Rheological and mechanical properties of microfine-cement-based grouts mixed with microfine fly ash, colloidal nanosilica and superplasticizer

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HIGHLIGHTS

- Rheological and mechanical properties of microfine-cement-based grouts were studied.
- The incorporation of MFA and SP each improved the fluidity and spreading ability of fresh grouts.
- 0.5% NS decreased the apparent viscosity of fresh grouts.
- An increase in the NS content improved the early strength and bonding strength.

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Abstract

To ensure desirable fluidity, less leaching and mechanical properties of grouts in geotechnical engineering, a microfine-cement-based grout mixed with microfine fly ash (MFA), colloidal nanosilica (NS) and superplasticizer (SP) was designed. In this paper, the rheological and mechanical properties of grouts with different additives were investigated. The results show that all microfine-cement-based grouts have satisfactory apparent viscosity, behave as Bingham fluids, are stable for water/solid (W/S) ratio = 1.2. The incorporation of MFA and SP each improve the fluidity and spreading ability of fresh grouts, while prolonging the setting time. The addition of NS has negative effects on fluidity and shrinkage property of fresh grouts, nevertheless, it has positive effects on shortening setting time, enhancing stability and mechanical properties.

1. Introduction

To improve the mechanical properties of rocks and soils by permeation grouting, compaction grouting, split grouting and jet grouting, using either cement-based grouts or chemical grouts, is required to ensure the safety and stability of underground construction process [1–3]. However, ordinary Portland cement grout is difficult to be injected into micro-fractures (<0.5 mm) [4,5]. Moreover, chemical grouts not only pose environmental and health hazards, but also show insufficient durability. Due to satisfactory injectability, environmental friendliness, less cost and excellent durability, microfine-cement-based grouts are widely used in grouting engineering, especially for micro-fracture grouting. Therefore, many scholars have focused on the development of microfine-cement-based grouting materials in recent years [6–8].

With respect to microfine cement (MC), there is no uniform definition until now. According to EN 12715, MC should have $d_{100} < 20 \mu m$ and a Blaine fineness >800 m$^2$/kg [9,10]. However, the American Concrete Institute Committee 552 and the International Society for Rock Mechanics define MC as having $d_{95} < 15 \mu m$ and $d_{max} < 20 \mu m$. Due to its high specific surface area, it is obligatory to add some additives to obtain a desirable grout with high fluidity and injectability [11–14].

As a common mineral additive, MFA is widely used in cement and concrete. It has many advantages, including lower cost, improve fluidity of grouts and later strength of hardened grouts due to its pozzolanic effect and micro-aggregate effect [15–17]. Because of the electrostatic interaction and humidity, MC particles agglomerate together. To overcome this limitation, SP is selected to
decrease interparticle attractive forces of the cement particles during mixing, therefore it can improve the fluidity of grouts due to its water reducing mechanism [18–21].

In recent years, NS has been widely used in concrete and cement due to its improved effect on the mechanical properties and durability [22,23]. According to Behfarnia and Salemi, a 16.67% 28-day compressive strength improvement of concrete can be obtained with an addition of 3% nano-silica [24]. The experiment of cement mortars with nanosilica conducted by Tobon found that the addition of nanosilica can significantly improve the compressive strength and durability of cement mortars owing to its positive effect on the pore refining [25]. Zahedi et al. found that the addition of nanosilica contributed to the high early strength development and durability of cement mortars [26]. Zhang et al. found that the compressive strength of high-volume fly ash concrete was increased by 30% and 25% at 3 and 7 days when 2% nano-silica by mass of cementitious materials was introduced [27]. However, very few studies regarding the combined effects of NS, MFA and SP on the rheological and mechanical properties of microfine-cement-based grouts have been completed.

The experimental investigation reported herein is to develop a microfine-cement-based grout by adding various admixtures, suitable for micro-fracture grouting. In this research, the viscosity, fluidity, spreading capacity, bleed capacity, setting time, shrinkage and the synergistic effects of MFA, NS and SP on the rheological and mechanical properties are analyzed, while the synergistic effects of MFA, NS and SP on the rheological and mechanical properties of microfine-cement-based grouts have been completed.

