [29,30].

3.2. Load–displacement curves

The load–displacement behaviour of all mixtures is illustrated in Fig. 4. As expected, standard mortar and plain micro-concrete mixtures exhibited extremely brittle behaviour (Fig. 4a, b and c).

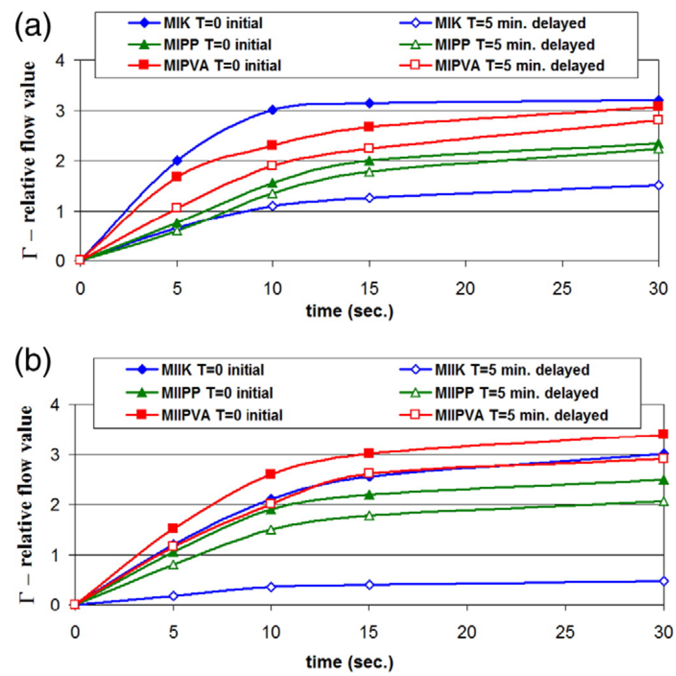
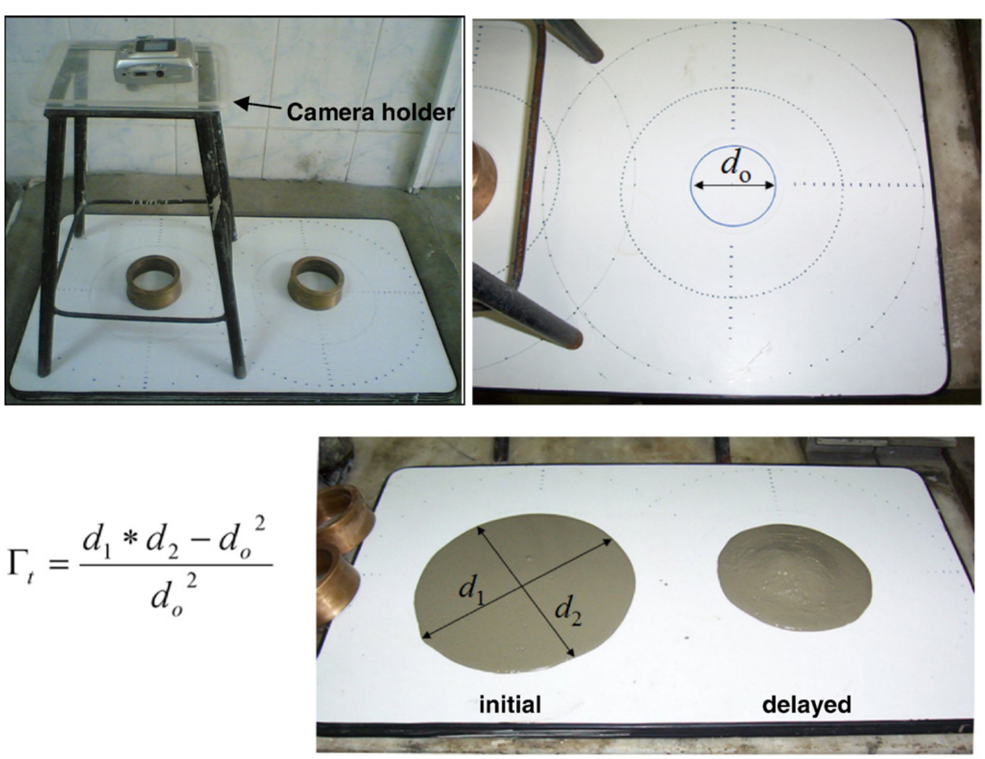


Fig. 3. Relative flow value–time relations of micro-concrete mixtures determined by using video images.

