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

Keywords: Fly ash, nano silica, micro silica, bond behaviour, pull-out force, steel fibre, polypropylene fibre, hook end.

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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 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^{o}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.

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 in to 12×24×42mm 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 make sure that half of the length of the fibre is embedded in to the mortar. Then it was placed inside the mould in such a way that the paper board is perpendicular to the mould's longitudinal wall. The mortar was then poured very carefully in to the mould in order to avoid possible misalignment of the fibre inside the mortar. In addition 50mm cubes were also cast for each mortar series to measure their 7 and 28 days compressive strength. The fibre-matrix bond characteristics were determined by applying a single fibre pull-out test that is a common method used by many researchers. The schematic diagram of pull-out test setup used in this study is shown in Fig. 3. In the close-up of Fig. 3 it can be seen that the pull-out specimen was placed inside a stiff steel tube with a centrally located hole on top through which the fibre was clamped to the upper jaw of the universal testing machine, while a long screw bolt which connected to the bottom of the tube was clamped by the lower jaw of the machine. This setup prevented any lateral confining pressure on the mortar specimen, which might influence the bond behaviour of fibre and the mortar specimen was only fixed on top of the steel tube. The capacity of the load cell was 5kN and a loading rate of 1mm/min was applied. Similar loading rate was also used by others [11]. The pull-out load vs displacement (extension) curves were recorded for each series of mortar. Some important parameters such as maximum (peak) pull-out load, displacement at peak pull-out load, bond stress and absorption energy (area under the pull-out load - displacement curve of each mortar) were calculated by analysing the pull-out load- displacement curves.

Results and discussion

Workability and compressive strength

Measured workability of all mortars are shown in Fig. 5. It can be seen that the flow value of all HVFA mortars is higher than the OPC mortar and increases with increase in fly ash contents. This is expected and due to spherical shape of the fly ah particles as well as its high contents. The effects of NS, MS and combined use of NS and MS on the workability of FA40 mortar can also be seen in the same figure. It can be seen that the flow of FA40 mortar is reduced by about 5% when 2% NS is added to the mortar. On the other hand the flow is reduced by about 8% when 10% MS is added and about similar reduction is also noticed when both NS and MS are used. The higher reduction in flow of mortars containing 10% MS and combined 2% NS and 10% MS is due to their higher amounts compared to the lower amount (only 2%) of NS. Nevertheless it can be seen that the addition of nano and micro silica in HVFA mortar reduced its workability and is due to significantly higher surface area of nano and micro silica particles than the fly ash and the OPC particles.

The effects of NS and MS on the compressive strength development of HVFA mortar containing 40% fly ash (FA40) is shown in Fig. 6. It can be seen that the both 7 and 28 days compressive strengths of FA40 are increased due to addition of 2% NS, 10% MS and combined 2% NS and 10% MS. It can also be seen that the improvement in compressive strength of HVFA mortar containing 40% fly ash is almost similar in the case of 2% NS and 10% MS addition. However, the combined addition of 2% NS and 10% MS showed good improvement in 28 days compressive strength. The improvement in both 7 and 28 days compressive strength of FA40 mortar due to addition of nano and micro silica can be attributed to the significantly higher finesses of these ultrafine pozzolans and higher amorphous content of SiO_2 than the class F fly ash. The better particle packing of nano and micro silica due to their extremely small particle size is also believed to contribute to the compressive strength development.

Pull-out load vs displacement behaviour of steel fibres at 7 days

The effects of different fly ash contents, 2% NS, 10% MS and 2%NS+10%MS on the bond behaviour of three types of hook-end steel fibres in HVFA mortar is shown in Figs. 7a-c. It can be seen that the maximum pull-out load of hook-end steel fibres decrease with the increase in fly ash content. It can also be seen that the displacement at maximum pull-out load increases with the increase in fly ash content for the above fibres. The above behaviour shows that the bond strength of steel fibres is affected by the high fly ash contents. It is known and already observed in this study that the early age strength (7 days) of HVFA mortar is lower than the OPC mortar and it decreases with increase in fly ash content due to slow pozzolanic reaction of fly ash in HVFA system. It is also reported that the porosity of HVFA matrix increase with increase in fly ash content [6]. Therefore, the observed low maximum pull-out loads (shown in Fig. 8) of steel fibres in HVFA mortars is influenced by the above factors. It can also be seen that with increase in number of bends at the ends of the steel fibres, the maximum pull-out loads are increased. This is due to extra energy absorbed by the bends at the end of the steel fibres during debonding and pull-out process. It was also observed that the peak pull-out load increased significantly when number of bends is increased to triple and quadruple from the double bend in OPC mortar, which was not observed in the case of HVFA mortars or even the HVFA mortar containing nano and micro silica. This could be due to absence of fly ash in this mortar which gained good strength at early age.

The effects of 2%NS, 10% MS and 2%NS+10%MS as partial replacement of cement on the pull-out load-displacement behaviour and the maximum pull-out loads of steel fibres in HVFA mortar containing 40% fly ash (FA40 mortar) are also shown in Figs. 7-8. It can be seen that the maximum pull-out load of double bend type hook end steel fibre is increased slightly due to addition of NS and MS. No significant improvement is observed in the case of triple bend type hook end steel fibre. However, slight improvement is observed in the case of quadruple bend type hook end. Interestingly, good improvement in the maximum pull-out load is observed when both NS and MS are used in the HVFA mortar. It is also interesting to see that no significant improvement in the post maximum pull-out behaviour is observed when nano and micro silica are added in the HVFA mortar, except in the case of double bend hook-end steel fibre where a long displacement tail up to 20mm can be seen with slip hardening in the case of FA30MS10 mortar. It is also interesting to notice that with increase in number of bends, the displacement decreases and no slip hardening is also observed. It was also observed during the bond tests that matrix cracked in many specimens near the hook-end area. This could be explained by the low strength of HVFA mortar at 7 days that caused cracking due to extra energy required by the triple and quadruple bend hook-end steel fibres to pull out from the matrix.

Pull-out load vs displacement behaviour of steel fibres at 28 days

The pull-out load – displacement behaviour of steel fibres in different HVFA mortars after 28 days of curing is shown in Fig. 9 and the maximum pull-out loads are plotted in Fig. 10. It can be seen, by comparing to Fig. 7, clear indication of curing effect on the pull-out load – displacement behaviour, especially after the post-peak tail of the curves in all three bends of hook-end steel fibres in HVFA mortars. Even after 28 days of curing the maximum pull-out loads are still lower in FA50 and FA60 mortars than the FA40 mortar, indicating inadequate pozzolanic reaction in HVFA mortars at 28 days consistent with the compressive strength development results. The addition of nano and micro silica improved the maximum pull-out loads of steel fibres in the HVFA mortars. By comparing between Figs. 7 and 8 it can be seen that peak pull-out load is increased due to addition of nano and micro silica after 28 days of curing. Significant improvement is found in the friction dominated stage in the post-peak region where in many cases second and more peaks after the first peak are observed and is due to the improved frictional bond of hook-end steel fibres with the HVFA matrix, which is associated with the reduction of pores and formation of more C-S-H in the matrix due to reaction of nano and micro-silica with the C-H in the system. The second and more peaks after the first peak in the case of triple and quadruple bends hook-end steel fibres in HVFA mortar containing NS and MS could also be due to extra energy associated with their additional bends during pull-out process. The conducted mercury intrusion porosity (MIP) test results of HVFA mortar containing 40% fly ash and that containing nano and micro silica shown in Fig. 11 can explain the observed better post peak behaviour. By comparing porosity distribution at 7 and 28 days, it can be clearly seen that after 28 days of curing the pore volumes of all three types of pores e.g. gel, medium capillary and large capillary pores are reduced in HVFA mortars. Significant reduction is observed in the case of 2% NS and 10%MS compared to those at 7 days. It can be seen that the large capillary pores are reduced in HVFA mortar containing 40% fly ash when 2%NS and 10% MS with no significant reduction in medium capillary and gel pores. The reduction in large capillary pores as well as overall pore volume reduction at 28 days might explain the better post-peak behaviour of steel fibres in those HVFA mortars, which indirectly indicates the better frictional bond of fibres with above matrix.

Absorbed energy

Absorbed energy was calculated from the area under each pull-out load-displacement curve shown in Figs. 7 and 9. Fig. 12 summarises the calculated absorbed energy by steel fibres embedded in HVFA mortar containing 40% fly ash and that containing nano and micro silica cured at both 7 and 28 days. By comparing the results at 7 and 28 days in Fig. 12 it can be seen that significant improvement in energy absorption by all three types of bends of hook-end steel fibres is observed during pull-out in HVFA mortar and that containing nano and micro silica. This again correlates well with the MIP results presented in Fig. 11 and improved frictional bond of steel fibre with mortar matrix after 28 days is due to the reduction of large capillary pores observed in the MIP tests. Interestingly, no correlation of number of bends of the hook-end with the absorbed energy at both ages is observed in this study. The reason is not clear but the general trend is the higher the number of bends the higher is the energy absorption by the steel fibres during pull-out process from the matrix. However, in many cases sudden drop in pull-out load is observed which is believed to be associated with the cracking near the bended area due to relatively low strength of HVFA matrix.