The fluidity of fresh grouts commonly represented by the flow time and the test method was V-funnel test based on SL 62-2014 [28]. The internal orifice diameter of the V-funnel is 4.8 mm and it was filled with 1500 mL fresh grout after preparation. The elapsed time of 946 mL fresh grout through the V-funnel was defined as the flow time in this research. It should be noted that the flow time of 946 mL potable water was approximately 26 ± 0.5 s. The mini-slump test can be expressed as the spreading ability of fresh grouts. According to GB/T 8077-2012 [29], the fresh grouts were filled into a mini-slump cone, then the mold was slowly raised vertically to spread out the fresh grouts on the glass plate. The spread diameter of fresh grouts at 30 s was measured, and the cone mold dimensions are 60 mm of height, 60 mm of top diameters and 36 mm of bottom diameters.

Bleed capacity was measured by conducting sedimentation tests based on SL 62-2014 [28] and the bleed capacity is defined as the final value of ΔV/V0, where ΔV is the volume of bleed water and V0 is the initial volume of fresh grouts [30–32]. The fresh grouts were placed in a graduated cylinder of 1000 mL for 2 h, then measured the volume of bleed water at every 30 min interval until observation time reached.

Setting time was measured by conducting Vicat needle tests. According to ASTM Standard C191 [33], the initial setting time is defined as the time from grouts preparation when the penetration height of the Vicat needle in the specimen is 25 mm and the final setting time is defined as the time when the penetration height of the Vicat needle in the specimen is less than 1 mm in this research. It should be noted that the bleed water was removed, leaving the mold full with grout after the completion of bleeding.

Early strength development was tested using a pocket penetrometer, which has a maximum value of 0.45 MPa. The 28-day unconfined compressive strength of hardened grouts was conducted according to GB/T 17671–1999 [34]. The dimension of specimens was 40 × 40 × 160 mm and the loading rate was 0.3 mm/min. Based on ASTM C78-16 [35], the 28-day flexural strength of hardened grouts was tested, the dimension of specimens was 40 × 40 × 160 mm and the loading rate was 50 N/s. The bonding strength was evaluated by measuring the failure value of the bonding interface between the hardened grout and concrete. The halves of the concrete cylinders were placed in a mold, and then poured the fresh grouts into the mold until the mold was filled with grouts. The concrete cylinders were 100 mm of height, 50 mm of diameter and split into two halves with an angle of 60°, and the compressive strength was 30 MPa. The specimens were placed in a cement concrete standard curing box and cured in the humid room at 20 ± 2°C and relative humidity (RH) above 95%. For the drying shrinkage test, the specimens with 25 × 25 × 250 mm were prepared according to ASTM C531-12. The specimens for shrinkage test were cured at about 50% RH and 23°C, and the readings for shrinkage values were taken at 3, 7, 14, 21, 28, 35 and 42 days.

### 3. Results and discussion

#### 3.1. Grain size analysis

The grain size plays an important role in rheological behavior and mechanical performance. In this research, the grain sizes were
determined using the laser diffraction technique by a laser particle size analyzer LS900. Presented in Fig. 1 is the grain size distribution of MC and MFA.

As shown in Fig. 1, the average grain size \((d_{50})\), \(d_{95}\) and \(d_{100}\) of MC were 4.91, 12.41 and 17.12 \(\mu\)m, respectively. For the grain size distribution of MFA, the \(d_{50}\), \(d_{95}\) and \(d_{100}\) were 3.56, 7.28 and 13.74 \(\mu\)m, respectively. In this research, the maximum grain size of MFA was finer than MC, and the maximum grain size values for both MFA and MC were less than ‘Microfine’ requirements of EN 12715 and other standards. Accordingly, the microfine-cement-based grouts can be used to penetrate in micro-fractures or medium sands.

3.2. Rheological properties

3.2.1. Apparent viscosity

It is generally desirable that grouts have low initial apparent viscosity to ensure satisfactory initial fluidity and spreading ability. Fig. 2 are the initial apparent viscosity values of fresh grouts mixed with different SP contents and W/S ratios as measured immediately after preparation at the rotation speed of 60 rpm.

