ESCUELA DE CONSTRUCCIÓN CIVIL
FACULTAD DE INGENIERÍA

Revista de la Construcción
Journal of Construction

Research Article

Effects of mix-design variables on the workability, rheology and stability of self-consolidating concrete

Mohammad Musa Alami[1], Tahir Kemal Erdem[2,*]

[1] Izmir Institute of Technology, Civil Engineering Department, Urla, İzmir (Turkiye), Email: musa_afghanistan@yahoo.com ,
[2] Marmara University, Civil Engineering Department, Maltepe, İstanbul (Turkiye), Email: kemal.erdem@marmara.edu.tr
*Correspondence: kemal.erdem@marmara.edu.tr

Received: 31.01.2022; **Accepted:** 23.11.2022; **Published:** 29.12.2022

Citation: Alami, M. and Erdem, T. (2022). Effects of mix-design variables on the workability, rheology and stability of self-consolidating concrete. Revista de la Construcción. Journal of Construction, 21(3), 703-716. https://doi.org/10.7764/RDLC.21.3.703.

Abstract: This study investigates the effects of basic mix design variables such as water/cement ratio (w/c), slump flow, coarse-to-total aggregate ratio (CA/TA), and maximum aggregate size (D_{max}) on the main characteristics of self-consolidating concrete. The w/c of the mixtures was either 0.42 or 0.50. The CA/TA ranged between 0.45 and 0.53. Slump flow was adjusted to 550, 650 or 720 ±20 mm by varying the superplasticizer content. D_{max} was varied as 10, 15 and 20 mm. V-funnel, L-box, rheometer, sieve segregation tests and a new test method, recently developed by the authors, for dynamic segregation resistance were performed. The effect of each variable on the test results were effectively summarized in a table. Increasing the w/c, CA/TA and D_{max} decreased the superplasticizer demand and increased the flowability. When the slump flow, w/c and CA/TA were higher, viscosity was found to be lower. Higher values of CA/TA and D_{max} were found to reduce the passing ability. Increasing the slump flow (or superplasticizer content), CA/TA and D_{max} disturbed the stability. Generally, the effects of w/c and slump flow on the SCC characteristics were more pronounced when compared to those of CA/TA and D_{max}. Good correlations were obtained between several test results.

Keywords: Self-consolidating concrete, workability, rheology, stability, mix-design.

1. Introduction

The highly flowable nature of self-consolidating concrete (SCC) comes from the use of superplasticizers and some other special considerations for mix proportioning, such as using more fine aggregate, less coarse aggregate, lower maximum size of the aggregate (D_{max}) and more paste. The ability of fresh mixture to flow like a homogenous fluid requires a sensitive balance between sufficient deformability and good stability (ACI 237 R, 2007). Accordingly, high workability is related with both high consistency and high cohesiveness.

The main characteristics of SCC in fresh state are flowability, viscosity, passing ability and segregation resistance (EFNARC, 2005). In most cases, a good SCC can only be obtained by simultaneously satisfying the specific requirements for all of these characteristics. Although these properties are related with the fresh state of the SCC, they are crucial for the mechanical characteristics of hardened SCC (Domone, 2006; Ma, Feng, Long, Xie, & Chen, 2017).

Flowability can be defined as the ability of an SCC to flow freely when there is no confinement while passing ability shows the ability to flow through confined spaces and narrow openings. Slump flow is the most widely test for flowability while L-box test is suitable for passing ability (Kamal H. Khayat, Assaad, & Daczko, 2004). Viscosity is related with the speed of the flow and it is defined as the resistance to flow once flow has started (EFNARC, 2005). T500 and V-funnel tests are commonly used for evaluating the viscosity. Yield stress and plastic viscosity values obtained from rheometers can be well correlated with the one-point tests such as slump flow and viscosity (T500 or V-funnel) tests, respectively (Erdem, Khayat, & Yahia, 2009).

