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Properties of self-compacting mortar made with various types of sand

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ABSTRACT

Higher cement and fines content is needed in self-compacting mortars (SCMs) to increase their flowability and stability. Different inert fillers and supplementary cementitious materials are usually added. The use of sands rich in fines may be a cost effective alternative source of filler. This paper presents the results of an experimental study on the rheological and mechanical properties of self-compacting mortars (SCMs) made with various types of sands: crushed sand (CS), river sand (RS), dune sand (DS) and a mixture of different sands. The mini-slump flow, V-funnel flow time and viscosity measurement tests were used to study the rheological properties. The experimental results indicate that the rheological properties and strength improve with mixtures of crushed and river sands but decrease with mixtures of crushed and dune sands especially for higher dune sand content. Crushed sand with (10–15%) of limestone fines can be used successfully in production of SCM with good rheological and strength properties. However, a reduction in compressive strength with increasing dune sand content (up to 50%) in mortar with binary and ternary sands was observed.

1. Introduction

The self-compaction of fresh concrete is often described as the ability of such concrete to flow under its own weight while maintaining adequate homogeneity without segregation and bleeding [1,2]. This ability is achieved by ensuring suitable rheological properties of fresh concrete and adequate plastic viscosity together with a low yield stress. The flow properties and segregation resistance of self compacting concrete (SCC) are consequently controlled via proper adjustment of the rheology of the mortar and adequate selection of the content of coarse aggregates. For a given type and content of coarse aggregates, proper viscosity of the matrix is required to ensure the homogenous suspension of particles and reduce interparticles collision that can cause a local increase of internal stress and flow resistance.

The incorporation of supplementary cementitious materials could help improving the rheological properties of SCC as well as enhancing the particle distribution, reducing the risk of thermal cracking and improving some mechanical properties [3–5]. The use of superplasticisers (SPs) and high powder content is also another aspect of improving SCC mixture proportioning [6]. With the use of efficient superplasticizer, self-compactability can be maintained without increasing water/cement ratio, thereby the drawbacks of increasing water content are somewhat limited. However, it should be noted that, if the admixture content is excessively increased, some drawbacks such as delayed setting time or delayed demoulding can also be expected. In SCC applications optimization of admixture dosage should always be aimed [7].

Limestone filler are traditionally used to increase the powder content of SCC mixes [8,9]. More recently mineral additives have also been considered [10,11]. For example, the use of limestone filler can enhance many aspects of cement-based systems through physical or chemical effects. Some physical effects are associated with the small size of limestone particles, which can enhance the packing density of powder and reduce the interstitial void, thus decreasing entrapped water in system. For example, the use of a continuously graded skeleton of powder is reported to reduce the required powder volume to ensure adequate deformability of concrete [12]. Chemical factors include the effect of limestone filler in supplying ions into the phase solution, thus modifying the kinetics of hydration and the morphology of hydration products [13]. The influence of finely ground limestone and crushed limestone dust on the fresh properties and strength characteristics of SCC mixes was investigated by Bosiljkov [14]. The successful use of limestone dust in SCC mixes would not only lower the cost of SCC, but could also provide a solution regarding the disposal and environmental problems connected with this filler [14].

The use of sands rich in fines may be an alternative source of filler. These sands may also improve the cost effectiveness of SCC, by reducing the demand for external filler addition. Using quarry fines

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in SCC is expected to provide significant economic benefits to concrete producers [15–17]. In crushed fine aggregates production process, a high proportion of fine aggregates may sometimes be very fine [18–20]. This proportion can be as high as 10–15% of total aggregate production by weight. This very fine proportion may act as a viscosity enhancer in SCC production [21–23].

The addition of fines may improve concrete performance. Improvements in compressive and flexural strength and a decrease in permeability, absorption and porosity of concrete are reported for concrete with addition of fines [7,24,25].

It should be noted that no detailed investigation has been done to study the effect of type and quality of sand on the rheological and mechanical properties of self-compacting mortars. Hence, the main objective of this research work is to examine the influence of various types of sand with different morphologies and origins on the properties of mortars. Another objective is to provide more information about the effects of various proportions of limestone fines content as a partial replacement of crushed fine aggregates on fresh and hardened properties of self compacting mortar. Tests used to characterize the rheological and mechanical properties of mortars include: slump flow, flow time, viscosity measurements and compressive strength.

