Viscosity and hardened properties of self-compacting mortars with binary and ternary cementitious blends of fly ash and silica fume

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HIGHLIGHTS

- To provide greater sustainability in construction, use of mineral admixtures is inevitable.
- Thus, there will be pressures to maximize their effectiveness in many respects.
- Use of ternary blends improved the deficiencies of SCMs with binary blends of fly ash.

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ABSTRACT

The paper presented herein investigates the effects of using supplementary cementitious materials in binary and ternary blends on the fresh and hardened properties of self-compacting mortars (SCMs). For this purpose, a total of 25 mortar mixtures were designed having a total binder content of 640 kg/m³ and water/binder ratio between 0.41 and 0.50. The control mixture contained only Portland cement (PC) as the binder while the remaining mixtures incorporated binary and ternary cementitious blends of PC, fly ash (FA) and silica fume (SF). After mixing, the fresh properties of the mortars were tested for slump flow, V-funnel flow time and viscosity. Moreover, compressive and flexural tensile strengths of the hardened mortars were measured at 28 and 91 days whilst dry unit weight and the dynamic modulus of elasticity tests were performed at 28 days. Test results have revealed that at high shear rates, the fluidity of mortars increased regardless of the dosage and type of mineral admixtures. Also, ternary mixtures generally predominated the respective binary mixtures in terms of viscosity. The compressive strength of the control mortar performed better than binary blends of FA and all ternary mortars whilst the flexural tensile strength of the control mortar was in general higher than all binary and ternary mortars for all curing ages. The ternary use of PC, SF and FA improved the deficiencies of SCMs with binary blends of FA. Moreover, increases in SF and FA contents caused a decrease in 28-day dynamic modulus of elasticity of the mortars with binary and ternary blends.

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1. Introduction

Self-compacting mortars, as new technology products, are especially preferred for the rehabilitation and repair of reinforced concrete structures [1]. To place the fresh mortar without any external compaction and at the same time without causing any segregation, the water/cementitious materials ratio of mortar and the type of chemical admixtures should be determined. In other words, the paste phase rheology of repair mortar should possess suitable properties from the viewpoint of fluidity and segregation [2–5]. In addition to these, the self-compactability of mortars may provide considerable advantages such as reducing the construction time and labor cost, enhancing the filling capacity of highly congested structural members [6,7]. The use of the fine mineral admixtures in SCMs is inevitable to enhance its self-compactibility characteristics and to reduce the material cost of the self-compacting concrete (SCC). In general, the increase in fine-grounded materials content in cements brings about the modification of rheological properties of pastes and consequently influences the workability of mortars and concrete mixtures. The observed changes can be advantageous or not. This is because of many factors influencing the rheology of cement pastes [8]. It is usually expected that, if the volume concentration of a solid is held constant, for a specific workability, the replacement of cement with a fine powder will increase the water demand due to the increase in surface area. This is valid for silica fume [9]. Silica fume, for example, provide a marked early age strength but imparts sharp fall in workability to fresh concrete [10]. It is therefore important to note that the beneficial assets of one mineral admixture may compensate the shortcomings of the
other by interchanging them within ternary cementitious blends of SF and FA. Lange et al. [11] concluded that for a specific workability, the inclusion of specified amount of fly ash reduced the water content and improved the workability. The workability enhancement is explained by the spherical shape of fly ash which causes the particle to easily roll over one another, reducing the interparticle friction [12]. The spherical shape also minimizes the particle’s surface-to-volume ratio, resulting in low fluid demands. The use of such powder may also provide greater cohesiveness by improving the grain-size distribution and particle packing [13]. Alternatively, a viscosity modifying admixture (VMA) along with a superplasticizer (SP) may be used to impart high fluidity accompanied by the adequate viscosity [14–17]. Using of chemical admixtures, however, may increase the material cost such that the savings in labour cost might offset the increased cost. But the use of mineral admixtures not only reduced the material cost but also improved the fresh and hardened properties of SCC [18,19].

Furthermore, SCC rheology can be optimized if the fine part of the concrete is designed properly. Self-compacting mortar (SCM) may serve as a basis for the design of concrete and properties of SCMs highlight the workability of SCM mixtures [20,21]. According to Domone and Jin [21] mortars are being tested for the following reasons: (i) SCC has a lower coarse aggregate content than that of normal concrete (typically 31–35% by volume), and therefore the properties of the mortar are dominant. (ii) Assessing the properties of the mortar is an integral part of many SCC mix design processes, and therefore knowledge of the mortar properties is itself useful. (iii) The combination of powder materials is also used to control the hardened properties, such as strength. (iv) Testing mortar is more convenient than testing concrete.

