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Effect of nano and micro-silica on bond behaviour of steel and polypropylene fibres in high volume fly ash mortar

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HIGHLIGHTS

- Bond slip behaviour of hooked end steel fibres and PP fibre in HVFA mortar is studied.
- Effects of nano silica and micro silica on the above are evaluated.
- Nano silica and micro silica significantly improved the pull-out load of steel and PP fibres in HVFA mortar.

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ABSTRACT

This paper presents the effects of nano silica (NS), micro silica (MS) and combined NS and MS on bond behaviour of steel and polypropylene (PP) fibres in high volume fly ash (HVFA) mortar. Three types of bend configuration of hook-end steel fibre commercially available are considered, while the PP fibre was crimped shape. Three different fly ash contents of 40%, 50% and 60% (by wt) as partial replacement of ordinary Portland cement (OPC) are considered in HVFA mortar, while a control mortar containing 100% OPC was also considered. The NS and the MS was added as 2% and 10% (by wt), respectively as partial replacement of OPC in HVFA mortar containing 40% fly ash. In the case of combined NS and MS, 2% NS and 10% MS was used as partial replacement of OPC in HVFA mortar. However, in the case of HVFA mortars containing 40% fly ash and different NS and MS, total OPC content of 60% was kept constant in all HVFA mixes containing NS, MS and NS + MS. This was considered to compare these mixes with HVFA mortar containing 40% fly ash. Results indicate that maximum pull-out force of both steel and PP fibres decreases with increase in fly ash contents in HVFA mortars at both 7 and 28 days. The addition of 2% NS and 10% MS showed almost similar improvement in the maximum pull-out force of steel and PP fibres at both ages in HVFA mortar containing 40% fly ash. The combined use of 2%NS + 10%MS also improved the maximum pull-out force and higher than 2% NS and 10% MS. The reduction in large capillary pores in HVFA mortars containing nano and micro silica observed in Mercury Intrusion Porosity test improved the bond of steel and PP fibres in those mortar due to formation of additional calcium silicate hydrate (C-S-H) gel is believed to be the reason behind this improvement. The maximum pull-out force also increased with increase in number of bends in the hook-end of steel fibre in all mortars in this study at both 7 and 28 days. Extra energy absorbed by the higher number of bends is the reason of such improvement in maximum pull-out force. However, in the case of absorbed energy mixed results are observed in the case of different number of bends in steel fibre ends. Good correlations also exist between the maximum pull-out forces of all three types of steel fibres with compressive strength of mortars showing strong influence on the bond behaviour.

1. Introduction

The concrete industry is blamed to contribute 5–7% of total carbon-di-oxide emission into the atmosphere and the manufacturing of cement is the key contributor of that carbon-di-oxide emission [1]. On the other hand, huge amount wastes e.g. fly ash, blast furnace slag and silica fume are generated from coal fired power stations, steel and ferrosilicon manufacturing industries, respectively which are generally used for land filling. However, a significant amount of those wastes are used in concrete as supplementary cementitious materials (SCM) around the world. The use

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of high volume fraction of SCM e.g. fly ash and slag show improvement in long-term mechanical and durability properties of concrete, while maintaining sustainability due to significant amount of ordinary Portland cement (OPC) replacement [2].

The addition of fibres in concrete to overcome its low tensile strength and brittle behaviour is a common practice in concrete technology. Improvement in tensile and flexural strengths of fibre reinforced concrete (FRC) is reported by many researchers. Most significant improvements in FRC are the bridging of cracks by the fibres, which improve the ductility of the concrete. Many types of fibres with different geometries are used to reinforce the OPC concrete, e.g. steel, polymeric (polypropylene, polyvinyl alcohol (PVA), polyethylene, etc.), carbon fibres, etc. The sustainability of conventional fibre reinforced concrete can also be increased through partially replacing OPC using the above SCMs. A number of researches have investigated the effect of high volume fly ash on mechanical properties of FRC [3,4].