Correlations of compressive strength of HVFA mortars with maximum pull-out loads of steel fibres are also established and are shown in Fig. 13. It can be seen that there is an increasing trend of maximum pull-out load with increase in compressive strength at both ages, which is reasonable as the higher the compressive strength of mortar, the lower the pores in the matrix and better the bond of fibres with the matrix. It can also be seen that the correlations coefficients are very good for triple and quadruple bends steel fibres except the double bend steel fibre and this is consistent with the maximum pull-out loads summarised in Figs. 8 and 10, where slight inconsistency in maximum pull-out load of this steel fibre type in various mortars can also be seen.

Effect of NS, MS and their combination on the bond behaviour of PP fibre in HVFA mortar

The effects of addition of NS and MS on the bond behaviour of PP fibre in HVFA mortar cured at 7 and 28 days are shown in Fig. 14. It can be seen that the maximum pull-out load increased at both ages due to addition of 2% NS, 10% MS and 2%NS+10%MS. It can also be seen that the post peak load-displacement behaviour of PP fibre in HVFA mortar containing 40% fly ash is also improved due to addition of NS and MS, where several peaks can be seen in the post-peak tail indicating good frictional bond between the PP fibre and the HVFA matrix containing nano and micro silica. Similar to steel fibre, second and more peaks after the first peak are also observed in the case of PP fibre, indicating better frictional bond of PP fibre with the matrix. The maximum pull-out loads of PP fibre in all the HVFA mortars and those containing NS and MS are summarised in Fig. 15. Similar to that observed in the case of steel fibre, the maximum pull-out load of PP fibre also increased in HVFA mortar containing 40% fly ash and nano and micro silica at both ages with significant improvement at 28 days. The effect of nano and micro silica on the absorbed energy of PP fibre in HVFA mortar at both 7 and 28 days is shown in Fig. 16. By comparing between 7 and 28 days results it can be seen that the absorbed energy by PP fibres is slightly higher at 28 days than 7 days, which was completely different in the case of steel fibre where at 28 days significant improvement in energy absorption is noticed. These results clearly indicate that the frictional bond of PP fibre with HVFA matrix is not as strong as in the case of steel fibre. It should be noted that the bend configurations at steel fibre ends might have played an important role in the higher energy absorption. It is also interesting to see that the effects of nano and micro silica on the energy absorption of PP fibre in HVFA mortar at 7 days is better than that observed at 28 days, although in the case of steel fibre good improvement was observed at 28 days presumably due to the effects of bends. A very good correlation with R^2 value >0.8

between the compressive strengths of HVFA mortars and the maximum pull-out load of PP fibres at both ages is also observed and is shown in Fig. 17. It can be seen that the correlation of maximum pull-out load of PP fibre with compressive strength at both ages is very similar to that observed in the case of steel fibres, indicating that the compressive strength of mortar or matrix plays an important role on the pull-out load of fibre embedded into the matrix.

Conclusions:

This paper presents the bond-slip behaviour of a new type of hook-end steel fibre containing three types of bends and crimped shape PP fibre in sustainable mortar containing high volume fly ash as partial replacement of cement as well as in OPC mortar. The positive effects of nano and micro silica on the bond-slip behaviour of above fibres in the sustainable mortars are also investigated. Based on limited experimental results the following conclusions can be made:

1. The peak pull-out loads of both steel and PP fibres in HVFA mortars decreases with increase in fly ash contents at both 7 and 28 days. The same is also true even the number of bends at the ends of the steel fibre is increased.
2. The number of bends at both ends of the steel fibre has positive influence in the peak pull-out load as it increases with increase in number of bends. This is valid for all HVFA mortars as well as for OPC mortar.
3. The post-peak pull-out load-displacement behaviour of steel and PP fibres in HVFA mortars is significantly improved after 28 days of curing, where second and more peaks after the first peak are observed in the softening tail of the curves.
4. The effect of 28 days water curing significantly influenced the peak pull-out loads of steel fibre in HVFA mortars. However, no such big improvement is seen in the case of PP fibre in HVFA mortars.
5. The positive effects of addition of 2% NS and 10% MS on the peak pull-out load of both steel and PP fibres in HVFA mortars containing 40% fly ash are found very similar at both 7 and 28 days. The combined use of 2%NS+10%MS in HVFA mortar showed slightly higher peak pull-out load of both steel and PP fibres compared to 2% NS and 10% MS in HVFA mortar.
6. The post peak pull-out load–displacement behaviour of steel fibre in HVFA mortar containing 40% fly ash due to addition of nano and micro silica is much better after 28 days of curing than that at 7 days, indicating improved frictional bond of steel fibre

with the HVFA mortar due to addition of nano and micro silica. This result also correlates well with the observed pore size distribution results.

7. The energy absorption of three types of steel fibres in HVFA mortar with and without nano and micro silica is significantly improved due to longer wet curing. The addition of nano and micro silica also positively influenced the energy absorption of steel fibres in HVFA mortars at both curing ages. However, in the case of PP fibre no significant improvement in energy absorption is observed after 28 days curing.

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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

Table 2 Properties of fibres

Types of Fibre	Geometry	Length (mm)	Diameter (mm)	Aspect ratio	Modulus (GPa)	Tensile strength (MPa)
Polypropylene	waved	65	0.85	75	3	250
Steel	Hook end	60	0.90	65	210	1345

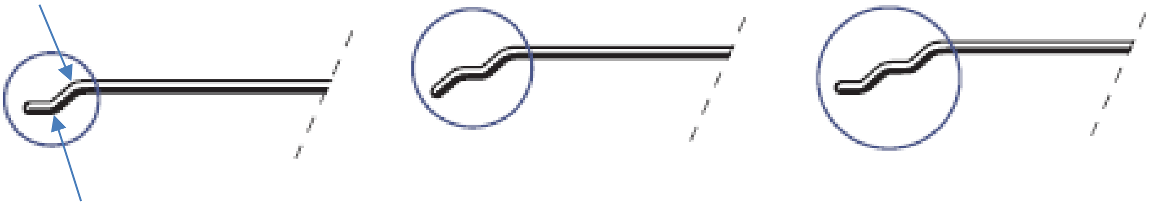
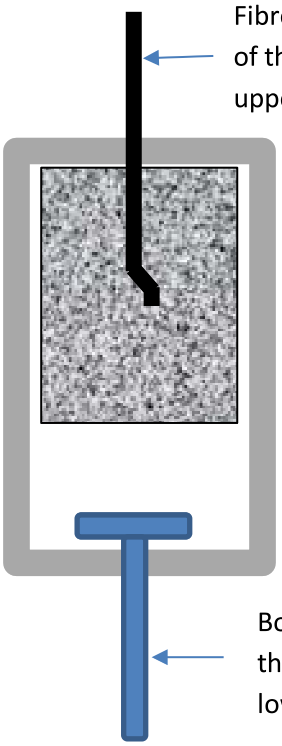


Fig. 1 Configurations of three different hook ends of steel fibres. They are termed as double bend (left), triple bend (middle) and quadruple bend (right). (**Note:** bends numbering is based on number of bends shown in arrows)

Fig. 2 Casting of bond specimens in the moulds.

Fig. 3 Test setup of pull-out specimen. (Close-up shows the pull-out specimen inside the steel tube and the fibre passed through the top circular hole)



Fibre passed through the top opening of the steel tube to connect to the upper jaw of the testing machine

Bolt connected to the bottom of the steel tube to connect to the lower jaw of the testing machine

