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FRESH AND HARDENED STATE PROPERTIES OF SCCs PREPARED WITH LIMESTONE-BASED MANUFACTURED AGGREGATES AND POWDER

KİREÇTAŞI ESASLI KIRMATAŞ AGREGA VE TAŞ TOZU İLE HAZIRLANAN KYB'LERİN TAZE VE SERTLEŞMİŞ HAL ÖZELLİKLERİ

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ABSTRACT

Because the amount of sand and gravel extracted from natural resources is quickly depleting, the use of manufactured aggregates is becoming increasingly important in terms of sustainability. In this study, crushed limestone and filler material were used as both sand and coarse aggregate and powder material. As a result, all of the concrete components' grains had an angular form and a rough surface. Self-compacting concretes (SCC) were made with a maximum aggregate size of 10 or 16 mm and cement content of 350 kg/m^3. The amount of limestone fine was raised in increments of 100 kg/m^3 up to 300 kg/m^3. The effects of fine material amount and maximum coarse aggregate size on spreading, flow, passing ability through the obstacles, segregation, and rheological properties of SCCs were determined. Although the mixtures' slump flow performances remained in the SF2 and SF3 classes according to EFNARC standards, longer V-funnel times and larger J-ring differences were obtained when compared to slump flow values, particularly for 16 mm aggregate size. The hardened state properties of concretes were examined by measuring the compressive and splitting tensile strengths, modulus of elasticity and Poisson ratio.

Keywords: SCC, passing ability, segregation, strength, Poisson ratio

ÖZET

Doğal kaynaklardan çıkarılan kum ve çakıl miktarı hızla tükendiği için kırmataş agregaların kullanımı sürdürülebilirlik açısından giderek önem kazanmaktadır. Bu çalışmada hem kum hem de iri agrega ve toz malzeme olarak kırma kalker ve filler malzemesi kullanılmıştır. Tüm beton bileşenlerinin tanecikleri köşeli bir şekle ve pürüzlü bir yüzeye sahiptir. Kendiliğinden yerleşen betonlar (KYB), maksimum agrega boyutu 10 veya 16 mm ve çimento içeriği 350 kg/m^3 olacak şekilde hazırlanmıştır. Kireç taşı filleri miktarı 100 kg/m^3'lük artışlarla 300 kg/m^3'e kadar yükseltilmiştir. İnce malzeme miktarı ve maksimum iri agrega boyutunun KYB'lerin taze haldeki yayılma, akış, engeller arasından geçme, ayrışma ve reolojik özellikleri üzerindeki etkileri belirlenmiştir. Karışımların çökme akış performansları EFNARC standartlarına göre SF2 ve SF3 sınıflarında kalmasına rağmen özellikle 16 mm iri agrega boyutlu betonlar için çökme akış değerlerine göre daha uzun V-hunisi akış süreleri ve daha büyük J-halkası farklılıkları gözlenmiştir. Sertleşmiş haldeki özellikleri, basınç ve yarma-çekme dayanımları, elastisite modülü ve Poisson oranları ölçülerek incelenmiştir.

Anahtar Kelimeler: KYB, geçiş yeteneği, ayrışma, dayanım, Poisson oranı

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INTRODUCTION

Sand and gravel aggregate extraction is the largest-volume mining operation in the world (Peduzzi, 2014). It is estimated that soon, the extraction rate of sand and gravel will exceed their regeneration rate (Bendixen et al., 2021). Sand and gravel are often obtained from riverbeds, seabeds, lakes, and floodplains, causing serious environmental problems. Therefore, the use of other aggregate options, such as crushed sand and recycled aggregates makes concrete more sustainable. Dune sand, which is abundant in the world, should also be investigated as another source of fine aggregates. On the other hand, in self-compacting concretes, the amount of fine aggregate should be increased along with the amount of fines. For this reason, using alternative sand in SCCs is critical.

Self-compacting concrete (SCC) has unique properties; it consolidates under its weight without the help of vibration (Okamura & Ouchi, 2003). SCCs exhibit higher flowability and passing ability through obstacles (steel bars) than normal vibrated concretes (NVC) and high segregation resistance. SCCs owe these properties to the powerful superplasticizer (SP) and the modification of mixing composition. The viscosity of the mixture should be increased to a moderate level to balance the segregation effect of powerful SP, either by increasing the fine material paste with a reduced water/fine material ratio or by using a viscosity modifying agent (VMA) (Nanthagopalan & Santhanam, 2009; Girish et al., 2010).

The number of studies on self-compacting concretes in which only crushed sand is used as fine aggregate is rare. There are several differences between crushed sand and natural sand. Crushed sand has angular particles, a rough surface texture, and the particles have different dimensions of length, width, and thickness, whereas natural sand particles are round in shape and their surfaces are smooth. Similar to river sand, dune sand particles have a rounded shape and smooth surface, but they have a much smaller size than river sand particles; their fineness modulus usually remains under 1.0 (Al-Harthy et al., 2007). When used in the production of SCC, it was observed that crushed sand requires a relatively higher amount of paste than river sand to obtain a certain level of slump flow (Nanthagopalan & Santhanam, 2011). This high paste volume was attributed to the difference in shape between the sands used. Crushed sand (CS), river sand (RS), and dune sand (DS) were used in SCCs as binary or ternary mixtures. Increasing CS in RS-CS binary and RS-CS-DS ternary systems decreased the slump flow and increased the V-funnel times (Bouziani, 2013). The effects of sand types on strength properties of SCCs were investigated by using the same type of sands in binary and ternary systems, and it was stated that the mixtures containing CS displayed the highest compressive strength, while those containing DS were the lowest (Bouziani, 2013; Benabed et al., 2012). In another study, Zeghichi et al. (2014) achieved high compressive and tensile strengths when DS was mixed with 50% CS.

Using crushed stone aggregate instead of gravel in concrete is a sustainable approach because gravel is a rapidly depleted material like natural sand. Gravel, crushed gravel, and crushed limestone were used in SCC as coarse aggregate and fresh and hardened concrete properties were compared (Khaleel et al., 2011). Slump flow, V-funnel, L-box, and U-box tests were carried out and it was reported that gravel concrete showed the best performance, followed by crushed gravel and crushed limestone due to the differences in shape and surface texture. However, they found the highest strength (compressive and flexural) and modulus of elasticity on concretes with crushed stone, followed by crushed gravel, with gravel having the lowest strength. Furthermore, they reported higher mechanical properties with a maximum aggregate size of 10 mm than with 20 mm.

