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Effects of Micro-silica and Nano-silica on Fresh Properties of Mortar

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Like micro-silica (MS), nano-silica (NS) can also be considered as a supplementary cementitious material for production of high-performance mortar and concrete. To investigate the influence of MS and NS on the fresh properties of mortar or the mortar phase of concrete, an experimental program encompassing mortar mixes with various water, cement, MS and NS contents was launched for undergoing flowability, cohesiveness and adhesiveness measurements. It was found that the NS added, albeit at much smaller dosage, has greater effects than the MS added on the fresh properties of mortar. More importantly, NS has negative effects on flowability, but positive effects on cohesiveness and adhesiveness. These results suggest that by enhancing the cohesiveness and adhesiveness, the addition of NS in conjunction with MS is a promising method for producing mortar with high adhesiveness requirement, as reflected by the results of the newly developed stone rod adhesion test.

Keywords: adhesiveness, cohesiveness, flowability, micro-silica, nano-silica.

1. INTRODUCTION

With the advent of modern chemical and mineral admixtures, it is now possible to produce many different types of high-performance concrete (HPC) each having high performance in certain attributes [1 – 4]. However, the production of HPC having all round high performance at both the fresh and hardened states is not easy. Moreover, because of conflicts between different performance requirements, such as high strength, high flowability, high cohesiveness, high passing ability and high dimensional stability etc. (the achievement of high performance in one of these attributes often leads to lower performance in the other attributes) and the many mix parameters involved, the mix design of HPC is fairly complicated and so far most of the HPC mixes are still designed by a trial and error process of varying the various mix parameters and conducting trial mixing to determine the suitable mix parameters for meeting with the specified performance requirements, especially those at the fresh state. To conduct the mix design of HPC in a more systematic manner, it has been suggested that the mortar phase should first be engineered to optimize its performance before carrying out trial mixing of the concrete [5 – 10]. Hence, proper mix design of the mortar portion is an important step in the development of a HPC.

A common HPC is self-consolidating concrete (SCC), which offers the advantages of being able to spread under its own weight, flow up to a certain distance, pass through narrow gaps without segregation, fill into far-reaching corners and consolidate without applying compaction. To achieve these desired properties, the mortar phase of SCC has to possess a high flowability [7 – 8] and a high cohesiveness [11]. Furthermore, the mortar phase also needs to possess a high adhesiveness (the ability to adhere to solid surfaces) in order to avoid separation between the mortar and the coarse aggregate particles [10]. However, it is often difficult to achieve high flowability, cohesiveness and adhesiveness simultaneously. The reasons are that the use of higher superplasticizer (SP) dosage to enhance the flowability would substantially decrease the cohesiveness [12] and probably also the adhesiveness, and measures to increase the cohesiveness or adhesiveness would generally decrease the flowability. Besides, despite the widespread employment of high-adhesiveness mortar in concrete repair, spray plastering/rendering and masonry works [13 – 17], a suitable test method for measuring the adhesiveness of paste and mortar is yet to be established.

Apart from SP, micro-silica (MS), sometimes called condensed silica fume, also has important effects on the fresh properties of paste/mortar/concrete. Firstly, the addition of MS could effectively increase the cohesiveness to improve the segregation stability [18 – 20]. However, the effects of MS on flowability are very complicated and may be detrimental or beneficial. For example, Park *et al.* [21] measured the yield stress and viscosity of cement pastes containing MS and found that these rheological properties would increase with the MS content. Artelt and Garcia [22] examined a number of mortar mixes with or without MS and concluded that the presence of MS would impair the flowability, as evidenced by the smaller flow spread and longer flow time of the MS mortars. On the other hand, beneficial effects of MS on the flowability have also been reported. Zhang and Han [23] showed that the yield stress and viscosity of a cement paste could be decreased if MS is added to replace 10 % by weight of cement. Rao [19] conducted a study on mortar and found that at a constant water/binder ratio equal to 0.45 or 0.50, the flow of mortar would increase with the MS content until a maximum

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value is reached at a MS content of about 10 to 15 % by weight. Further research on the root cause of such complicated effects is needed. Moreover, up to now, there has been little or basically no research on the effect of MS on adhesiveness.

Recently, the development of nano-technology and advent of nano-particles have attracted great interests in finding applications of such advanced nano-materials. Particularly, the possible use of nano-silica (NS) in civil engineering construction has become a hot topic of research because proper use of NS could lead to improvements in the physio-chemical properties, mechanical properties and durability of concrete [24 – 29]. Generally, NS is produced by hydrolysis of silicon tetrachloride in oxyhydrogen gas flame at high temperature to yield the nano-size amorphous silica particles.

Some studies on the effects of NS on the rheology of paste/mortar/concrete have been reported. Kong *et al*. [30] examined a number of cement paste samples added with colloidal silica sol or nano-silica powder and found that the colloidal silica sol has greater influence on the rheological behavior of cement paste than the nano-silica powder. Senff *et al*. [31] found that at a fixed water/binder ratio and a fixed SP dosage, the presence of NS considerably increased the yield stress and decreased the flow spread of fresh mortar. Quercia *et al*. [32] demonstrated that a SCC mix added with 3.8 % NS by mass of cement exhibited similar flowability and viscosity as the reference mix without NS.

The interim research findings open up vast possibilities of utilizing NS, or NS in combination with MS, to enhance the rheological performance of mortar and concrete. However, due to the different mix parameters such as paste volume and type and dosage of admixtures adopted by different researchers, there were disparities regarding the effect of NS on workability reported in the literature. Moreover, there has been little research on the effects of NS on cohesiveness and adhesiveness, which are important factors governing the rheological performance of mortar and concrete.

