Afyon Kocatepe Üniversitesi Fen ve Mühendislik Bilimleri Dergisi

Afyon Kocatepe University Journal of Science and Engineering

AKÜ FEMÜBİD **22** (2022) 015601 (187-198) AKU J. Sci. Eng. **22** (2022) 015601 (187-198)

DOI: 10.35414/akufemubid.1025031

Araştırma Makalesi / Research Article

Effects of Fines Content and Type, and Coarse Aggregate Size on the Workability Properties of Self-Compacting Concretes

Hayati HİLMİOĞLU[1], Cengiz ŞENGÜL[1], Mustafa Hulusi ÖZKUL*[1]

[1]*Istanbul Teknik Üniversitesi, İnşaat Fakültesi, Maslak 34469 Istanbul.*

e-posta: hayatihilmi@gmail.com ORCID ID: http://orcid.org/0000-0001-7345-6912

cengizsengul.79@gmail.com ORCID ID: http://orcid.org/0000-0003-4748-7269

**Sorumlu yazar e-posta: hozkul@itu.edu.tr ORCID ID: http://orcid.org/0000-0002-6453-8956*

Geliş Tarihi: 17.11.2021 Kabul Tarihi: 02.02.2022

Abstract

Self-compacting concretes (SCC) were prepared with 10 mm and 16 mm coarse aggregate sizes and using limestone powder (LS) and fly ash (FA) as fine material. The amount of fines in concrete, where the amount of cement and the water / cement ratio were kept constant, was increased in 36 dm^3 increments up to 108 dm^3. The effect of the type and amount of fines and coarse aggregate size on flowing, passing, segregation and blocking properties of SCCs were examined. Experimental results indicated that slump flow increases with increasing fines content. Opposite to this, V-funnel times increased with increasing fines content, however, they were shorter for FA than those of LS, which can be attributed the balling and lubrication effect of the former and arching effect of the latter particles. For both fines, higher segregation was obtained for SCCs with 16 mm than those of 10 mm. The SCCs with low amount of fines displayed higher blocking step in general and FA-added concretes had higher segregation than those of LS. The difference in the behaviors of LS and UK added concretes is most probably due to the differences in the particle shape and surface properties.

Keywords

SCC; Slump flow; Passing ability; Segregation; Blocking; Fines

İnce Malzeme Miktarı ve Cinsi ile İri Agrega Boyutunun Kendiliğinden Yerleşen Betonların İşlenebilirlik Özelliklerine Etkisi

Öz

Kendiliğinden yerleşen betonlar (KYB), 10 mm ve 16 mm iri agrega boyutlarında ve ince malzeme olarak kalker tozu (KT) ve uçucu kül (UK) kullanılarak hazırlanmıştır. Çimento miktarı ve su/çimento oranının sabit tutulduğu betonlardaki ince malzeme miktarı 36 dm^3'lük artışlarla 108 dm^3'e kadar çıkarılmıştır. İnce malzeme tipi ve miktarının ve iri agrega boyutunun KYB'lerin akma, dar açıklıktan geçme, ayrışma, bloke olma gibi özelliklerine etkisi incelenmiştir. Deneysel sonuçlar, artan ince malzeme içeriği ile çökme akışının arttığını göstermiştir. Bunun tersine, artan ince tane içeriği ile V-hunisi süreleri artmıştır, ancak UK için KT'den daha kısa süreler elde edilmiştir. UK küresel tanecik yapısında olduğu için beton karışımı içinde yağlayıcı etki gösterir. Her iki ince malzeme için de 16 mm'lik KYB'ler için 10 mm'lik olanlardan daha yüksek segregasyon elde edilmiştir. Düşük miktarda ince malzeme içeren KYB'ler genel olarak daha yüksek blokaj adımı sergilemiştir ve UK katkılı betonlar KT'ye göre daha yüksek ayrışma göstermiştir. KT'li ve UK'lı KYB'lerde gözlenen bu farklı davranış muhtemelen tane şekli ve yüzey özelliklerindeki farklılıklardan kaynaklanmaktadır.

Anahtar kelimeler

KYB; Yayılma akış; Geçme yeteneği; Ayrışma; Blokaj; İnce malzeme

1. Introduction

The innovation of self-compacting concrete (SCC) can be regarded as a revolution in concrete technology. SCC was originally developed in 1988, to improve the durability of concrete structures (Okamura and Ouchi 2003). In recent years, it has found wide applications in construction due to its ability to fill molds without vibration. The production of SCCs requires a powerful superplasticizer, usually polycarboxylate-based, as well as a powder, mostly limestone filler (LS), fly ash (FA), granulated blast furnace slag or silica fume, or a viscosity modifying agent (VMA), such as polysaccharides, or both (Shindoh and Matsuoka 2003).

The maximum aggregate size, grading, shape and angularity are important properties of aggregates which affect the fresh state behavior of SCC (Koehler and Fowler 2007a). In the production of SCCs, crushed stone, crushed gravel or uncrushed gravel can be used as coarse aggregate (CA), and river sand, crushed sand or dune sand (or combinations of them) can be used as fine aggregate, in a similar way to those used for normal vibrated concretes (NVC). Khaleel *et al*. (2011) used gravel, crushed gravel and crushed limestone as CA in SCC, obtaining the best performance on fresh concrete with gravel, followed by crushed gravel and then crushed limestone because of the differences in the particle shape and surface texture. Likewise, Kraenkel *et al*. (2009) prepared SCCs by using gravel, crushed granite or crushed basalt as CA and they observed that the concretes with crushed aggregates had longer V-funnel and J-ring times than those of the former due to the difference in surface roughness.

Maximum aggregate size is reduced in SCC, compared to that of NVC, in order to obtain passing ability and segregation resistance (Koehler and Fowler 2007b). Workability properties measured as T500, V-funnel flowing time, U-box and L-box (for passing ability and filling ability) showed improvement for a maximum size of 10 mm compared to that of 20 mm (Khaleel *et al*. 2011). Mueller and Wallevik (2009) measured the rheologic properties of SCCs by using a BML viscometer and found that, although the plastic viscosity showed a slight change with an increase in maximum aggregate size, the yield stress increased significantly. Bouzian (2013) used river sand (RS), crushed sand (CS) and dune sand (DS) as fine aggregate in SCCs and observed that CS and DS in binary and ternary systems with RS should be lower than 65 and 24%, respectively, in order to obtain sufficient flowability. Similarly, Zeghichi *et al*. (2014) used DS and CS in the production of SCCs; they observed that the addition of DS into CS lowered the viscosity of the SCC and also improved the flowability due to the rounded shape of the dune particles.