To provide greater sustainability in construction, use of mineral admixtures will inevitably increase, hence, there will be pressures to maximize their effectiveness with regard to cost, environmental impact, durability, and performance. The objective of this study is to investigate the influence of mineral admixtures used as a partial replacement of Portland cement on the rheological and hardened properties of SCM mixtures.

2. Experimental program

The experimental programs consist of two stages. In the first stage, the fresh mortar flow diameter, V-funnel flow time and viscosity measurements were conducted; in the second stage, compressive strength and flexural tensile strength of the specimens prepared from the mortar mixtures were determined after 28 and 91 days of curing in water whilst the dry unit weight and the dynamic modulus of elasticity of mortars were determined at 28 and 91 days of curing in water whilst the dry unit weight and the mens prepared from the mortar mixtures were determined after viscosity measurements were conducted; in the second stage, the fresh mortar flow diameter, V-funnel flow time and

2.3. Preparation and casting of test specimens

In the production of SCMs, the mixing process was kept constant to achieve the same homogeneity and uniformity in all mixtures. First, cement, mineral admixture and sand were dry mixed for 1 min using a standard mixer described by ASTM C 109/C 109M-99 [24]. Then, HRWRA chemical admixture with water was added and mixed for an additional 4 min. The compatibility of fresh mortar mixtures was investigated by using the mini slump and V-funnel tests in conformity with EFNARC [20] standards.

After the mixing process was completed, tests were carried out on fresh mortar to assess mini slump flow diameter, mini V-funnel flow time and viscosity. Segregation and bleeding were visually observed during the slump flow test. The $160 \times 40 \times 40$ mm prisms were used to determine the flexural tensile and compressive strengths after 28 and 91 days of curing in water. Moreover, $75 \times 150$ mm cylinder type specimens at the age of 28 days were prepared for the evaluation of the dry unit weight and the dynamic modulus of elasticity of mortars. The modulus of elasticity was calculated using the ultrasonic pulse velocity (UPV) determined on mortar specimens at an age of 28 days as per the following equation:

$$E = \left( \frac{V^2 \rho}{g} \right) \cdot 10^{-2}$$

where $E$ is the modulus of elasticity (GPa), $V$ is the ultrasonic velocity (km/s), $\rho$ is the density of mortar secimens (kg/m$^3$) and $g$ is the acceleration due to gravity (9.81 m/s$^2$) [25]. After demolding, all specimens were cured in water at room temperature (21 ± 2 °C) until testing.
2.4. Test methods

The mini slump flow test for SCM is described by EFNARC [20]. In this test, a truncated cone mould was placed on a smooth plate, filled with mortar, and lifted upwards. The subsequent diameter of the mortar was measured in two perpendicular dimensions and the average was reported as the final diameter. The mini V-funnel flow test for SCM is also described by EFNARC [20]. In this test, the funnel was filled completely with mortar and the bottom outlet is opened, allowing the mortar to flow out. V-funnel flow time of mortar was the elapsed time ($t$) in seconds between the opening of the bottom outlet and the time when the light becomes visible from the bottom, when observed from the top. Deformability and viscosity of the mixtures was evaluated through the measurement of mini slump flow diameter and mini V-funnel flow time. The workability values and unit weight of fresh mortar mixtures and EFNARC [20] limits are summarized in Table 3.

Viscosity measurements were performed using a Brookfield DV-E model viscometer. It is a rotational viscometer with a smooth-walled concentric cylinder so that at low stress values, wall slip (nearly yield stress) occurs resulting in inaccurately low yield stress measurements. Slip appeared to be more influential at low

### Table 2
Weights of constituents of the mixtures.

<table>
<thead>
<tr>
<th>Mixture codes</th>
<th>W/CM (%)</th>
<th>PC (%)</th>
<th>FA (%)</th>
<th>SF (%)</th>
<th>Binder (kg/m³)</th>
<th>Sand 0–2 mm (kg/m³)</th>
<th>HRWR (kg/m³)</th>
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### Table 3
Fresh properties and dry unit weight of SCMs.