Herein, in order to investigate the effects of MS and NS on the fresh properties of mortar, a number of mortar samples with varying water, cement, MS and NS contents were made for testing. For each mortar sample, the static flowability (slump and flow spread) and dynamic flowability (V-funnel flow rate) were measured by means of the mini slump flow test and mini V-funnel test, whereas the cohesiveness and adhesiveness were measured by means of the sieve segregation test and a newly developed stone rod adhesion test. Based on the test results so obtained, the pros and cons of adding NS, or NS in conjunction with MS, are studied.

2. EXPERIMENTAL DETAILS

2.1. Mix proportions

To investigate the effects of MS and NS on the fresh properties of mortar, an experimental program was launched, in which a series of mortar mixes with different water/cementitious materials (W/CM) ratios, MS contents and NS contents were tested. The mix parameters, W/CM ratio, MS content and NS content, were quantified in terms of volumetric ratios because the fresh properties of mortar are solely determined from the volumetric ratios rather than weight ratios. The paste volume (solid volume of cementitious materials + volume of water, expressed as a percentage of total volume) was fixed at 60 % and the fine aggregate volume was fixed at 40%, while the W/CM ratio by volume was varied among 0.8, 1.0 and 1.2. On the other hand, the MS content by volume of the total cementitious materials was varied among 0 %, 10 % and 20 %, and the NS contents by volume of the total cementitious materials was varied among 0 %, 1 %, 2 % and 3 %. The SP was added at a constant dosage of 3 % measured in terms of liquid mass of SP to the mass of cementitious materials. Such dosage corresponded to the maximum dosage recommended by the manufacturer. For ease of reference, each of the mortar samples was assigned a mix number in the form of X-Y-Z, where X denotes the W/CM ratio, Y denotes the MS content and Z denoted the NS content, as listed in the first column of Table 1.

2.2. Materials

An ordinary Portland cement (OPC) of strength class 52.5 N, which had been tested to comply with European Standard EN 197-1: 2011, was used as the cement. A condensed silica fume in powder form imported from Norway and tested by the supplier to comply with American Standard ASTM C 1240-15 was used as the MS. A powder form NS manufactured in China with particle size ranging from 5 to 20 nm (as can be seen from the transmission electron microscopy images presented in Fig. 1) and high purity (> 99.6 %) was used.

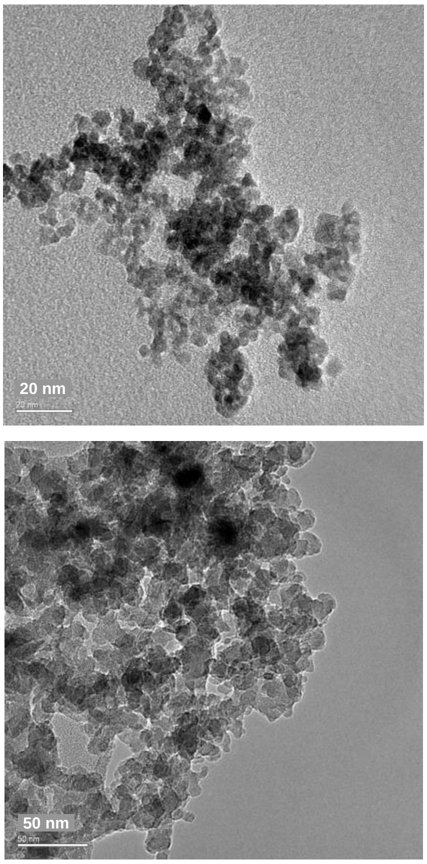

Fig. 1. Transmission electron microscopy images of NS

Regarding the fine aggregate, river sand with a maximum size of 1.18 mm and a water absorption of 1.1 % by mass was used. The relative densities of the OPC, MS, NS and fine aggregate were measured as 3.11, 2.20, 1.94 and 2.58, respectively. A laser diffraction particle size analyser was used to measure the particle size distributions of the OPC, MS and fine aggregate and the results are plotted in Fig. 2. The SP employed was a polycarboxylate-based chemical admixture in liquid solution form. It had a solid mass content of 20%, and a relative density of 1.03.

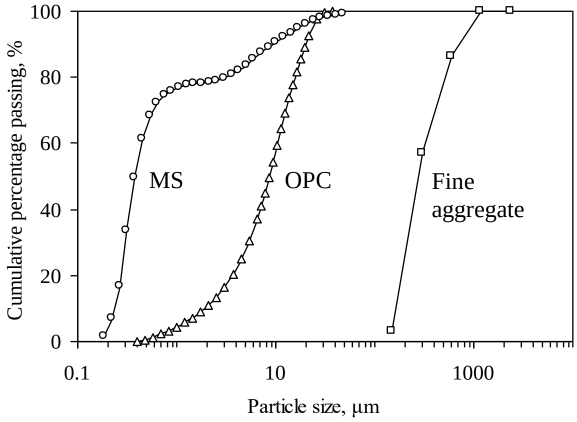

Fig. 2. Particle size distributions of MS, OPC and fine aggregate

2.3. Measuring static flowability

The mini slump flow test was employed to measure the slump and flow spread of the mortar samples. The mini slump flow tests for mortar mimicked the slump flow test for concrete with reduced scale [33]. The mini slump cone adopted in this study was described by Okamura and Ouchi [6]. It had a base diameter of 100 mm, a top diameter of 70 mm, and a height of 60 mm. In performing the slump flow test, the fresh mortar mix was filled into the slump cone until full, the top surface of mortar was trowelled flat, and the slump cone was lifted up vertically to allow the mortar mix slumping downwards and spreading outwards under gravity to form a patty. When the mortar had stopped flowing and deforming, the slump (drop in height of the mortar) and the flow spread (average of two perpendicular diameters of the patty formed) were measured. The slump and flow spread were taken as measures of the static flowability of the mortar.