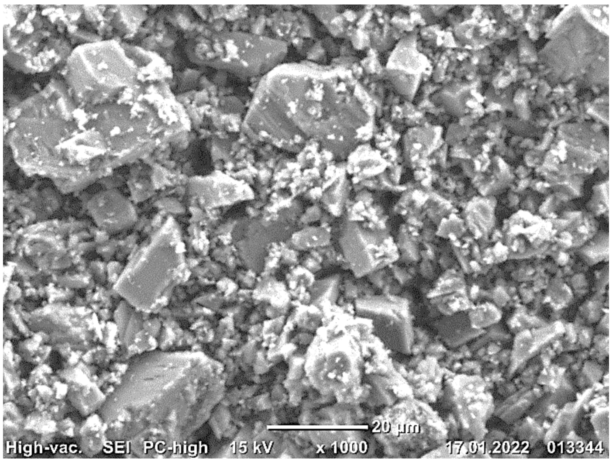
The most widely used filler in SCC is LS, followed by FA and granulated blast furnace slag (GBFS). The grading, fineness, amount, particle shape and surface roughness of the filler are important factors for the performance of SCCs in their fresh state. Skender *et al*. (2021) found decreased slump flows with increasing LS content in the case of cement substitution, while T_{500} and V-funnel flow times increased. On the contrary, LS was used as a cement replacement; larger amounts of filler caused lower yield stress and, as a result, higher slump values were obtained but plastic viscosity increased (Varhen *et al*. 2016). Askarian *et al*. (2018) used a natural pozzolan, pumice powder, as cement replacement in SCCs and obtained higher SP dosage to reach the target slump flow, however; the slump flow retention was improved compared to the mixtures with fly ash or slag. Barbhuiya (2011) used dolomite powder and FA in binary and ternary mixtures, and although the slump-flow results fell into the SF1 class (EFNARC 2005), SCCs with a high amount of dolomite powder showed lower spreads than those of the latter. SCCs were designed by using F-type FA up to 15% cement replacement; higher slump-flow and lower T500 and V-funnel times than those of the concrete without FA were reported (Jalal *et al*. 2013). It seems that the spherical shape of the FA particles gives more deformability to the SCCs than the angular particles of the cement. Class F type FA was used at cement replacement rates of 10 to 50% and yield stress decreased by up to 30% (Laskar and Talukdar 2008). Plastic viscosity showed an initial increase for the 10% rate, and then gradually decreased up to 30% rate. Both yield stress and plastic viscosity showed insignificant changes beyond the 30% level. Likewise, the rheological properties, yield stress and plastic viscosity increased with a high-calcium FA content (Ponikiewski and Golaszewski 2013).

In this study, 2 different fine materials (LS and FA) were used to produce SCCs at 3 different volumes (36, 72 and 108 dm^3/m^3) and with different aggregate sizes (10 and 16 mm). The effects of concrete composition on flowing, passing ability through the barriers, segregation, and blocking were investigated.

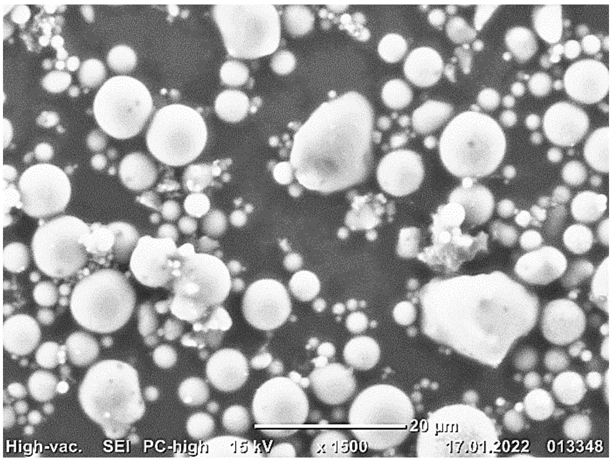
2. Materials and Methods

2.1 Materials

CEM I 42.5 R type cement was used in accordance with EN 197-1 (2011). Two types of fine materials, LS (98.5% CaCO3) and FA (Its chemical composition is given in Table 1), were employed in the production of SCCs. The specific gravities of LS and FA were 2.77 and 2.52, respectively. The SEM images of the particles of both fines, LS and FA, are shown in Fig. 1.



(a)



(b)

Figure 1. The SEM images of LS (a) and FA (b) particles

The grading curves of cement, LS and FA are presented in Fig. 2.

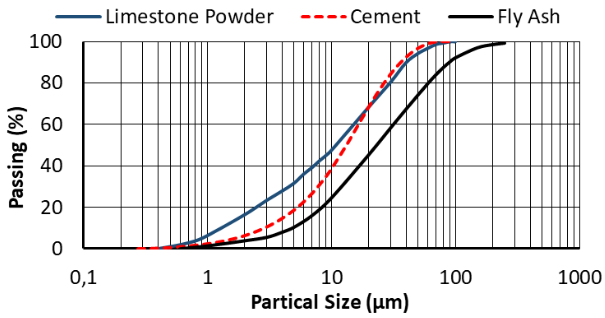


Figure 2. Gradings of fines used

Crushed stone 1, with a maximum size of 10 mm and specific gravity of 2.72, and Crushed stone 2, with a maximum size of 16 mm and specific gravity of 2.71, were used as CA. Crushed stone sand and natural sand (with specific gravities of 2.68 and 2.65, respectively) were employed as fine aggregate.
The Fuller parabola was used to determine the mixing proportions of the aggregates.

$$p_i = 100\,(d_i/D_{max})^{1/2} \quad (1)$$

where p_i shows passing percentage through a sieve, d_i is a sieve size and D_{max} is the maximum aggregate size.
Polycarboxylate ether-based admixture (density: 1.03 g/cm^3) was used as a superplasticizer. Polysaccharide-based admixture with a density of 1.01 g/cm^3 was employed as VMA.