As shown in Fig. 2, the initial apparent viscosity values of fresh grouts decreased remarkably with the increase of W/S ratio. In terms of the different SP contents (2.0–0%), the initial apparent viscosity ranges were 65.4–226.4, 49.2–95.3, 40.5–65.1 and 9.1–26.2 mPa\(\cdot\)s for W/S ratios of 1.0, 1.2, 1.5 and 2.0, respectively. It can be observed that initial apparent viscosity values at the W/S ratio of 1.0 decreased nearly by an order of magnitude when the W/S ratio was 2.0, regardless of the SP contents. The results obtained in this research are in agreement with other researchers. Pantazopoulos et al. [8] found that the apparent viscosity values decreased, on the average, by one order of magnitude as the W/C ratio increased from 1 to 3.

The addition of SP can reduce the initial apparent viscosity of grouts due to the water reducing mechanism. It can be explained that the agglomeration of cement particles is eliminated by a combination of electrostatic and steric repulsion; the flocculated structure that can be produced at rest is destroyed by the adsorbed surface of SP and therefore the initial apparent viscosity is reduced. However, the water reducing mechanism of SP was not obvious when the W/S ratio exceeded 1.5. It can also be observed that the initial apparent viscosity decreased slowly when the SP contents and W/S ratio exceeded 1.0% and 1.5. This finding is in confirmation of the results of the study by Li et al. [39].

Fig. 3 shows the variations in apparent viscosity of fresh grouts with different MFA contents, W/S ratio of 1.2 and 1.0% SP. As shown in Fig. 3, the apparent viscosity values decreased with the increase of MFA contents during the first 120 min. Specifically, when the MFA contents ranged from 0 to 40%, the apparent viscosity values of fresh grouts were 60.7–134.6, 56.3–125.9, 46.7–112.4, 30.9–92.5 and 27.9–79.3 mPa\(\cdot\)s, and these values are in agreement with those reported in the literature [39]. Furthermore, with the amounts of 30% and 40% MFA, the ranges of decrease of initial apparent viscosity and apparent viscosity at 120 min were approximately 29.8–32.8 mPa\(\cdot\)s (49.1%–54.0%) and 42.1–55.3 mPa\(\cdot\)s (31.3%–41.1%). It can be concluded that MFA improve the fluidity of fresh grouts due to the ‘ball effects’, as also reported in available literature for cement pastes [36].

As for the effect of NS on rheological properties of fresh grouts, there is no uniform conclusion. On the one hand, the addition of NS increases the density of cement particles, reduces the gap between cement and increases the amount of free water, resulting in improvement on fluidity of fresh grouts. On the other hand, the NS specific surface area is very large, and the surface water will
increase greatly, resulting in thickening and poor rheological properties of fresh grouts [37,38]. Consequently, there should be a limit to the NS content for ensuring desirable fluidity of fresh grouts.

To make clear this question, the apparent viscosity values of fresh grouts with W/S ratio of 1.2 and different NS contents are presented in Fig. 4.

As shown in Fig. 4, the apparent viscosity values of fresh grouts with different NS contents, as tested immediately after preparation for a rotation speed of 60 rpm, had low initial values ranging below 40 mPa·s and below 150 mPa·s at 120 min. It can be observed that the apparent viscosity values increased with the increase of NS contents and hydration time. The apparent viscosity values of fresh grouts with NS, had bigger initial values than those without NS, except for 0.5% NS content. As reported in available literature i.e. [19,40,41], the use of NS has a strong effect on suspension apparent viscosity compared to grouts without NS. This effect can be attributed to the significant increase of the specific surface area of NS compared to MC, resulting in a remarkable reduction of free water in fresh grouts and the apparent viscosity obviously increased. Specifically, the increase of NS contents from 0 to 0.5% led to a decrease of initial apparent viscosity values by approximately 20.4%. This indicated that proper addition of NS (<0.5% in this study) can improve the viscous behavior and enhance fluidity of fresh grouts in a short time (about the first 55 min) when compared with grouts without NS. This was in line with other work found in the literature, the addition of 0.5–4.0% NS to the cement paste can reduce water demand when compared with ordinary cement paste by using the mini spread-flow test [38]. It can be interpreted as follows: for the addition of NS, the reduced void fraction comes along with a reduction in the water demand according to the theories of particle packing of continuously graded mixes, thus it is possible to enhance fluidity of fresh grouts.