The first cracking load and maximum load were approximately equal and the corresponding midpoint displacement value was very low (0.05–0.08 mm). The load–displacement curves after the maximum load has been obtained from six samples of the standard mortar. The crack formation in other samples was unstable and tail data (post-peak) couldn't be measured (Fig. 4a). It should be noted that; micro-concretes with maximum aggregate size below 100 µm were more brittle than the standard mortar. In all cases, the tail of load–displacement curves of high strength micro-concretes could not be



$$\Gamma_t = \frac{d_1 * d_2 - d_o^{\,2}}{d_o^{\,2}}$$

Fig. 2. The relative flow value measurement test setup.

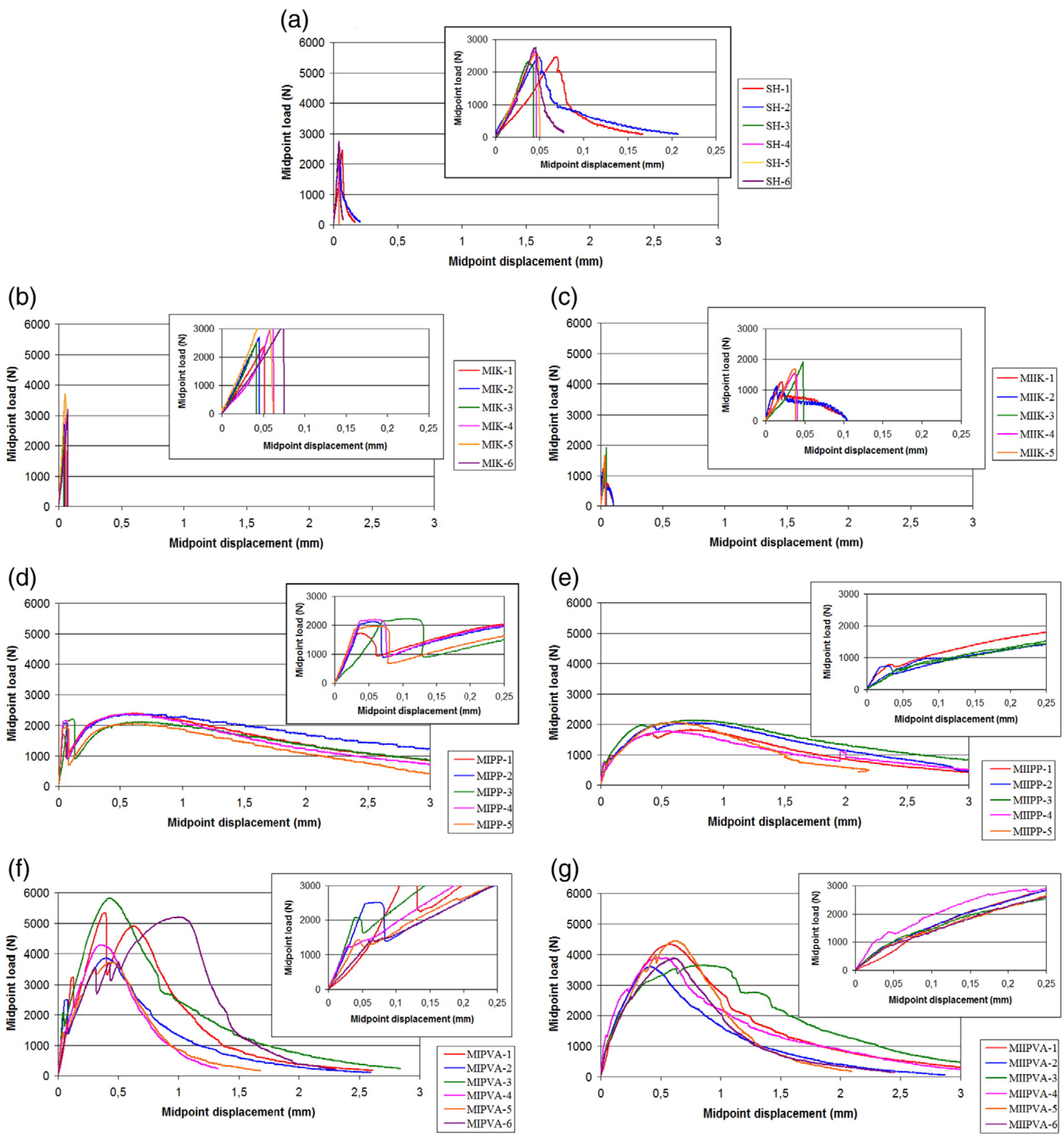


Fig. 4. Load–displacement curves of composites at two different scales: a) Standard mortar, b) Plain micro-concrete (matrix I), c) PP reinforced micro-concrete (matrix I), d) PVA reinforced micro-concrete (matrix I), e) Plain micro-concrete (matrix II), f) PP reinforced micro-concrete (matrix II), g) PVA reinforced micro-concrete (matrix II).

observed due to the sudden and quick formation of initial (and final) crack (Fig. 4b) except fly ash incorporated mixtures as expected (Fig. 4c). This behaviour is expectable since cementitious materials are unstable in tension stresses. Furthermore, cracking starts on the weakest link of chain of cross-section which is statistically a random variable.

In case of PP fibre incorporated MI matrix, there is a linear portion in the load–displacement curve (Fig. 4d). A sudden crack formation and a large displacement took place (After 2000–2100 N). At this point, load drop with a magnitude of approximately 1000 N was also observed. After this load drop, fibres bridged the initial crack and regain load by stretching and elongation. As the crack progress, new fibres at the upper levels of the cracking plane also activate and increased the load carrying capacity of the composite. This behaviour continued till the midpoint displacement is about 0.6 mm. At approximately this displacement level, maximum load has been obtained. Above this point the load carrying capacity of the composite decreased due to fibre slippage from the matrix. Some fibres also

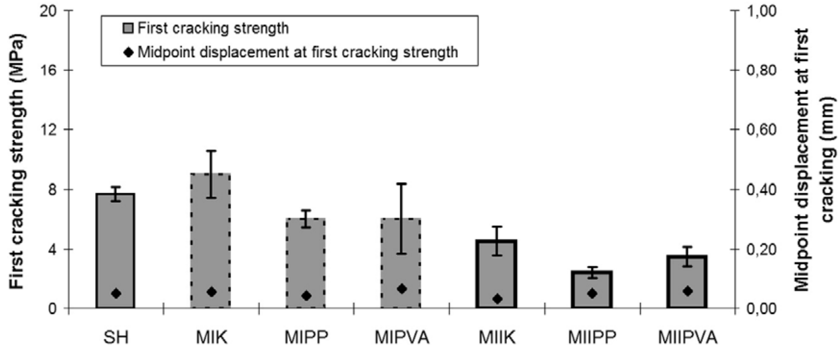


Fig. 5. First cracking strengths and displacements at first cracking of composite mixtures.

elongate more than their elongation capacity or slip off from the matrix. As the fibres near the lower levels of samples loses their load carrying capacity, composite performance decreases. However, this drop is rather slow due to the high elongation capacity of PP fibres. It should be noted that, a single crack was formed at all samples and this crack widened till the end of testing (Fig. 8). No other crack was observed at other cross-sections of matrix.