Segregation resistance, or stability, of SCC is the ability of concrete to remain homogeneous in composition until setting (EFNARC, 2005). Stability must be maintained while the concrete is in motion and when it is stationary. Accordingly, there are two types of stability (Shen, Struble, & Lange, 2009): dynamic and static stability. Dynamic stability is the resistance to segregation during the handling operations of the fresh SCC such as transportation and placement. In contrast, static stability is the resistance to segregation and bleeding in the formworks and until concrete gains rigidity. Segregation can cause low strength, improper filling of formworks and weak bonding between steel reinforcement and concrete (Assaad, Khayat, & Daczko, 2004; Bui, Montgomery, Hinczak, & Turner, 2002; Libre, Khoshnazar, & Shekarchi, 2010; Valcuende, Jarque, & Parra, 2007). Moreover, the durability of SCC will also decrease in case of segregation because the settlement of aggregate will increase the paste amount at the top, increasing the potential of shrinkage cracking. This can trigger more durability problems such as lower resistance to freezing-thawing cycles (Panesar & Shindman, 2012).

The 4 main characteristics described above are interrelated with each other. For example, low flowability and/or high viscosity can cause low passing ability (EFNARC, 2005). Very high flowability and/or low viscosity can cause low segregation resistance (Libre et al., 2010). Therefore, making changes in the mixtures by considering only a single property may result in problems in concreting. A successful mix-design of SCC requires both a proper selection of materials and careful tailoring of the ingredients to secure a proper balance between opposing properties (K. H. Khayat, Ghezal, & Hadriche, 2000). Accordingly, the present study focused on investigating the effect of basic mix design variables on all of the main characteristics, determined by different test methods.

Water-to-cement ratio (w/c) has a great effect not only on the hardened concrete properties but also on the fresh concrete (Bouziani, 2013). High water content in a mixture can cause severe segregation. SCC has already high fluidity due to its superplasticizer content and therefore high w/c may have more risk for the stability of the mixtures (El-Chabib & Nehdi, 2006). W/c affects also the flowability, viscosity and passing ability by the fluidizing effect of the water, which can increase the inter-particle distance and reduce the intrinsic friction (Long, Lemieux, Hwang, & Khayat, 2012).

Another mix design parameter for SCC is slump flow which is requested by the end user considering the consistency requirement of a specific application. W/c and superplasticizer content are among the parameters which significantly affect the slump flow (Erdem et al., 2009). For a given w/c, increasing the superplasticizer content results in higher slump flow values, higher flowability and passing ability however the mixtures containing high amounts of superplasticizers are more prone to segregation (Kamal H. Khayat et al., 2004).

Maximum aggregate size (D_{max}) and coarse aggregate-to-fine aggregate ratio (CA/TA) are other parameters which can be specified by the end users especially in case of narrow sections and congested reinforcements. When the D_{max} is large or when the aggregate grading is coarser, the aggregate surface becomes less, enabling more paste to fluidize the SCC (Hu & Wang, 2011; Struble, Szecsy, Lei, & Sun, 1998). However, large D_{max} and coarse aggregate can also cause more friction between the particles which can decrease flowability and passing ability (Jiao et al., 2017). Therefore, generally an optimum value for D_{max} and CA/TA exists for better SCC performance (Aïssoun, Hwang, & Khayat, 2016).

This study investigates the effects of water/cement ratio (w/c), slump flow (or indirectly superplasticizer content), the ratio of coarse aggregate amount to the total amount of aggregate (CA/TA), and D_{max} on the main characteristics of SCC in detail by conducting several one-point (or field oriented) and two-point tests. A new method was also used to investigate the dynamic segregation resistance (Alami, Erdem, & Khayat, 2016).

2. Materials and methods

2.1. *Materials*

CEM IV/B (P-W) 32.5 R blended cement with Blaine fineness and specific gravity of 3620 cm^2/g and 2.60 was used. Limestone filler with a Blaine fineness of 3945 cm^2/g was used because it can increase the slump flow, stability, and reduce the dynamic yield stress (Artigas, Positieri, Quintana, Oshiro, & Cortez, 2021; Kim, Noemi, & Shah, 2012). The increase in the fluidity and decrease in the viscosity of limestone filler are stated also by other researchers (Artigas et al., 2021).

Four aggregate groups were used in this research. Three of them were crushed limestone with varying D_{max} values (10, 15 and 20 mm). The specific gravity of the limestone aggregate groups was 2.56. The fourth group was river sand with a specific gravity of 2.59. The water absorption capacity of the crushed limestone and river sand was 1.37% and 2.67%, respectively.