Fig. 4 Schematic of setup of the specimen in the testing machine

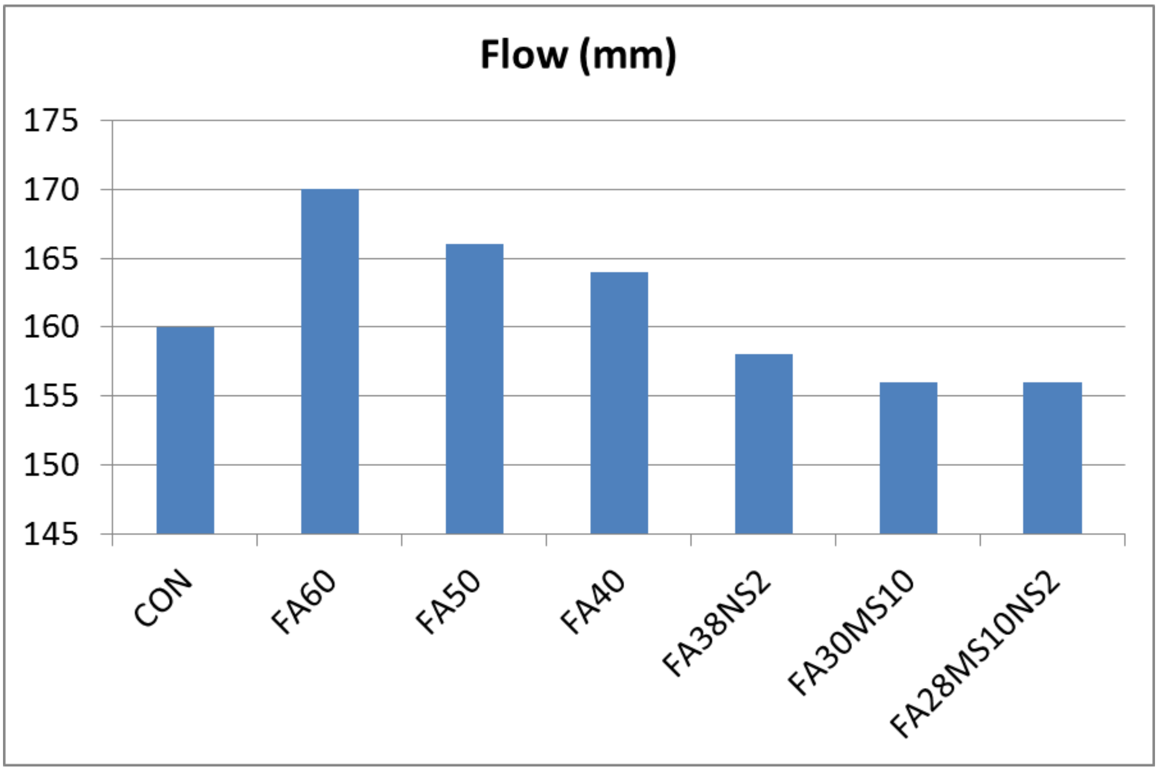


Fig. 5 Workability of mortars

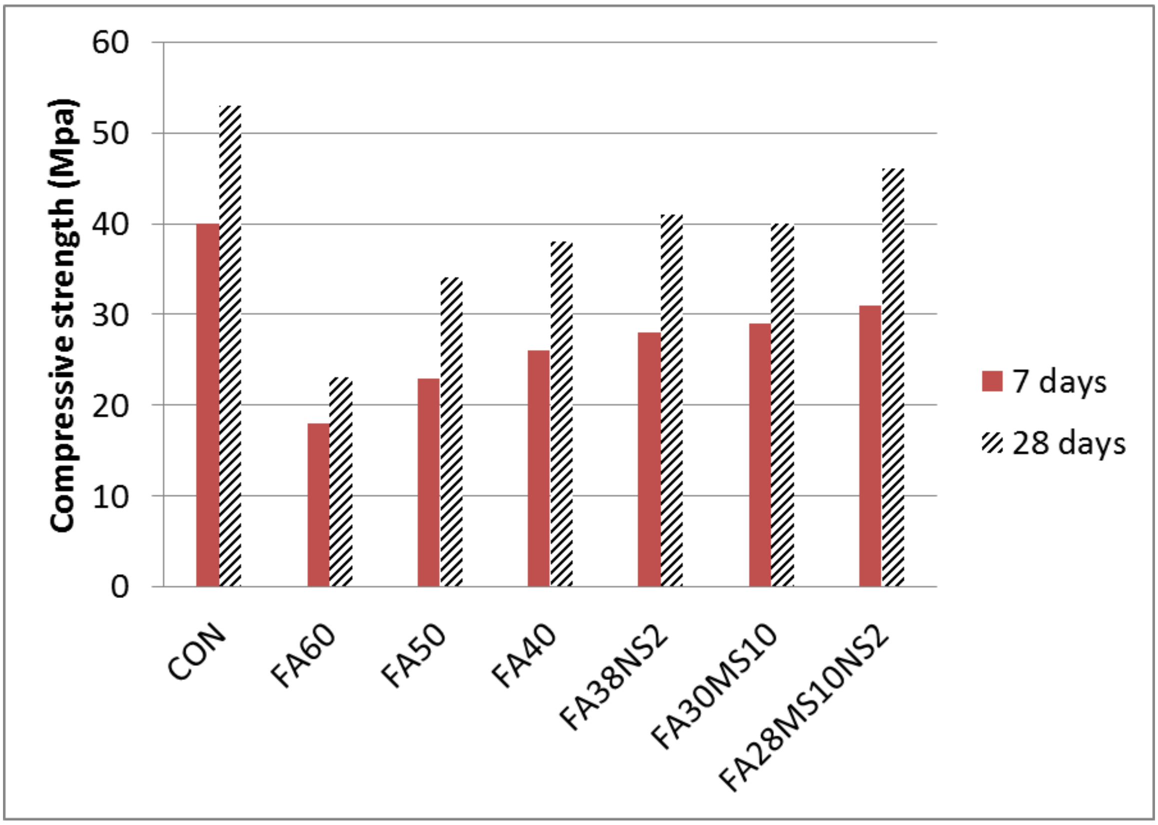
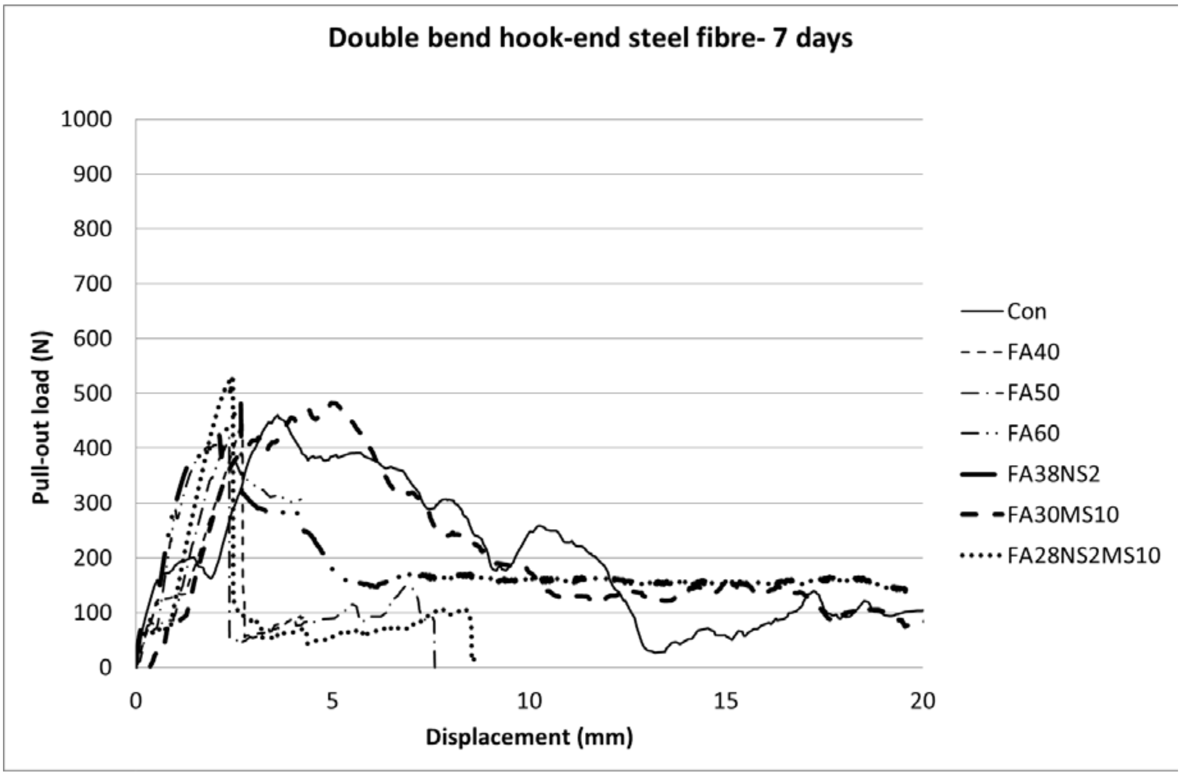
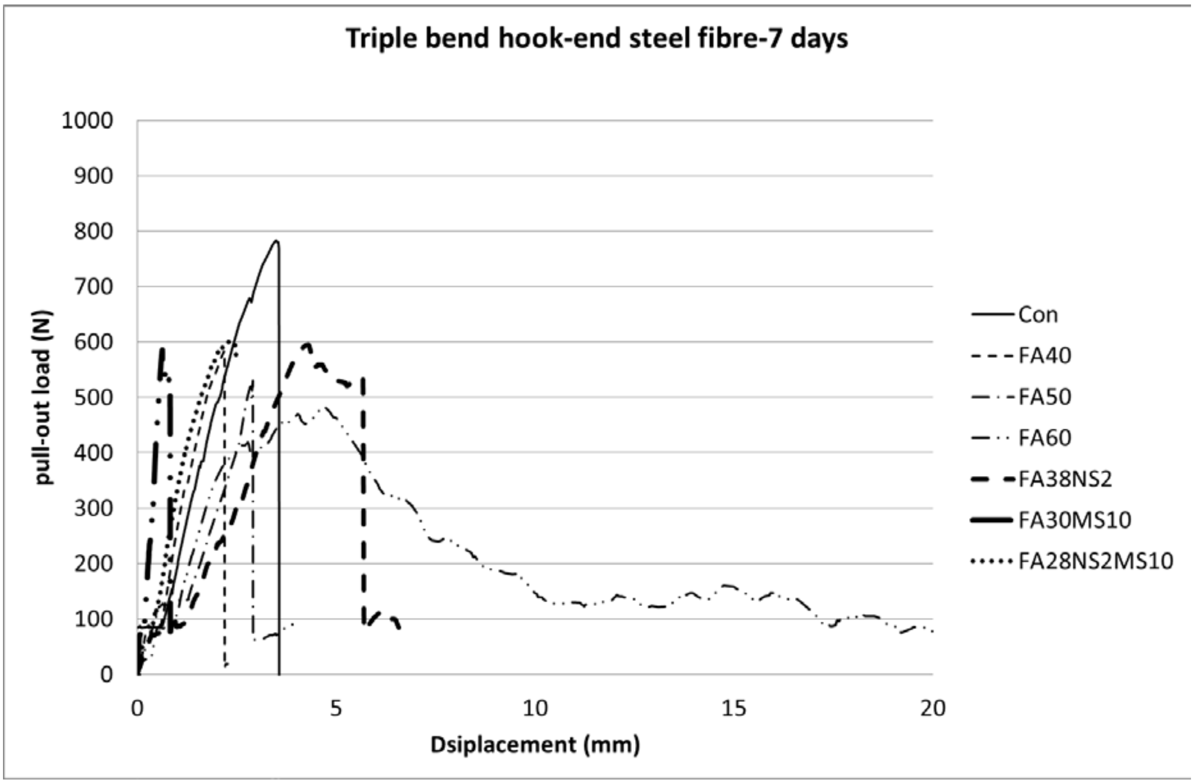