2. Experimental program

2.1. Materials

All mixtures were prepared using an ordinary Portland cement (CEM I 42.5). The chemical and physical properties of cement are given in Table 1. The physical and chemical properties of the limestone fines used are also given in Table 1.

Various types of sand were used: crushed sand (CS), river sand (RS), dune sand (DS) and a mixture of these sands. The physical properties and sieve analysis results of these sands are given in Table 2 and Fig. 1 respectively.

2.2. Mixture proportion and test program

The mixture proportions were based on Okamura's method, with improvements made on the methods of selecting the fine aggregates content. The sand–mortar (Vs/Vm), the water–powder (Vw/Vp) and the superplasticiser–powder (Sp/P) ratios were selected by a simple evaluation test for assessing the stress transferability of fresh mortar as recommended by [26].

Two groups of mortars were prepared, the first one with crushed sand which was partially replaced by limestone fines at varying percentages of 0%, 5%, 10%, 15%, 20%, 25% and 30%.

Table 1
Chemical and physical properties of cement and limestone fines.

Chemical analysis (%)	Cement (OPC)	Limestone fines
SiO_2	21.7	1.0
CaO	65.7	52.6
MgO	0.7	2.1
Al_2O_3	5.2	0.2
Fe_2O_3	2.7	0.2
SO_3	0.6	0.07
MnO	–	–
K_2O	0.4	0.04
TiO_2	–	0.01
Na_2O	0.7	0.06
CI	0.01	–
Loss on ignition	0.3	43.63
Specific density	3.15	2.7
Fineness (m^2/kg)	300	350

Table 2
Physical properties of the investigated sands.

Properties	Sand type		
	Crushed sand (CS)	River sand (RS)	Dune sand (DS)
Specific gravity	2.68	2.67	2.65
Unit weight (kg/m^3)	1541	1758	1520
Fineness modulus	2.21	2.45	0.78
Sand equivalent (%)	71	87	83

The second group of mortars was prepared with different types of sand: crushed sand in which 15% is replaced with limestone fines, river sand, dune sand and binary or ternary sands.

For all mixtures the sand/mortar and water/cement ratios were kept constant. The mixture proportions are given in Tables 3 and 4. The self-compactability of mixtures was obtained by increasing the SP dosage. SP requirement of all mixtures to reach the slump flow value of 280 ± 20 mm were determined.

2.3. Mixing procedure

The mixing procedure consisted of mixing the fine aggregates with cement for half a minute before adding 70% of necessary water during 1 min then adding the remaining 30% of water containing SP during another 1 min. The mixing procedure continues for 5 min, after that the whole mix was kept settling for 2 min before remixing for just half a minute.

2.4. Test methods

The experimental investigation consists of two stages. In the first stage, flow diameter, V-funnel flow time and viscosity measurements were conducted on fresh mortar. In the second stage, compressive strength was determined on $4 \times 4 \times 16$ mm prisms at 3, 7 and 28 days. All the test specimens were stored in water tank saturated with lime at a temperature (20 ± 2) °C until the test age.

2.4.1. Fresh mortar

2.4.1.1. Mini slump. The apparatus for the mini slump test of self-compacting mortar consists of a mould in the form of frustum of cone, 60 mm high with a diameter of 70 mm at the top and 100 mm at the base. The cone was placed at the centre of a steel base plate, and was filled with mortar. Immediately after filling, the cone was lifted, the mortar spreads over the table and the average diameter (in mm) of the spread measured. The mortar spread was visually checked for any segregation or bleeding.

2.4.1.2. V-funnel flow time. This test, suggested by Okamura et al. [24], was used to select a suitable water powder ratio in the mix design. The funnel was filled with 1.1 l of mortar, the gate was then opened and stopwatch simultaneously started. The watch was stopped when light first appeared, looking down into the funnel from above. The flow time (in s) was then recorded.

2.4.1.3. Viscosity measurement. Viscosity measurements were conducted with a rotational viscometer. The viscosity measurements were conducted at different rotational speeds. The fresh mortar was placed in the pot of the viscometer. A program of nine steps was performed upwards and downwards of different rotational speeds from 0.5 to 100 rpm and an average viscosity values computed.