2.4. Measuring dynamic flowability

The mini V-funnel test was employed to measure the flow rate of the mortar samples. The mini V-funnel test for mortar mimicked the V-funnel test for concrete with reduced scale [34]. The mini V-funnel adopted in this study was described by Okamura and Ouchi [6]. It had a base opening of 30 mm × 30 mm, a top opening of 30 mm × 270 mm, and an overall height of 300 mm. To perform the mini V-funnel test, initially the gate at the bottom of funnel was closed so that the bottom orifice was shut off. Fresh mortar was gently poured into the funnel up to its top. The surplus mortar was removed and the top surface was trowelled, then the bottom gate was opened sharply to discharge the mortar through the bottom orifice. The time taken for the mortar mix to completely discharge as indicated by light passing through the bottom orifice was recorded as the flow time. Then, the flow rate was calculated as the volume of mortar in the funnel divided by the flow time. The flow rate so obtained was taken as a measure of the dynamic flowability of the mortar.

2.5. Measuring cohesiveness

The cohesiveness of the mortar samples was measured by using a modified version of the sieve segregation test stipulated in the European Standard EN 12350-11: 2010 [35]. In contrast to the sieve segregation test for SCC which employs a sieve size of 5.0 mm, the modified sieve segregation test for mortar in this study used a smaller sieve size of 1.18 mm. To conduct the test, mortar sample of approximately 0.2 litre in volume was poured from a height of 300 mm onto a 1.18 mm sieve and allowed to drip through the sieve to the base collector. After two minutes, when the dripping is basically ceased, the mortar collected in the base receiver was weighed, and the sieve segregation index (SSI) of the mortar sample was evaluated as the percentage of mortar by mass dripped through the sieve and collected by the base receiver. For a mortar with low cohesiveness, a larger portion of the mortar would drip through the sieve, and vice versa. Consequently, a larger value of SSI indicates a lower cohesiveness, and vice versa.

2.6. Measuring adhesiveness

A novel test, named the stone rod adhesion test, has been developed to measure the adhesiveness of mortar (the ability of the mortar mix to adhere to rock aggregate surfaces) [10]. The test setup consists of a handle with six stone rods vertically fixed underneath (as illustrated in Fig. 3) and a container.

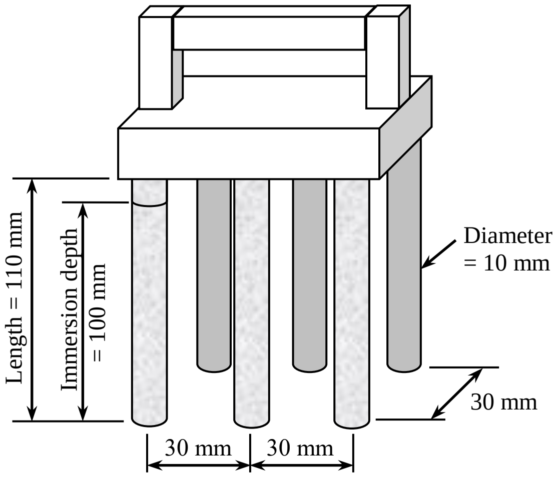

Fig. 3. Details of stone rods for adhesiveness measurement

The stone rods are made of granite, a commonly used rock for coarse aggregate in concrete. To perform the adhesion test, the mortar was poured into the container up to a depth of at least 110 mm. Then the six stone rods were immersed into the mortar with an immersion depth of 100 mm as indicated by the mortar surface reaching the mark on the stone rods. The stone rods were left immersed in the mortar for at least 1 minute and afterwards taken out slowly and steadily. Then the handle holding the stone rods was placed on a stand to allow dripping to take place. After 2 minutes, when no more dripping occurred, the increase in mass of the handle (this represented the mass of mortar adhering to the stone rods) was measured. The mass of mortar adhering to the stone rods divided by the surface area of the stone rods immersed into the mortar was taken as the stone rod adhesion. Such stone rod adhesion may be regarded as a measure of the adhesiveness of the mortar.

3. EXPERIMENTAL RESULTS

3.1. Slump and flow spread

The slump and flow spread results are tabulated in the second and third columns of Table 1 and plotted against the NS content in Fig. 4 and Fig. 5. It is noted from these results that at a NS content of 0%, the slump was generally within the narrow range of 53 to 57 mm and the flow spread was generally within the narrow range of 285 to 355 mm, regardless of the W/CM ratio and MS content. As NS was added, both the slump and flow spread decreased. At a NS content of 1 %, the slump decreased to within the range of 51 to 56 mm while the flow spread decreased to within the range of 230 to 352 mm. At a NS content of 2 %, the slump decreased to within the range of 46 to 55 mm while the flow spread decreased to within the range of 203 to 328 mm. As the NS content was increased to 3 %, both the slump and flow spread further decreased.

The decreases in slump and flow spread with increasing NS content were generally larger at lower W/CM ratio. For instance, when the NS content was increased from 0 % to 2 %, at a W/CM ratio of 0.8 and a MS content of 0 %, the slump decreased from 55 to 50 mm by 9 % while the flow spread decreased from 352 to 240 mm by 32 % but at a W/CM ratio of 1.2 and a MS content of 0 %, the slump decreased from 55 to 54 mm by 2 % while the flow spread decreased from 355 to 328 mm by 8 %. Likewise, at a W/CM ratio of 0.8 and a MS content of 20 %, the slump decreased from 53 to 48 mm by 9 % while the flow spread decreased from 285 to 203 mm by 29 % but at a W/CM ratio of 1.2 and a MS content of 20 %, the slump decreased from 56 to 53 mm by 5 % while the flow spread decreased from 341 to 300 mm by 12 %. The percentage decreases in flow spread were generally larger than the respective percentage decreases in slump.