2.2 Concrete Mixtures and Production

In all SCC mixtures, 350 kg/m^3 cement and LS or FA was used as filler material. Filler content was increased by 100 kg/m^3 increments for LS (80 kg/m^3 for FA) up to 300 kg/m^3 (or 240 kg/m^3 for FA) so that the volume of fine material in each mixture (LS or FA) was equal.
The water/cement ratio was 0.48 for all mixtures and the slump-flow was maintained within the SF2-SF3 limits (EFNARC 2005) by adjusting the superplasticizer content. For the mixtures with a total fines content (including cement) of 350 and 450 kg/m^3 (for both 10 and 16 mm maximum aggregate sizes), VMA was added to maintain the flow and prevent the segregation of concrete. The mixing proportions for both concretes are given in Table 1. In the coding of the mixtures, the first letters represent the type of the fines (CNT: control mixture without fines), the numbers following the letters show the volume of the fines (in dm^3/m^3) and max. aggregate size (mm), respectively.

Table 1. Materials proportions of SCCs

Materials Proportions (kg/m^3)								
Max. Agg. Size	10 mm				16 mm			
Mix Codes	CNT.0.10	LS.36.10/ FA.36.10	LS.72.10/ FA.72.10	LS.108.10/ FA.108.10	CNT.0.16	LS.36.16/ FA.36.16	LS.72.16/ FA.72.16	LS.108.16/ FA.108.16
Fines (LS or FA) volume (dm^3/m^3)	0	36	72	108	0	36	72	108
Cement	350	350	350	350	350	350	350	350
Water	178	178	178	178	178	178	178	178
LS/FA	0/0	100/82	200/164	300/246	0/0	100/82	200/164	300/246
Natural sand	537	509	483	454	537	509	483	454
Crushed sand	513	486	461	433	513	486	461	433
Crushed stone 1	777	737	699	657	389	368	348	328
Crushed stone 2	0	0	0	0	390	369	349	330
Superplasticizer	5.3/5.3	6.8/5.2	7.7/5.1	6.5/5.4	5.3/5.3	6.8/6.5	6.7/7.7	6.3/6.0
VMA (LS/FA)	3.2/3.2	2.7/2.2	0/0	0/0	3.2/3.2	2.7/2.6	0/0	0/0
Total Materials (LS/FA)	2363.5/ 2363.5	2369.5/ 2349.4	2378.7/ 2340.1	2378.5/ 2323.4	2365.5/ 2365.5	2369.5/ 2351.1	2375.7/ 2340.7	2379.3/ 2325
W/C ratio	0.508	0.508	0.508	0.508	0.508	0.508	0.508	0.508
W/P ratio (LS/FA)	0.508 / 0.508	0.395 / 0.412	0.323 / 0.346	0.273 / 0.298	0.508 / 0.508	0.395 / 0.412	0.323 / 0.346	0.273 / 0.298

For concrete production, a concrete pan mixer, with a capacity of 500 dm^3, was used. First, the aggregates and LS or FA were dry mixed for 2 minutes. After this, 75% of the mixing water was added and mixed for a further 2 minutes. Then the cement was introduced and an additional minute of mixing followed. Finally, the superplasticizer and VMA (if necessary) and the rest of the water were included and mixed for 3 minutes.

2.3. Testing Procedures

Slump flow and T_{500}, V-funnel (VF), and J-ring tests were carried out on fresh concrete in accordance with EN 12350-8 (2010), EN 12350-9 (2010) and EN 12350-12 (2010), respectively. Segregation resistance of the fresh concrete was determined by using two methods: sieving and penetration tests (in accordance with EN 12350-11 (2010) and modified ASTM C1712 (2014), respectively). A weight of 54 g was used in this study, as recommended in other studies (Bui *et al*. 2002), but unlike the requirements in ASTM C1712 (2014) (where 45 g is specified).

3. Test Results and Discussion

3.1. Admixture Requirements

The mixing compositions of the SCCs given in Table 1 shows that the amount of SP was increased with the amount of LS up to 200 kg/m^3 (volume: 72 dm^3) and slightly less for 300 kg/m^3 (LS volume: 108 dm^3) for both CA sizes. On the other hand, the required SP contents for FA added mixtures with a maximum aggregate size of 10 mm were less than those for 16 mm and less than those for the mixtures with LS. However, for 16 mm aggregate, a similar trend was obtained with the LS mixtures. When the SP/P ratios are considered, all mixtures showed a decreasing tendency with increasing the fines content, as Table 1 indicates. Similarly, in order to obtain a target slump flow of 600 to 650 mm, an SP/P of 2.2% was required for the added LS (25%), while it was 1.2% for the addition of 55% (Zhu and Gibbs 2005). Furthermore, the SCCs with FA and 10 mm aggregate size required the lowest SP/P ratios among the mixtures prepared in this study. The relation between the superplasticizer dosage and FA content was investigated and it was found that the superplasticizer dosage necessary to obtain the same filling property decreased with an increase in FA content (Liu 2010). Furthermore, for the two lower fines contents of 350 and 450 kg/m^3 (or 422 kg/m3 for FA), the use of VMA was needed to maintain the segregation resistance and flow for both types of fines. The amounts of VMA required for the SCCs with the higher fines content were less than those required for lower fine contents, as expected.