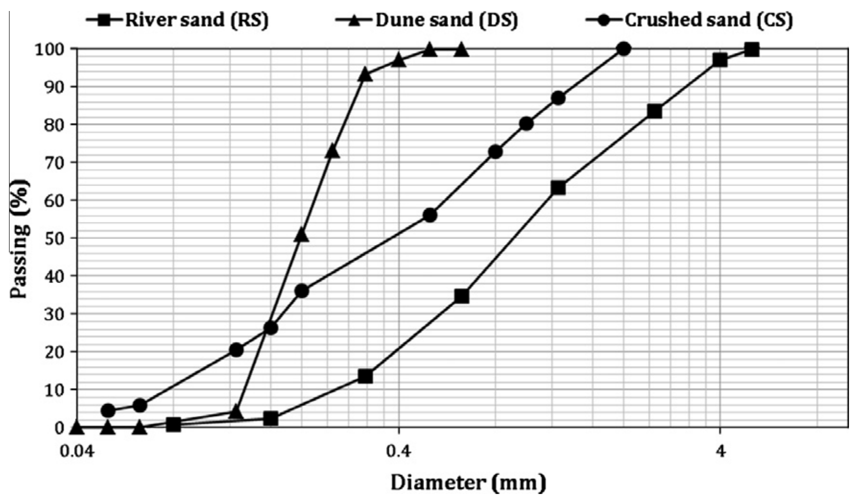

Fig. 1. Particle size distributions of different sands.

Table 3
Mix proportions of mortar made with various limestone fines content.

W/C = 0.4, S/M = 0.5							
Cement (kg/m^3)	697						
Fine aggregate (kg/m^3)	1340	1273	1205	1139	1072	1005	938
Limestone fines (%)	0	5	10	15	20	25	30
Limestone fines (kg/m^3)	0	67	135	201	268	335	402
Water (kg/m^3)	279						
Superplasticiser (%)	0.6						

2.4.2. Hardened mortar test specimens

After the completion of initial fresh mortar test, mixtures were poured into 40 × 40 × 160 mm steel moulds without any vibration and compaction. Specimens were demoulded 24 h after casting. After demoulding, specimens were cured in lime water at a temperature of (20 ± 2) °C until age of testing. The average compressive strength test results of six specimens for different ages (3, 7 and 28 days) were determined.

3. Results and discussion

3.1. Effect of limestone fines on properties of mortars

3.1.1. Slump flow

Results of slump flow test are given in Fig. 2. From this figure, it is evident that, as the percentage of limestone fines in mortar increases, the slump flow decreases. This could be explained by the increase in the fineness and specific surface area of the fine aggregates due to the increase in fines content and hence more water is required to wet the surface of particles as also reported by Bosiljkov [14].

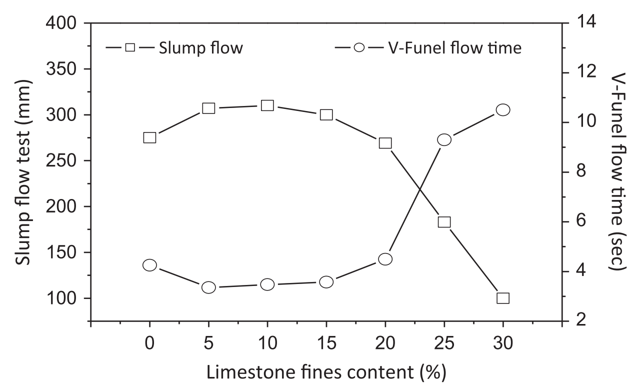

Fig. 2. Slump flow and V-funnel flow time of mortar made with various limestone fines content.

3.1.2. V-funnel flow time test

V-funnel flow times of fresh mortar test results are given in Fig. 3. It can be seen from this figure that while the limestone fines content of fresh mortar increases, the flow time of fresh mortar increases. It is observed that when limestone fines content is, respectively 10% and 15%, the mortar achieved better flowability. However, for limestone fines content more than 15% a loss of flowability was obtained.

3.1.3. Compressive strength

The results of compressive strength at 3, 7 and 28 days are shown in Fig. 3. It can be seen noted that the compressive strength at 3, 7 and 28 days increases to a maximum at limestone fines

Table 4
Mix proportions of mortar made with binary and ternary sands.