Similarly, both the slump and flow spread decreased with increasing MS content and the decreases in slump and flow spread with increasing MS content were generally larger at lower W/CM ratio. For instance, when the MS content was increased from 0 % to 20 %, at a W/CM ratio of 0.8 and a NS content of 0 %, the slump decreased from 55 to 53 mm by 4 % while the flow spread decreased from 352 to 285 mm by 19 % but at a W/CM ratio of 1.2 and a NS content of 0 %, the slump remained almost the same while the flow spread decreased from 355 to 341 mm by 4 %. Likewise, at a W/CM ratio of 0.8 and a NS content of 2 %, the slump decreased from 50 to 48 mm by 4 % while the flow spread decreased from 240 to 203 mm by 15 % but at a W/CM ratio of 1.2 and a NS content of 2 %, the slump decreased from 54 to 53 mm by 2 % while the flow spread decreased from 328 to 300 mm by 9 %.

Such reduction of static flowability due to the addition of NS or MS was also reported from other studies. Senff *et al.* [31] found that increasing the NS content up to 2.5 % by weight would reduce the spread diameter of cementitious paste by 19.6 %. Sonebi *et al.* [36] suggested that both NS content and SP dosage are the main parameters affecting the spread and they established the correlation between spread, NS content and SP dosage. On the other hand, Jalal *et al.* [37] used fly ash (FA), NS and MS to produce SCC mixes and reported that the addition of 2 % NS did not change the workability significantly but the rheological properties of SCC were influenced more by FA and MS.

Table 1. Test results of mortar mixes

Mix no.	Slump, mm	Flow spread, mm	Flow rate, ml/s	SSI, %	Stone rod adhesion, g/cm^2
0.8-0-0	55	352	156	44.0	0.011
0.8-0-1	53	317	105	22.3	0.073
0.8-0-2	50	240	61	0.2	0.119
0.8-0-3	40	177	36	0.4	0.154
0.8-10-0	53	325	163	29.2	0.057
0.8-10-1	55	289	114	4.5	0.109
0.8-10-2	46	221	72	0.0	0.129
0.8-10-3	44	182	36	0.0	0.171
0.8-20-0	53	285	171	18.3	0.090
0.8-20-1	51	230	93	3.5	0.132
0.8-20-2	48	203	63	0.6	0.181
0.8-20-3	37	140	16	0.0	0.163
1.0-0-0	55	350	277	58.5	0.005
1.0-0-1	56	349	241	41.0	0.024
1.0-0-2	52	314	192	21.4	0.046
1.0-0-3	53	293	155	6.2	0.086
1.0-10-0	56	349	338	37.0	0.019
1.0-10-1	56	334	275	27.4	0.043
1.0-10-2	54	313	210	12.7	0.067
1.0-10-3	50	256	145	1.7	0.110
1.0-20-0	54	326	305	27.4	0.047
1.0-20-1	53	294	257	16.2	0.074
1.0-20-2	52	255	189	9.3	0.096
1.0-20-3	48	212	94	4.3	0.123
1.2-0-0	55	355	485	70.8	0.005
1.2-0-1	56	352	431	66.1	0.008
1.2-0-2	54	328	397	57.9	0.025
1.2-0-3	55	314	346	27.7	0.064
1.2-10-0	57	335	525	48.8	0.015
1.2-10-1	54	334	487	44.4	0.011
1.2-10-2	55	326	390	24.8	0.022
1.2-10-3	53	312	305	14.2	0.056
1.2-20-0	56	341	518	41.1	0.023
1.2-20-1	53	312	454	25.9	0.047
1.2-20-2	53	300	328	19.4	0.069
1.2-20-3	52	270	228	11.7	0.086

Comparing the decreases in slump due to addition of 2 % NS (≈ 9 % at W/CM = 0.8 and 2 % – 5 % at W/CM = 1.2) with those due to addition of 20% MS (≈ 4 % at W/CM = 0.8 and 0 % – 2 % at W/CM = 1.2), it can be seen that the 2 % NS added has greater effect on slump than the 20 % MS added. Comparing the decreases in flow spread due to addition of 2 % NS (29 % – 32 % at W/CM = 0.8 and 8 % – 12 % at W/CM = 1.2) with those due to addition of 20 % MS (15 % – 19 % at W/CM = 0.8

and 4 % – 9 % at W/CM = 1.2), it can also be seen that the 2 % NS added has greater effect on flow spread than the 20 % MS added. Hence, the NS added, albeit at much smaller dosage, has greater adverse effects than the MS added on both the slump and flow spread. This may be attributed to the substantially smaller size and larger surface area of the NS than the MS.

It was also observed that at the same MS content and NS content, the slump and flow spread were both higher at a higher W/CM ratio. This was expected because a mortar mix with more water should have higher slump and flow spread.