The incorporation of PP fibres into MII matrix resulted in a similar load–displacement behaviour with a few differences (Fig. 4e). For example, first cracking strengths of these samples were not distinctive compared to the one's made by high strength matrix. The magnitude of first crack load was not as high as that of MI matrix. At this load level, fibres are capable of sustaining the load at similar values and a sudden load drop was not observed. As expected, both the first cracking strength and flexural strength were lower than MI samples. However, differences are not very distinctive. The flexural strength values and displacement at this value of all specimens were higher than the first crack strength and displacement respectively. Additionally some of the specimens showed multiple cracking behaviour. This is possibly due to the improved interface adhesion and frictional bond between MII matrix and PP fibres by the incorporation of fly ash particles. Interface compactness seems to be improved by possible formation of additional CSH by the reaction between fly ash and CH [31]. Improvement in PP fibre–matrix adhesion may also be responsible for the load conservation capacity of this composite just after the first cracking. The improved frictional bond properties between PP fibres and matrix prevent the slippage of fibres, at this point fibres can only elongate and stretch. If the strength of fibres exceeds the tensile strength of any cross-section of the composite, second cracking may form. Any additional cracking results with the formation of many additional fibre bridges. By this way, the toughness of the composite can be improved by increasing load carrying capacity even at higher displacements. It should be noted that, when load–displacement curves of MI-PP (Fig. 4d) and MII-PP (Fig. 4e) compared, relatively lower strength matrix can be accepted as higher performance in terms of toughness improvement and load carrying capacity at higher displacement values. This is due to the improved frictional bondage of composite by incorporation of fly ash. If surface properties of PP fibres or matrix adhesion are improved further improvements in load carrying capacity of this composite may be obtained. Such an improvement on the surface roughness of polyolefin fibres (PP and PE) was successfully applied by Wu & Li [1] and Li & Stang [4]. In their test setup, the pull-out loads of fibres from composite were nearly doubled by using plasma treatment [4]. In another comprehensive study, Felekoğlu et al. [32] modified the PP fibre surfaces by argon and oxygen plasmas. The modified fibres' flexural performances in cementitious matrices were compared to unmodified fibres. Significant flexural strength and toughness improvements were reported [32].