3.2.2. Yield stress and plastic viscosity

In this research, the rheological properties of fresh grouts were determined using a rotational viscometer at different shear rates and the fresh grouts behaved generally as non-Newtonian fluids. The rheological curves of fresh grouts (W/S ratio of 1.2 and 30% MFA) with or without SP are presented in Fig. 5. The values of the Bingham model parameters as well as the correlation coefficients, $R^2$, of the Bingham model to experimental data are presented in Table 4. It can be observed that the correlation coefficients ranged from 0.98 to 0.99 and were in most cases, equal to 0.99 indicating a satisfactory fitting of the Bingham model to the experimental data. This observation is in good agreement with reports by Li et al. [5], Jiang et al. [40]. In grouting engineering, cement grouts are usually described as Bingham fluids and the Bingham model is considered as sufficiently effective and particularly practical. Therefore, it can be concluded that the fresh grouts tested in this research behaved as Bingham fluids.

As shown in Fig. 5, the yield stress (shear stress axis intercept), obtained by conducting rheological properties tests, increased with

![Fig. 4. Variations in apparent viscosity of fresh grouts with different NS contents.](image)

![Fig. 5. Rheological curves of fresh grouts with different NS contents (a) 0% SP (b) 1.0% SP.](image)

<table>
<thead>
<tr>
<th>Table 4: Rheological properties of fresh grouts.</th>
<th>0% SP</th>
<th>1.0% SP</th>
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<td>NS content (%)</td>
<td>$\tau_\eta$</td>
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<tr>
<td>0.5</td>
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$\tau_\eta$: yield stress (Pa), $\eta$: plastic viscosity (mPa·s), $R^2$: correlation coefficient.
shear rate while the plastic viscosity (curve slope) kept constant. It can be observed that the NS had negative effects on the rheological properties of fresh grouts, since an increasing NS contents results, in increased plastic viscosity and yield stress (Table 4). As NS absorbs water, the particle interlocking becomes greater and the yield stress increases [40]. Moreover, the addition of SP reduced the values of Bingham model parameters obviously. The yield stress of fresh grouts without SP ranged between 2.15 and 2.73 Pa. However, for fresh grouts with 1.0% SP, the range was 1.07 to 1.65 Pa. In regard to the plastic viscosity, the ranges were 20.9 to 37.9 mPa s without SP and 14.1 to 23.1 mPa s with 1.0% SP. Specifically, the influence of SP was more remarkable on yield stress rather than on plastic viscosity, as it has been stated by other researchers [5,41]. This can be attributed to the mutual effect of SP stress rather than on plastic viscosity, as it has been stated by other researchers [5,41].

3.3. Flow time

Fig. 6 shows the flow times of fresh grouts from V-funnel with W/S ratio of 1.2 and 1.0% SP. As shown in Fig. 6, at the W/S ratio of 1.2 and 1.0% SP content, the flow times of fresh grouts decreased obviously with the increase of MFA contents (0–40%) and increased with the increase of NS contents (1.0–2.0%). Regarding the different NS contents (1.0–2.0%), the flow times of fresh grouts were approximately 35.52–38.21, 33.95–35.32, 32.99–34.43, 32.23–33.65 and 31.73–33.21 s for MFA contents of 0, 10, 20, 30 and 40%, respectively. However, when the NS content was 0.5%, the increase of NS content from 0 to 0.5% led to a decline in flow time, with an average decrease of flow time by 0.9%. Although NS increased the flow time significantly when the content exceeded 1.0%, but NS content within 0.5% were relatively satisfactory if high fluidity was needed.