A polycarboxylate ether based superplasticizer with solids content of 37.3% was used.

2.2. *Methods*

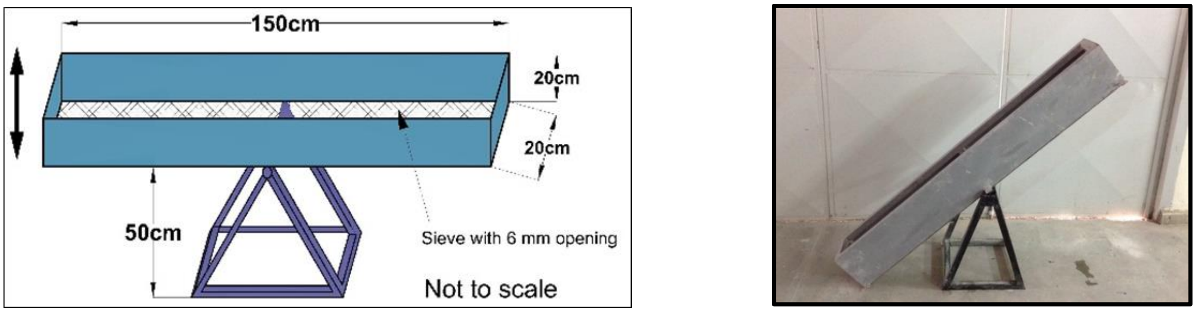
Slump flow, T500, visual stability index (VSI), V-funnel, L-box, static sieve segregation, and rheology tests were performed to evaluate the main characteristics of the fresh SCC mixes. Additionally, the so-called dynamic sieve segregation test (DSST) (Alami et al., 2016) was performed for dynamic stability. There are no standardized protocols for the rheology and dynamic stability tests but the others are well-described in the literature (EFNARC, 2005). Therefore, only a summary of these tests are given here.

The rheology tests were performed by using Contec 4SCC rheometer with a Tattersall type impeller. The torque value (T) corresponding to each of the 6 different rotational speed values (N = 0.8, 0.70, 0.55, 0.40, 0.25, and 0.10 rps) was recorded starting from the highest speed (down curve). Then, Bingham model (T=g+hN) was established by fitting a linear line to the T Vs N data, and the apparent yield stress (g) and torque plastic viscosity (h) were determined.

The DSST test resembles the T-box test of another study (Esmaeilkhanian, Khayat, Yahia, & Feys, 2014) for the simulation of SCC flow. The DSST test (Figure 1) consists of a rectangular channel box with a 6-mm opening sieve at the bottom. The box stands on a support positioned at the middle of the box. After the weight of the empty box (W_b) is determined, it is placed on the support and an 18-kg SCC sample (W_i) is poured into the box from the middle. Then, by the raising and lowering the ends of the box, it is cycled four times, which corresponds to travelling of SCC by around 5 m. The duration of each cycle is 15 sec. Afterwards, the box stayed in a horizontal position for 10 sec. In the final step, the weight of the box with the remained concrete is measured as W_r. Then, Eqn.1 is used to calculate the dynamic segregation ratio (DSR), which is the ratio of the weight that passed through the sieve ($W_p = W_b + W_i – W_r$) to W_i.

$$DSR = (W_p / W_i) \times 100 \qquad (1)$$

Type of the mixer, temperature, and mixing sequence and duration can affect the SCC test results (Ferraris, Larrard, & Martys, 2001). Therefore, all procedures were performed in the same manner and sequence.



(a) (b)

Figure 1. a) Schematic view, and b) photo of the DSST test apparatus.

2.3. *Mixtures*

Twelve SCC mixtures (Table 1) with constant cement (420 kg) and limestone filler (20 kg) contents were prepared by varying the w/c, CA/TA, slump flow, and D_{max}. The w/c of the mixtures was either 0.42 or 0.50. The CA/TA was 0.45, 0.50 or 0.53. For the mixtures with CA/TA=0.50, the slump flow was varied by only varying the superplasticizer content. For such mixtures, the slump flow was adjusted to 550, 650 or 720 ±20 mm. For only one mixture type (w/c=0.42, CA/TA=0.50, and slump flow=650 mm), D_{max} was varied as 10, 15 and 20 mm.