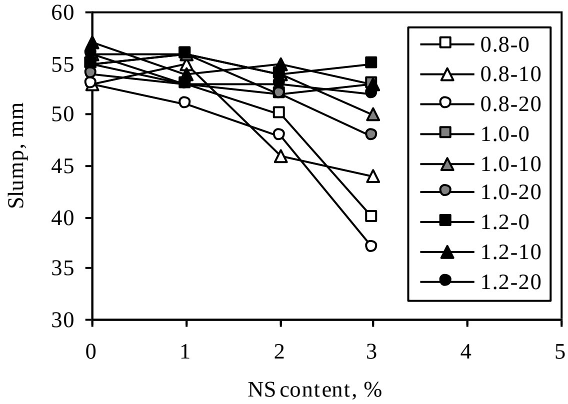

Fig. 4. Slump versus NS content

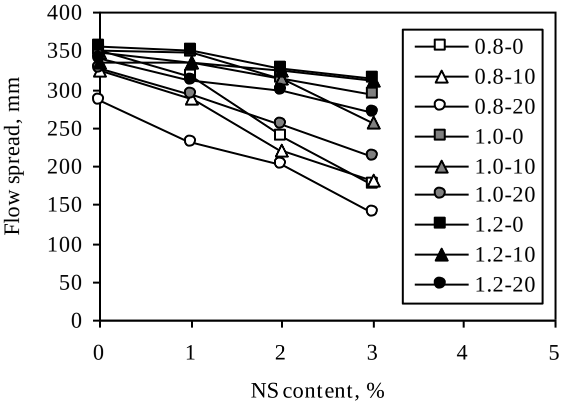

Fig. 5. Flow spread versus NS content

3.2. Flow rate

The flow rate results are tabulated in the fourth column of Table 1 and plotted against the NS content in Fig. 6. It is noted from these results that the flow rate decreased quite substantially as the NS content was increased. The decrease in flow rate was generally larger at lower W/CM ratio. For instance, when the NS content was increased from 0 % to 2 %, at a W/CM ratio of 0.8 and a MS content of 0 %, the flow rate decreased from 156 to 61 ml/s by 61 % but at a W/CM ratio of 1.2 and a MS content of 0 %, the flow rate decreased from 485 to 397 ml/s by 18 %. Likewise, at a W/CM ratio of 0.8 and a MS content of 20 %, the flow rate decreased from 171 to 63 ml/s by 63 % but at a W/CM ratio of 1.2 and a MS content of 20 %, the flow rate decreased from 518 to 328 ml/s by 37 %. Such substantial decreases in flow rate indicate that the addition of NS could seriously hamper the dynamic flowability and pumpability of mortar and concrete.

However, the flow rate changed with the MS content in a fairly complicated manner. Roughly speaking, the addition of MS could increase the flow rate at low W/CM ratio and/or low NS content and decrease the flow rate at high W/CM ratio and/or high NS content. For instance, when the MS content was increased from 0 % to 20 %, at a W/CM ratio of 0.8 and a NS content of 0 %, the flow rate increased slightly from 156 to 171 ml/s by 10 % and at a W/CM ratio of 1.2 and a NS content of 0 %, the flow rate increased slightly from 485 to 518 ml/s by 7 %. Furthermore, at a W/CM ratio of 0.8 and a NS content of 2 %, the flow rate increased marginally from 61 to 63 ml/s by 3 % and at a W/CM ratio of 1.2 and a NS content of 2 %, the flow rate decreased from 397 to 328 ml/s by 17 %.

Some other researchers also carried out tests to investigate the effects of NS or MS on the dynamic flowability of cement based materials. For instances, Quercia *et al.* [32] applied powder NS and colloidal NS to SCC and found that to maintain short V-funnel time, NS should be added along with very high dosage of SP. On the other hand, Benaicha *et al.* [38] used MS and viscosity modifying agent (VMA) in SCC and found that the V-funnel time increased with the amount of MS and VMA.

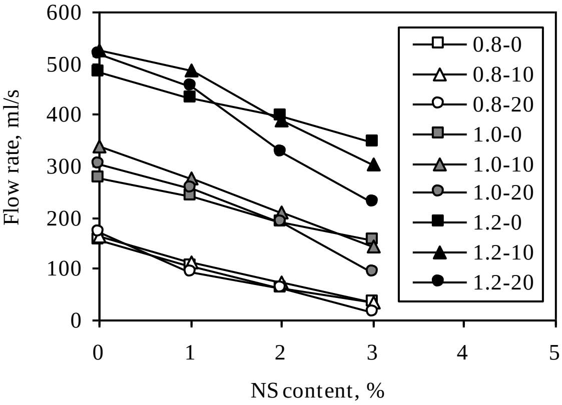

Fig. 6. Flow rate versus NS content

Comparing the changes in flow rate due to addition of 2 % NS (decrease by at least 60 % at W/CM = 0.8 or decrease by at least 18 % at W/CM = 1.2) with those due to addition of 20 % MS (increase by up to 10 % or decrease by up to 17 %), it can be seen that the 2 % NS added has greater effect on flow rate than the 20 % MS added. Hence, the NS added, albeit at much smaller dosage, has greater adverse effect than the MS added on the flow rate. Again, this may be attributed to the substantially smaller size and larger surface area of the NS than the MS.

Finally, it was also observed that at the same MS content and NS content, the flow rate was higher at a higher W/CM ratio. This was expected because a mortar mix with more water should have higher flow rate.