3.4. Mini-slump

The mini-slump test was commonly used to evaluate the spreading ability of fresh grouts, the results are presented in Fig. 7. As shown in Fig. 7, the mini-slump diameters of fresh grouts decreased significantly with the increase of NS and increased with the increase of MFA. The effect of MFA in increasing mini-slump diameter was not remarkable when the fresh grouts with W/S ratio of 1.2 and 1.0% SP. It can be observed that the mini-slump diameters of fresh grouts with W/S ratio of 1.2 and 1.0% SP exceeded 330 mm, therefore the fresh grouts had an acceptable spreading ability. Specifically, when the NS contents were 0%, 0.5%, 1.0%, 1.5% and 2.0%, the mini-slump diameters of fresh grouts were 365–375, 360–373, 353–360, 345–352 and 334–343 mm, respectively. Moreover, the maximum mini-slump diameters were obtained when the MFA content was 40% and there was a significant reduction in mini-slump of fresh grouts when the NS content was more than 0.5%. The reduction in mini-slump diameter can be attributed to the increased water demand of the NS. It can be concluded that the working principles of NS and MFA on spreading ability were consistent with those on flow time. In particular, the addition of MFA can increase the fluidity and spreading ability of fresh grouts, while NS has negative effects on the fluidity and spreading ability. This phenomenon is in good agreement with previous research efforts that the addition of MFA exhibits a better flowability due to its greater water reducing effect, which can be explained by the morphology of MFA [42]. The remarkable reduction of mini-slump diameter can be attributed to the much finer particle size of NS ($d_{50}$ of 30 nm) than MC and MFA ($d_{50}$ of 4.91 μm and 3.56 μm, respectively), therefore a larger surface area in total is shown as a result, which leads to a significant decrease in slump flow.

3.5. Bleed capacity

The bleed capacity of fresh grouts prepared with or without SP was tested and the results are shown in Fig. 8. According to EN 12715, the fresh grout is characterized as stable when the bleeding is less than 5% after 120 min from preparation. It is necessary to use stable grouts because unstable grouts may lead to a partial filling of rock fractures due to a high bleeding.

As shown in Fig. 8, the bleed capacity of fresh grouts decreased with the increase of NS contents and increased significantly with an increase in W/S ratios. This is indicated that the addition of NS can remarkably enhance the stability of fresh grouts, as reported in available literature [19,22]. More concretely, when the NS contents were 0%, 1% and 2%, the bleed capacity of fresh grouts with W/S ratio ≤1.5 and without SP were 1.9–5.8%, 1.9–4.2% and 1.3–3.5%, respectively. Correspondingly, the bleed capacity of fresh grouts with W/S ratio ≤1.5 and 1.5% SP were 2.2–6.2%, 2.3–4.7% and 1.6–4.0%. It can be observed that fresh grouts with
the addition of NS were stable when the W/S ratio was less than 1.5. However, the addition of 1.0% SP reduced the stability of fresh grout due to an increase of bleed capacity. From the above results, it can be seen that NS can offset the increase in bleed capacity of grouts by the addition of SP. What's more, the addition of MFA did not have an obvious effect on bleed capacity of fresh grouts.

3.6. Setting time

The setting time of grouts is a link which needs strict control in the construction of grouting engineering. Because a short setting time may cause the damages of grouting machine while a long setting time lead to a slow construction schedule. According to ASTM Standard C191, the initial and final setting time of grouts were measured on the sediments after the bleed water was negligible. The results of initial and final setting times are presented in Fig. 9. The W/S ratio was selected as 1.2.

As shown in Fig. 9, the initial and final setting times of grouts increased obviously with the increase of MFA contents. With the addition of 0, 0.5% and 1.0% NS, the initial setting times of grouts were 6.1–8.3, 5.3–7.8 and 4.2–6.8 h, respectively. The final setting times of the sediments were 10.8–13.5, 9.7–12.7 and 8.6–11.9 h, respectively. The addition of MFA prolonged the setting times, because MFA did not participate in the early hydration process and the pozzolanic effect of MFA was slow, as reported in available literature [43]. As a result, the hydration rate of grouts was reduced and the setting time was prolonged. However, the effect of NS on setting times was quite the opposite of MFA. It was apparent that NS shortened the initial and final setting times of grouts. With the increase of NS contents, the initial and final setting times were both decreased obviously, as also obtained by other researchers [27]. This behavior can be attributed to the effect of NS on the nucleation and high pozzolanic reaction during hydration process. The addition of NS can promote the gelling process of effective hydration products such as C-S-H gels, thus reduced the setting time of the sediments. Although the addition of MFA delayed the setting time of grouts, while the addition of NS can greatly eliminate this adverse effect.

3.7. Mechanical properties

3.7.1. Early strength development

Fig. 10 shows the early strength development of grouts prepared with different NS contents. The W/S ratio, MFA and SP content were 1.2, 30% and 1.0%.