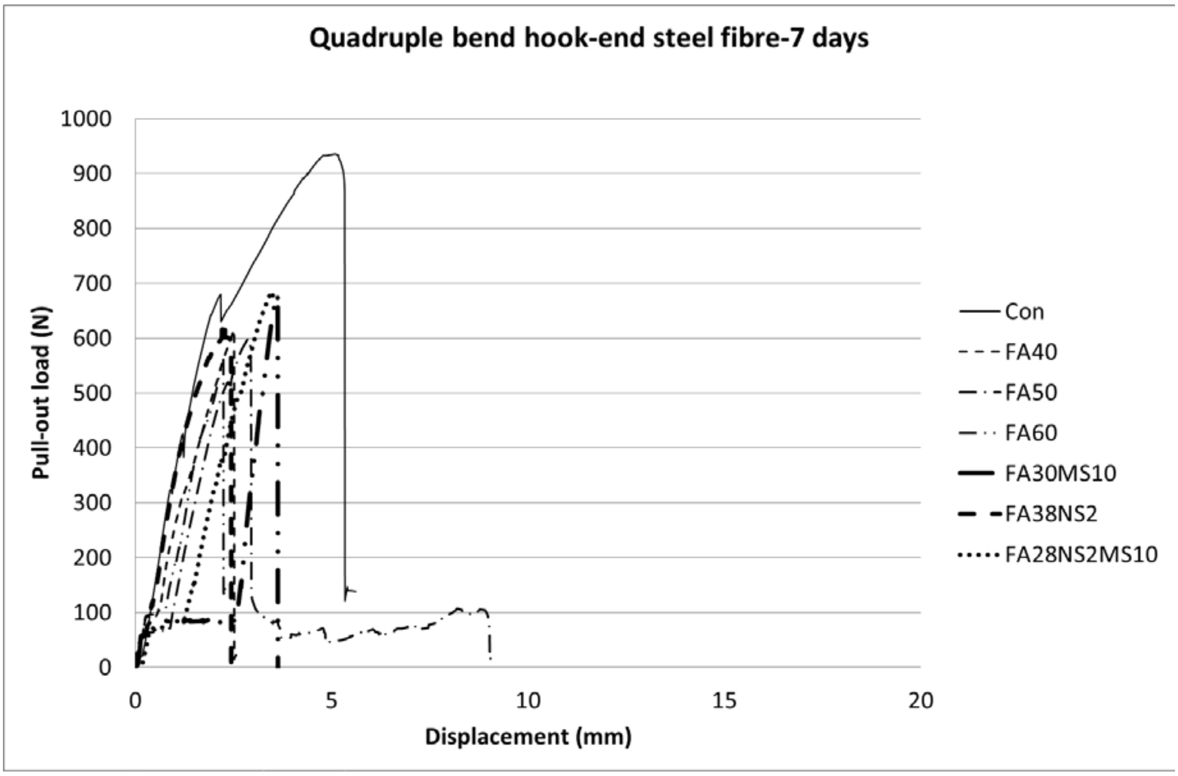
Fig. 6 Compressive strength development of mortars


Double bend hook-end steel fibre- 7 days
Pull-out load (N)
1000
900
800
700
600
500
400
300
200
100
0
0
5
10
15
20
Displacement (mm)
Con
FA40
FA50
FA60
FA38NS2
FA30MS10
FA28NS2MS10

(a)


Triple bend hook-end steel fibre-7 days
pull-out load (N)
1000
900
800
700
600
500
400
300
200
100
0
0
5
10
15
20
Dsiplacement (mm)
Con
FA40
FA50
FA60
FA38NS2
FA30MS10
FA28NS2MS10

(b)



(c)

Fig. 7 Pull-out load – displacement behaviour of steel fibres in mortars after 7 days of curing

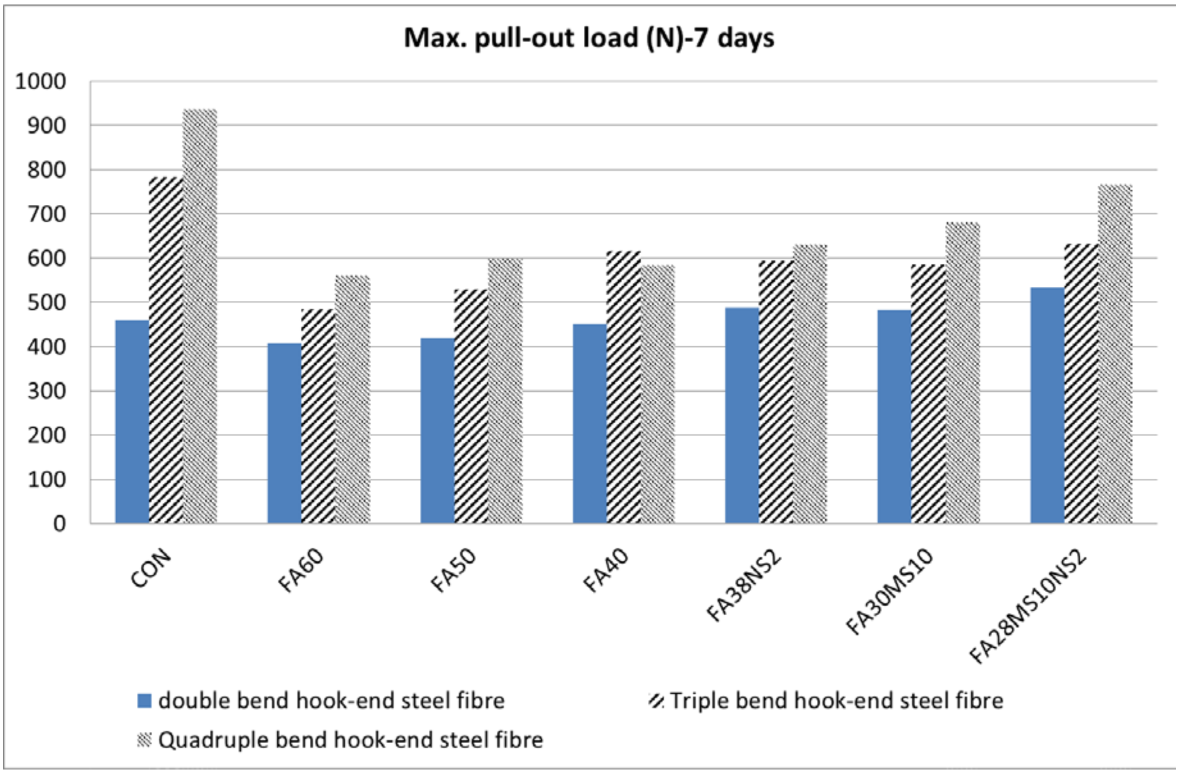
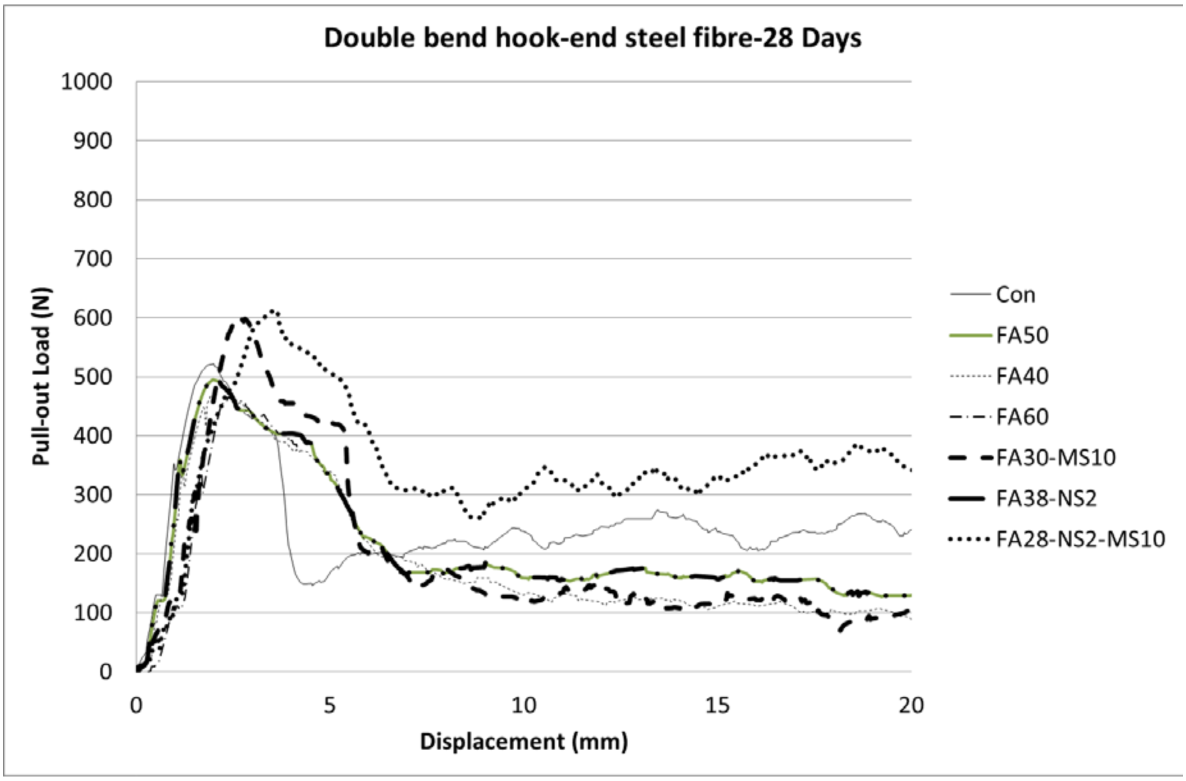
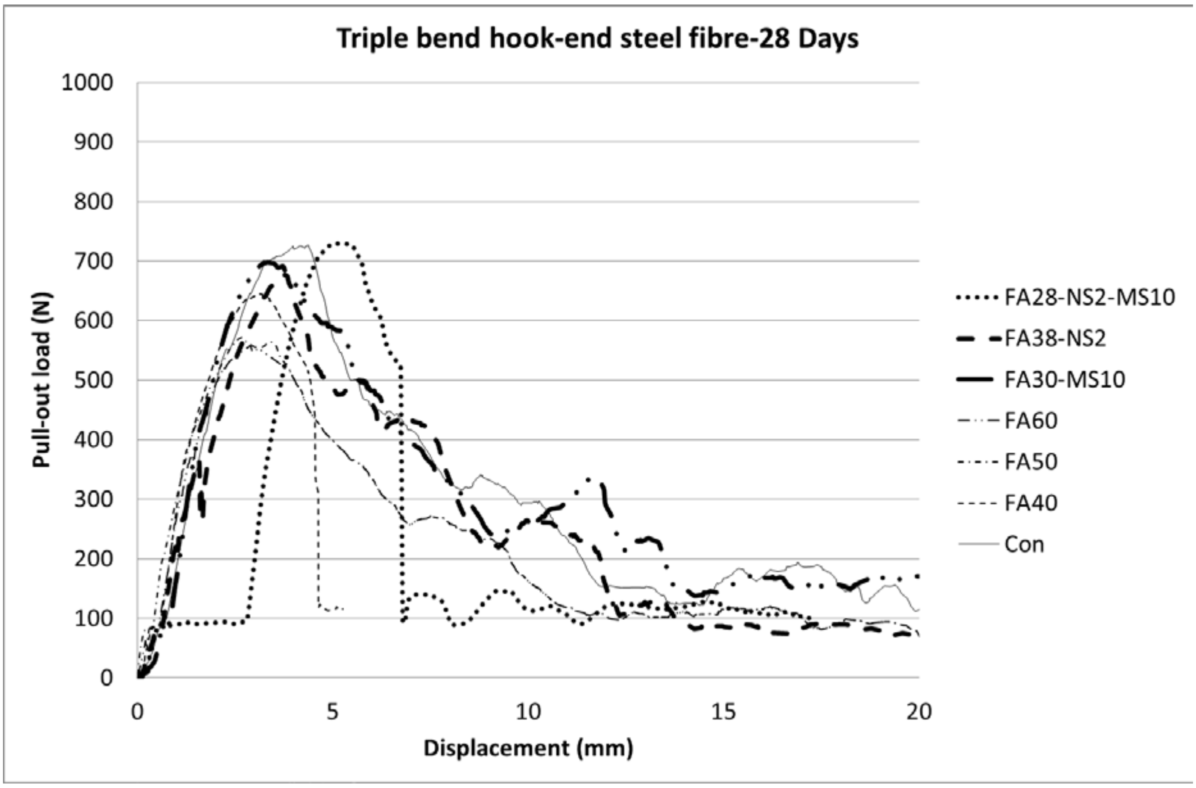