3.3. Cohesiveness

The SSI results are tabulated in the fifth column of Table 1 and plotted against the NS content in Fig. 7. From these results, it is evident that the SSI always decreased when NS was added. At a NS content of 0 %, the SSI ranged from 70.8 % to 18.3 %, indicating that the mortar mixes with no NS added have rather low cohesiveness. As the NS content was increased to 2 %, the SSI decreased to within the range of 57.9 % to 0.0 %, which are much lower than before. The decrease in SSI was generally larger at lower W/CM ratio. For instance, when the NS content was increased from 0 % to 2 %, at a W/CM ratio of 0.8 and a MS content of 0 %, the SSI decreased from 44.0 % to 0.2 % by a percentage of more than 90% but at a W/CM ratio of 1.2 and a MS content of 0 %, the SSI decreased from 70.8 % to 57.9 % by a percentage of only 18 %. Likewise, at a W/CM ratio of 0.8 and a MS content of 20 %, the SSI decreased from 18.3 % to 0.6 % by a percentage of more than 90 % but at a W/CM ratio of 1.2 and a MS content of 20 %, the SSI decreased from 41.1 % to 19.4 % by a percentage of 53 %.

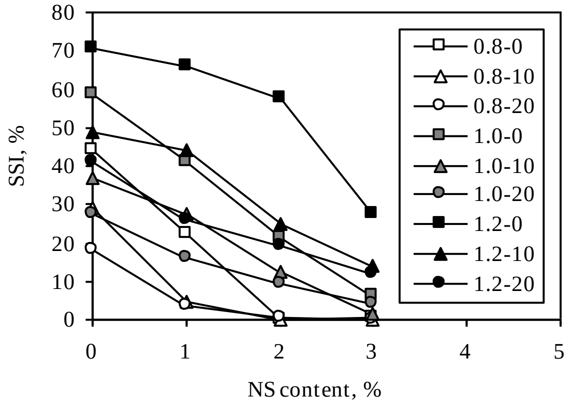

Fig. 7. SSI versus NS content

The SSI also decreased when MS was added and the decrease in SSI so caused was also generally larger at lower W/CM ratio. For instance, when the MS content was increased from 0 % to 20 %, at a W/CM ratio of 0.8 and a NS content of 0 %, the SSI decreased from 44.0 % to 18.3 % by a percentage of 58 % but at a W/CM ratio of 1.2 and a NS content of 0 %, the SSI decreased from 70.8 % to 41.1 % by a percentage of 42 %. Likewise, at a W/CM ratio of 0.8 and a NS content of 2 %, the SSI remained at almost zero (the SSI could not be further decreased to below 0 %) but at a W/CM ratio of 1.2 and a NS content of 2 %, the SSI decreased from 57.9 % to 19.4 % by a percentage of 66 %.

Such improvement of cohesiveness due to the addition of NS or MS was also indicated in other studies. Collepardi *et al.* [39 – 40] reported that when NS is mixed with cement composite, a reduction in bleeding and segregation occurred when SP was added. Besides, Chen *et al.* [41] found that MS has great positive effect on the cohesiveness of cementitious paste.

Comparing the decreases in SSI due to addition of 2 % NS with those due to addition of 20 % MS, it can be seen that with only NS added up to 2 %, the SSI could be decreased to as low as 0.2 % but with only MS added up to 20 %, the SSI could be decreased to only 18.3 %. Hence, the NS added, albeit at much smaller dosage, has greater beneficial effect than the MS added on the cohesiveness. This may be attributed to the bridging effect of the NS particles, which, being finer than the MS and cement particles, would fill into the gaps between the larger size particles to form bridges for transmitting attractive forces between the larger size particles. Such substantial increase in cohesiveness could be utilized to minimize bleeding, avoid segregation and improve homogeneity of mortar and concrete mixes.

Lastly, as expected, at the same MS content and NS content, the SSI was higher at a higher W/CM ratio. This is reasonable because a mortar mix with more water is generally thinner and less cohesive.

3.4. Adhesiveness

The stone rod adhesion (weight of mortar adhered to stone rod surfaces per surface area) results are tabulated in the last column of Table 1 and plotted against the NS content in Fig. 8.

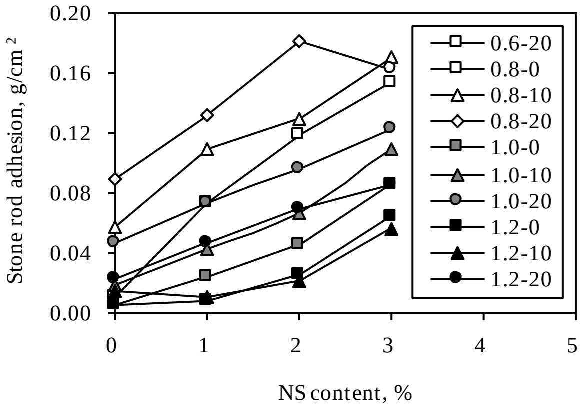

Fig. 8. Stone rod adhesion versus NS content

From these results, it is seen that the stone rod adhesion always increased when NS was added, regardless of the W/CM ratio and MS content. The increase in stone rod adhesion due to the addition of 2 % NS was often larger than 100 %. For instance, when the NS content was increased from 0 % to 2 %, at a W/CM ratio of 0.8 and a MS content of 0 %, the stone rod adhesion increased from 0.011 to 0.119 g/cm^2 by about 10 times, at a W/CM ratio of 1.2 and a MS content of 0 %, the stone rod adhesion increased from 0.005 to 0.025 g/cm^2 by about 4 times, at a W/CM ratio of 0.8 and a MS content of 20 %, the stone rod adhesion increased from 0.090 to 0.181 g/cm^2 by 101 %, and at a W/CM ratio of 1.2 and a MS content of 20 %, the stone rod adhesion increased from 0.023 to 0.069 g/cm^2 by 200 %.