As shown in Fig. 10, the approach time of 0.45 MPa decreased with the increase of NC contents. When the NS contents were 0%, 0.5% and 2.0%, the time needed for approaching a strength value of 0.45 MPa were 6.8, 6.5 and 5.8 h, respectively. It means that the addition of NS can improve the early strength of grouts. Zhang et al. [27] reported a similar trend for fly ash concrete containing NS. This can be attributed to the following reasons: (i) the NS particles can fill up the voids between the cement grains and the MFA particles, therefore, it is beneficial to strength growth due to the reduced porosity; (ii) the hydration of C3S can be accelerated by the addition of NS, and the early formation of calcium silicate hydrate (CSH) gel can provide a higher strength; (iii) the high pozzolanic reactivity of NS can react with calcium hydroxide (CH) owing to the presence of SiO2 and generate additional CSH gel, which is the main contribution for the strength development.
3.7.2. Flexural and compressive strength

Fig. 11 shows the 28-day flexural strength of hardened grouts with different MFA and NS contents. The SP content and W/S ratio were selected as 1.0% and 1.2, respectively.

As shown in Fig. 11, the flexural strength of hardened grouts increased first and then decreased with the increase of MFA contents. It can be observed that the flexural strength obtained the largest values when the MFA content was 20%. In the case of NS, the influence of NS content on flexural strength was similar to that of MFA. The addition of NS in strength improvement was significant and ascending trend can be observed for NS content up to 1% and after that the flexural strength decreased. When the content of NS was 1.0%, the flexural strengths of hardened grouts (0–40% MFA) were 3.46, 3.51, 3.67, 3.29 and 3.02 MPa, respectively.

Toward this phenomenon, there are quite few literatures to explain the combined effects of MFA, NS and SP on the flexural strength of microfine cement grouts. The reduction in flexural strength by adding more than 1% NS may due to this fact that the NS nanoparticles presented in the grouts exceed the amount required to combine with the liberated lime during the hydration process, thus leading to excess silica leaching out and causing a decline in flexural strength as it replaces part of cementitious material but does not contribute to strength. It can also be due to the deficiency occurred during dispersion of NS nanoparticles in the grouts that causes weak zones.

All the test data of compressive strength of hardened grouts with different MFA and NS contents are given in Fig. 12.

It can be observed from Fig. 12 that the 28-day compressive strength of hardened grouts decreased with the increase of MFA contents. This can be attributed to that the addition of MFA decreased the concentration of hydration minerals such as tricalcium silicate, while the compressive strength development provided by the hydration of cement was greater than that provided by pozzolanic effects. By contrast, the 28-day compressive strength of hardened grouts increased with increasing NS contents. It can also be observed that the hardened grouts showed a slower growth rate of compressive strength when NS contents exceeded 1.0%, therefore the NS contents for compressive strength should be less than 1.0% for lower cost. Specifically, when the amounts of NS were 0%, 0.5%, 1.0%, 1.5% and 2.0%, the compressive strengths of hardened grouts were 5.68–10.23, 7.01–11.94, 8.48–13.15, 9.06–13.68 and 9.37–13.89 MPa, respectively. It can be concluded that at least two possible mechanisms contribute to the increase on compressive strength of hardened grouts. The first enhancement mechanism is the packing effect of NS acted as filler to fill into the interstitial spaces inside the skeleton of hardened grouts to increase its compressive strength. The second enhancement mechanism is the pozzolanic effect that combines silicon elements in NS with the lime elements of calcium oxide and hydroxide in cement to add the bonding strength, resulting in compressive strength enhancement of hardened grouts.

3.7.3. Bonding strength

Bonding strength is an important parameter in the mechanical properties of cement grouts. In grouting engineering, the development of strong bonding between cement grouts and rocks is essential for strength enhancement and water plugging for a prolonged time. Fig. 13 shows the bonding strength of hardened grouts (30% MFA and 1.0% SP) with different NS contents and W/S ratios after 28 days of curing.