<table>
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<tr>
<th>Mixture codes</th>
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<th>V-funnel flow time (s)</th>
<th>Unit weight (kg/m³)</th>
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Acceptance criteria of SCM suggested by EFNARC

Range 24–26 7–11 –
strain rates, thus resulting unusual low viscosity. However, a decreasing in the influence of slip was observed at higher rotational speeds. Therefore, the viscosity measurements were conducted at different rotational speeds. The measurements based on the plastic viscosity were realized at the seven rotational speeds (1, 2.5, 5, 10, 20, 50, 60 and 100 rpm) immediately after mixing.

The hardened mortar specimens were also tested for the compressive strength, the flexural strength, the dry unit weight and the dynamic modulus of elasticity. The measurements for the compressive and flexural strengths were performed at 28 and 91 days of curing in water whilst the dry unit weight and the dynamic modulus of elasticity tests were carried out at 28 days of curing in water as per relevant ASTM standards. The average of three test specimens was calculated for each property.

3. Results and discussion

3.1. Fresh mortar properties

The test results relevant to the slump flow diameter, V-funnel flow time and the unit weight are presented in Table 3. All of the SCMs were designed to give a slump flow diameter of 25 ± 1 cm which was acquired by adjusting the dosage of HRWR chemical admixture used. Thus, all of the fresh mixtures had slump flow diameter conforming EFNARC [20] recommendation. SCMs with binary blends of FA showed highest V-funnel flow times followed by mixtures incorporating SF5FA40, SF5FA35, SF10FA40, SF5FA30, SF5FA25 and control mixtures. That is, it can clearly be said from this result that the flowability of mortars reduced with increasing the amount of cement replaced by FA. However, the use of ternary cementitious blends of SF and FA reduced this effect; moreover, lower flow time was noted in the control mix except for mixtures incorporated ternary cementitious blends of SF5FA25-30-35-40 and SF10FA40. Even, the V-funnel flow times of mixtures with ternary cementitious blends of SF20FA25, 30, 35 and 40 could be measured hardly due to the high flowability nature of mixtures. This may be attributed to the increasing of the smaller particle size due to SF and thus, water required for the surface covering increases. Finally, the incorporation of SF with FA in ternary blends in general improved the V-funnel time of the mortars with binary cementitious blends according to acceptance criteria of SCM suggested by EFNARC. This finding is consistent with that of Sahmaran et al. [26] who found the ternary mixtures increased the workability of the mortars.

The relationships between the V-funnel flow time and viscosity measurements at different rotational speeds for SCMs with binary and ternary cementitious blends of SF and FA were investigated. The results obtained in this study are similar to those reported by Felekog˘lu et al. [27] which indicated that the best correlated results were derived from 10 rpm as shown in Fig. 1. In certain cases, there is a correlation between the V-funnel flow time measurements and the viscosity. However, the coefficient of correlation may only reflect the general tendency because it does not seem very strong. In V-funnel test, the flow time of a constant volume of paste flowing from a definite opening is measured. In viscosimeter measurements, the resistances of fresh paste against the viscosimeter mill rotating at a set of constant rotational speeds are measured. The above mentioned two methods may be alternatively used in optimization of paste viscosity for comparison purpose if the viscosity is in the range of viscosimeter employed. However, at low viscosity changes, the V-funnel test can also be insufficient to measure the magnitude of change.

Apparent plastic viscosity changes of mixes were measured only at the beginning after mixing. As shown in Figs. 2 and 3, the viscosity of all mixes at all measurements has a similar tendency. This similar tendency was noticed by Felekog˘lu et al. [27] who found that Eq. (2) was well fitted with the measurements.

\[
\mu = a \cdot \gamma^b
\]  

where, \(\mu\) is the viscosity in centipoise, and \(\gamma\) is the rotational speed in revolutions per minute. The constants \(a\) and \(b\) were calculated by the help of the best fit equations. Viscosity changes of all mixtures at different rotational speeds are shown in Figs. 2 and 3. The behaviour of all mortar mixtures is viscous at low deformation rates, while at high deformation rates, flowable behaviour is dominant regardless of the dosage and type of mineral admixtures. From this point of view, it can be said that if mortar is mixed with an efficient liquidizer with a high shear rate, self-compactibility and filling ability of mixture may be improved due to its much higher fluidity. Thereby, the increasing of the shear rate applied on mixture by pumping at the placement stage may be an alternative way, and thus, it may be also reduced the effect of wall slip problem [27].