Table 1. SCC mixture proportions.

Mix No	Slump-flow, mm	D_{max}, mm	w/c	CA/TA	C	W	LP	CA	FA	SP, L/m^3
					kg/m^3					
1	650	15	0.42	0.45	400	168	20	775	948	6.4
2	550	15		0.50	400	168	20	862	862	4.9
3	650	15			400	168	20	862	862	5.6
4	720	15			400	168	20	862	862	6.6
5	650	10			400	168	20	862	862	6.6
6	650	20			400	168	20	862	862	5
7	650	15		0.53	400	168	20	913	810	5.3
8	650	15	0.50	0.45	400	200	20	739	903	4.1
9	550	15		0.50	400	200	20	820	820	3.3
10	650	15			400	200	20	820	820	3.4
11	720	15			400	200	20	820	820	3.8
12	650	15		0.53	400	200	20	869	771	3.3

Table 2. Test results.

Mix No	T_{500} (s)	VSI	VF time (s)	H2/H1	L-box time (s)	SR (%)	g (N.m)	h (N.m.s)	DSR (%)
1	3.66	1	22.3	0.82	6.5	3.90	0.57	3.24	25.0
2	4.53	1.5	35.1	0.65	14.0	1.40	0.53	4.81	17.3
3	3.50	1.5	21.0	0.75	8.3	4.75	0.50	2.98	26.2
4	2.03	2	14.5	0.81	4.2	5.55	0.39	2.20	27.9
5	5.09	1.5	19.8	0.79	5.0	3.40	0.24	3.21	24.2
6	2.19	2	38.0	0.60	9.4	6.65	0.66	4.34	33.1
7	2.25	2	19.2	0.70	12.1	5.25	0.30	1.88	28.4
8	1.25	0.5	13.1	0.85	3.2	0.40	0.68	1.26	21.2
9	2.96	0.5	32.3	0.66	9.1	0.25	0.89	1.67	14.0
10	1.10	1	11.2	0.81	4.3	1.75	0.60	1.12	24.0
11	1.03	1	7.0	0.88	2.8	2.60	0.42	0.61	26.7
12	0.85	1.5	8.2	0.79	6.0	2.05	0.42	0.90	24.9

3. Results and discussions

3.1. *Superplasticizer demands, T500 and VSI*

Superplasticizer demand to achieve the desired slump flow values are summarized in Table 1. For a given w/c, the mixtures with higher slump flow required higher amount of superplasticizer as seen in Figure 2, where the results for 550 mm slump flow mixture was taken as 100% and the results of other mixtures were expressed as percentages of this mixture. Superplasticizers can separate the cement particles and release the water that would be trapped between the cement particles (Benaicha, Hafidi Alaoui, Jalbaud, & Burtschell, 2019).

For a constant slump flow diameter, the superplasticizer demand decreased by increasing the CA/TA (Figure 3) or D_{max} (Figure 4). In Figures 3 and 4, the results of the CA/TA=0.45 mixture and D_{max}=10mm mixture were taken as reference, respectively, and the results of other tests were expressed relative to the reference mixtures. When CA/TA or D_{max} increases, the surface area of the aggregates to be wetted decreases and more free water becomes available to reach the target slump flow diameter (Hu & Wang, 2011; Struble et al., 1998).

In Figure 5, the results of the w/c=0.42 mixtures were taken as 100% and the results of the mixtures with same parameters except w/c were expressed relative to these mixtures. As expected from a previous research (Long et al., 2012) and as seen in Figure 5, the mixtures with higher w/c required less superplasticizer because water has already an effect to fluidize the mixtures. Figure 5 also shows that T500 time decreased when the w/c increased. The decrease in T500, which is a useful indication of viscosity, can be due to the fact that higher water content decreases the viscosity and makes a favorable effect on the speed of the flow. Similarly, when slump flow was higher, the T500 time got lower (Figure 2) since higher superplasticizer content to get higher slump flow decreases the viscosity (as will be experimentally shown later).