	Binary sand (CS/RS)				Binary sand (CS/DS)			Ternary sand (CS/RS/DS)		
Cement (kg/m^3)	697				697			697		
Water (kg/m^3)	279				279			279		
W/C	0.4				0.4			0.4		
SP (%)	0.6				0.6			0.6		
CS (kg/m^3)	1340	1005	670	335	1005	670	335	670	335	335
RS (kg/m^3)	0	335	670	1005	0	0	0	335	670	335
DS (kg/m^3)	0	0	0	0	335	670	1005	335	335	670
CS/RS/DS	100/0/0	75/25/0	50/50/0	25/75/0	75/0/25	50/0/50	25/0/75	50/25/25	25/50/25	25/25/50
S/M	0.5				0.5			0.5		

CS: crushed sand; RS: river sand and DS: dune sand.

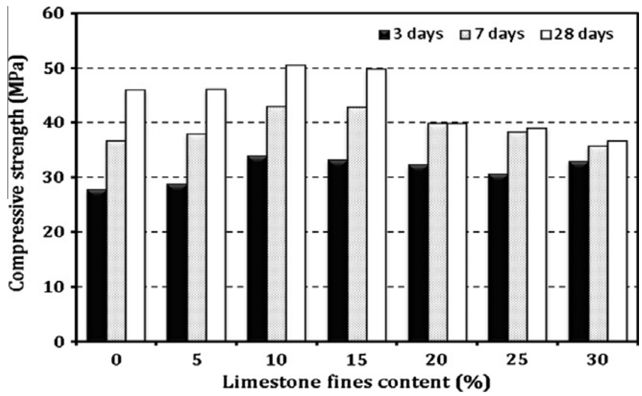

Fig. 3. Compressive strength at (3, 7 and 28 days) of mortar made with various limestone fines content.

content between 10% and 15%. For limestone fines content higher than 15%, the compressive strength decreases. This is probably due to insufficient cement paste to coat all the fin aggregate particles which consequently leads to a decrease in compressive strength. Similar results have been reported by Menadi et al. [17] on the strength of mortar incorporating crushed sand with 15% limestone fines content. For specimens without or with only 5% limestone fines, there are not enough fine particles to fill all voids between cement paste and fine aggregates particles and hence lower compressive strength values as compared to specimens with 10–15% of limestone fines content.

3.2. Effect of type of sand on properties of mortars

3.2.1. Slump flow test

Slump flow results of mortar with different types of sands are shown in the Fig. 4. Slump flow diameters of all mixtures were kept in the range of (250–300 mm) recommended by Domone and Jin [25]. However, for mortars made with mixed sand in which the content of dune sand is up to 50% in binary and ternary mortars, the dune sand remarkably reduced the slump flow. This is due to the finesses of dune sand which requires high water demand and a larger amount of cement than crushed or river sand in order to achieve high fluidity. The river sand increases the slump flow of mortar with a mixture of river and crushed sands.

3.2.2. Flow time test

The flowability of SCM was evaluated by means of mini-v funnel. It was observed from Fig. 5 that apart from 25CS/75DS mixture, all the other SCM gave flow time values in the recommended range of 2–10 s [27]. The flow times measured depend mainly on the type of sand. For mortars with high dune sand content (75%), there was no flow via the V-funnel and this loss of flowability could be related to the high surface area of dune sand. These results show that dune sand requires more water than coarser sands (crushed and river sands) to yield a mortar of the same workability. The minimum value of V-funnel flow time obtained at 25% of dune sand content may be due to the higher compactness of aggregates, which results in a smaller volume of void to be filled and hence larger amount of excess paste is gained for lubrication purpose.

3.2.3. Viscosity test

Variations in viscosity of SCM according to the rotational speed and type of sand used in preparing mortar are given in Fig. 6. It was observed that the high rotational speed reduced the viscosity of all mixtures whatever the type of sand used. The mortars with dune sand in both binary and ternary sands had consistently higher viscosity values than that of mortar with crushed or river sands. The slump flow and flow time results demonstrated that using dune sand in binary and ternary sands requires higher water content to achieve the desired workability. In general, it was observed that at low rotational speed a viscous behaviour is marked, whereas at high rotational speed a flowable behaviour is governing.