For up to 10% and 15% LS replacement in self-compacting mortars, workability as measured by slump flow and V-funnel flow time showed slight improvement; however, workability declined beyond these rates (Benabed et al., 2012). In another study, LS was used by reducing crushed sand or as a cement substitute (Skender et al., 2021). When the percentage of LS was increased, the slump flow decreased, but the decrease was higher for LS-added mixtures than for LS-substituted mixtures. On the other hand, an increased amount of LS for SCCs has been reported to reduce the demand for superplasticizers required to achieve the target slump flow, regardless of their fineness (Zhu & Gibbs, 2005). Nikbin et al. (2016) investigated the effect of LS content on compressive strength of SCCs. They found that when the LS content was increased from 25% to 100%, the compressive strength increased by 20% and 38% for 0.6 and 0.47 w/c ratios, respectively. This increase was attributed to the increase in packing density and improvement in the bond between the aggregate and paste with increased powder. The SCCs prepared with the addition of LS obtained approximately 40% higher compressive strength than NVCs at the same w/c ratios (Zhu & Gibbs, 2005). Splitting tensile strength and modulus of elasticity of SCCs made with LS were compared with those of NVCs (Parra et al., 2011). Average reductions of 15% in splitting strength and 2% in modulus were reported for SCC relative to NVC.

In this study, both coarse and fine aggregates and a powder as fine material are made of limestone by crushing or grinding processes; the grains are therefore angular and rough. In previous studies, the total amount of fine material was kept constant, and binary or ternary mixtures of crushed sand and river or dune sand were used in the production of SCCs. In this study, in addition to 350 kg/m^3 cement, the fine material was increased to 300 kg/m^3 in increments of 100 kg/m^3, and another mixture without filler but with VMA additive was prepared. The maximum coarse aggregate size was chosen as 10 mm or 16 mm. Most of the tests given by EFNARC (2005), as well as rheological tests, have been performed on SCCs to determine fresh state performance. The compressive and splitting tensile strengths, the modulus of elasticity, and the Poisson's ratio were investigated in the hardened state.

EXPERIMENTAL STUDY

Materials

In the experiments, CEM I 42.5 R type cement was used in accordance with TS EN 197-1 (2012), the grade of which is given in Figure 1. LS (98.5% $CaCO_3$) with a maximum size of 100 µm and a specific gravity of 2.77 was used as the fine material, and the gradation curve and SEM image of the particles are shown in Figures 1 and 2, respectively.

SCCs were prepared with two types of limestone-based crushed stone as coarse aggregate, crushed stone 1 with a maximum size of 10 mm and a specific gravity of 2.72, and crushed stone 2 with a maximum size of 16 mm and a specific gravity of 2.71. The fine aggregate was limestone-based crushed stone sand with a specific gravity of 2.68. The mixing proportions of aggregates were determined by using the grading curve of Fuller parabola. The grading curves of the aggregates are given in Figure 1.

Polycarboxylate ether-based admixture with a density of 1.03 g/cm^3 was used as SP. Polysaccharide-based admixture with a density of 1.01 g/cm^3 was employed as VMA.

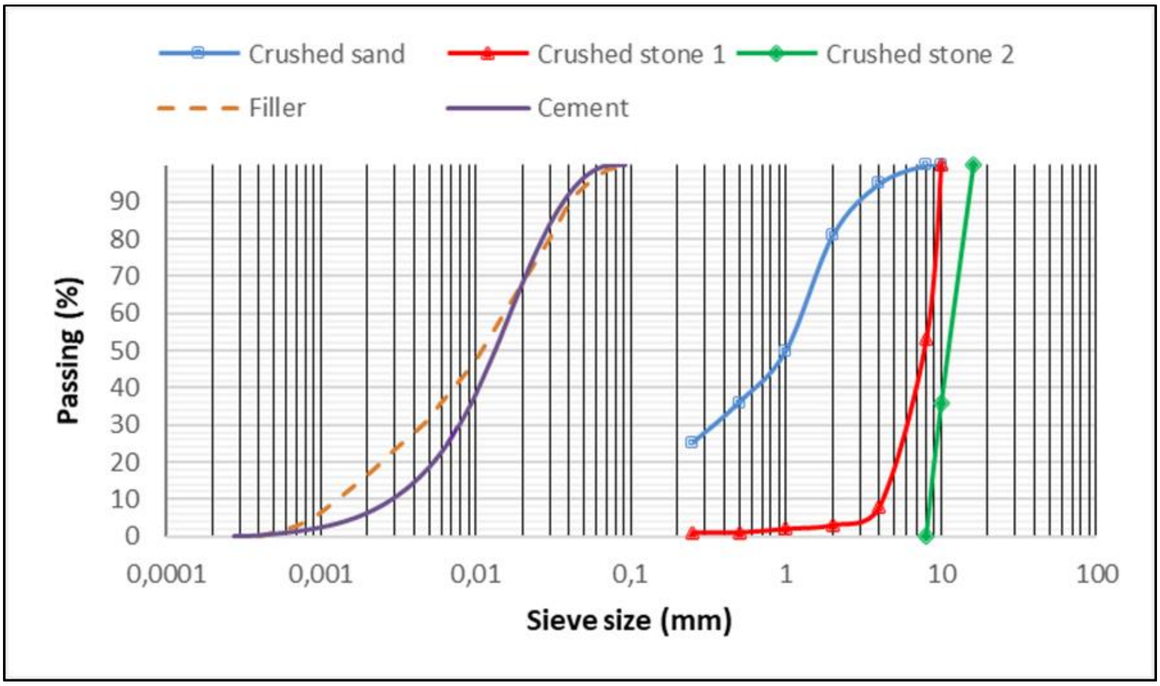


Figure 1. Grading Curves

Concrete Mixtures And Production

Cement content for all concrete mixes was 350 kg/m^3. Fine material (LS) content other than cement was increased up to 300 kg/m^3 in 100 kg/m^3 increments. Another SCC was prepared without any additional fine material. The water/cement ratio for all mixtures was 0.48 and the SP content was adjusted to keep the slump flow within the SF2