The development of plastic viscosity of SCMs with binary and ternary blends of FA and SF measured at different rotational speeds is graphically shown in Figs. 2 and 3, respectively. It was observed that the high rotational speed reduced the viscosity of all of the mixtures. As it is shown in Fig. 2, at one rotational speed, the effects of using FA in binary blends increased the viscosity of the mortar,
especially the effect being more pronounced with increasing the
replacement level whilst the mortars with binary blends of SF dis-
played less viscous behaviour when the SF content in mixture in-
creased. Indeed, SCMs with binary blends of FA40 had the highest
viscosity at the lowest rotational speed whilst SCMs with
binary blends of FA. However, when the rotational speed increased,
the viscosity of SCMs with binary blends of SF was higher than
those of control and SCM with FA mixtures though there was not
an important difference between the viscosity behaviour of SCMs
with binary blends of FA and SF. It can be said that the energy
needed to reach a flowable consistency should be lower for FA
rather than SF incorporated mortars with binary blends, especially
at high rotational speeds.

In Fig. 3, a reconciling could be found by combining the decreas-
ing effect of FA and increasing effect of SF at all rotational speed
except for 1 rpm when the mortars were made with ternary blends
of SF and FA. Even though the viscosity of binary FA mortars was
less than that of the control mixture except for FA40 at 1 rpm, all
SCMs with ternary cementitious blends had higher viscosity than
that of the control mixture at all rotational speed except for
1 rpm. Finally, it can be said that the ternary mixtures generally
predominated the respective binary mixtures in terms of viscosity. Because the properties of the SCMs can be characterized by a relatively low yield value for high flowability and a moderate viscosity to resist segregation and bleeding [19,28].

3.2. Hardened mortar properties

3.2.1. Dry unit weight

The unit weights of SCMs with binary and ternary blends of FA and SF were measured at 28 days (see Table 3). As expected, the unit weight of the mortars with binary and ternary blends decreased with an increase in FA and SF content due to their low unit weight compared to that of cement. The unit weight of mortars with binary blends of FA/SF varied between 1999 and 2118 kg/m³ whilst the unit weight of mortars with ternary blends of FA and SF ranged between 1896 and 2063 kg/m³, depending on total mineral admixture content. In general, decrease in the unit weight of mortars with binary blends of FA was more than that of mortars with binary blends of SF, because fly ash had lower unit weight with 2.08 gr/cm³ compared to that of silica fume (i.e., density or specific gravity).

3.2.2. Compressive strength

The compressive and flexural tensile strength development of SCMs with binary and ternary blends of FA and SF was presented in Table 4 and the percent difference in the compressive strengths of SCMs with binary or ternary blends of mineral admixtures with respect to that of the control mixture were shown in Fig. 4. The compressive strength of the control mixture at 28 days was measured to be 55.9 MPa which increased to 60.6 MPa with an increase of about 8% at 91 days. It can be clearly seen from Fig. 4 that the compressive strength of the control mortar performed better than those of mortars with binary blends of FA and all ternary mortars. However, SCMs with binary blends of SF except for SF5 had the highest the compressive strength compared to all SCMs tested at the ages of 28 and 91 days. Results obtained from many studies have shown that the rate of hardening slows due to FA replacement [29–31]. As shown in Fig. 4, replacing PC with SF contributed to strength gain of the mortars with SF10, SF15 and SF20 at the rate of 3%, 5% and 8%, respectively, at 91 days whilst an increase in compressive strength at 28-day ages was 3%, 2% and 1% for SF10, SF15 and SF20, respectively. This development in the compressive strength can be attributed to the fact that increase in the SF content tends basically to consume the calcium hydroxide crystals released from the hydration process leading to the formation of further calcium–silicate–hydrate (secondary C–S–H) and contributing to the interfacial bond strength between aggregate particles and matrix [32,33]. The ternary use of mineral admixtures improved by decreasing the deficiencies of SCMs with binary blends of FA. Indeed, 40% FA replacement in binary blends induced a decrease of 26% and 19% for 28- and 91-day compressive strength of the mortars, respectively. SCMs with ternary blends of SF15FA40 exhibited a decrease of 12% for 28 days and 8% for 91 days. This is consistent with the previous studies which have shown that the ternary use of mineral admixtures helped in decreasing the shortcoming of the mixtures with binary blends of FA [34,35].