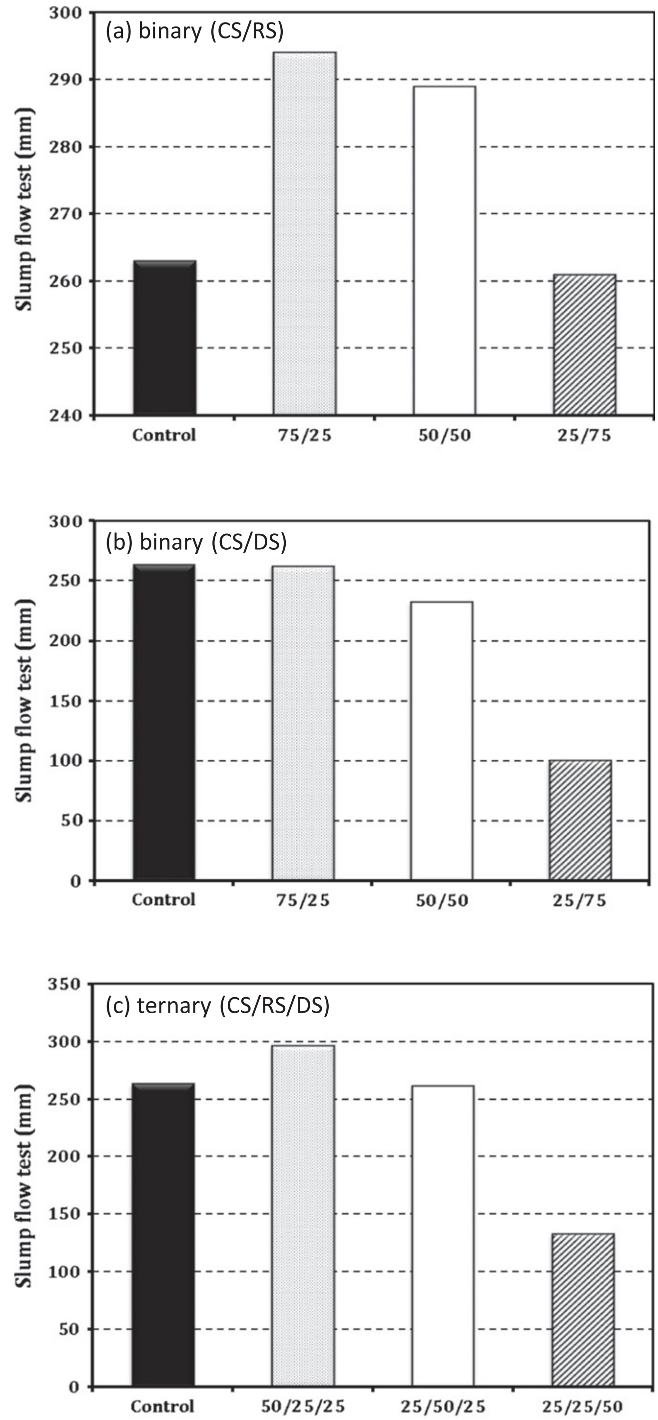

Fig. 4. Slump flow test of mortar made with: (a) binary sand (CS/RS), (b) binary sand (CS/DS), and (c) ternary sand (CS/RS/DS).

An example of the curve obtained of viscosity change of mortar at different rotational speeds is illustrated in Fig. 7. The best fit relation for all mortar mixes is of the type:

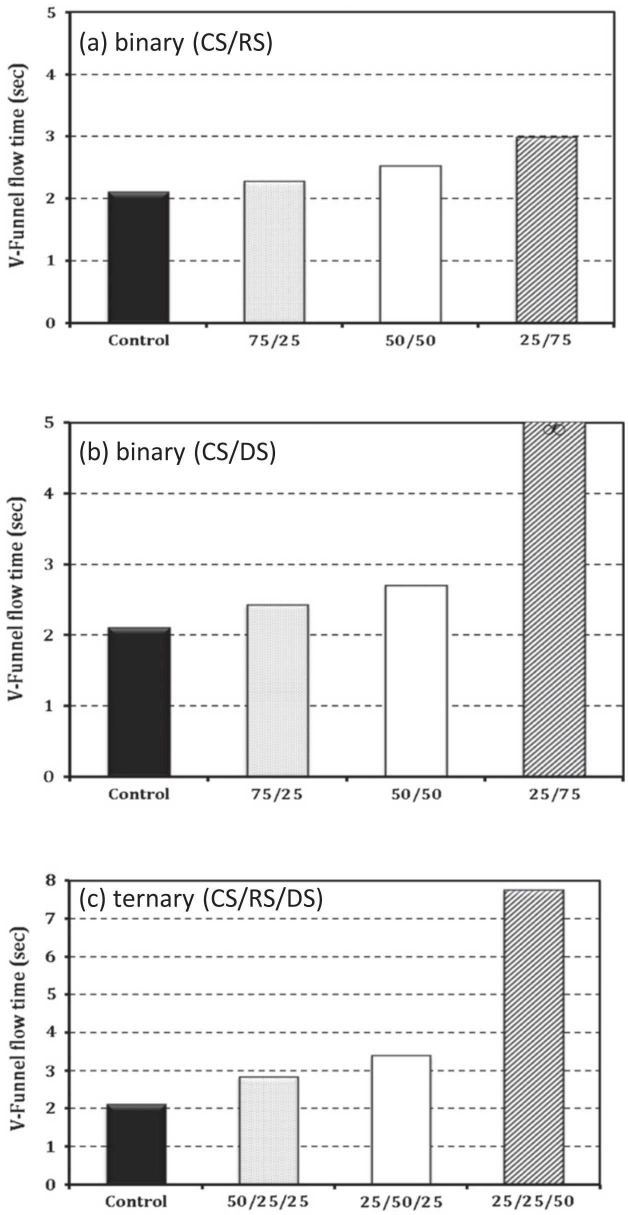

Fig. 5. V-funnel flow time test of mortar made with: (a) binary sand (CS/RS), (b) binary sand (CS/DS), and (c) ternary sand (CS/RS/DS).

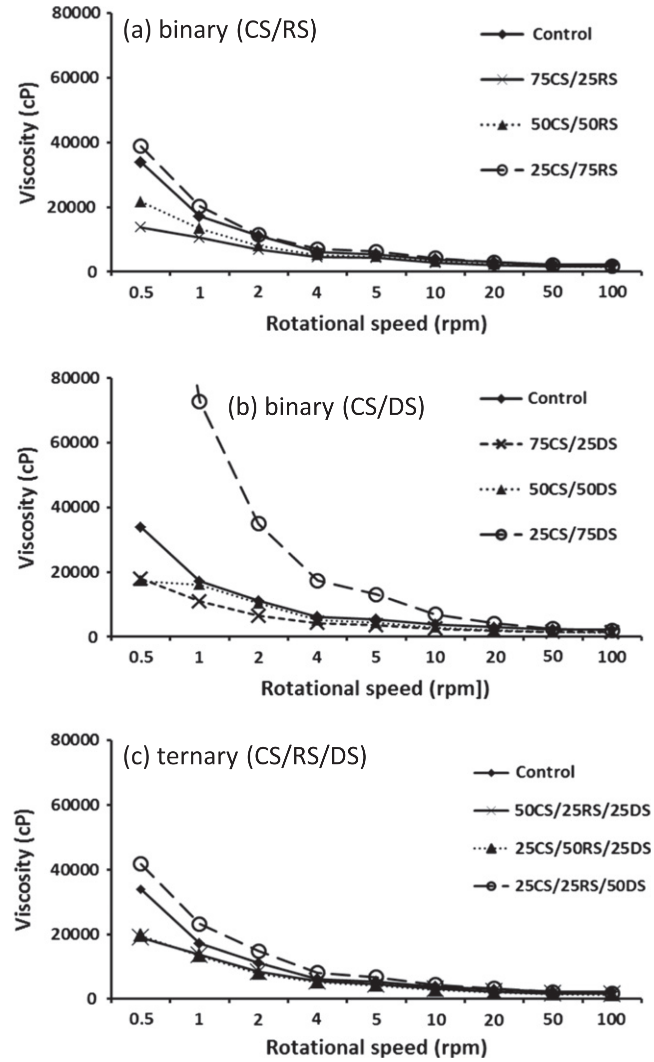

Fig. 6. Viscosity of mortar made with: (a) binary sand (CS/RS), (b) binary sand (CS/DS), and (c) ternary sand (CS/RS/DS).