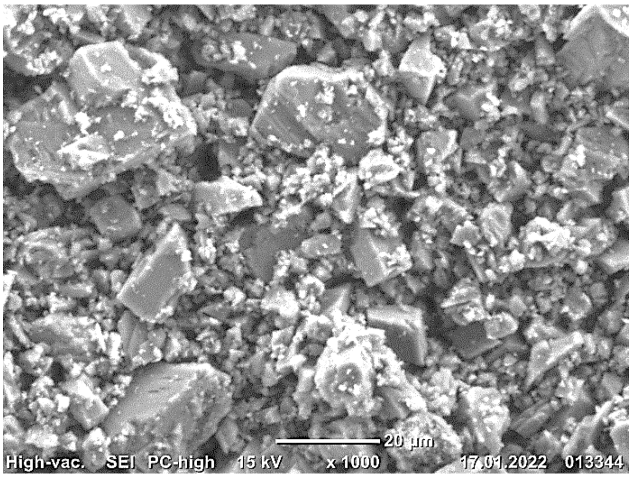


Figure 2. SEM Image of Limestone Powder

limits. For mixtures with a total fines content (including cement) of 350 kg/m^3 (for both 10 and 16 mm max. aggregate sizes) and 450 kg/m^3 (only for 16 mm max. aggregates), VMA was added to allow concrete to flow and prevent segregation. Mixing ratios of concretes are given in Table 1.

A pan mixer with a capacity of 50 dm^3 was used for concrete production. First, the aggregates and LS were mixed for 2 minutes, then 3/4 of the mixing water was added and mixing was continued for another 2 minutes. After the cement addition, the ingredients were mixed for additional 1 minute, then SP, VMA (if necessary), and the remaining water were added, and finally, more mixing was applied for 3 minutes.

Tablo 1. Mixing Proportions of SCCs

Component	Materials proportions (kg/m^3)							
	Maximum aggregate size: 10 mm				Maximum aggregate size: 16 mm			
	LS0	LS100	LS200	LS300	LS0	LS100	LS200	LS300
Cement	350	350	350	350	350	350	350	350
Water	169	169	169	169	169	169	169	169
Limestone filler	0	100	200	300	0	100	200	300
Crushed sand	1184	1124	1063	1000	981	930	880	828
Crushed stone 1	676	642	607	571	469	445	421	397
Crushed stone 2	0	0	0	0	412	390	369	348
Superplasticizer	9.5	8.6	8.6	11.8	9.5	9.0	8.2	8.2
VMA	0,34	0	0	0	1,68	1,52	0	0
w/c	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
w/p*	0.48	0.38	0.31	0.26	0.48	0.38	0.31	0.26

*w/p: Water/powder ratio

Testing Procedures

Slump flow and T500 tests were performed on fresh concrete in accordance with TS EN 12350-8 (2011). V-funnel and J-ring tests were performed according to TS EN 12350-9 (2011) and TS EN 12350-12 (2011), respectively. In order to determine the segregation resistance of fresh concrete, sieve and penetration tests were applied according to the modified form of TS EN 12350-11 (2011) and ASTM C1712 (2014), respectively. ASTM C1712 (2014) requires a weight of 45 g, but a weight of 54 g was used in this study, as suggested in other studies (Bui et al., 2002).

ICAR rheometer was used to measure the rheological performance of the SCCs (Figure 3). ICAR is based on the rotation of a vane and allows plotting shear stress versus rotational rate (Koehler & Fowler, 2004). It is possible to measure the static and dynamic yield stresses and plastic viscosity of concretes. The static yield stress was obtained from a stress growth test by rotating the vane at a low speed (0.025 rps) by determining the peak shear stress. In the flow curve test, shear stresses at decreasing speeds (0.5 to 0.05 rps in seven steps) were recorded after the vane was rotated at a high speed. The slope of the linear plotting stress versus rotational speed gives the plastic viscosity, and the intercept of the line corresponds to dynamic shear stress. In this study, negative dynamic yield stresses were obtained; therefore, only static yield stresses were presented.

After 90 days of water curing, compressive strength, and splitting tests were performed on 150x300 mm cylindrical specimens. The upper surfaces of the cylindrical specimens were ground to make them smooth and parallel to the lower surface. Three specimens were prepared and tested for each mixture. Longitudinal and lateral deformations were recorded during the compression test using two frames with LVDTs attached to the specimen (Figure 4).

Figure 3. ICAR Testing Instrument

Figure 4. Testing Frame for Compression Testing

TEST RESULTS AND DISCUSSION

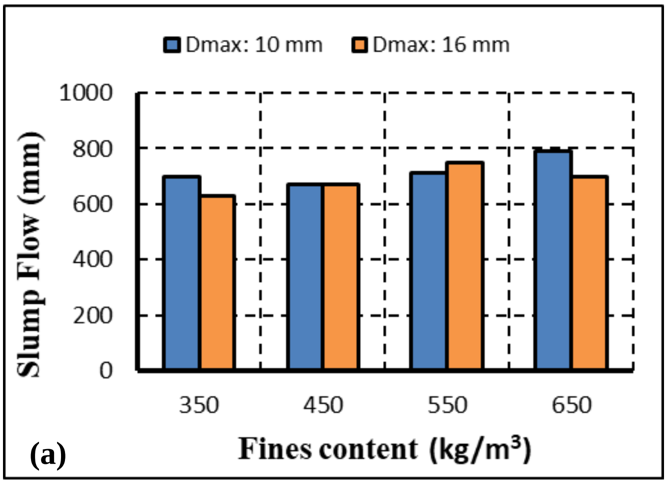
Fresh Concrete Results

Slump Flow And T_{500} Tests

The results of the slump flow test are shown in Figure 5a. One of the aims of the study was to obtain SCCs of at least SF2 slump flow class; however, one concrete (16 mm size and 350 kg fine content) fell slightly below this class. For 350 kg of cementitious (without added fines) concrete, the addition of VMA was required for both aggregate sizes (Table 1). In addition, for the aggregate size of 16 mm, VMA was used to maintain flow and prevent segregation when the total fine material was 450 kg/m^3. Figure 5a shows a slight increase in slump flow as the total fine content increases. Likewise, the slump flow increased as the paste increased (Nanthagopalan & Santhanam, 2009). However, for concrete with a maximum aggregate size of 16 mm, the slump flow decreased at a total powder content of 650 kg/m^3 (Figure 5a).