As shown in Fig. 13, similar to compressive strength, the bonding strength of hardened grouts with NS was all lager than that without NS. When the NS content from 0% to 1.0%, resulted, gener-
ally, in a significant increase of the bonding strength by 19.9%–40.5% with an average of 27.8%. However, NS content from 1.0% to 2.0%, resulted in a small increase by 4.1%–12.6% with an average of 7.1%. The results obtained in this research are in agreement with other researchers. Phoo-ngernkham et al. [44] found that nano-SiO₂ could increase shear bond strength between concrete sub-
strate and geopolymer pastes. This finding may be because NS can penetrate the concrete effectively, thus, the bonding strength improved significantly. Also, it may be attributed that the increased reaction products at the interface transition zone between hardened grouts and concrete substrate due to the reac-
tion between the alkaline activator and surface product of old sub-
strate, thus lead to denser interface zone and higher bonding strength. Moreover, the suggested dosage of NS should be con-
trolled less than 1.0%.

It can also be observed that the bonding strength decreased with the increase of W/S ratios. When the W/S ratios were 2.0, 1.5, 1.2 and 1.0, the bonding strength values were 15.32–19.12, 13.74–18.53, 10.16–13.26 and 5.43–8.59 MPa, respectively. It should be noted that the bonding strength of hardened grouts with a W/S ratio of 1.2 was close to that of 1.0. Moreover, when the W/S ratio from 1.5 to 2.0, resulted in a significant decrease of the bond-
ing strength by 54.4–87.1% with an average of 68.0%. Thus, the W/S ratio should be controlled within 1.5 to ensure a satisfactory bonding strength.

3.8. Shrinkage property

Shrinkage is a common phenomenon generally encountered in almost cement-based grout due to the loss of moisture in dry envi-
ronments and it can result in decreasing of bonding strength and reopening of cracks. Fig. 14 shows the shrinkage of grouts with dif-
ferent admixtures at different time periods. The SP content and W/ S ratio were selected as 1.0% and 1.2, respectively.

As shown in Fig. 14, the shrinkage of grouts increased with respect to the curing ages from 3 to 42 days, due to the self-
desiccation and diffusion of water to the outside of the grouts. The shrinkage of grouts containing MFA were, generally, lower than those of grouts without MFA at all ages. It means that the addition of MFA reduced the dry shrinkage of hardened grouts. This was mainly because less heat being generated when high amounts of MFA were used to replace MC. It can also be observed

that the grouts containing NS experienced higher shrinkage than that of grouts without NS. The 42-day drying shrinkage strains of grouts containing 100% MC, 1.0% NS, 30% MFA and 30% MFA + 1.0% NS were 2272.47, 2336.31, 1637.72 and 1811.49, respectively. The results obtained in this study are in agreement with those of other researchers. For example, Sadrmomtazi et al. [45] studied the effect of NS on the properties of mortar and they found that the drying shrinkage increased with increasing NS content, also higher than that of ordinary cement mortar. The mechanism that the NS increases the shrinkage of cementitious materials can be interpreted as follows [46,47]: (i) NS particles act as an activator to accelerate cement hydration and generate higher CSH gels, which holds higher amount of gel water and releases during dry-
ing, thus the degree of hydration increases as the NS content increases, resulting in a higher level of dry shrinkage; (ii) it may be due to a higher volume of mesopores, which causes a higher driving force by the tortuosity of the transport passage through the capillary network, thus tends to induce contraction of the cement paste. From the above results, it can be seen that MFA con-
tributes a considerable positive effect on the shrinkage when com-
pared with the grouts without MFA which was consistent with the finding of others [48,49] and eliminate the negative effect of NS on the shrinkage of grouts. It can be explained that cement replace-
ment by MFA reduced the lime content from the mix as MFA has a remarkably low lime content (3.98% in this research). Due to the lower lime content, the hydration rate of cement paste reduced signifi-
cantly, which resulting a lower degree of drying shrinkage compared to cement paste without MFA.

4. Conclusions

Based on the experimental results obtained and within limited ranges of parameters studied in this research, the following conclu-
sions can be drawn:

1) The incorporation of MFA and SP each reduce the viscosity and yield stress of fresh grouts, while lead to the disadvan-
tages of high bleeding, longer setting time and lower com-
pressive strength.

2) The increase of W/S ratio enhances the fluidity of fresh grouts, nevertheless, high W/C ratio adversely affects the mechanical properties of grouts: the higher the W/S ratio, the greater the reduction in strength development.
Conflict of interest

None.

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