In addition to flexural response, the performance of fibres can be studied by using pull-out test setup. A linear post-peak branch in a pull-out curve would be expected in pull-out process, if the frictional stress between fibre and matrix is constant (as observed in PP fibre reinforcement). However, in case of rough surface (PVA fibres), due to the abrasion during fibre pull-out, damage of different extents may occur on fibre or matrix and result in either slip-weakening or slip-hardening. Li [33], showed that, this is also an age-dependent process for PVA fibres. Since the matrix interface properties are closely related to the age. At early age the cement matrix is not fully hydrated. The abrasion due to fibre slip may cause damage on the matrix and result in poor contact between fibre and hydrated cement paste. Hence slip-weakening may be observed. On the other hand, a fully hydrated cement paste might have a higher hardness than the polymeric fibres which are usually weaker in lateral direction due to molecular structure. As a result, fibre pull-out causes damage on fibre surface and the peeled-off tiny fibrils could increase the resistance to further slip by jamming the fibre [33]. However, effect of aging is not the main topic of this study and all samples were 2 months old at the stage of testing.

The performance of PVA fibres in both matrices was extremely superior compared to the PP fibres. In case of high strength matrix

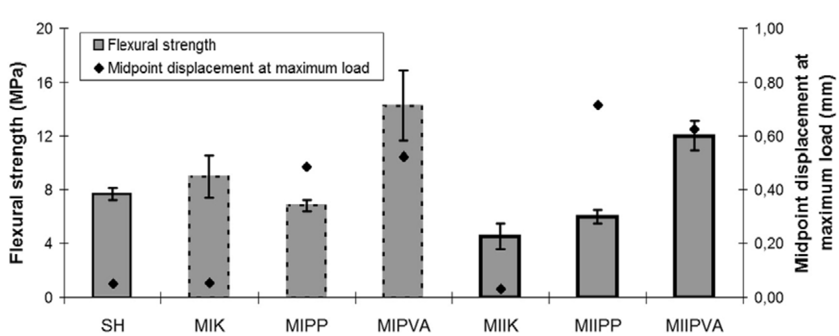


Fig. 6. Flexural strengths and displacements at maximum load of composite mixtures.

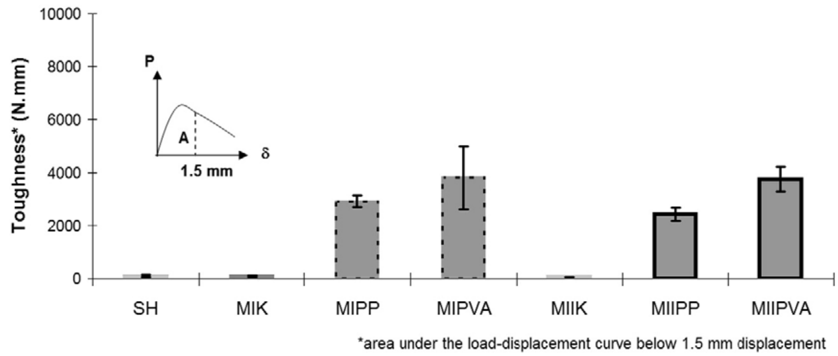


Fig. 7. Toughness of composite mixtures.