Increasing the paste content in SCC improves flow property by reducing inter-particle friction (Girish et al., 2010). The paste in a concrete fills the voids between the aggregate grains and the excess covers the grains; the coating thickness depends on the amount of paste (Oh et al., 1999). Besides, a high paste thickness increases the distance between the particles; hence the friction between the particles reduces, which improves the slump flow of a concrete. For the concretes with smaller size aggregate, the surface area of the particles is larger than that of coarser particles, for this reason, the paste thickness becomes thicker for the concretes with the latter particles. This shows why the SCCs with 16 mm size have slightly larger slump flows than 10 mm for up to the maximum powder content. On the other hand, the flowing properties can increase up to a certain paste level, and beyond that a drop can be experienced (Girish et al., 2010). It seems that the SCCs with 10 mm coarse aggregate size have this critical paste content over the maximum powder content used in this study (650 kg/m^3); however, for the 16 mm aggregate size it was less than the maximum powder content.

T_{500} flow rates remained within 3-4 s (Figure 5b), corresponding to viscosity class VS2 according to EFNARC (2005), except one mixture without LS, which showed slightly higher rate (6 s) than the others, probably due to the VMA it contained. It seems that there is no definite trend of T_{500} times with fine contents and maximum aggregate size. EFNARC (2005) advises this test to use as a way of confirming uniformity of a SCC from batch to batch.



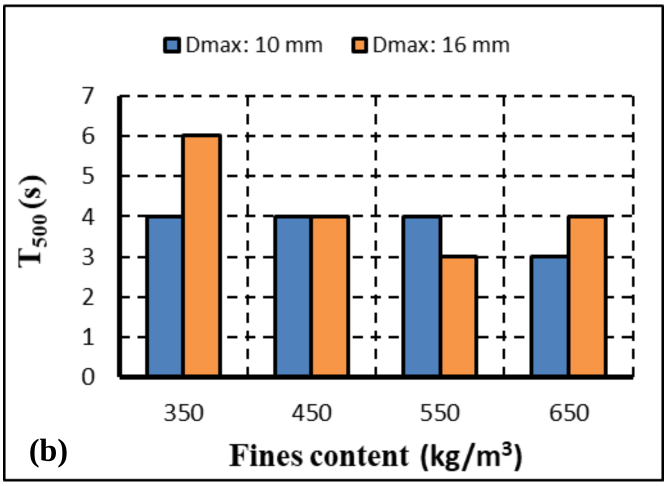


Figure 5. Variation of Slump Flow (a) and T_{500} (b) with Fines Content

V-Funnel Test

As shown in Figure 6, V-funnel flow rates were obtained between 15-25 s while staying within the limits of the VF2 viscosity class. Similarly, V-funnel times of 18-26.3 s have been reported for SCCs prepared with crushed sand (Gálvez-Moreno et al., 2016). It was stated that replacing the natural aggregate with crushed material did not have a significant effect on the slump flow value, but fine aggregates with a fraction of 0-2 mm had a greater effect on the V-funnel flow time (Carlsward et al., 2003). Figure 6 shows that V-funnel flow times of 16 mm concretes are generally longer than 10 mm concretes, possibly due to the arching effect of larger coarse aggregates (Nanthagopalan & Santhanam, 2009; Su et al., 2001). Also, LS, as well as all aggregates used in this study, have rough and angular surfaces, which can further increase the arching effect as a result of interlocking (Kwan & Ng, 2010). Fig. 6 also shows that increasing the LS content increased the V-funnel flow time due to the increase in the viscosity; because V-funnel test was also suggested to measure the viscosity (EFNARC, 2005). However, increasing the fine content to 650 kg/m^3 resulted in a decrease in the V-funnel time for both aggregate sizes due to the increased coating thickness of paste on the aggregate grains, and reduction of coarse aggregate content.

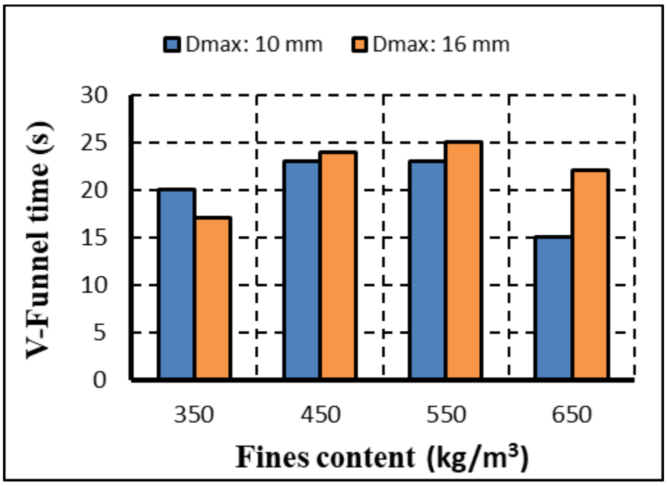


Figure 6. Variation of V-Funnel Flow Time with Fines Content

J-Ring Test

The differences between slump flow and J-ring spreads (J-ring blockage) are displayed in Figure 7a. This figure shows that 16 mm-sized SCCs have greater reduction in spread than 10 mm SCCs and exhibit a greater blocking effect. Figure 7a also shows that SCCs with a maximum aggregate size of 10 mm meet the criteria for "J-ring blockage ≤ 50 mm" (Hwang et al., 2006); however, the 16mm SCCs exceed the criteria limit for all fines content. The value obtained closest to the criterion limit for the aggregate size of 16 mm is 60 mm (instead of 50 mm), and it belongs to the fine grain content of 550 kg/m^3. Likewise, J-ring blockages between 50-125 mm have been reported for SCCs prepared with crushed sand and crushed coarse aggregate (Gálvez-Moreno et al., 2016).

During the J-ring test, the difference between the heights of the concrete inside the bars and just outside the ring, defined as the blocking step, was measured and is given in Figure 7b. This figure shows that concretes with 16 mm aggregates remain in the ring in greater amounts than those with 10 mm, due to the difficulty of passing larger particles through obstacles. According to the Precast/Prestressed Concrete Institute (PCI) Interim Guidelines (2003), the blocking step for SCCs should not exceed 15 mm; however, Figure 7b indicates that only two SCCs with a maximum aggregate size of 10 mm and a total fines content of 550 and 650 kg/m^3, respectively, meet this limit.