3.2. Slump Flows

Slump flows obtained for SCCs with added LS and FA can be seen in Table 2 and Fig. 3 for both maximum aggregate sizes. Slump flow increased slightly with an increase in LS, although the W/C ratio was kept constant and W/P ratio was decreased, as Fig. 3 indicates. For LS contents up to 72 dm3/m3 (550 kg/m3) the slump flows remained between 70 and 80 cm (SF2 and SF3 in accordance with EFNARC 2005) [14] and 71 to 75 cm (SF2) for the 10 mm and 16 mm CA sizes, respectively; this shows the positive effect of lower aggregate size on slump flow. In this range of LS contents, the SP/P ratio showed a slight decrease, from 1.5% to 1.4%, with an increase in fines. However, when the LS content was increased

Table 2. Fresh state properties of SCCs

Mix Codes	LS/FA Volume (dm^3/m^3)	Max. Agg. Size (mm)	Slump Flow (cm)	T_{500} (s)	Blocking Step (mm)	V-Funnel Time (s)	Sieve Segregation (%)	Penetration (mm)
CNT.0.10	0	10	70	3	15	6	4	3
LS.36.10	36	10	80	2	3	13	4	6
LS.72.10	72	10	79	3	5	15	3	6
LS.108.10	108	10	87	3	3	13	10	7
CNT.0.16	0	16	72	2	14	5	11	3
LS.36.16	36	16	71	2	6	16	9	8
LS.72.16	72	16	75	3	5	17	11	9
LS.108.16	108	16	87	3	6	17	13	9
CNT.0.10	0	10	70	3	15	6	4	3
FA.36.10	36	10	70	3	12	6	3	3
FA.72.10	72	10	77	3	8	8	7	3
FA.108.10	108	10	85	2	3	9	18	8
CNT.0.16	0	16	72	2	14	5	11	3
FA.36.16	36	16	72	2	13	5	10	6
FA.72.16	72	16	73	2	11	5	7	6
FA.108.16	108	16	82	2	8	7	16	6

from 72 dm^3/m^3 to 108 dm^3/m^3, a sharp increase of slump flow from 79 cm to 87 cm and from 75 cm to 87 cm (slightly exceeding SF3 for both sizes) were obtained for the CA sizes of 10 mm and 16 mm, respectively, although SP/P ratio was further decreased down to 1.0%.

With the use of FA, the ratio of SP/P decreased with an increasing amount of fine material, similar to LS, as can be seen in Table 1. Fig. 3 shows that slump flow increases with increasing FA content for the maximum aggregate size of 10 mm, similar to the LS mixtures. On the other hand, for the FA SCCs with 16 mm size, the slump flow does not change as FA content increases up to 72 dm^3/m^3, but it does show an increase beyond that. The W/C ratio was kept constant for both fine types and, also, both maximum aggregate sizes. However, W/P decreased with increased fines content, from 0.48 to 0.26 for the LS and from 0.48 to 0.28 for the FA added SCCs, respectively. Despite the decrease in W/P and SP/P, the increase in slump flow can be attributed to the decrease in CA volume due to the increase in fines in the mixtures. Furthermore, it was shown that the exchange of cement with LS powder decreased both the plastic viscosity and yield shear stress of the cement pastes, which was attributed to better packing of the LS particles (Diamantonis *et al* 2010). Similarly, Jalal *et al*. (2013) observed an increase in slump flow for the SCCs when the cement was replaced with FA, up to 15%, and also when the total binder increased from 400 kg/m^3 to 500 kg/m^3. The improvement obtained in the FA containing SCCs was attributed to the reduction in water demand (Khatib 2008) as well as its lubricant (Liu 2010) and ball bearing (Laskar and Talukdar 2008) effects, due to its spherical particles, as can be seen in Fig. 1. When the slump flows of LS and FA added concretes are compared, Fig. 3 shows that the SCCs with LS have slightly higher slump flows than those with FA. This can be due to the slightly higher SP/P ratios of the former mixtures (Table 1) and the higher mass of the LS used, since the comparison was made for an equal volume of powder content. Likewise, lower viscosity was reported for cement pastes with added LS (with SP) than those with FA pastes (Felekoglu *et al*. 2006),

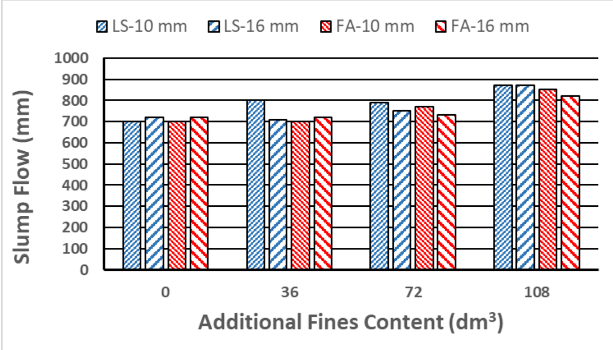


Figure 3. Variation of slump flow with fines contents

which was attributed to the difference between the zeta potentials of these mixtures.

3.3. T500 and V-Funnel Flow Times

During the slump flow tests, T500 was also measured and their variations with both fines are given in Fig. 4 for both aggregate sizes. Flow rates to 500 mm remained at 2 to 3 second levels, as can be seen in Fig. 4. Although T500 rates are known to be an indirect measure of plastic viscosity [14], the results obtained here do not show any definite trend. However, it was reported that T500 can only be related to the plastic viscosity of concretes if they have similar slump flows (Takada and Tangtermsirikul 2000).

Fig. 5 indicates that V-funnel flowing times are longer than those of the SCCs without LS but with VMA, showing that the addition of fine material decreases flow properties. This result is to be expected because the V-funnel test was proposed to measure the plastic viscosity of an SCC (EFNARC 2005) and the addition of fines increases the viscosity of a mixture. Since the flow times obtained for LS-added mixtures are greater than 9 s, the SCCs are classified as VF2, however, those without fines are VF1. Fig. 5 also shows that the flow times for 10 mm CA size were shorter than those for 16 mm. The flow times initially increased with an increase in fines but then returned to the level of the lowest amount of fines added-mixture for 10 mm size aggregate concrete. When the SCCs prepared with 16 mm CA are considered, flow times first increased up to the fines of 72 dm^3 and then remained at the same level for the next amount of fines.