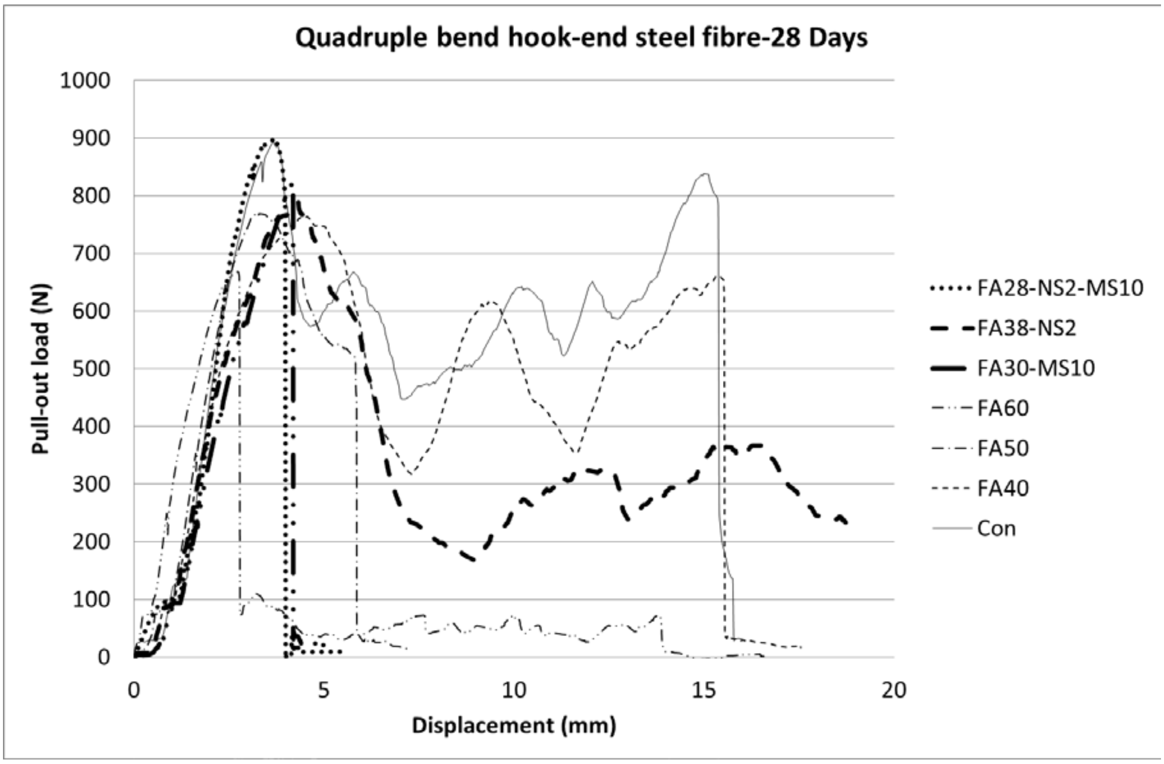
Fig. 8. Maximum Pull-out load of steel fibres in mortars after 7 days of curing.


Double bend hook-end steel fibre-28 Days
Pull-out Load (N)
1000
900
800
700
600
500
400
300
200
100
0
0
5
10
15
20
Displacement (mm)
Con
FA50
FA40
FA60
FA30-MS10
FA38-NS2
FA28-NS2-MS10

(a)


Triple bend hook-end steel fibre-28 Days
Pull-out load (N)
1000
900
800
700
600
500
400
300
200
100
0
0
5
10
15
20
Displacement (mm)
FA28-NS2-MS10
FA38-NS2
FA30-MS10
FA60
FA50
FA40
Con

(b)



(c)

Fig. 9 Pull-out load – displacement behaviour of steel fibres in mortars after 28 days of curing