(MI), first cracking load was in the order of 1000–3500 N (Fig. 4f). After the first crack, additional multiple cracks formed in some of the samples. Due to the high frictional bond between rough surface of PVA fibres and matrix and high tensile strength of PVA fibres, the load carrying capacity of composite has improved significantly. Each new formed crack results in a sudden load drop and a following load gain. This situation can be observed on load–displacement curves of some samples as a "zig zag" form structure. Multiple cracking improved the load carrying capacity of composites even at higher displacement values to a certain extent. However, if fibre bridging strength after the first crack is not higher than the tensile strength of any other cross-section, no additional crack will form with the increased displacement. This situation results in a single crack and rupture of PVA fibres as observed in some samples. For this reason, the tensile strength of the cross-section should be reduced to exhibit a multiple cracking behaviour. Addition of lightweight particles or polymer pieces is the successfully employed alternative for this enhancement [34,35] Another possible alternative to further improve the composite performance is proposed by Li [9]. The challenge of using PVA fibres in cementitious matrix reinforcement is that, PVA fibres tend to develop very strong chemical bonding with cement due to the presence of the hydroxyl group in its molecular chains. This high chemical bonding leads to a tendency of fibre rupture and limits the tensile strain capacity of the resulting composite. Furthermore, Redon et al. [36], observed a strong slip-hardening response during fibre pull-out that can lead to a shear-delamination failure of the PVA fibre. In order to reduce the frictional bond, Li [9] applied an oiling agent to the surface of PVA fibres. By this way, fibre slipping from the matrix can be obtained. Increased displacement capacity results in formation of a higher area under the load–displacement curve.

After the maximum load, PVA fibres in MI matrix ruptured beginning from the bottom of the crack plane. The sound of fibre rupture can be heard and at this period the tail of load–displacement curve is formed. However, no sound was heard at this part in case of PP fibre employment. Furthermore, the slope of the descending part is extremely higher compared to composites prepared with PP fibres. The quick drop of strength with increased displacement can be attributed to the gradual fibre rupture starting from the bottom. Loss of each fibre is more detrimental to toughness compared to gradual slip of fibre (as observed in PP fibres).

When PVA fibres used in the second matrix incorporating fly ash, first cracking and flexural strengths of composites were decreased (Fig. 4g). However, flexural strength reduction was not very distinctive. The mechanism of PVA fibre performance is similar to that of first matrix. Both multiple and single cracking behaviour randomly observed in the composites.

In order to clarify the effect of fibres in collapse mechanism composites, cracked surfaces of MI matrix were investigated by naked eye (Fig. 9) and on small particles by using a scanning electron microscope (SEM). In case of PP fibres, main mechanism of fibre collapse was elongation and slipping, while PVA fibres ruptured without any sign of slippage. In SEM analysis, cracked surfaces of PP and PVA incorporated MI matrix were detached and gold coated under vacuum. Investigations were conducted on secondary electron mode under 15 kV voltages. Two representative images of MI-PP and MI-PVA matrices at 50× and 30× are presented in Fig. 10 respectively. In Fig. 10a, the PP fibres both elongated and slipped from the other part of the matrix can be observed. Additionally, many fibre holes can be seen that are emptied by fibres at the other part (Fig. 10b). On the other hand, as presented in Fig. 10c, it is hard to observe any elongated or slipped fibre on the surface of MI-PVA matrix. At higher magnification levels (1000×), many ruptured PVA fibres near the

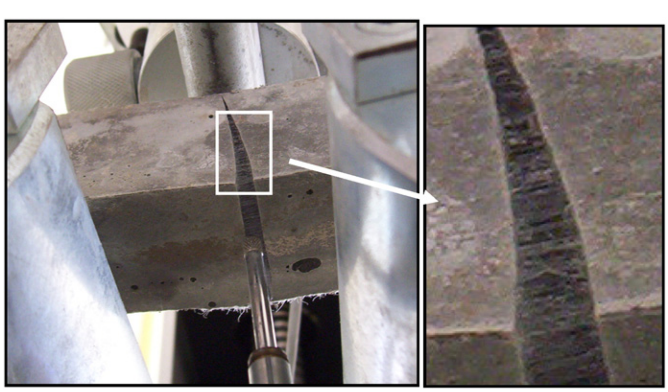


Fig. 8. The bottom of sample MI-3 near the end of testing. A single crack formed and widened while fibres are stretching and slipping.