In the case of FA-added SCCs, the flow times showed a continuous increase with increasing amount of fine material for 10 mm aggregate size, as can be seen in Fig. 5. For 16 mm aggregate size, V-funnel times remained constant up to the FA content of 72 dm^3/m^3 and increased beyond that. However, in these SCCs, the flow times for 16 mm aggregate size were obtained shorter than those of 10 mm, as opposed to LS concrete. When the V-funnel times of SCCs prepared with LS or FA additions are compared, Fig. 5 indicates that the flowing times are longer for the former fines than the latter for both CA sizes. It is well known that when the maximum aggregate size of a concrete increases, the total surface area of aggregate particles decreases. This results in two things; the first is a reduction in the wetting of aggregate particles (Khatib 2008), which increases the amount of free water; hence the workability of concrete increases. The second effect is an increase in the thickness of the cement paste which coats the CA particles (Hu and Wang 2011). Increasing the coating thickness of particles reduces the friction between them and hence, flow properties show improvement. As a result of this, it is expected that when the CA size increases, the flowing times and plastic viscosity of a concrete should decrease. However, most studies show the opposite of this prediction to be true; increased CA size causes an increase in flowing times for V-funnel testing. This result could be due to the character of the V-funnel test. In this test, there is a funnel with a narrow bottom outlet and during testing, concrete should pass through this outlet. It is obvious that flow properties, such as the friction between the CA particles, affects the flowing time, however there is another factor, the arching effect of coarse particles close to the bottom outlet, which also increases the flowing time (Su *et al*. 2001, Nanthagopalan and Santhanam 2009). Furthermore, the LS particles have an angular shape and rough surface texture, similar to the crushed CA used in the mixture. This may cause more arching effects as a result of interlocking between the particles (Kwan and Ng 2010). However, F type FA particles, show lubrication (Jiao *et al*. 2017) and ball bearing effects (Jalal *et al*. 2013, Laskar and Talukdar 2008) due to their spherical shape and smooth surface (Fig. 1),

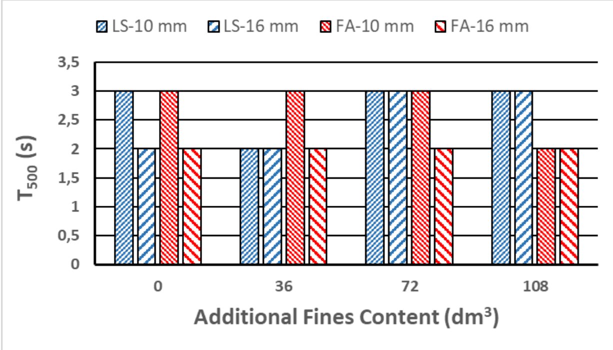


Figure 4. Variation of T_{500} with fines contents

which may reduce the arching effect, as a result of which the flowing times of the SCCs with larger CA becomes shorter than those of smaller size because the latter have a greater surface area than the former. Also, for the same reason, the FA-added mixtures have either the same or slightly longer flowing times than the control mixture without additional fines, although the difference between the flowing times of the LS-added mixtures and control mixtures (and also between the former mixtures and FA-added ones) are larger (Fig. 5). Similarly, the V-funnel times measured on FA-added SCCs were shorter than those of dolomite powder (2011) and LS (Silva and Brito 2013).

3.4. Segregation Resistance

Two methods (sieving and penetration) were used to determine the segregation resistance of SCCs and the results are given in Figs. 6 and 7 for both methods, respectively. These figures show that as the maximum size of CA increases, the sieve segregation also increases in general (except the SCCs with maximum amount of FA).

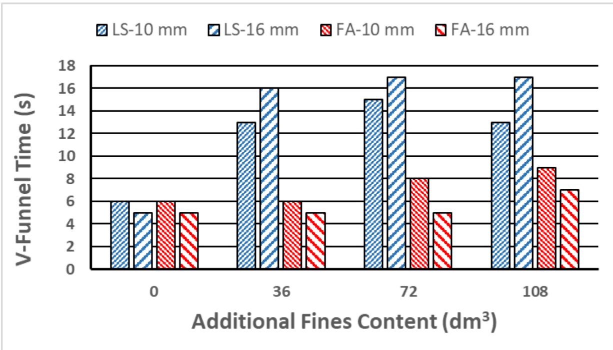


Figure 5. Variation of V-funnel flowing time with fines content.

It is known that as the maximum aggregate size of a concrete increases, the specific surface area decreases, which reduces the frictional force between the CA particles and mortar. Because of this, large particles can settle more than small particles in concrete. It was suggested by using Stokes' Law that, the spherical particles (CAs) in a liquid (mortar) can settle when the dimensionless parameter Yg (Eq. 1) remains under 0.143 (Beris *et al*. 1985).

$$Y_g = \frac{3.\tau_0}{2.R.|\Delta\rho|.g} \qquad (2)$$

where τ_0 is the yield stress (N/m^2) of the mortar part of SCC, $|\Delta\rho|$ is the density difference (kg/m^3) between the CA and mortar, R is the maximum radius (m) of the CA, and g is the gravity acceleration. Eq. (2) indicates that when the size of CA increases, Yg decreases, causing settlement of the larger CA particles, which results in segregation. Maximum limits of 10% (Khayt *et al*. 1999) and 8 mm (Bui *et al*. 2002) were suggested for the sieving and penetration tests, respectively. Fig. 6 shows that for the SCCs with 10 mm CA size, the sieve segregation test results remained under the segregation limit for both fines, except the mixture with the highest amount of FA content. However, for 16 mm CA size, a considerable segregation was predicted for the highest amount of fines; higher for that with FA than that of LS. The high segregation obtained for the highest FA content can be attributed to the low viscosity of this concrete compared with that of the LS-added concrete.

Static segregations depends on the CA size, the density difference between the aggregate and paste, the viscosity and yield stress of the paste, the aggregate volume fraction and grading, and the type of cement paste (Shen *et al*. 2009). Fig. 6 also indicates that segregation increases with an increase in fines in general. For the concretes with constant W/C ratio, increases in fines content causes increases in paste volume, which separates the CA particles from each other and enables them to settle more easily (Esmaeilkhanian 2014).