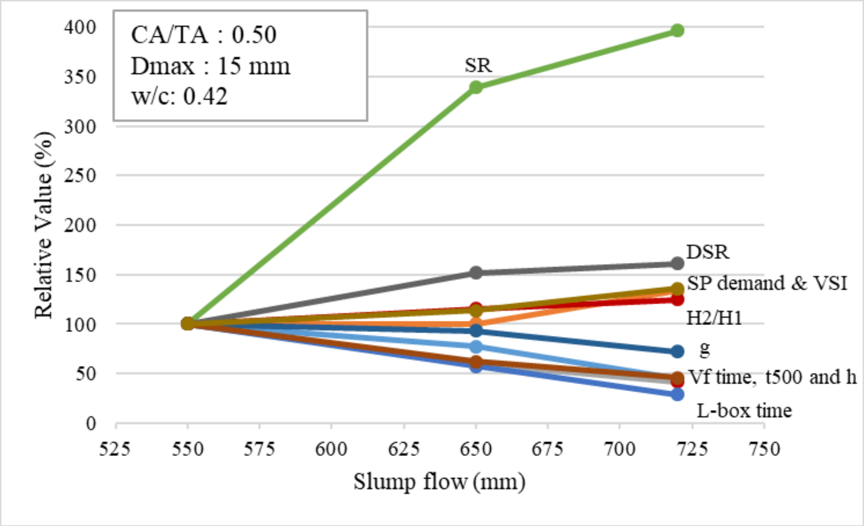


Figure 2. Effect of slump flow on the test results.

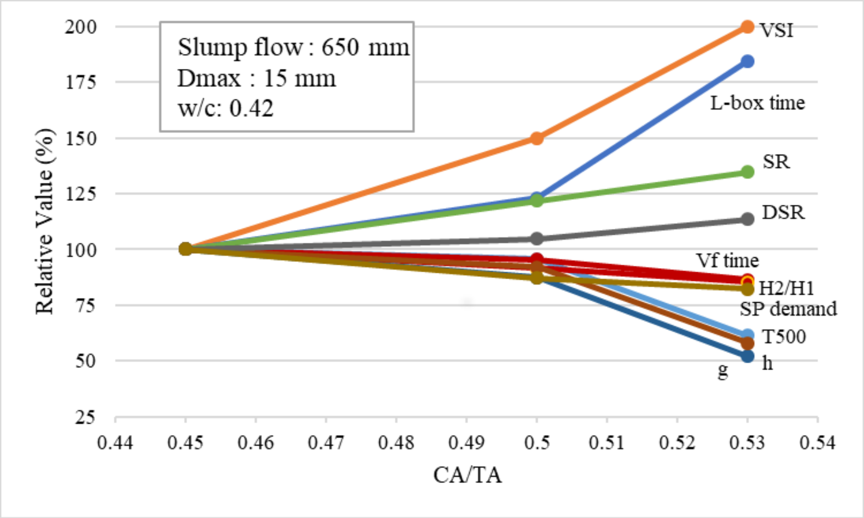


Figure 3. Effect of CA/TA on the test results.

The paste in fresh SCC fills the voids between aggregate particles, covers the aggregates and enable the SCC flow by separating and pushing the aggregate particles (Jiao et al., 2017; Reinhardt & Wüstholz, 2006). When the D_{max} and CA/TA are high, the surface of the aggregates to be covered becomes less, and therefore more paste can be available to separate and push the particles. This may enhance the flow and reduce the viscosity (and yield stress) of the SCC. On the other hand, higher D_{max} and higher CA/TA can also cause more internal friction causing an increasing effect on the viscosity. Therefore, the effect of D_{max} and CA/TA on T500 is generally not as clear as the other variables such as w/c and slump flow (Hu & Wang, 2011). Nevertheless, it was found in this study that the T500 time decreased with increasing the CA/TA and D_{max} as demonstrated in Figures 3 and 4, respectively. It means that the former effect discussed above was superior to the latter.