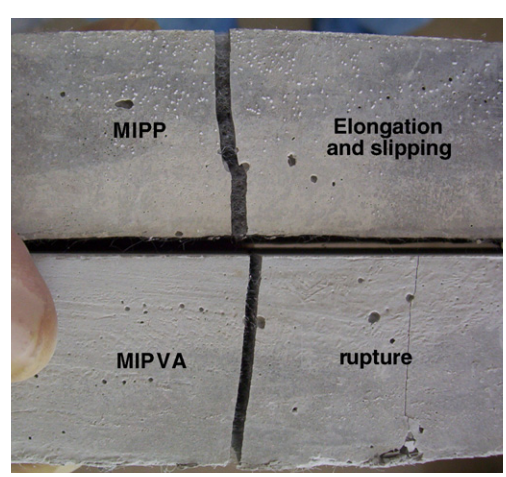


Fig. 9. Difference between fibre collapse forms.

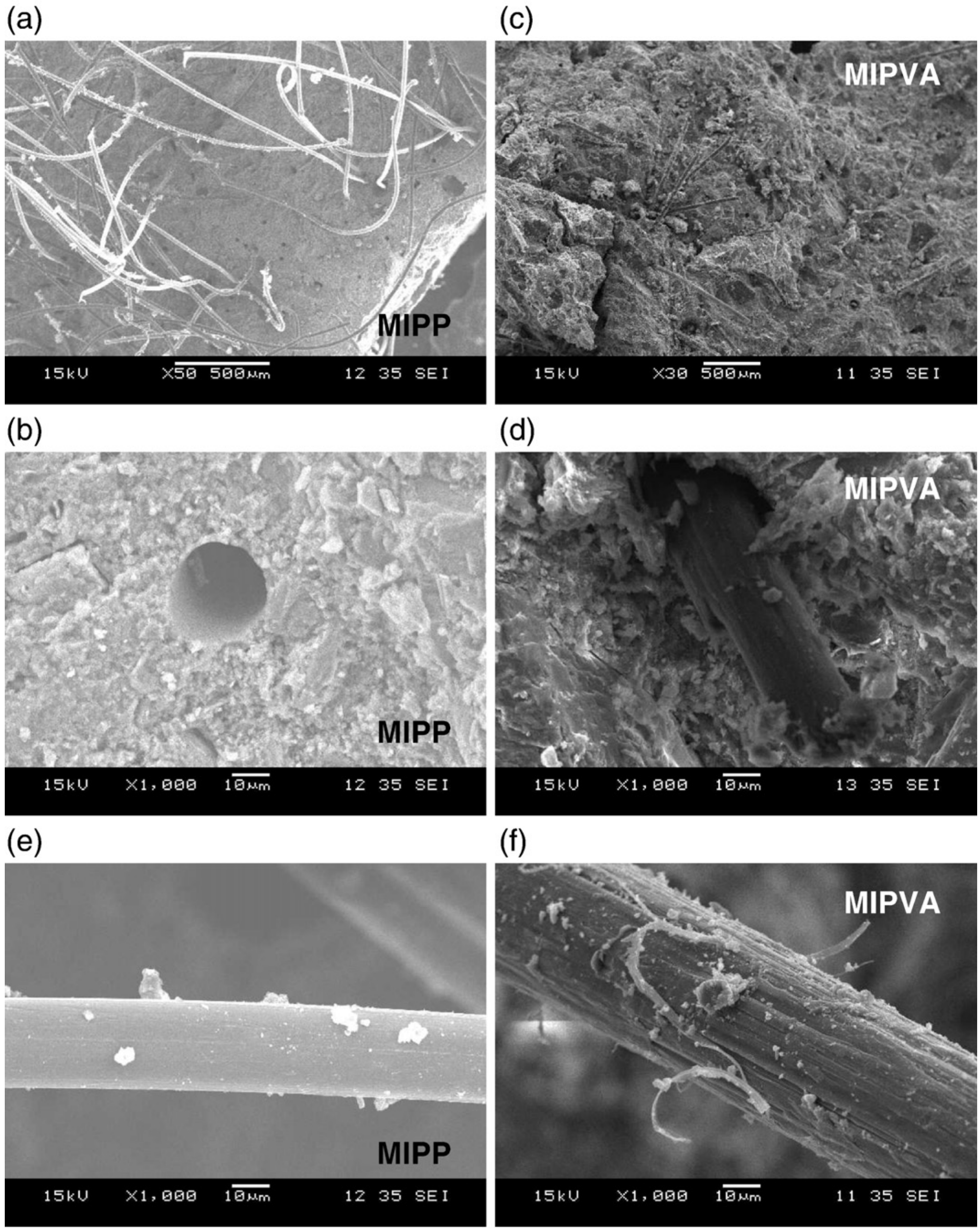


Fig. 10. Scanning electron microscope (SEM) images of cracked surfaces of MI matrix.

cracked surface was observed (Fig. 10d). These images proved the importance of fibre surface roughness and its role in composite behaviour. Proper tailoring of fibre surface and matrix properties will help the site practisers to reach the desired composite performance (to control the interface bond and slip-hardening behaviour) [9]. Fig. 10e illustrates the PP fibres detached from the matrix. The diameter of fibres decreased due to the high elongation rate. While PP fibres detached from matrix, no visible wear distortion was observed. However, this was not the case for PVA fibres. PVA fibres severely delaminated at the previous embedded ending after the extraction, suggests a strong inter-facial bond. In fact, failure always occurs in the weakest point through which load is transferred between the matrix and fibre, in this case the failure is shifted to the fibres in proximity of the interface, as the fibre–matrix bond strength is greater than the fibre shear strength [37]. For this reason, these fibres usually ruptured without elongation (they preserve their initial diameters) or fibre surface extremely damaged if slippage occurs (Fig. 10f).

To make a general consideration first cracking strengths and displacements at this strength are plotted in Fig. 5. Incorporation of fibres usually decreased the first cracking strengths. However, the variations of results illustrated as bar charts are considerably high in some samples (Fig. 5). Due to this reason, it is hard to comment on this behaviour. Higher first cracking strength values are expectable in case of plain matrices, since the elastic modulus and slope of load–displacement curves are higher. On the other hand, no distinct difference was observed when midpoint displacement values at first cracking are in consideration.

The incorporation of PVA fibres considerably improved the flexural strength values in both matrices (Fig. 6). The rate of improvement is in the range of 100%. However, effect of PP fibres was variable depending on the matrix type. While the addition of PP reduced the flexural strength of MI matrix, its incorporation improved the strength in the second matrix. This is expectable, since fly ash improved the frictional bonding capacity of matrix with PP fibre. On the other hand, both fibres at two matrices improved the load carrying capacity of composites at comparatively high displacement values.