In order to achieve the full efficiency of the fibres in the FRC, bond between the fibres and the matrix plays an important role. The fibre-matrix interface characteristic (known as fibre-matrix transition zone) is the most important factor which affects the bond strength. It is well known that the fibre-matrix transition zone in matured composite is porous and also filled with calcium hydroxide (CH) that is in direct contact with the fibre surface [5]. In a study by Wang and Li [6] on the bond strength of PVA fibre in HVFA matrix, they observed reduction in both frictional and chemical bonds in PVA fibre with increase in fly ash contents. In numerous studies, it has been observed that the porosity of HVFA matrix is higher than its counterpart OPC matrix [7,8]. These indicate that, in the case of fibre reinforced high volume fly ash (HVFA) composite, the interfacial transition zone between the matrix and the fibre will be more porous, which might affect the bond behaviour of the fibre with HVFA matrix. The addition of ultrafine SCM in the HVFA matrix improves the microstructure through reducing the porosity. Generally, silica fume, ultrafine fly ash and various nano particles are finer and more amorphous than conventional SCM e.g. ordinary fly ash, slag, rice husk ash, etc. and they provide two benefits, one in the form of generating additional C-S-H gels in the matrix due to their high fineness and amorphous nature, and the other is through particle packing. In limited studies, the effect of silica fume, metakaolin, slag and fly ash on the bond behaviour of fibres in cement matrix are evaluated. Yalcinkaya et al. [9] reported about 12% and 10% increase in pull-out load of hook end steel fibre in cement matrix due to partial replacement of cement with 15% and 30% metakaolin, respectively. In the case of straight steel fibre this improvement was below 5% in both metakaolin contents. The addition of metakaolin increased the pull-out load and debonding toughness (area under the pull-out load-slip curve) of hook end steel fibre by 180–199% and 129–187%, respectively compared to the smooth steel fibre. Chan and Chu [10] evaluated the effect of different amounts of silica fume addition on the bond behaviour of smooth steel fibre in cement matrix. Their results show that the 20% and 30% silica fume improved the bond behaviour compared to 10% and 40% silica fume contents. In another study, Tuyan and Yazici [11] evaluated the effects of fly ash, slag and micro silica each at 50% replacement of cement on the bond behaviour of hook end steel fibre in cement matrix and observed that the pull-out load is slightly higher in the case of cement matrix containing 50% micro silica than fly ash and slag. Beglarigale and Yazichi [12] also evaluated the effects of 10% silica fume, 40% fly ash, 40% slag and combined 5% silica fume and 20% fly ash on the bond behaviour of hook end steel fibre in cement matrix subjected to curing in water and NaOH solution at 80 °C. Surprisingly, they reported slight reduction in maximum pull-out load of steel fibre in the matrices containing fly ash, slag, silica fume and combined silica fume and fly ash at 28 days.

While in above studies the effects of different SCMs on the bond behaviour of steel fibre in OPC matrix are evaluated, no studies have so far reported the effects of micro silica and nano silica on the bond behaviour of hook end steel fibre in HVFA matrix. Due to increasing awareness of sustainability of OPC concrete and FRC, the use of high volume fly ash in FRC is increased in recent years and expected to increase in future. Better understanding of bond behaviour of fibres in HVFA matrix will be useful for design of such composite in order to enhance its mechanical properties and crack resistance, which in turns will contribute to the sustainability during their life cycle. Recently, three different end configurations of the hook end steel fibre are introduced in the market along with crimped polypropylene (PP) fibre. Better understanding on bond behaviour of these new types of fibres in HVFA matrix as well as in OPC matrix is also essential to maximise their use in the FRC. This paper presents a comprehensive experimental study on the bond behaviour of above new types of hook end steel fibres and crimped PP fibres in HVFA mortars containing 40%, 50% and 60% fly ash as partial replacement of cement as well as in OPC mortar. The effects of 2% nano silica (NS), 10% micro silica (MS) and combined 2% NS and 10% MS on the pull-out behaviour of above fibres in HVFA mortars containing 40% fly ash are also evaluated in this study. The selected NS content of 2% (by wt) was based on previous study [7] using the same type of NS where 2% NS was found as the optimum amount. On the other hand, the selected 10% (by wt) MS was based on many previous studies [13–16] where this amount was found to be an optimum content. It is also interesting to note that in HVFA mortar containing 40% fly ash where NS, MS and combined NS + MS are used the total OPC content of 60% is kept constant for better comparison.

2. Experimental program, materials and methodology

The properties of ordinary Portland cement (OPC), class F fly ash, MS and NS used in all mortar mixes are shown in Table 1. The properties of steel and PP fibres are shown in Table 2. The steel fibres are straight with smooth surface except the ends, which are bent in three different configurations as shown in Fig. 1 and are termed as double, triple and quadruple bends hook-end steel fibres depending on the number of bends. The PP fibres are in crimped shape along the length of the fibre for better bonding with the matrix. The mortar mixes were prepared with constant water/ binder ratio of 0.4 and sand/binder ratio of 2. Total seven types of mortars were considered. The first series was control mortar consisted of OPC and sand. The second, third and fourth series were HVFA mortars containing 40%, 50% and 60% (by wt) fly ash as partial replacement of OPC, respectively. In the fifth, sixth and seventh series the effects of 2% NS, 10% MS and combined 2% NS + 10% MS, respectively on bond behaviour of steel and PP fibres in the HVFA mortar containing 40% fly ash were evaluated.

The mortars that were prepared for the pull-out tests were poured into 12 × 24 × 42 mm plastic moulds. After placing the mortar into the mould, a single fibre was centrally embedded into the fresh mortar by a system which allowed the fibre to remain perpendicular to the surface of the specimen as shown in Fig. 2. First a fibre was inserted at the centre in to a hard paper board of 12 × 24 mm size (same as cross-section of the mould) and was placed at the middle of each fibre in order to

Table 1
Chemical composition and physical properties of cementitious materials.

Chemical analysis	Cement (wt%)	Class F fly ash (wt%)	Micro silica (wt%)	Nano-silica (wt%)
SiO_2	21.1	63.13	89.6	99
Al_2O_3	5.24	24.88	–	–
Fe_2O_3	3.1	3.07	–	–
CaO	64.39	2.58	–	–
MgO	1.1	0.61	–	–
K_2O	0.57	2.01	0.225	–
Na_2O	0.23	0.71	0.11	–
SO_3	2.52	0.18	–	–
LOI	1.22	1.45	3.8	–
Particle size	–	73% < 45 μm	95% < 1 μm	25 nm
Specific gravity	3.17	2.68	0.625	2.2–2.6
BET Surface area (m^2/g)	–	1.53	15–30	160