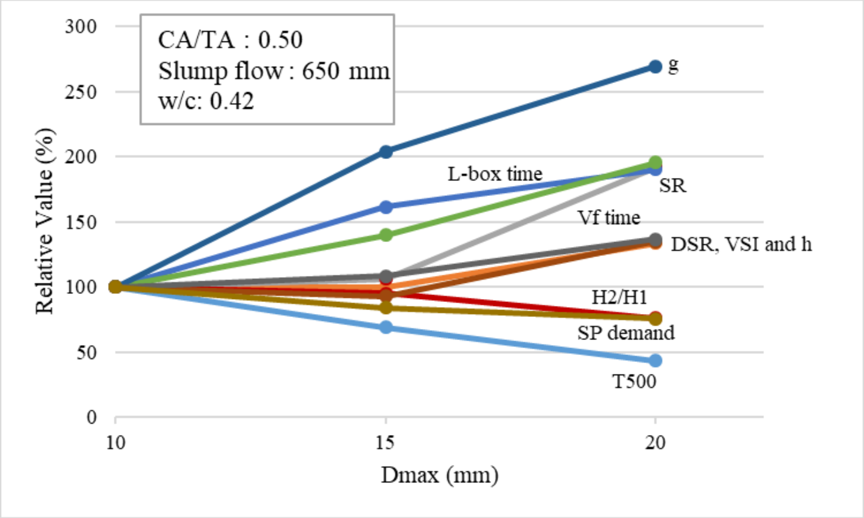


Figure 4. Effect of D_{max} on the test results.

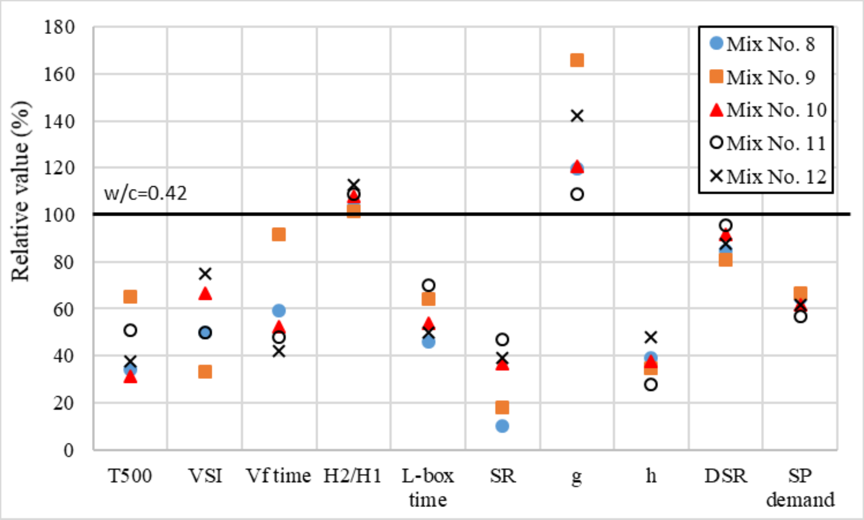


Figure 5. Effect of w/c on the test results.

VSI values given in Table 2 show that most of the mixtures displayed good spread with little or no segregation; however, the mixtures with w/c=0.42 showed some bleeding, which can be attributed to their higher superplasticizer requirements for the desired slump flow values. (it should be noted that the mixtures in this study were purposely designed to show some instability to investigate the effect of design variables on the stability.) VSI was higher when w/c was lower (Figure 5). This seems contradictory but such mixtures contained more superplasticizer, indicating that superplasticizer amount has more effect on VSI when compared to the effect w/c for a given slump flow. VSI values were higher for the higher values of CA/TA and D_{max} (Figures 3 and 4).

3.2. *V-funnel test*

Table 2 shows that the V-funnel values of the mixtures except Mix no 2, 6 and 9, which have 550 mm slump flow or 20 mm D_{max}, are below 25 seconds as recommended by EFNARC (EFNARC, 2005). As stated previously, not all of the mixtures were supposed to perform perfectly to differentiate the effects on SCC performance.