Toughness values determined from the area under the load–displacement curve below 1.5 mm displacement are plotted in Fig. 7. Depending on the fibre type, fibre reinforcement improved the toughness values at about three orders magnitude. The comparative performance of PVA fibres is better. However, the variation of results is very scattering due to random multiple or single cracking behaviour of PVA incorporated fibres. Fibre bridging and crack width limiting performance of PVA fibres are the possible explanations for the high toughness of PVA incorporated composites. Fibre bridging provides closing traction to a crack and transmits stresses across the crack. Due to relatively strong fibre bridging, composite can expect the multiple roles of fibre bridging [37]. The following are a few notable examples. Composite exhibits smaller crack widths or delayed cracking at the same loading level. This is beneficial to activate the aggregate interlock on a crack and the reduction of shear modulus after cracking can be avoided. Also, composite provides the transmission of stresses across a crack; thereby it shares the tensile stress with reinforcement. In case of reinforced concrete, this leads to the improved ultimate load capacity and ductility of a column member, as it shares stress with transverse reinforcement [38].

High performance fibre reinforced composites are characterised by enhanced elastic limit, strain hardening response and toughened post-peak response. If the composite is adequately reinforced with proper fibres, the bridging fibres will share the load and transfer it to the other parts of the composite. During the strain hardening response, number of cracks increase and cracks widen slowly. Multiple cracking occurs when the subsequent transferred load cracks the matrix again [39]. Hence, the initial flaw size and the fibre dispersion play important role on the initiation of the cracking and toughness [40]. Fibre reinforced cement composites contain pre-existing flaws and defects. It is the size of these flaws that determines the critical load required for crack initiation. Far-field stresses, well away from the location of the flaw, will be equal to the applied stress. However, the presence of the flaw along the cross-section perpendicular to the applied load would cause stress concentration at the tip of the flaw [39].