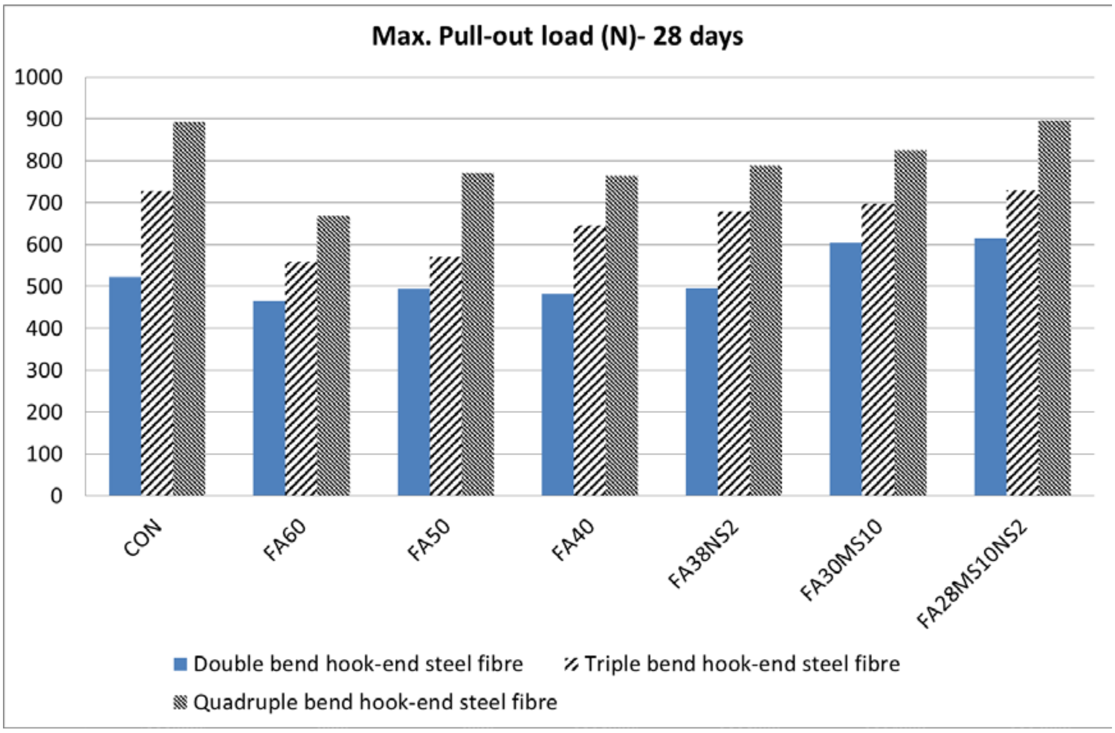
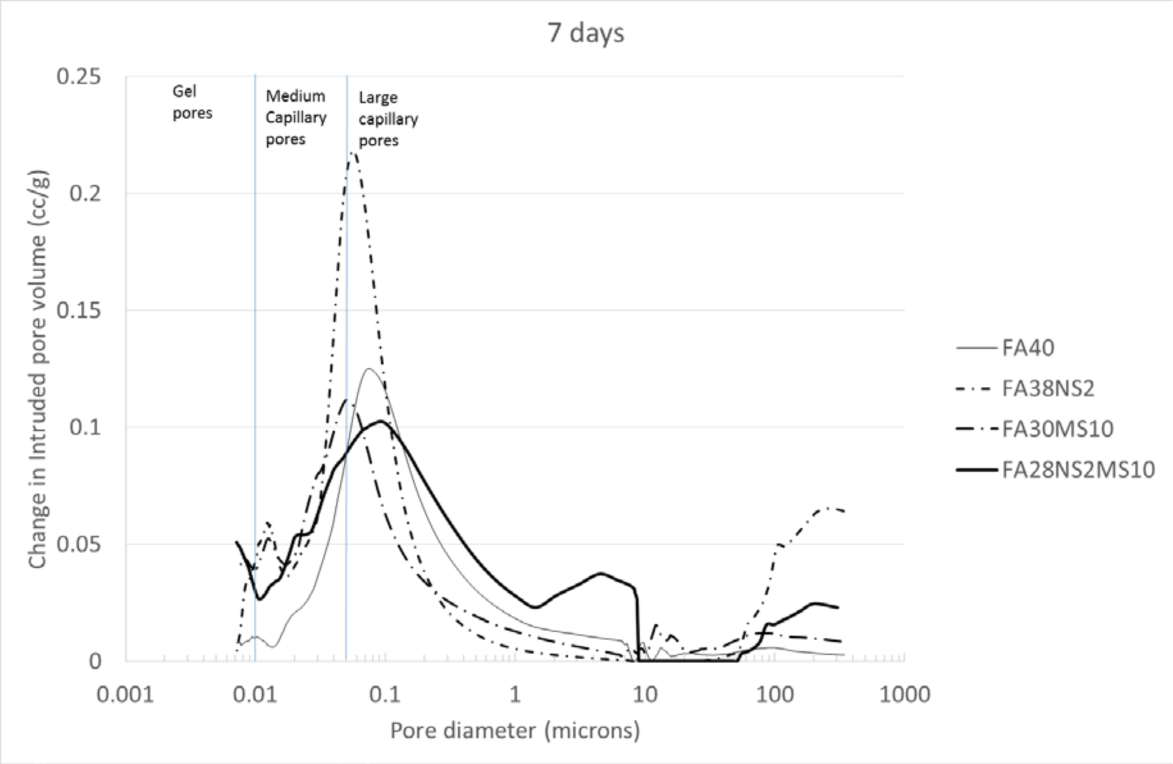
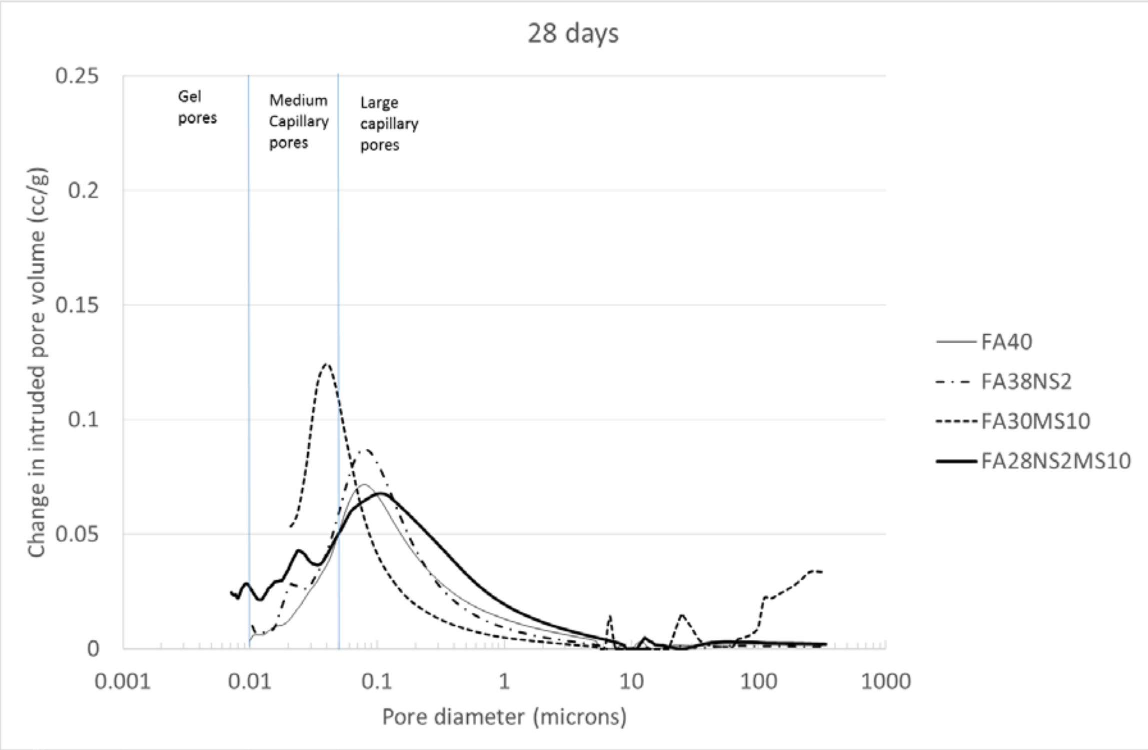


Fig. 10 Maximum pull-out load of steel fibres in mortars after 28 days of curing.



(a)



(b)

Fig. 11 Effects of NS, MS and combined NS+MS on porosity of HIVFA mortar containing 40% fly ash (a) 7 days curing and (b) 28 days curing.