3.2.3. Flexural tensile strength

Fig. 5 shows the percent difference in the flexural tensile strengths of SCMs with binary and ternary blends of mineral admixtures with respect to that of the control mixture. As shown in Fig. 5, the flexural tensile strength of the control

![Fig. 4. Percent difference in compressive strength of SCMs with binary and ternary blends of FA and SF at 28 and 91 days.](image-url)
mortar performed better than all of binary mortars for all curing ages except for SF20 mixture at the ages of 91-day. With increasing amount of FA content, difference in the flexural tensile strength of the mortar with binary blends of FA increased. However, for the mortar with binary blends of SF this finding is not valid. Because, the FA is somewhat coarser so it is a little slower to react [36]. It can clearly be seen from Fig. 5 that the ternary use of mineral admixtures improved the deficiencies of SCMs with binary blends of FA. Indeed, the incorporation of SF with FA in ternary blends in general decreased the difference in the flexural tensile strength compared to the mortar with binary blends of FA.

Fig. 5. Percent difference in flexural tensile strength of SCMs with binary and ternary blends of FA and SF at 28 and 91 days.

Fig. 6. Dynamic elasticity of SCMs with binary and ternary blends of FA and SF at 28 days.

Fig. 7. Correlation between compressive strength and dynamic elasticity of SCMs with binary and ternary blends of FA and SF at 28 days.
3.2.4. Dynamic modulus of elasticity

The percent difference in 28-day dynamic modulus of elasticity of SCMs with binary and ternary blends of FA and SF was shown with respect to that of the control mixture in Fig. 6. As shown in Fig. 6, the dynamic modulus of elasticity of the control mortar performed better than all mortars with mineral admixtures. Moreover, the dynamic modulus of elasticity of SCMs with binary blends of FA remarkably decreased when FA content in mortars increased from 25% to 40%. However, the dynamic modulus of elasticity of mortars with binary blends of SF exhibited slightly a decrease with the average of 3% when SF content in mortars increased from 5% to 20%. It is clear from Fig. 6 that the dynamic modulus of elasticity of the mortar mixtures with ternary blends except for SF15FA40, SF20FA25, SF20FA30, SF20FA35 and SF20FA40 was in general higher than that of the mortar mixtures with binary blends of FA. Finally, it was observed that there was generally a decrease in the dynamic modulus of elasticity whilst the percentage of total mineral admixture content in mortars with ternary blends increased. It should especially be pointed out that if this test was performed more than 28 days ago (for instance, at 56 or 90 days), including mineral additives, might be expected higher dynamic modulus of elasticity than control mixture.

Fig. 7 shows the correlation between compressive strength and dynamic elasticity of SCMs with binary and ternary blends of FA and SF at 28 days. It is clear from this figure that there is a very good correlation between the dynamic modulus of elasticity and the compressive strength of SCMs with both SF and FA, however, for the mortar mixtures with ternary blends of SF and FA this finding is not valid.

4. Conclusions

Based on the data developed and results in this study the following conclusions may be drawn:

1. V-funnel time reduced with increase in SF content in binary mixtures whilst the flowability of mortars reduced when the amount of cement replaced by FA increased. However, the use of ternary cementitious blends of SF and FA reduced this effect.
2. It can be emphasized that at high deformation rates, flowable behaviour was dominant regardless of the dosage and type of mineral admixtures. Moreover, the energy needed to reach a flowable consistency should be lower for FA rather than SF incorporated mortars with binary blends, especially at high rotational speeds.
3. The ternary mixtures generally predominated the respective binary mixtures in terms of viscosity. Because, all SCMs with ternary cementitious blends had higher viscosity than that of the control mixture at all rotational speed except for 1 rpm although the viscosity of binary FA mortars was less than that of the control mixture except for FA40 at 1 rpm.
4. Dry unit weight of the mortar decreased with an increase in the mineral admixtures content due to their low unit weight compared to that of cement.
5. The compressive strength of the control mortar performed better than binary blends of FA and all ternary mortars whilst the flexural tensile strength of the control mortar was in general higher than all binary and ternary mortars for all curing ages. Moreover, the ternary use of PC, SF and FA improved the deficiencies of SCMs with binary blends of FA.
6. Increase in SF and FA contents caused a decrease in the dynamic modulus of elasticity of the mortars with binary and ternary blends whilst the dynamic modulus of elasticity of the control mortar performed better than all mortars with SF and FA. Moreover, there is a very good correlation between the dynamic modulus of elasticity and the compressive strength of SCMs with binary blends whilst this finding is not valid for the mortars with ternary blends.

References