The stone rod adhesion also always increased when MS was added. For instance, when the MS content was increased from 0 % to 20 %, at a W/CM ratio of 0.8 and a NS content of 0 %, the stone rod adhesion increased from 0.011 to 0.090 g/cm^2 by 7.2 times, at a W/CM ratio of 1.2 and a NS content of 0 %, the stone rod adhesion increased from 0.005 to 0.023 g/cm^2 by 3.6 times, at a W/CM ratio of 0.8 and a NS content of 2 %, the stone rod adhesion increased from 0.119 to 0.181 g/cm^2 by 52 %, and at a W/CM ratio of 1.2 and a NS content of 2 %, the stone rod adhesion increased from 0.025 to 0.069 g/cm^2 by 176 %.

Since the stone rod adhesion test is a new test developed by the authors, there is no comparable studies by other researchers and it is also the first time by the authors to apply to measure the adhesiveness of mortar with NS. Through the use of stone rod adhesion test, the authors' research group had found that the addition of fly ash microsphere would increase the adhesiveness of mortar significantly [42].

Comparing the increases in stone rod adhesion due to addition of 2 % NS with those due to addition of 20 % MS, it can be seen that the 2 % NS added has greater effect on adhesiveness than the 20 % MS added. Hence, the NS added, albeit at much smaller dosage, has greater beneficial effect than the MS added on the adhesiveness. This may be attributed to the bridging effect of the NS particles, which, being ultrafine, would fill into the gaps between the larger size particles and the gaps between the mortar particles and the rock surface to form bridges for transmitting attractive forces between the larger size particles and attractive forces between the mortar particles and the rock surface, as illustrated in Fig. 9.

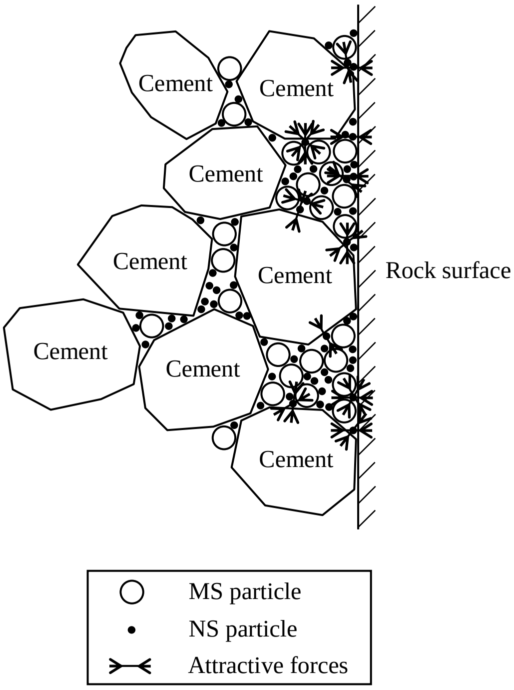

Fig. 9. Bridging effect of NS particles

The above findings on the effectiveness of adding NS, or NS in conjunction with MS, in improving the adhesiveness of mortar are of high significance in practical applications. For use in repair mortar, sprayed mortar, rendering and plastering works, mortar mixes with high adhesiveness are generally required. To achieve the desired adhesiveness, NS, or NS in conjunction with MS, can be added to the mortar mix. Furthermore, in production of HPC, such as SCC, a high cohesiveness is often required for the concrete mix. Since the cohesiveness of concrete is closely dependent on the adhesiveness of mortar phase, the above methodology of adding NS to improve the adhesiveness of mortar should be also applicable to the mix design of concrete.

Lastly, as expected, at the same MS content and NS content, the stone rod adhesion was higher at a lower W/CM ratio. This is reasonable because a mortar mix with less water is generally thicker and more sticky.

4. DISCUSSION

4.1. Flowability-adhesiveness relation

Overall, the above results reveal that generally, when the cohesiveness or adhesiveness was increased by decreasing the W/CM ratio, adding more MS or adding more NS, the static and dynamic flowability decreased, and when the static or dynamic flowability was increased by increasing the W/CM ratio, adding less MS or adding less NS, the cohesiveness and adhesiveness decreased. It is not easy to achieve both high static/dynamic flowability and high cohesiveness/adhesiveness at the same time. To study the concurrent flowability-adhesiveness performance of the mortar mixes tested, the flow spread is plotted against the stone rod adhesion for different NS contents in Fig. 10. From the figure, it can be seen that the data points plotted are all very close to a common trend line which takes the form of a second-order polynomial, regardless of the NS contents of the mortar mixes represented by the data points. The coefficient of correlation R^2 between the data points and the trend line is as high as 0.921. Therefore, the stone rod adhesion test results can serve as good indicator of the flowability of mortar.

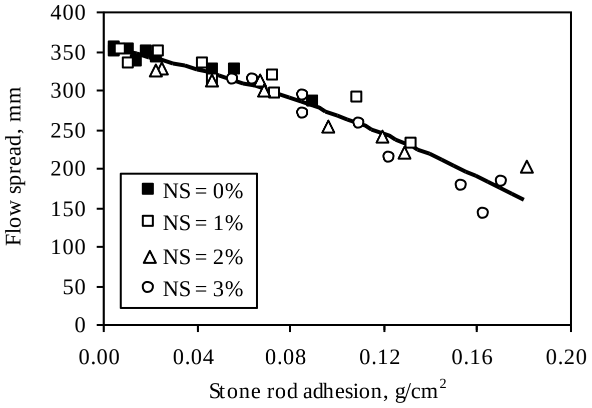

Fig. 10. Flow spread versus stone rod adhesion

The trend line shows clearly that as the adhesiveness is increased by adding NS, the flowability would decrease concurrently. This has two implications. First, for a mortar with high adhesiveness requirement, the addition of NS to improve the adhesiveness would lead to a lower flowability. If both high adhesiveness and high flowability are desired, then after adding the NS to improve the adhesiveness, the loss in flowability should be compensated by increasing the paste volume of the mortar mix (increasing the paste volume would increase the mortar flowability). Second, for a concrete with high cohesiveness requirement such as SCC and sprayed concrete, the addition of NS to improve the cohesiveness (the cohesiveness is closely related to the adhesiveness) would lead to a lower flowability. If both high cohesiveness and high flowability are desired, then after adding the NS to improve the cohesiveness, the loss in flowability should be compensated by increasing the mortar volume of the concrete mix (increasing the mortar volume would increase the concrete flowability). The same applies after adding MS to improve the cohesiveness of concrete.