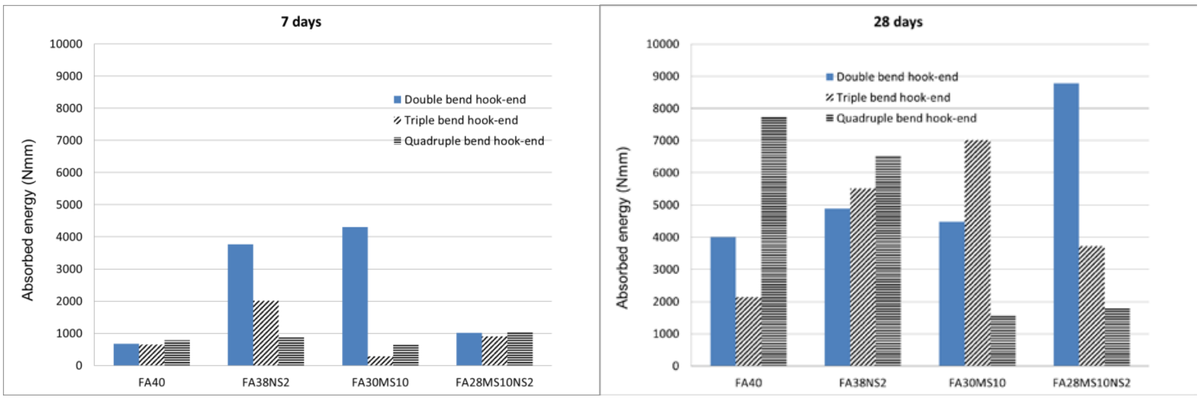
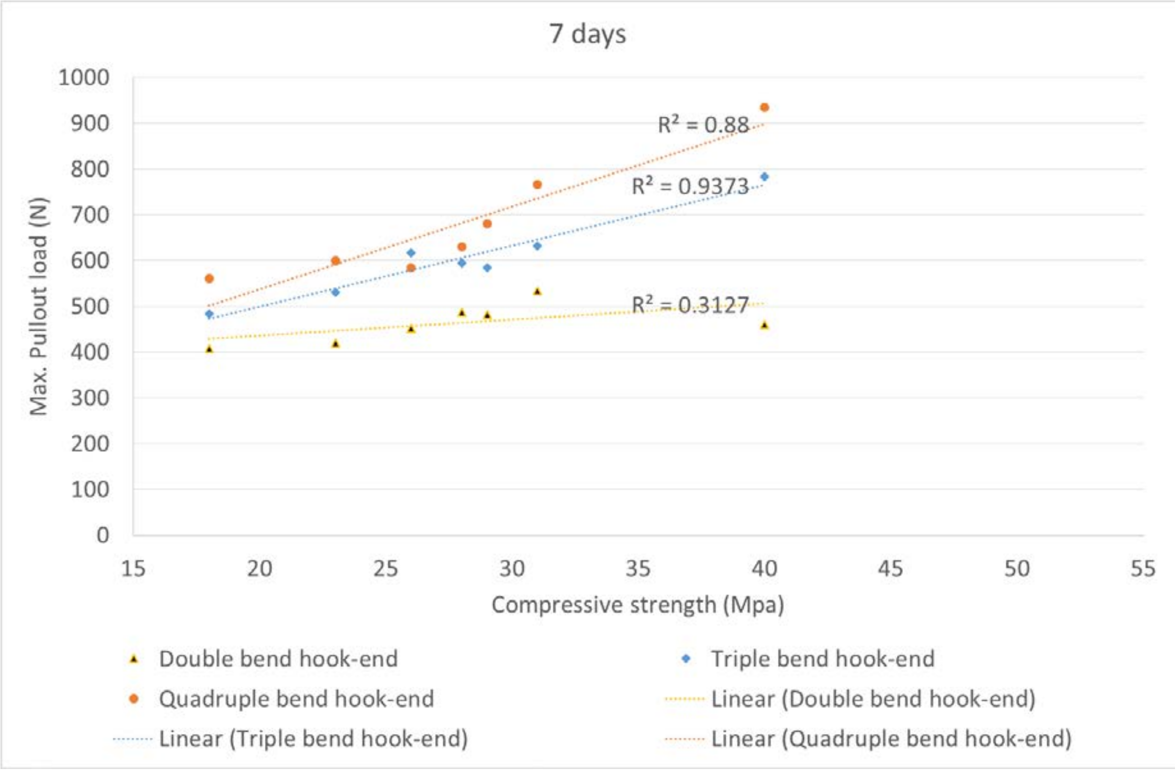
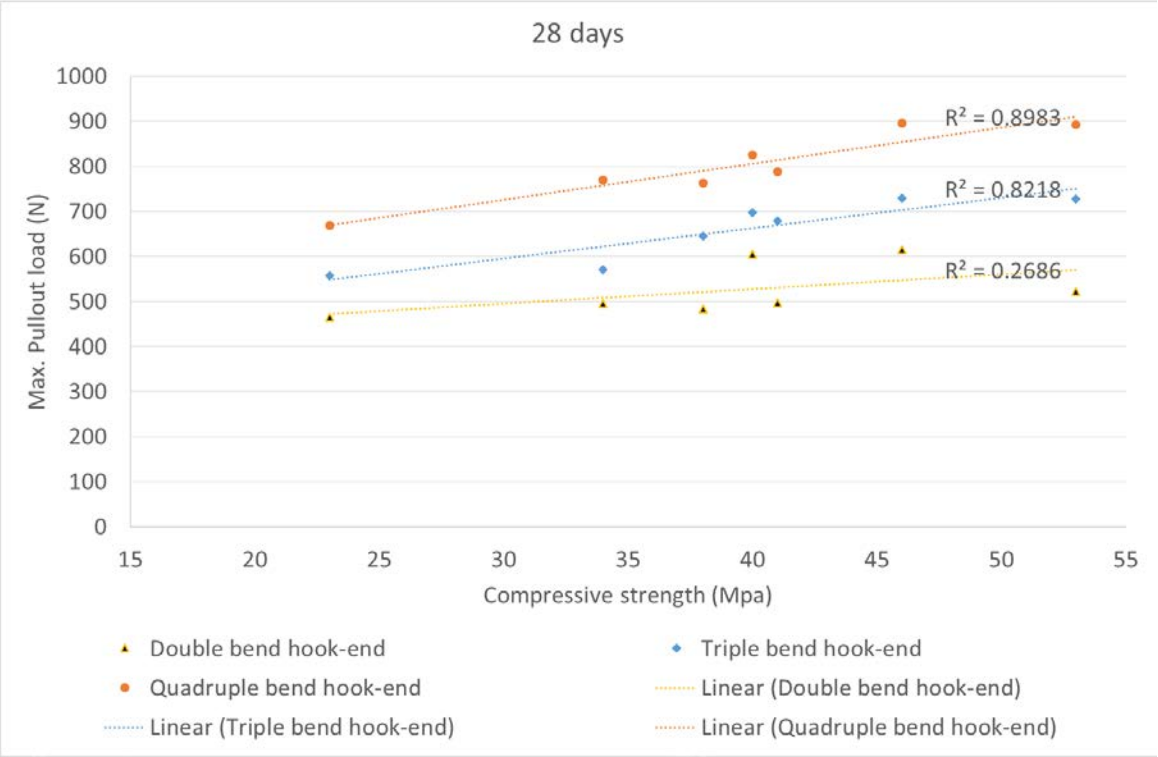


Fig. 12 Absorbed energy of steel fibres in HVFA mortars (Left: 7 days and right: 28 days)

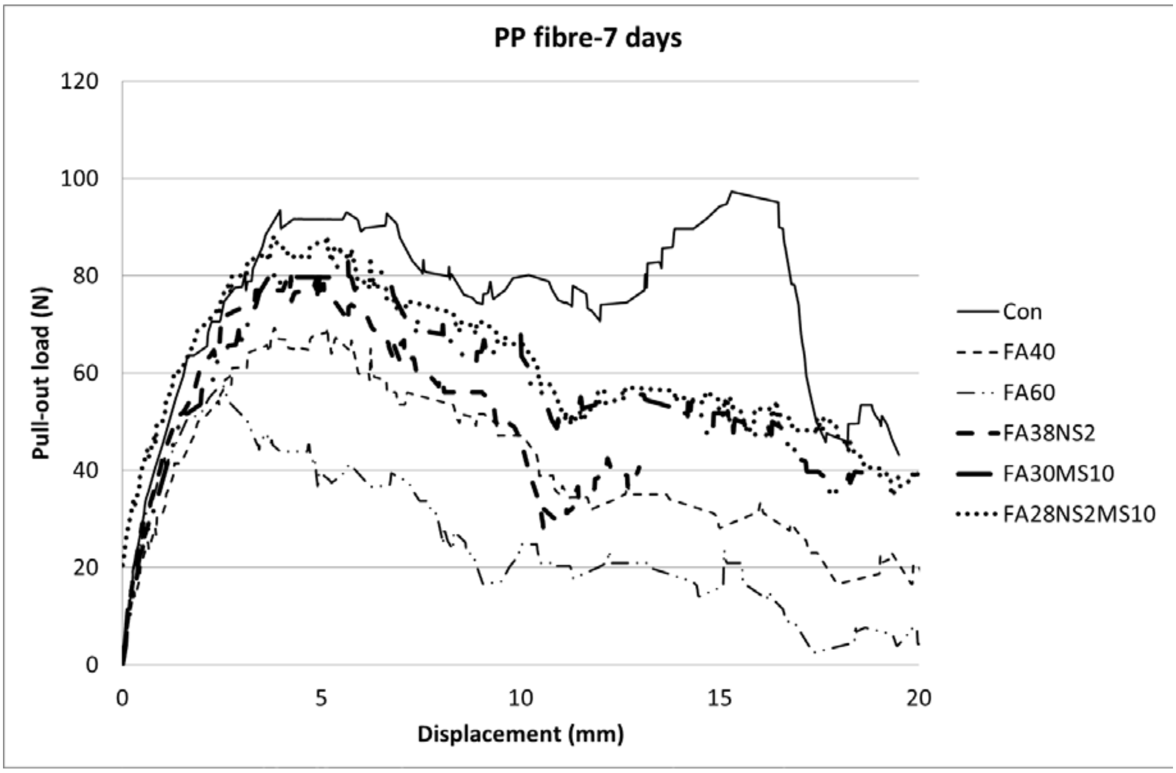


(a)