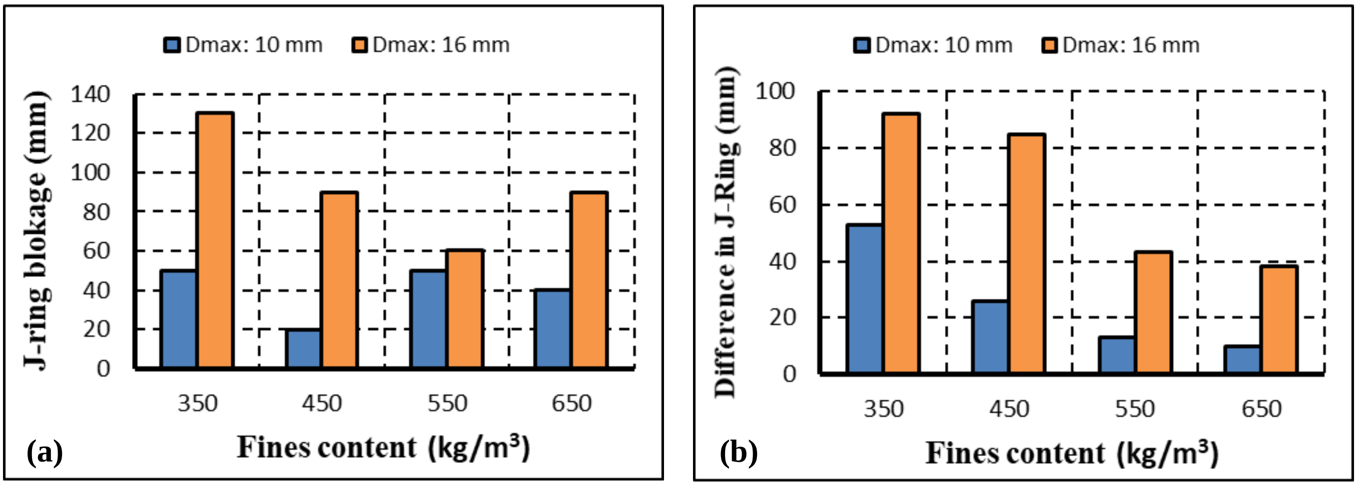


Figure 7. Variations of J-Ring Blokage (a) and Difference in J-Ring (b) with Fines Content

Figure 7b also shows that the higher the fine material content, the smaller the differences between the inner and outer parts. Similarly, poor filling rate (as well as passing rate) as measured by L-box has been reported for SCCs prepared with crushed sand and limestone filler (Necira et al., 2017).

As can be seen in Figures 7a and 7b, the mixture with 350 kg/m^3 cement, without extra fines but containing VMA, showed the poorest J-ring test result when compared to the fines added mixtures, due to the lack of fines. Likewise, Georgiadis et al. (2010) obtained low L-box and slump flow values for concretes prepared with 374 kg/m^3 cement dosage (without other fines) and VMA. In Figure 8, the variation of J-ring blockage with blocking step is plotted.

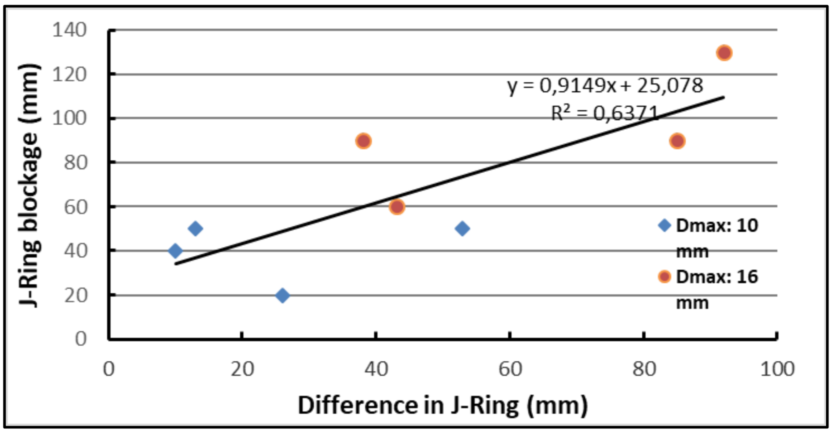


Figure 8. The Relationship Between J-Ring Blockage and Difference in J-Ring

A linear correlation was obtained with a coefficient of determination of R^2=0.64, although Wustholz (2003) reported a large scattering between these two variables. It can be concluded that SCCs prepared with limestone-based crushed aggregates (both fine and coarse) and LS can only show sufficient passing ability with small maximum coarse aggregate size (Dmax ≤ 10 mm) and high amount of fines (≥550 kg/m^3), due to the angular shape and rough surface texture of particles. This is because an increased amount of fines decreases the volume of coarse aggregate and reduces the inter-particle friction (Girish et al., 2010; Koehler & Fowler, 2004).

Segregation Resistance

The segregation resistance of fresh concrete was measured by two methods: sieving and penetration. As shown in Figure 9a, sieving test results remained between 4.6-12.2%, corresponding to SR2 class according to EFNARC (2005). All penetration test results shown in Figure 9b remained below 8 mm, which is indicated as the non-segregation limit for SCCs (Carlsward et al., 2003). It has been suggested that SCCs containing crushed sand exhibit high segregation resistance due to the particle shape and surface texture (Zeghichi et al., 2014). Although there was no parallel trend between the results of the two methods tested, the concrete prepared with 550 kg/m^3 LS and 16 mm aggregate size displayed maximum passing percentage and maximum penetration results.

In concretes, the drag force which keeps the grains in suspended position in the mortar are function of coarse aggregate particle size, the unit weight difference between the coarse aggregates and mortar, and the viscosity and the yield stress of the mortar (Navarrete and Lopez, 2016; Shen et al., 2009). For this reason, coarse aggregates of 16 mm settles more than 10 mm in SCCs, which causes more segregation in concretes with the former aggregates than the latter. In addition, the increase in powder content causes the aggregate particles to separate from each other and the coarser particles to settle more easily (Esmaeilkhanian et al., 2014). Moreover, increasing the paste will increase the amount of fine material passing through the sieve and make the penetration easier. On the other hand, due to keeping the water content constant and increasing the powder content, the w/p ratio decreased, and as a result, the viscosity increased, causing a decrease in segregation for the largest aggregate grains.