The segregation results measured by the penetration method are illustrated in Fig. 7 for both fines. Fig. 7 shows that for the 10 mm CA size, all of the penetration results indicated no segregation for the LS or the FA. However, for low fines contents the penetrations were slightly higher for LS-added SCCs than for those of FA. When the fines were increased to the highest level, penetration increased for both types of fines (slightly higher for FA) but still remained within the limits. When SCCs with 16 mm CA are considered, penetration slightly exceeded the segregation limit for the two highest LS contents. Similarly, Silva and Brito (2015) reported that the SCCs with FA are less prone to segregation compared with those of LS. Furthermore, the penetrations obtained for the LS were higher than those of FA for all levels of fines, including the highest fines content, which contradicts the results of the sieve tests. Dynamic and static segregations are defined as the separation of CA from mortar in fresh concrete during transporting or placing and during settlement, respectively (El-Chabib and Nehdi 2006). The penetration and sieve tests are acceptable static segregation methods (Shen *et al*. 2015) however; the latter method also includes the actions of flow, which may be the reason for the

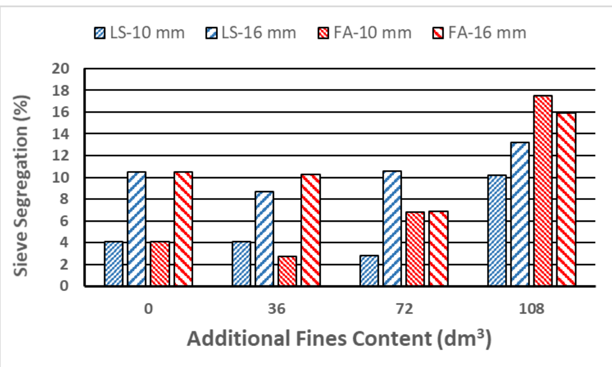


Figure 6. Variation of sieving segregation with fines content

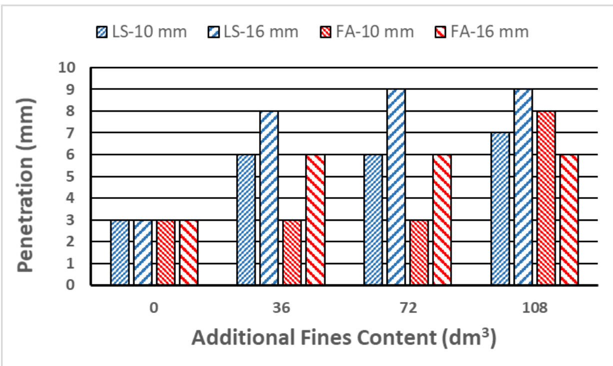


Figure 7. Variation of penetration segregation with fines contents

differences between the measured results.

3.5. J-Ring Results

In the J-ring test, concrete passes through steel bars representing reinforcement in reinforced concrete structures. This test measures the ability of an SCC to flow and pass through obstacles. The difference between the middle point inside the ring and the average heights of four points just outside the ring (blocking step) can be taken as a measure of the passing ability. Variations of blocking steps in J-ring tests, for varying amounts of LS and FA, are demonstrated in Fig. 8 for both CA sizes. The SCCs, without any extra fines but prepared with the addition of VMA, showed the higher blocking step for both maximum aggregate sizes than those of the mixtures using LS or FA. Similarly, by using the L-box test, the blocking of SCC was investigated by Petersson and Billberg (1999) and it was found that only up to 10% of SCC filler can be reduced by using VMA. Furthermore, the blocking steps of these concretes exceeded the limit of 10 mm (EFNARC 2002), showing that, although a concrete may have a high slump flow, it may still show blocking. However, the addition of 36 dm^3/m^3 LS into these concretes reduced the blocking step under the limit of 10 mm. Similarly, addition of ground stone powder beyond 50 kg/m^3 reduced the blocking step to under 10 mm (Mueller *et al*. 2014). Fig. 8 also shows that the blocking step is smaller for the CA size of 10 mm than for 16 mm, in general, with the exception of SCCs with fines of 72 dm^3, which have equal steps for both sizes.

When the SCCs prepared with FA are considered

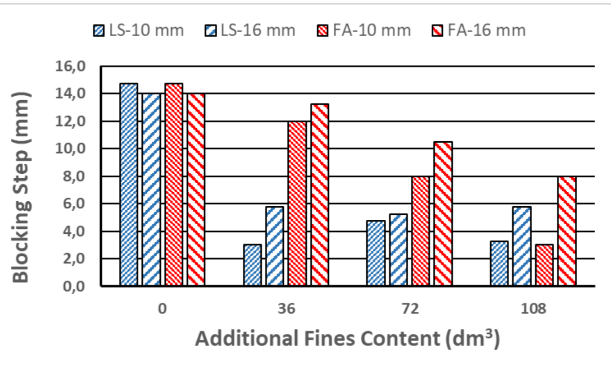


Figure 8. Variation of blocking step with fines content.

(Fig. 8), the blocking step reduced with an increase in FA content for both CA sizes. Besides, the greater the aggregate size, the higher the blocking step. For low amounts of FA, the blocking exceeds the limit and it was necessary to include at least 72 dm^3/m^3 FA for the 10 mm aggregate size but more than that for the 16 mm aggregate size in order to remain under the limit. Similarly, Pandurangan *et al*. [49] reported that when the size of the CA was increased from 10 to 20 mm, the blocking step increased 83.8% and 34.9% for low (40% of cement) and high (60%) FA contents, respectively.

Fig. 8 shows that the FA-added SCCs have higher blocking steps than those of LS for all fines contents and both aggregate sizes, except for the 10 mm aggregate size and the maximum amount of fines, which are approximately equal. It seems that a certain amount of the CA in FA-added SCCs separates from the mortar while passing between the bars during the J-ring test. This behavior could be due to the low viscosity of FA-added concretes. It is known that viscosity is related to the cohesion between the particles in a concrete, which holds the particles together. A concrete with a higher viscosity, hence with a higher cohesion, can pass between the obstacles (bars) keeping its unity and without segregation. For this reason, the SCCs prepared with LS showed low blocking step, owing to the higher viscosities than those of FA-added ones. Okamura and Ouchi (2003) explained that highly viscous paste is required to avoid the blockage when concrete flows through reinforcing bars. Likewise, it was reported that the risk of blockage could be reduced by providing adequate viscosity, hence maintaining the solid particles in good suspension as they pass the obstacles (Khayat 1999). Similarly, increased blocking steps were obtained in SCCs with increased fly ash content (Liu 2010).

4. Conclusions

The following conclusions can be drawn from this study, regarding the effects of fines type and content as well as maximum aggregate size on the workability properties of SCCs.