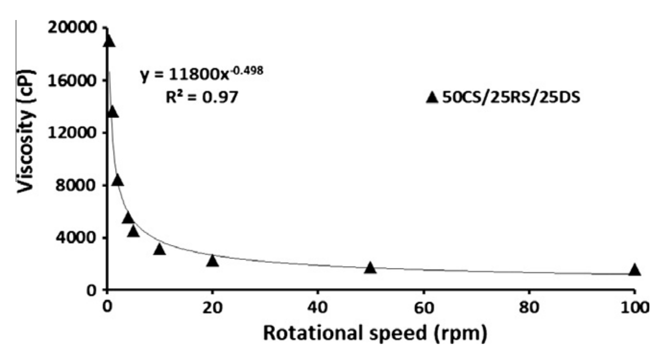

Fig. 7. The fitted equation curve of time-dependent viscosity of mortar made with ternary sand (50CS/25RS/25DS) at different rotational speeds.

$$\mu = a\gamma^b \quad (1)$$

where μ is the viscosity in centipoise (cP); γ is the rotational speed in revolutions per minute (rpm); *a* and *b* are constants of the best fit equations called also consistency index and flow index respectively.

The equation constants and regression coefficients of the best fit equations are presented in Table 5. From this table, the regression coefficients (R^2) were superior than 0.90 for all mortars with binary and ternary sands indicating a good exponential correlation. Felekoglu et al. [27] proposed a similar equation representing the variation of viscosity at different rotational speeds of self-compacting repair mortars containing fly ash and limestone fillers.

3.2.4. Correlation between viscosity and V-funnel flow time

Fig. 8 presents the relationship between the viscosity at 10 rpm and V-funnel flow time of SCM. As it is known, V-funnel flow test measures the flowability and viscosity of SCM. In the V-funnel flow test, the mortar starts to flow when the yield stress is exceeded. Once the fresh concrete starts to flow, shear stress increases linearly with an increase in strain as defined by plastic viscosity as a measure of the ease of flow. Therefore, as seen in Fig. 8 a linear relationship between the viscosity and V-funnel flow time of SCM with a reasonable correlation coefficient (R^2 = 0.75) was obtained. This relation suggests that with the increase in viscosity of SCM, the mortar is expected to have high V-funnel flow time.

Table 5
The equation constants and regression coefficients of the best fit curves.

	Control (CS)	Binary sand (CS/RS)			Binary sand (CS/DS)			Ternary sand (CS/RS/DS)		
$\mu = a\gamma^b$	100	75/25	50/50	25/75	75/25	50/50	25/75	50/25/25	25/50/25	25/25/50
A	16100	9180	12100	18900	9670	12400	67000	11800	11600	21700
B	−0.51	−0.43	−0.51	−0.57	−0.49	−0.54	−0.85	−0.49	−0.53	−0.60
R^2	0.93	0.96	0.97	0.97	0.95	0.96	0.97	0.97	0.97	0.97

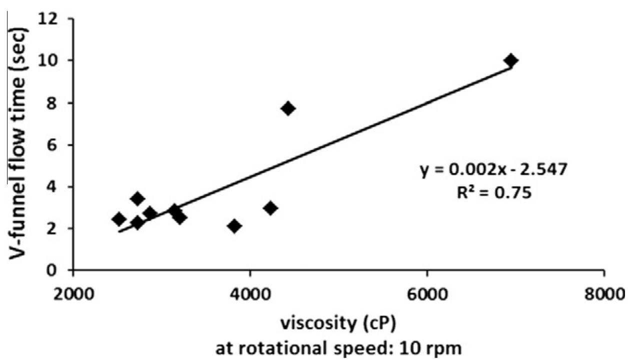

Fig. 8. Relationship between V-funnel flow time and viscosity of control mixture at rotational speed of 10 rpm.

Similar results were also reported by other researchers [27,28]. As a less sophisticated test, V-funnel flow time correlates in certain cases with viscosity at some rotational speed of viscometer. However, the coefficients of correlation seem not very strong and may only reflect the general tendency of the relation.

3.2.5. Compressive strength

Test results on the compressive strength of SCM having different composition are given in Fig. 9. It is clear that mortars containing river sand at different contents had high compressive strength than mortar made with crushed or dune sands. In addition, the strength of mortar with binary or ternary sands was superior than that of mortar made with only crushed sand at all ages. It was also observed that there was a reduction in compressive strength of the mortars with increasing dune sand content (up to 50%) in binary and ternary sands. An increase of dune sand content from 25% to 50% reduced the compressive strength by 13% at the age of 28 days. This decrease in strength is attributed to the increase in surface area of the fine aggregates requiring more cement to coat the surface of the aggregates.