Higher slump flow diameters resulted in shorter V-funnel times (Figure 2). However, it should be noted that this statement is valid within the limitations of the present study. Moreover, as expected (Benaicha et al., 2019; Felekoğlu, Türkel, & Baradan, 2007; Yahia, Tanimura, & Shimoyama, 2005), low w/c mixtures had longer V-funnel times (Figure 5). As known, V-funnel durations indicate the SCC viscosity, and an increase in w/c or superplasticizer content decreases the viscosity and, therefore, V-funnel times. With lower water content, the solids concentration, and therefore, viscosity of the mixture increases. As explained before, for higher superplasticizer content, more water becomes available for the fluidity.

When CA/TA is high, the possibility of collision of coarse aggregate particles at the V-funnel outlet increases, delaying the SCC flow through the trapdoor. However, as was the case for T500 results, the V-funnel times in this study decreased slightly with higher CA/TA (Figure 3). This can be explained by the similar discussions made previously for the T500 results (lower aggregate surface and more available paste for the flow).

An increase in D_{max} of coarse aggregate from 10 mm to 15 mm did not affect the V-funnel time significantly. However, it increased extremely (to 38 sec) when D_{max} was 20 mm as seen in Figure 4. Larger particles behaved as obstacles at the outlet of the V-funnel and increased the V-funnel flow times.

3.3. *L-box test*

The L-box test results (H2/H1 ratio and L-box flow time) are presented in Table 2. H2/H1 results show that increasing the w/c (Figure 5) or slump flow (Figure 2) resulted in greater passing ability. These findings confirm the results of other studies (Benaicha et al., 2019; Long et al., 2012). Moreover, Figures 3 and 4 show that when CA/TA or D_{max} was higher, passing ability was lower. This is an expected finding since higher content of coarse aggregates will experience more collision while passing through the reinforcing bars.

It is clear from Table 2 that Mixture 2, which has low w/c and low slump flow, had the longest L-box flow time. In the same way, the mixture with high w/c and high slump flow (Mixture 11), gave the shortest flow time. These findings, which can also be seen from Figures 2 and 5, can be attributed to the lower viscosity of the mixtures with high w/c or slump flow.
Figures 3 and 4 show that increasing the CA/TA ratio or Dmax resulted in longer L-box flow times. This can be explained by the delayed motion of the concrete due to more collision of coarse aggregates during the flow between reinforcement bars.

It should be noted that although aggregate type was not a parameter in this study, the angularity and surface roughness of the aggregates can affect the SCC properties significantly. A more angular morphology and a rougher surface can increase the aggregate friction and decrease the fluidity and passing ratio (Silva, Delvasto, Izquierdo, & Araya-Letelier, 2021).

3.4. *Rheology test*

Apparent yield stress (g) and torque plastic viscosity (h) values determined by Bingham model) can be seen in Table 2. As expected (Benaicha et al., 2019), increasing the slump flow decreased the g values (Figure 2) because the higher amount of superplasticizer, which was necessary to reach the target slump flow, provided better dispersion of cement particles and promoted the flow. Using more superplasticizer releases the water between cement particles and increase the water film thickness on the particles (Benaicha et al., 2019).

For a given slump flow diameter, increasing the w/c resulted in higher g values (Figure 5). When w/c was higher, the superplasticizer requirement was less when compared to the mixtures with low w/c. Consequently, giving a start to concrete flow became more difficult and, accordingly, apparent yield stress increased. It could also be expected to have lower yield stress for the mixtures with higher w/c due to dilution effect of more water in the mixture. However, such an expectation would be valid if the superplasticizer contents had been constant. Accordingly, it is important to consider the constant and varying parameters in comparing the results of different studies.

Increasing the CA/TA resulted in higher g values (Figure 3). The lower yield stress for the lower fine aggregate fractions were also noted by other researchers (Jiao et al., 2017). This can be explained by the following sequential facts: Increasing the CA/TA makes aggregate grading coarser, reduces aggregate surface area, increases the free paste amount between aggregate particles and decreases the stress necessary to start the SCC flow, which is quantified as g. The lower yield stress for higher CA/TA is contrary to the findings of a recent study (Aïssoun et al., 2016), where it was stated that a decrease in the coarse aggregate volume can reduce the inter-particle friction, and therefore, reduce yield stress. This discussion shows that the change in CA/TA can have both increasing and decreasing effect on the SCC rheology, and there exists an optimum value to achieve the desired performance. The optimum value is related with the packing density of the aggregates, which is influenced by the CA/TA (Aïssoun et al., 2016).