1. Slump flow either showed a slight increase or remained unchanged with both LS and FA additions up to 72 dm^3/m^3 and a large increase after this amount of fines. SP content decreased with increasing powder content for both types of fines and aggregate sizes.

2. T_{500} flowing times remained at between 2 to 3 seconds and did not show a particular trend with the addition of fines or aggregate size. However, V-funnel times increased with the addition of LS, probably due to the friction between the particles and as well as arching effects. The flow times either remained constant or increased with an increasing amount of FA content. Additionally, V-funnel times were shorter for the FA added mixtures than those of LS ones, due to the differences in shape and surface texture of the fine particles.

3. For both LS and FA fines, segregation measured by both methods displayed higher segregation for SCCs with 16 mm aggregate size than for those with 10 mm. By the sieving method, all the SCCs prepared remained in the SR2 segregation resistance class in general. The penetration method predicted segregations either under or equal to the limit of 8 mm for the SCCs prepared with 10 mm aggregate size, however, it slightly exceeded the limit for those prepared with 16 mm aggregate and LS mixtures.

4. SCCs prepared with VMA but without any extra fine material showed the highest blocking step in the J-ring test, but the addition of LS powder of 36 dm^3/m^3 and above reduced the blockage below the 10 mm limit for both aggregate sizes. Fly ash-added SCCs displayed higher segregation than those of LS.

Acknowledgments

The authors wish to thank the Scientific and Technological Research Council of Turkey (TUBITAK) for providing support for this study (MAG-115M483). The authors also thank ITU. BAP (Project No. 39476) for their support.

5. References

Askarian, M., Aval, S.F., Joshaghani, A., 2018. A comprehensive experimental study on the performance of pumice powder in self-compacting concrete (SCC). *Journal of Sustainable Cement-Based Materials,* **7**, 340–356.

ASTM. C1712. 2014. Standard Test Method for Rapid Assessment of Static Segregation Resistance of Self-Consolidating Concrete Using Penetration Test. ASTM-C1712. West Conshohocken, PA, USA.

Barbhuiya, S., 2011. Effects of fly ash and dolomite powder on the properties of self-compacting concrete. *Construction and Building Materials*, **25**, 3301-3305.

Beris, A. N., Tsamopoulos, J.A. Armstrong, R.C. and Brown, R.A., 1985. Creeping motion of a sphere through a Bingham plastic. *Journal of Fluid Mechanics*, **158**, 219–244.

Bouzian., T., 2013. Assessment of fresh properties and compressive strength of self-compacting concrete made with different sand types by mixture design modelling approach. *Construction and Building Materials*, **49**, 308–314.

Bui, V. K., Montgomery, D.,. Hinczak, I. and Turner, K., 2002. Rapid testing methods for segregation resistance of self-compacting concrete. *Cement and Concrete Research*, **32**, 1489-1496.

Diamantonis, N., Marinos, I., Katsiotis, M.S., Sakellariou, A., Papathanasiou, A., Kaloidas, V. and Katsioti, M., 2010. Investigations about the influence of fine additives on the viscosity of cement paste for self-compacting concrete. *Construction and Building Materials*, **24**, 1518–1522.

EFNARC 2002. (The European Federation of Specialist Construction Chemicals and Concrete Systems) Specification and Guidelines for Self-Compacting Concrete. EFNARC. Norfolk, UK.

EFNARC 2005. The European Guidelines for Self-Compacting Concrete: Specification, Production and Use. The Self-Compacting Concrete European Project Group. Norfolk, UK.

EN 197-1. CEN (European Committee for Standardization). 2011. Cement -Part1: Composition, Specifications and Conformity Criteria for Common Cements. Brussels, Belgium.

EN 12350-8. CEN (European Committee for Standardization). 2010a. Testing fresh concrete - Part

8: Self-compacting concrete - Slump-flow test. Brussels, Belgium.

EN 12350-9. CEN (European Committee for Standardization). 2010b. Testing fresh concrete - Part 9: Self-compacting concrete — V-funnel test. Brussels, Belgium.

EN 12350-11. CEN (European Committee for Standardization). 2010d. Testing fresh concrete - Part 11: Self-compacting concrete — Sieve segregation test. Brussels, Belgium.

EN 12350-12. CEN (European Committee for Standardization). 2010c. Testing fresh concrete - Part 12: Self-compacting concrete — J-ring test. Brussels, Belgium.

El-Chabib, H. and Nehdi, M., 2006. Effect of mixture design parameters on segregation of self-consolidating concrete. *ACI Materials Journal*, **103**, 374-383.

Esmaeilkhanian, B., Khayat, K.H., Yahia, A. and Feys, D., 2014. Effects of mix design parameters and rheological properties on dynamic stability of self-consolidating concrete. *Cement and Concrete Composites*, **54**, 21–28.

Felekoglu, B., Tosun, K., Baradan, B. Altun, A. and Uyulgan, B., 2006. The effect of fly ash and limestone fillers on the viscosity and compressive strength of self-compacting repair mortars. *Cement and Concrete Research*, **36**, 1719–1726.

Hu, J. and Wang, K., 2011. Effect of coarse aggregate characteristics on concrete rheology. *Construction and Building Materials*, **25**, 1196–1204.

Jalal, M., Fathi, M. and Farzad, M., 2013. Effects of fly ash and TiO2 nanoparticles on rheological, mechanical, microstructural and thermal properties of high strength self-compacting concrete. *Mechanics of Materials*, **61**, 11-27.

Jiao, D., Shi, C., Yuan, Q., An, X., Liu, Y. and Li., H., 2017. Effect of constituents on rheological properties of fresh concrete-A review. *Cement and Concrete Composites*, **83**, 146-159.

Khaleel, O. R., Al-Mishhadani, S. A. and Abdul Razak, H., 2011. The effect of coarse aggregate on fresh and hardened properties of self-compacting concrete (SCC). *Procedia Engineering*, **14**, 805–813.

Khatib, J.M., 2007. Performance of self-compacting concrete containing fly ash. *Construction and Building Materials*, **22**, 1963–1971.