The use of binary and ternary sands provided a positive effect in improving the compressive strength provided the amount of dune sand is limited to 25%.

4. Conclusions

Based on the results of this experimental investigation, the following conclusions may be drawn:

– The slump flow time decreased with the increase in limestone fines content whereas V-funnel flow time increased.
– Increasing the limestone fines content up to 10–15%, improved the compressive strength of mortar. For higher limestone fines content, the compressive strength decreased gradually.
– Crushed sand with (10–15%) of limestone fines can be used successfully in production of SCM with good rheological and strength properties.
– Mortars made with binary and ternary sand improved significantly the compressive strength and satisfied the SCM limits in terms of slump flow and V-funnel time. However, SCM

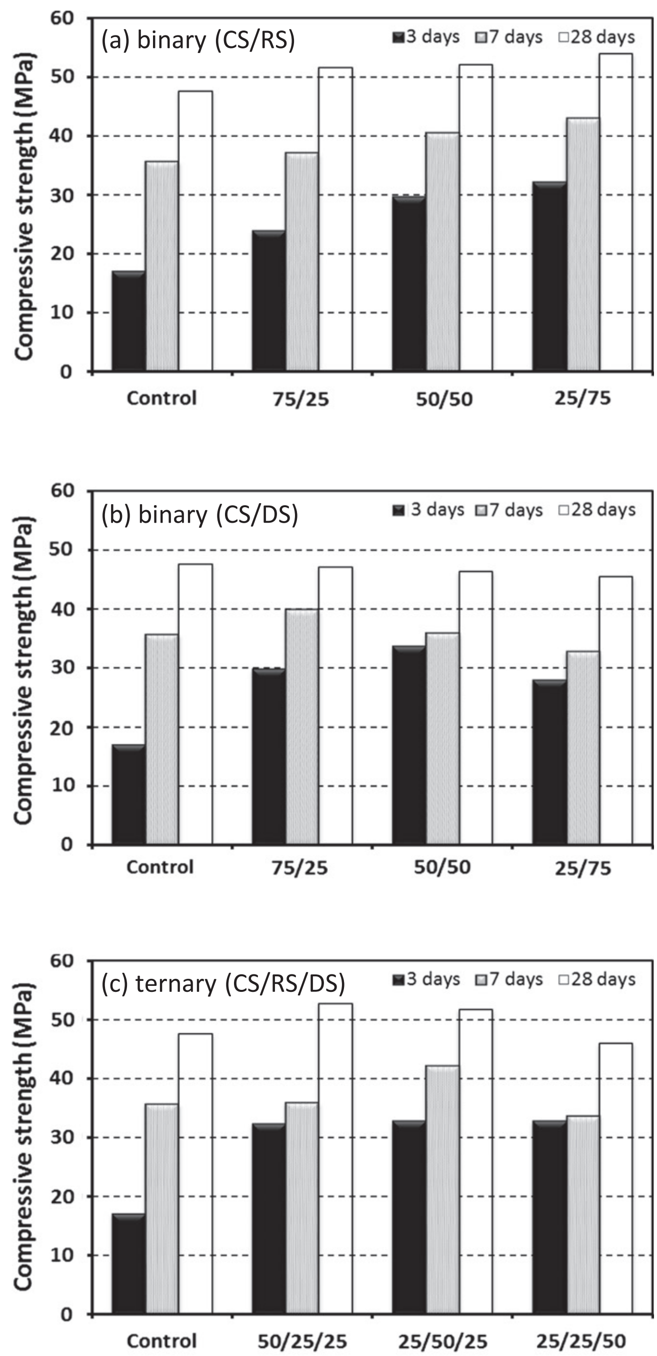

Fig. 9. Compressive strength at (3, 7 and 28 days) of mortar made with: (a) binary sand (CS/RS), (b) binary sand (CS/DS), and (c) ternary sand (CS/RS/DS).

mixture containing high content of dune sand (up to 50%) exhibited smaller flow diameter and longer flow time as compared with mortar containing no dune sand or only 25% of dune sand. This is due to the finesses of dune sand which requires high water demand and a larger amount of cement than crushed or river sand in order to achieve high fluidity.

– The V-funnel flow time has a direct relationship with viscosity as the increase in V-funnel flow time increases the viscosity of mortar.
– The use of binary and ternary sands in SCC application would lead to technical, economical and environmental benefits for concrete producers.

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