4.2. Cohesiveness-adhesiveness relation

Comparing the SSI results with the respective stone rod adhesion results, it appears that the cohesiveness and adhesiveness of mortar mixes are closely related. To study the cohesiveness-adhesiveness relation, the SSI is plotted against the stone rod adhesion for different NS contents in Fig. 11. From the figure, it can be seen that apart from a few scattered data points, which may be regarded as outliers, most of the data points are very close to a common trend line which takes the form of a logarithmic curve, regardless of the NS contents of the mortar mixes represented by the data points. The coefficient of correlation R^2 is as high as 0.937. Hence, there is a clear correlation between the cohesiveness and adhesiveness. However, there are a few data points with the same value of SSI equal to 0% but widely different values of stone rod adhesion, indicating that even when the SSI has been decreased to zero, the stone rod adhesion could continue to increase.

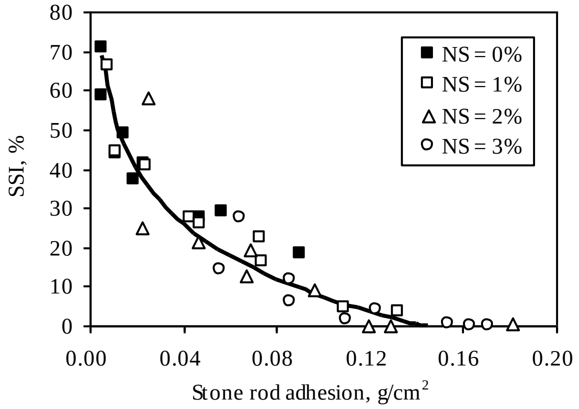

Fig. 11. SSI versus stone rod adhesion

This is because when the SSI is close to or equal to zero, any further increase in cohesiveness would not be revealed (the SSI could not be decreased to below zero). For instance, at a W/CM ratio of 0.8 and a MS content of 10 %, the increase of NS content from 2 % to 3 % should further increase the cohesiveness but there was no change in the SSI because the SSI was already equal to 0 %. Actually, in this case, the increase of NS content from 2 % to 3 % had increased the stone rod adhesion from 0.129 to 0.171 g/cm^2 by 33 %. For this reason, when the cohesiveness is so high that the SSI is close to zero, the adhesiveness should not be inferred indirectly from any cohesiveness measurement. There is a need to measure the adhesiveness directly by the proposed stone rod adhesion test, especially when the SSI has become insensitive to further increase in cohesiveness or adhesiveness.

By virtue of the above, further research is recommended to improve and tailor the modified sieve segregation test for mortar mixes, as well as to correlate the improved sieve segregation test and stone rod adhesion test results with rheological properties of mortar including the yield stress and viscosity. As interim measures, the authors advocate the use of stone rod adhesion test to evaluate the adhesiveness of mortar and to assess the cohesiveness of mortar especially for cohesive mixes (such as those with low W/CM ratio and with NS or MS altogether with NS added), where the cohesiveness might not be adequately described by the SSI alone.

5. CONCLUSIONS

A series of mortar mixes with varying W/CM ratios, MS contents and NS contents were made for static flowability, dynamic flowability, cohesiveness and adhesiveness measurements by means of the mini slump cone test, mini V-funnel test, sieve segregation test and a newly developed stone rod adhesion test. Based on the test results, the following conclusions are drawn:

1. As expected, the W/CM ratio or water content has positive effects on the static and dynamic flowability of mortar, but also negative effects on the cohesiveness and adhesiveness of mortar.
2. MS has slight negative effect on the static flowability of mortar, slight positive or negative effect on the dynamic flowability of mortar depending on the other mix parameters, but also significant positive effects on the cohesiveness and adhesiveness of mortar.
3. NS has significant negative effects on the static and dynamic flowability of mortar, but also substantial positive effects on the cohesiveness and adhesiveness of mortar.
4. Comparing the effects of adding NS with those of adding MS, it is found that generally, the addition of 2% NS has greater effects than the addition of 20% MS. Hence, the addition of NS, even at a much smaller dosage, is more effective in modifying the rheology of mortar than the addition of MS.
5. The addition of NS, or NS in conjunction with MS, is an effective way of producing mortar with high adhesiveness requirement, such as repair mortar, sprayed mortar, rendering and plastering. However, the flowability would be decreased. If both high adhesiveness and high flowability are required, then after adding NS to improve the adhesiveness, the loss in flowability should be compensated by increasing the paste volume of the mortar mix.
6. Plotting the cohesiveness (in terms of sieve segregation index) against the adhesiveness (in terms of stone rod adhesion), it is seen that there is a clear relation between the cohesiveness and adhesiveness. However, when the sieve segregation index has become very close to zero, it would not be sensitive to any further increase in cohesiveness or adhesiveness because it could not be decreased to below zero. Actually, even then, the adhesiveness could still be further increased. Hence, the authors advocate the use of the proposed stone rod adhesion test to directly measure the adhesiveness.

Acknowledgments

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