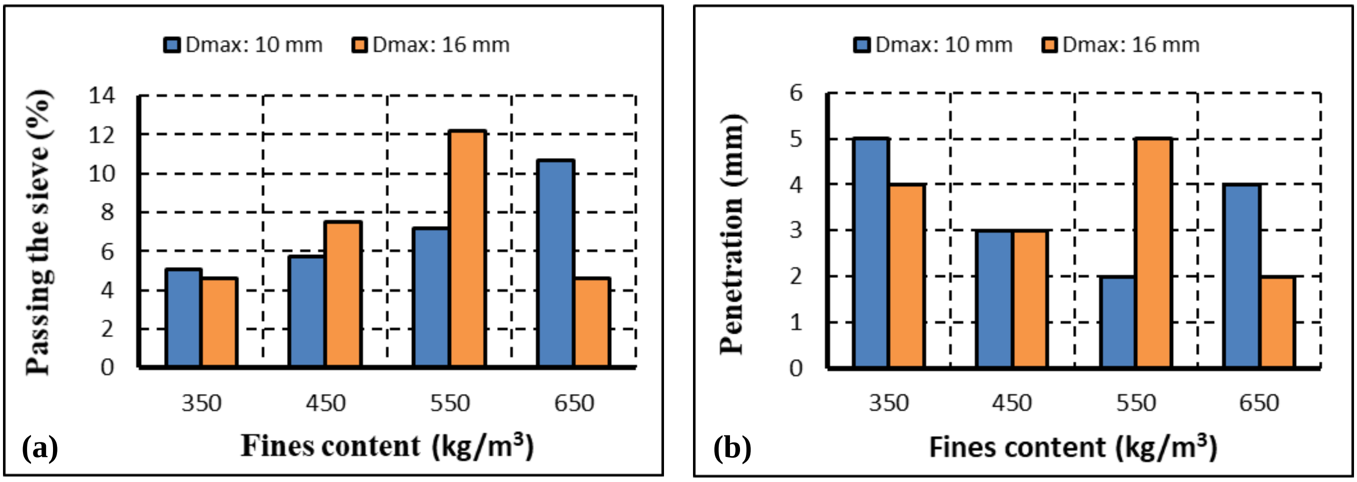


Figure 9. Segregation Resistance Measured by Sieving (a) and Penetration (b) Methods

Rheological Properties

Figures 10a and 10b show the variation of rheological properties, plastic viscosity, and static yield stress with fines content, respectively. The viscosity decreased when the fines content was increased from 350 to 450 kg/m^3 for both coarse aggregate sizes. Fine materials, if they are not in excessive quantities, tend to lubricate a mixture, which makes it easier for larger particles to roll and slide over each other (Cepuritis et al., 2016; Alexander & Mindess, 2005). The presence of these particles in a mixture increases the workability and reduces the need for water. The viscosity change between two fines contents of 450 kg/m^3 and 550 kg/m^3 is small for both aggregate sizes. However, the viscosity increased at 650 kg/m^3 fines amount, which indicates that this amount of fine powder is excessive for these concretes. It has been noted that a high amount of fine grains makes concrete sticky (Alexander & Mindess, 2005) and highly viscous and reduces mobility (Collepardi et al., 2007). The yield stress results given in Figure 10b, on the other hand, showed a decrease after a higher fine grain content, 450 kg/m^3, unlike the viscosity results, and remained at a similar level even at the highest fines content.

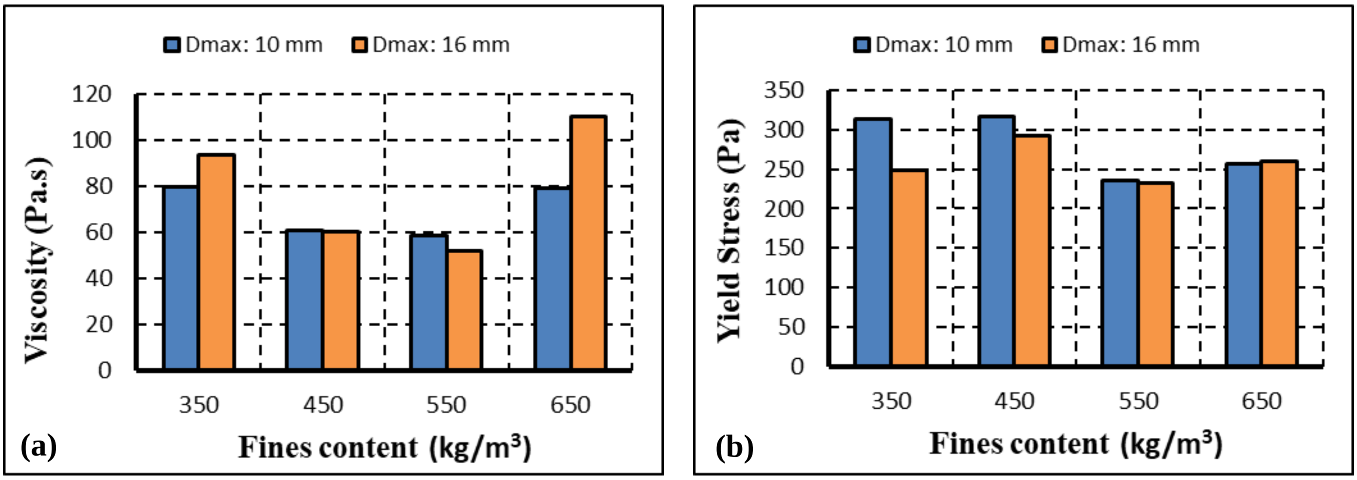


Figure 10. Variation of Rheological Parameters, (a) Viscosity and (b) Yield Strength with Fines Content

Mechanical Properties

Compressive Strength

The compressive strength of concrete, as is known, mainly depends on the w/c ratio. The w/c ratio was kept constant in the presented concretes; however, as shown in Figure 11a, the compressive strength increased slightly with the increase of fine grains. While the cement content was the same in all concretes, the LS content was increased up to 300 kg/m^3. SCCs without LS and those with a coarse aggregate of 16 mm and a fine material of 450 kg/m^3 contain VMA; however, it has been reported that VMA does not have a negative effect on strength characteristics (Isik & Ozkul, 2014). It is known that LS is not a pozzolanic material but shows improvement in strength properties due to better particle packing, increased cement hydration rate (Zhu & Gibbs, 2005), limestone activity (Roziere, Granger, Turcry, & Loukili, 2007), and filling effect. Similarly, it was noted that increasing the LS leads to an increase in compressive strength, which is attributed to the improvements in the packing density and the bond between aggregate and paste (Nikbin et al., 2014-a).