Khayat, K. H., Hu, C. and Monty, H., 1999. Stability of self-consolidating concrete, advantages and potential applications. Proc., 1st International RILEM Symposium on Self-Compacting Concrete, edited by A. Skarendahl, Ö. Petersson, PRO 7, RILEM Pub. SARL, Stockholm, Sweden, 143-152.

Khayat, K. H. 1999., Workability, testing, and performance of self-consolidating concrete. *ACI Materials Journal*, **96**, 346-353.

Koehler, E. P. and Fowler, D. W., 2007a. Aggregate in self-consolidating concrete. ICAR Project 108, The University of Texas at Austin: International Center for Aggregates Research, p. 362.

Koehler, E. P. and Fowler, D.W., 2007b. Proportioning SCC based on aggregate characteristics. Proc., 5th Int. RILEM Symp. on Self-Compacting Concrete, edited by G. De Schutter and V. Boel, Gent, Belgium, 67-72.

Kraenkel, T., Lowke, D. and Schiebl, P., 2009. Effect of coarse aggregate on properties of self-compacting concrete. Proc., 2nd Inter. Symp. on Design, Performance and Use of Self-Consolidating Concrete, SCC'2009-China, edited by C. Shi, Z. Yu, K.H. Khayat and P. Yan, Beijing, China, 201-211.

Kwan, A. K. H. and Ng, I.Y.T., 2010. Improving performance and robustness of SCC by adding supplementary cementitious materials. *Construction and Building Materials*, **24**, 2260–2266.

Laskar, A. I. and Talukdar, S., 2008. Rheological behavior of high performance concrete with mineral admixtures and their blending. *Construction and Building Materials*, **22**, 2345-2354.

Liu, M., 2009. Self-compacting concrete with different levels of pulverized fuel ash. *Construction and Building Materials*, **24**, 1245–1252.

Mueller F. V. and Wallevik O. H., 2009. Effect of maximum aggregate size in air-entrained eco-concrete. Proc., 2nd Inter. Symp. on Design, Performance and Use of Self-Consolidating Concrete, SCC'2009-China, edited by C. Shi, Z. Yu, K.H. Khayat and P. Yan, Beijing, China, 664-673.

Mueller, F. V., Wallevik, O. H. and Khayat, K. H., 2014. Linking solid particle packing of Eco-SCC to material performance. *Cement and Concrete Composites*, **54**, 117–125.

Nanthagopalan, P. and Santhanam, M., 2009. Experimental investigations on the influence of paste composition and content on the properties of self-compacting concrete. *Construction and Building Materials*, **23**, 3443–3449.

Navarrete, I. and Lopez, M., 2016. Estimating the segregation of concrete based on mixture design and vibratory energy. *Construction and Building Materials*, **122**, 384–390.

Okamura, H. and Ouchi, M., 2003. Self-compacting concrete. *Journal of Advanced Concrete Technology*, **1**, 5-15.

Pandurangan, K., Ramakrishna, G. and Kothandaraman, S., 2012. Effect of coarse aggregate size and shape on the strength and flow characteristics of self-compacting concrete. *Indian Concrete Institute Journal*, **13**, 1-7.

Petersson, Ö. and Billberg, P., 1999. Investigation on blocking of self-compacting concrete with different maximum aggregate size and use of viscosity agent instead of filler. Proc., 1st International RILEM Symposium on Self-Compacting Concrete, edited by A. Skarendahl and Ö. Petersson. RILEM Pub., SARL, Stockholm, Sweden, 333-344.

Ponikiewski, T. and Golaszewski, J., 2013. The rheological and mechanical properties of high-performance self-compacting concrete with high-calcium fly ash. *Procedia Engineering*, **65**, 33-38.

Shen, L., Struble, L. and Lange, D., 2009. Modeling static segregation of self-consolidating concrete. *ACI Materials Journal*, **106**, 367-373.

Shen, L., Jovein, H. B. and Wang, Q., 2015. Correlating aggregate properties and concrete rheology to dynamic segregation of self-consolidating concrete. *Journal of Materials in Civil Engineering*, **28**, 040150671.

Shindoh, T. and Matsuoka Y., 2003. Development of combination-type self-compacting concrete and evaluation test methods. *Journal of Advanced Concrete Technology*, **1**, 26-36.

Silva, P. and Brito, J., 2013. Electrical resistivity and permeability of self-compacting concrete with incorporation of fly ash and limestone filler. *Advances in Concrete Construction*, **1**, 65-84.

Silva, P. R. and Brito, J., 2015. Fresh-state properties of self-compacting mortar and concrete with combined use of limestone filler and fly ash. *Materials Research*, **18**, 1097-1108.

Skender, Z., Bali A., and Kettab, R., 2021. Self-compacting concrete (SCC) behavior incorporating limestone fines as cement and sand replacement. *European Journal of Environmental and Civil Engineering*, **25**, 1852–1873.

Su, N., Hsu, K.-C. and Chai, H.-W., 2001. A simple mix design method for self-compacting concrete. *Cement and Concrete Research*, **31**, 1799–1807.

Takada, K. and Tangtermsirikul, S., 2000. Self-Compacting Concrete - State-of-the-Art Report of RILEM TC 174-SCC. Edited by Å. Skarendahland, Ö. Petersson, RILEM Pub. SARL, 25-39.

Varhen, C., Dilonardo, I., de Oliveira Romano, R. C., Pileggi, R. G. and de Figueiredo, A. D., 2016. Effect of the substitution of cement by limestone filler on the rheological behaviour and shrinkage of microconcretes. *Construction and Building Materials*, **125**, 375-386.

Yahia A. and Khayat, K. H., 2006. Modification of the concrete rheometer to determine rheological parameters of self-consolidating concrete. Proc., 2nd International Symposium on Concrete through Science and Engineering, edited by J. Marchand, B. Bissonnette, R. Gagné, M. Jolin and F. Paradis, RILEM Publications SARL, Canada, 375-380.

Zeghichi, L., Benghazi, Z. and Baali, L., 2014. The effect of the kind of sands and additions on the mechanical behaviour of S.C.C. *Physics Procedia*, **55**, 485 – 492.

Zhu, W. and Gibbs, J.C., 2005. Use of different limestone and chalk powders in self-compacting concrete. *Cement and Concrete Research*, **35**, 1457–1462.