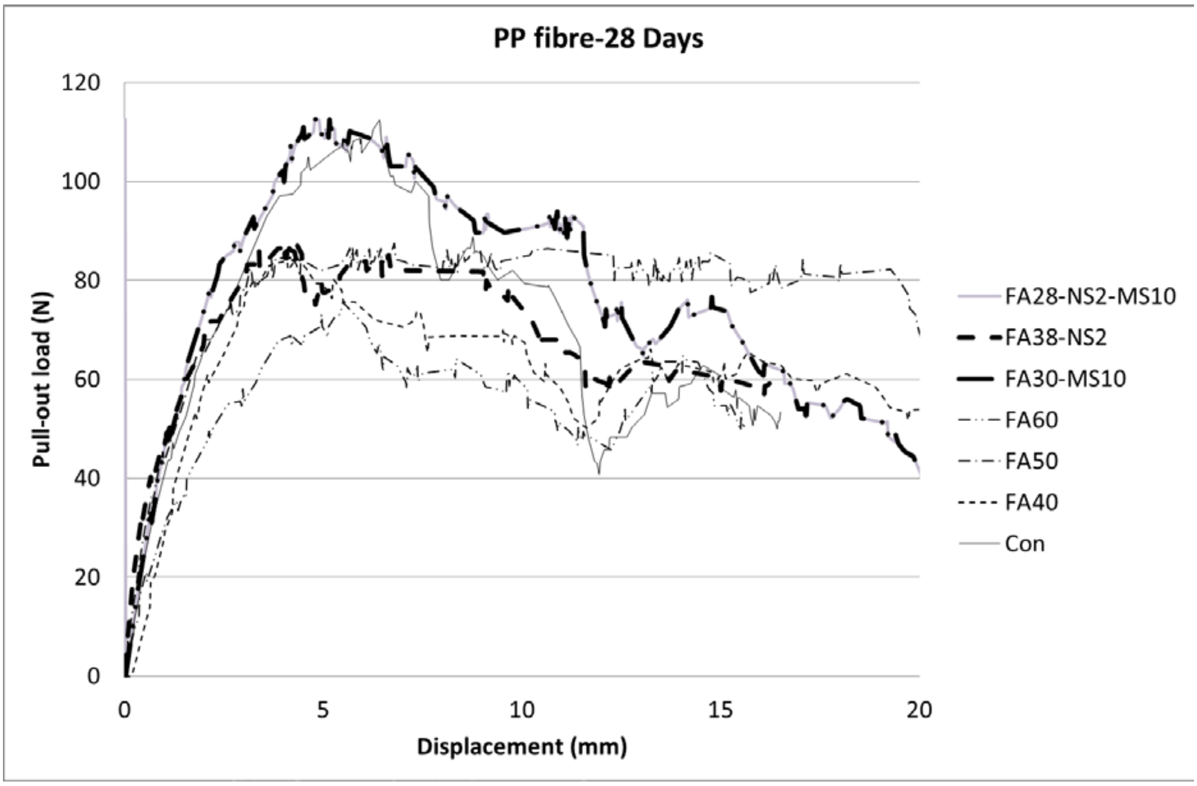


(b)

Fig. 13 Correlations of max. pull-out loads of steel fibres with compressive strengths at (a) 7 days and (b) 28 days.



(a)



(b)

Fig. 14 Pull-out load – displacement behaviour of PP fibre in mortars after (a) 7 days and (b) 28 days of curing

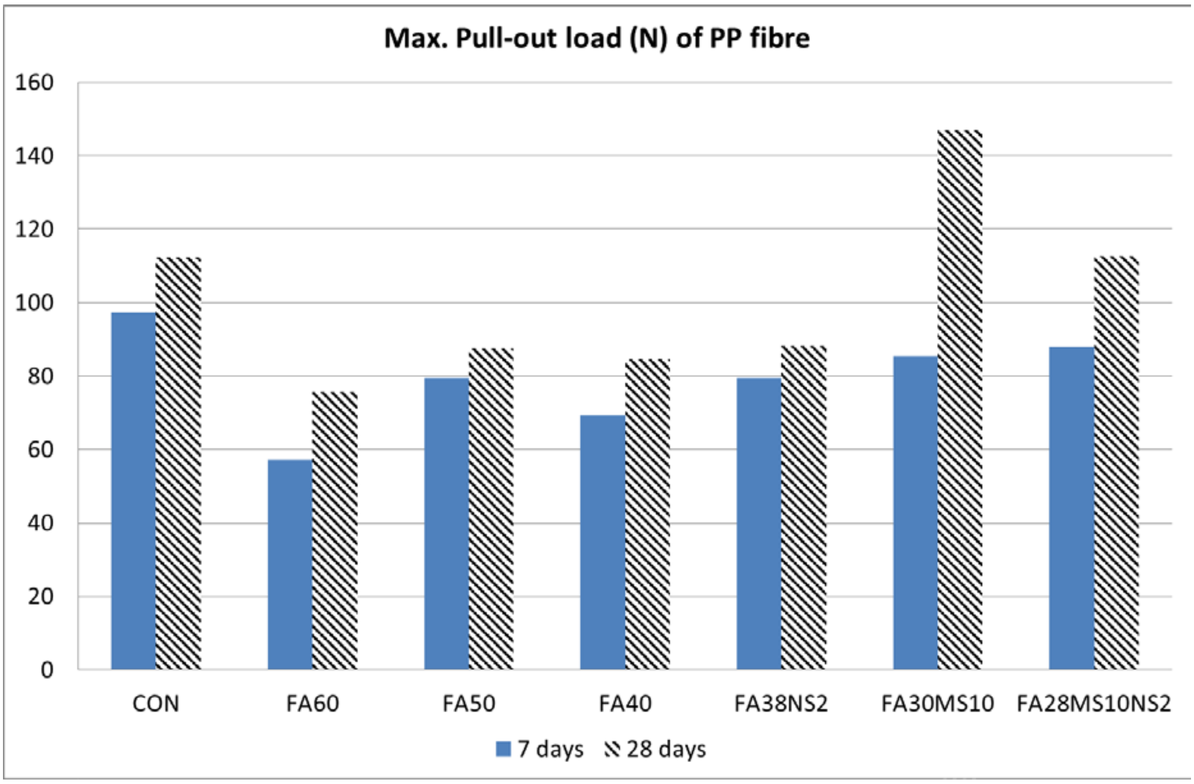


Fig. 15 Maximum pull-out load of PP fibre in mortars after 7 and 28 days of curing.

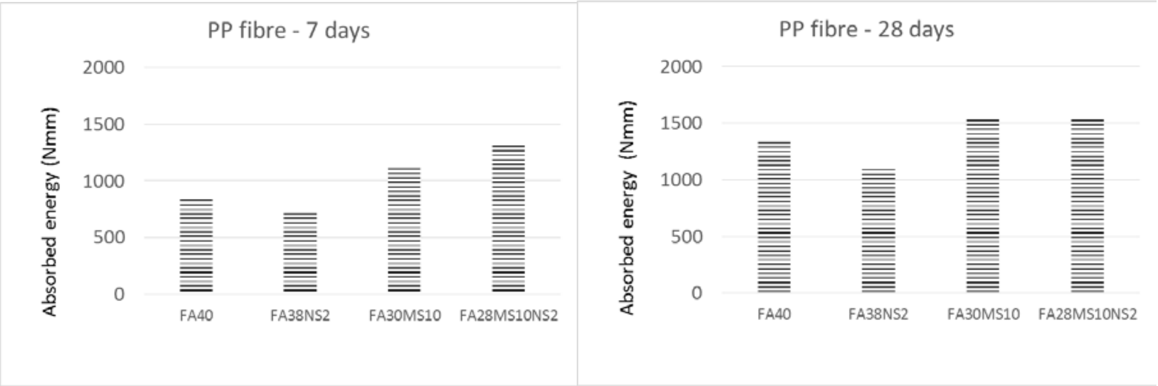


Fig. 16 Absorbed energy of PP fibres in HVFA mortars (Left: 7 days and right: 28 days)

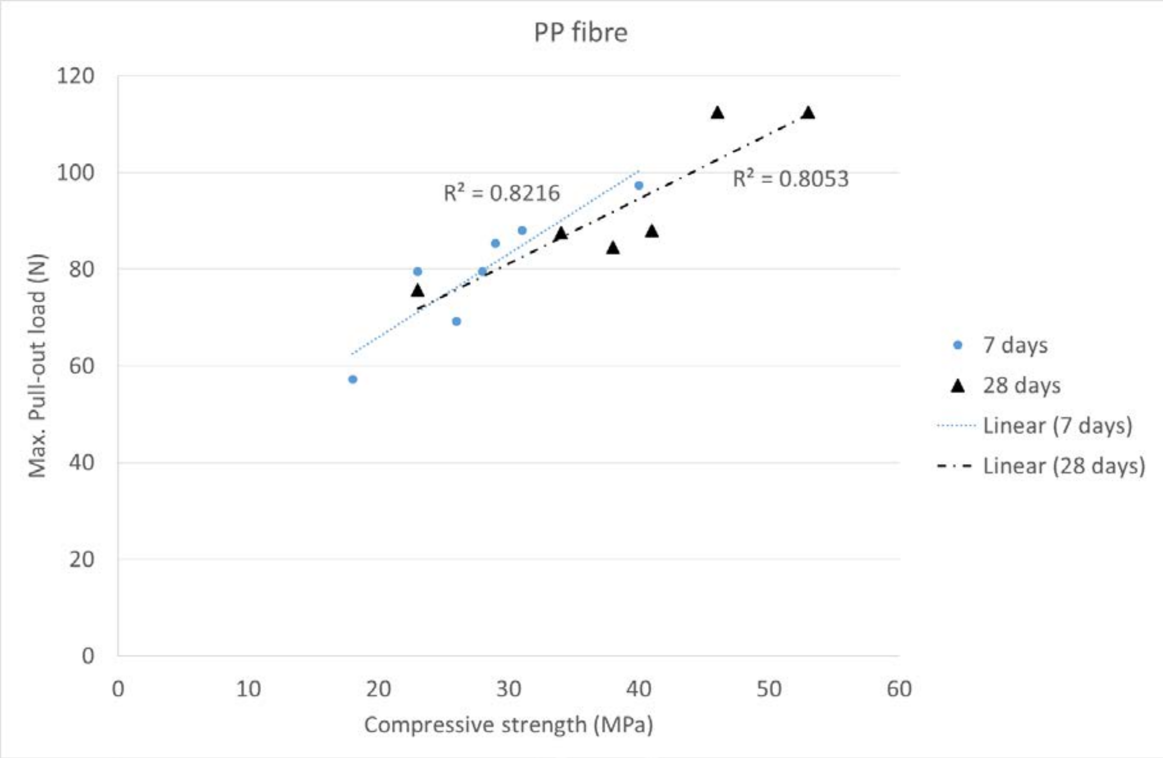


Fig. 17 Correlations of max. pull-out loads of PP fibres with compressive strengths at 7 days and 28 days.