Figure 11a shows that the increases in compressive strength for SCCs containing 300 kg/m^3 LS (total fines of 650 kg/m^3) compared to those without additional fines are 14% and 6.4%, for maximum aggregate sizes of 16 mm and 10 mm, respectively. Figure 15 also shows that for fines contents of 450 and 650 kg/m^3, those of size 16 mm have strengths of 6.9% and 6% higher, respectively, than those of 10 mm, but, conversely, for fine grains of 550 kg/m^3, that of size 10 mm have a strength of 2.9% lower than that of size 16 mm. There are conflicting results about the effect of large aggregate size on strength. Nikbin et al., (2014-b) reported a slight increase between the sizes of 9.5-19 mm, while Khaleel et al. (2011) found that SCCs with a maximum aggregate size of 10 mm have higher compressive and flexural strengths than those with a size of 20 mm. This was attributed to the formation of a higher bond strength between the aggregate and the paste due to the increased aggregate surface area in mixtures containing smaller-sized aggregates (Khaleel et al., 2011). On the contrary, the increase in strength with increasing aggregate size has been associated with the improvement of the concrete skeleton due to larger-sized aggregates (Nikbin et al., 2014-b).

Splitting Tensile Strength

The variation of the splitting strength given in Figure 11b shows a slight decrease (4.3% for 10 mm aggregate size and 6.8% for 16 mm) with the increase of limestone powder to 300 kg/m^3. The lowest splitting strength was obtained for SCC with 450 kg/m^3 fine material and 10 mm coarse aggregate, 7.2% lower than that without additional fine material. Conflicting results have been reported on this issue; for example, the tensile strength results of SCCs in splitting have been obtained up to 40% higher than predicted by the FIB Model Code 90 (Klug & Holschemacher, 2003) for NVC. Conversely, it has been reported that there is a 15% decrease in the splitting strength of SCCs compared to NVC (Parra et al., 2011). On the other hand, it has been shown that the volume of paste has a limited effect on strength (both compressive and splitting) and elastic modulus (Craeye, Van Itterbeeck, Desnerck, Boel, & De Schutter, 2006). The slight change in these characteristics was attributed to the decrease in the volume of aggregate, which is the higher-strength component of concrete, and also to the decrease in ITZ, the weaker part of concrete (Roziere et al., 2007; Nikbin et al., 2014-a). These two opposite effects counteract each other and the change in mechanical properties remains small. Figure 16 also depicts that the maximum aggregate size does not have a significant effect on the splitting tensile strength. Similarly, the analysis of the data obtained from forty-nine studies showed that the effect of coarse aggregate size or paste volume on the correlation between split tensile strength and compressive strength was not significant (Craeye et al., 2006).

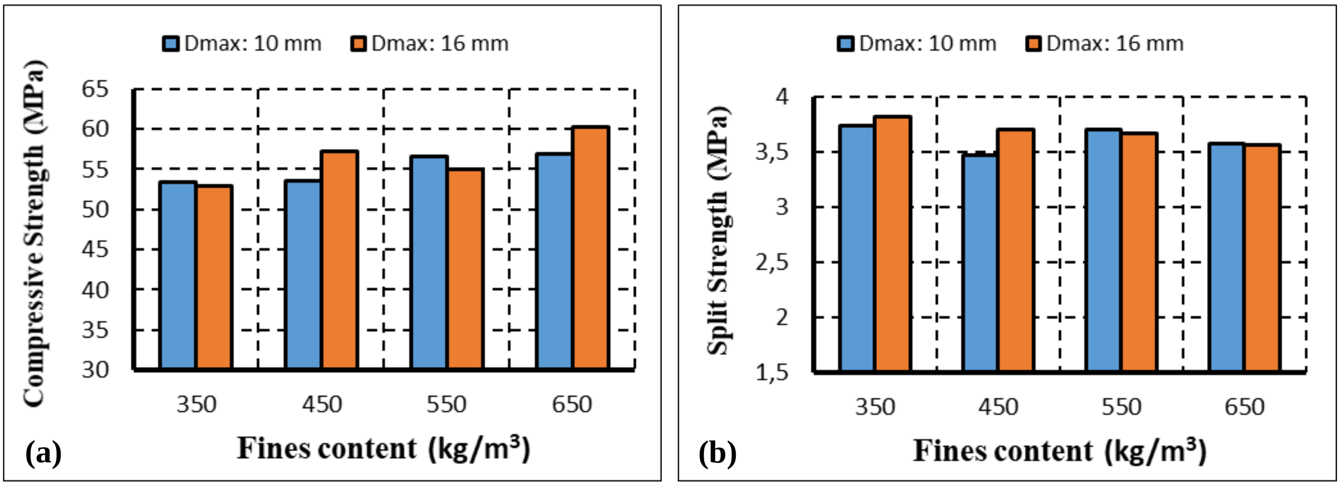


Figure 11. Variation of Compressive (a) and Splitting (b) Strengths with Fines Content

Modulus of Elasticity

The modulus of elasticity was calculated from the initial linear portion of the stress-strain curves and is given in Figure 12a. This differs from the approach proposed in ASTM C469 (2004), where at least three loads are required, and the slope between a stress equal to 40% of the ultimate stress and a strain of 50 microstrains is calculated as the modulus of elasticity. Figure 12a shows that the fine material content has little effect on the modulus of elasticity. By increasing the fines content from 350 kg/m^3 to 450 kg/m^3 for a maximum aggregate size of 10 mm, a slight decrease in the modulus of elasticity was observed, and in subsequent amounts of fine material it remains at a similar level as in the former concrete. Figure 12a also depicts that when the aggregate size is increased to 16 mm, the modulus increases by up to 3.8% compared to LS-free concrete for fines contents of 450 and 500 kg/m^3, and then decreases to the level of LS-free concrete for 650 kg/m^3. The test results of Das & Chatterjee (2012) showed that the ACI model, originally derived for NVC, underestimated the initial tangent modulus of elasticity of the SCC by about 9-12%. Similarly, the modulus of elasticity of the SCCs remained at the bottom of the region estimated by the FIB Model Code 90 (Klug & Holschemacher, 2003). A lower modulus of elasticity was obtained from the BIS model estimate, and these low values were attributed to the lower coarse aggregate content of the SCCs (Dinakar, Reddy, & Sharma, 2013). A database was analyzed and the modulus of elasticity of SCCs was found to be up to 20% lower than that of NVC at the same strengths (Holschemacher & Klug, 2002). Due to the assumption that aggregates are more rigid than paste, a decrease in the modulus of elasticity is predicted with a high amount of paste; on the other hand, paste with a high amount of LS also has a high rigidity (Craeye et al., 2006). However, there are studies showing that there is no difference between the moduli of elasticity of SCC and NVC at similar strengths (Persson, 2001). Figure 12a also shows that the modulus of elasticity values of SCCs with a size of 16 mm are higher than those of 10 mm. The difference was 5% in LS-free SCCs and up to 16% in SCCs with 450 kg/m^3 of total fines. As the maximum size of the coarse aggregate increased, the modulus of elasticity of the NVC increased slightly, which was attributed to the higher stiffness of coarser aggregates (Rao & Prasad, 2002). Likewise, Nikbin et al. (2014-b) found a negligible increase in the modulus of elasticity with an increase in the maximum aggregate size. There are different results about the effect of the maximum size of coarse aggregates on the modulus of elasticity. Khaleel et al. (2011) compared the modulus of elasticity of SCCs prepared with two different maximum aggregate sizes and observed that concrete with a size of 10 mm had a higher modulus than 20 mm.