3.3. Comparison of PVA fibre reinforced self-compacting micro-concrete (SCMC) with conventional steel fibre reinforced concrete (SFRC)

As a type of high performance material, PVA fibre reinforced SCMC has special properties compared to conventional fibre reinforced cementitious composites. A comprehensive literature survey on the classification of high performance fibre reinforced cementitious composites based on their tensile response can be found in [41]. The differences between PVA fibre reinforced SCMC developed in this study and SFRC will be discussed in the following paragraphs:

The behaviour after first cracking and crack propagation of SFRC are significantly different from the SCMC in particular PVA fibre reinforced ones. In case of SFRC, first cracking takes place and no further matrix crack will form until the full collapse. The mechanism of toughness improvement is solely due to the fibres slipping or rupturing at this single crack opening. Frictional adhesion between fibre and matrix is the key of toughness performance. Additionally, after the formation of first cracking, composite presents a huge amount of permanent deflection which is unrecoverable upon unloading in case of steel fibre reinforcement. However, in case of PVA fibre reinforced SCMC, additional crack formation at other sections of matrix (which is called as multiple cracking) is possible at increasing deflections. By this way, additional fibres will bridge the new cracked surfaces facing one another. Before a particular midpoint deflection, the fibres between these crack surfaces will work as non-linear elastic springs [42]. Hence most of the deflection before this particular midpoint deflection will be elastic. The critical elastic deflection value can be determined experimentally, by loading and unloading the composite at increasing load values. In conclusion, PVA fibre reinforced SCMC composite will serve as an elastic material with high deflection capacity until a limit of load or deflection. In practice, this behaviour can be advantageous when material is subjected to repetitive loading and unloading. Elastic flexibility of a composite can be improved by using PVA fibre reinforced SCMC. After the certain deflection value, PVA fibres begin to rupture due to their high chemical bond to matrix. Due to the loss of load bridging fibres at cracked sections, load carrying capacity of composite suddenly and quickly drops with increasing deflection [43]. This behaviour reduces the composites toughening performance after the certain deflection value.

The above mentioned steel fibres are conventional hooked fibres with circular cross-section. However, Naaman [44] developed special engineered steel fibres called Torex®, which are significantly different from conventional hooked steel fibres. Kim et al. [45] showed that it is possible to obtain multiple cracking behaviours and improve the composite flexural performance by using these twisted steel fibres with special cross-section geometry. For this reason, comparison of fibres should be made by taking both the origin of fibre materials, mechanical properties and geometrical differences into account. It should also be noted that fibre dosage and effects of fibres on matrix workability have significant roles on composite performance.

4. Conclusions

Fresh state self-compactability and thixotropy degree of polymer fibre reinforced micro-concretes can be monitored by video camera images and quantitatively determined by relative flow rate measurements. Adjustment of admixture dosage and water/cementitious materials ratio in combination with proper mixing time is the key parameters to achieve the desired fresh state performance with fibres.

Load–displacement curves of self-compacting micro-concretes incorporating different types of polymer based fibres and matrices has been characterised in detail. Among the investigated fibres, the polypropylene (PP) fibres elongate and slip from the matrix easily. Incorporation of fly ash resulted in a frictional bond improvement between matrix and fibre. On the other hand, polyvinyl alcohol fibres (PVA) performed similar in both matrices because of its relatively rough surface structure. Fibre rupture was the main collapse mechanism. First cracking strength of fibre reinforced micro-concretes was lower than that of plain composites. The flexural strength values and toughness improved significantly by incorporation of PVA fibres. However, the stability of this improvement depends on the proper adjustment of matrix and fibre properties.

There are significant differences between PVA fibre reinforced SCMC composites and conventional steel fibre reinforced composites from the view point of toughening improvement mechanisms. While the former deals with multiple cracking response, frictional forces due to slippage of steel fibres at a single crack opening is dominant in the latter. In case of PVA fibre reinforced SCMC composites, providing multiple cracking at the elastic region of a composite seems to be the most effective way of improving its toughness. Furthermore, extraordinary elastic flexibility of PVA fibre reinforced SCMC may open new ways of application for this newly developed composite material.

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