Poisson Ratio

As shown in Figure 12b, the Poisson ratios remained between 0.187 and 0.212, and the addition of LS decreased the ratio. SCCs with 16 mm aggregate size have 8.3% and 7.1% higher Poisson's ratios than 10 mm SCCs for fines content of 450 and 550 kg/m^3, respectively. It is seen that for these concretes of 16 mm size, larger aggregate particles limit the lateral deformation more than those with 10 mm size. In contrast, Guo et al. (2009) found that the Poisson ratio was similar for both concrete and mortar, and therefore coarse aggregate volume had no effect on the Poisson ratio. Das and Chatterjee (2012) obtained Poisson's ratios for SCCs between 0.21 and 0.23, which is close to the values obtained in this study. On the other hand, the Poisson ratios measured by Li and Li (2014) in SCCs are slightly smaller than those achieved in this study.

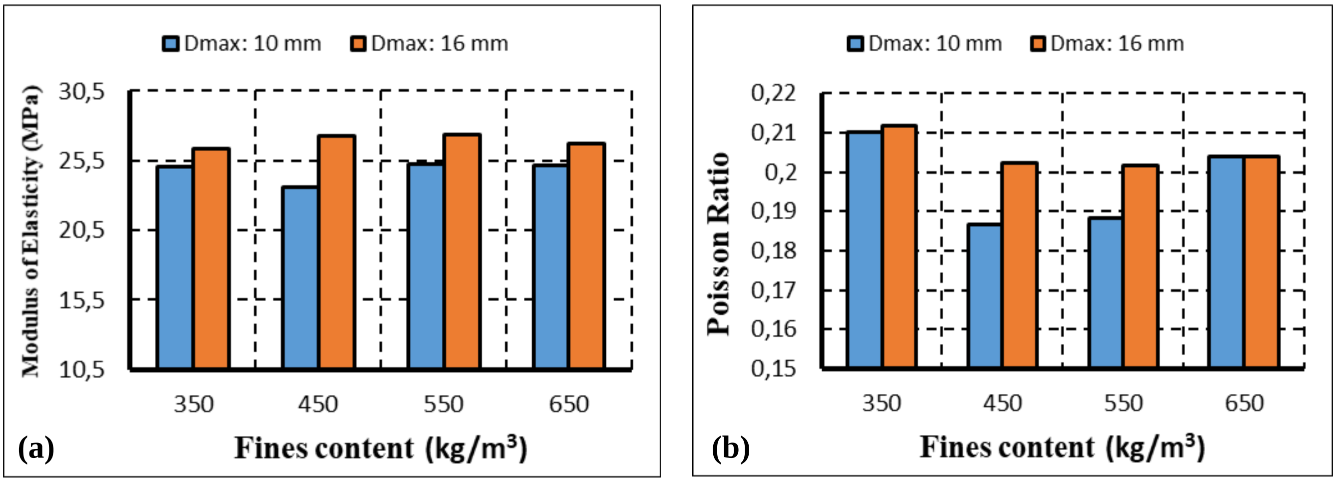


Figure 12. Variation of Modulus of Elasticity (a) and Poisson Ratio (b) with fines content

CONCLUSIONS

In this study, only manufactured aggregates, crushed stone coarse aggregate, crushed stone sand and limestone powder were used to produce more sustainable SCCs due to the high depletion of natural sand and gravel in the world. The following conclusions can be drawn from the study.

It is possible to produce flowable concrete in SF2 and SF3 classes by using only manufactured aggregates and LS. Slump flow increased with increasing the LS content in general due to increasing the paste thickness around the aggregate particles, which reduces the inter-particle friction. V-funnel flow times were within the limits of the VF2 class, showing a slow rate, most likely due to the angular shape and rough surface of the aggregate and LS particles. Increasing the LS content increased the flow time because of the increase in the viscosity of the mixture. When the J-ring results were compared, it was seen that SCCs prepared with 10 mm aggregate size were more successful in passing ability than those of 16 mm size, most probably due to the arching effect of the larger particles. All tested SCCs showed segregation resistance by both methods, sieving and penetration; however, the sieve segregation was higher for the maximum aggregate size of 16 mm than 10 mm in general. Plastic viscosity, one of the rheological properties measured, showed decrease up to a LS content of 550 kg/m^3; however, it showed an increase for the highest LS content. The other rheological property, yield stress, exhibited a decrease after the LS content of 450 kg/m^3, and remained approximately at the same level with increased LS.

Up to 14% increase in compressive strength with an increase in LS content was achieved, probably due to the better packing and filler effect, and the influence of coarse aggregate size was not found significant. On the contrary to compressive strength results, a slight decrease (4.3% for 10 mm aggregate size and 6.8% for 16 mm) in splitting tensile strength was obtained. SCCs with 16 mm coarse aggregate size exhibited higher modulus of elasticity than those of 10 mm size. The change in modulus with LS content is slight for SCCs with 16 mm aggregate size; however, up to 6% increase was obtained for those with 10 mm, when the LS content was increased from 450 kg/m^3 to 650 kg/m^3. The Poisson ratio remained between the 0.187 and 0.212 interval, showing no difference with respect to those of NVC found in the literature.

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