As shown in Figure 4, an increase in D_{max} increased the g values. For the higher values of D_{max}, frictional force between coarse particles increased, and it became more difficult to give a start to concrete flow.

Similar to the results of a research (Erdem et al., 2009), increasing the slump flow decreased the h values (Figure 2) because for a given w/c, more superplasticizer was used to increase the slump flow, which made the flow easier by separating the cement particles and decreasing the viscosity. For the mixtures with same slump flow diameter, increasing the w/c decreased the h values (Figure 5) as found in (Erdem et al., 2009; Libre et al., 2010), where it was also stated that w/c is the most important parameter that affects the viscosity. Higher amount of water has already an effect to separate the solid particles. Moreover, higher water content results in higher paste volume for a constant binder content, and the reduction in plastic viscosity due to higher paste volume is also mentioned by (E. Koehler & Fowler, 2004). Due to these reasons, viscosity was lower for high w/c mixtures.

Similar to the discussions made for g, higher values of CA/TA resulted in lower h values (Figure 3). Again, CA/TA or packing degree of the aggregate has an important effect on viscosity. It was stated by other researchers (K H Khayat, Hu, & Laye, 2000; E. P. Koehler & Fowler, 2007) that increasing the aggregate packing density can reduce plastic viscosity. In other words, both lower and higher values of CA/TA than its optimum ratio can increase the viscosity.

Figure 4 shows that an increase in D_{max} resulted in an increase in the h. Similar to the explanation made for the g values, the higher frictional force between coarser particles increased the viscosity.

3.5. *Static sieve segregation test*

This test can evaluate the SCC stability when the concrete is at rest, for example after placement of the concrete into a formwork. The results of the sieve segregation test, denoted as segregation ratio (SR), are given in Table 2. Figures 2 and 5 show that the SCC mixtures with higher slump flow or lower w/c have higher SR. This may be due the fact that when it is aimed to increase slump flow of a mixture with low w/c, the superplasticizer demand increases, which may trigger instability. The lower stability of the mixtures containing more superplasticizer was noted also by (Chia & Zhang, 2004; El-Chabib & Nehdi, 2006; Shen, Jovein, & Wang, 2016). It can be expected that using lower w/b can decrease segregation (El-Chabib & Nehdi, 2006; Libre et al., 2010) but it was stated in (Zhang et al., 2021) that this is true for constant superplasticizer contents. In addition, there is another research which found lower stability for lower w/b (Wong & Kwan, 2008).

Figure 3 indicates that increasing the CA/TA resulted in higher SR. This finding confirms the results of other studies (Okamura & Ozawa, 1994), where it was concluded that the coarse aggregate volume should be limited in order to increase the segregation resistance. Likewise, as Figure 4 shows, higher D_{max} caused an increase in the SR. It should be noted that the effects of design variables on SR have the same tendency with the VSI findings. Therefore, similar discussions made for VSI also hold for explaining the SR results.

Figure 2 also indicates that SR results were affected from slump flow to a much greater extent when compared to the other tests.

3.6. *Dynamic sieve segregation test*

Dynamic segregation ratio (DSR) results are given in Table 2. According to Figure 2, the DSR values were higher as slump flow increased. As was the case in static sieve segregation test, low w/c resulted in higher DSR (Figure 5) due to higher superplasticizer requirement.

Figures 3 and 4 show that DSR values increased as CA/TA ratio or D_{max} increased. The lower dynamic stability for higher CA/TA and D_{max} can be attributed to the lower drag force that stems from lower aggregate surface area/mass ratio (Esmaeilkhanian et al., 2014; Shen et al., 2009). Figure 5 also indicates that although the effect of design parameters on static and dynamic sieve segregation tests showed similar tendency, the effects on the dynamic segregation test was less pronounced because its results showed less deviations from 100%. It was stated in (Zhang et al., 2021), that the mix proportion variables have the same trend on static stability and dynamic stability, and only the degree of influence is different.

Although the DSST test is a relatively new method, the findings for the effects of the mix design variables were found to be similar to those obtained from other dynamic stability test results stated in the literature (Esmaeilkhanian et al., 2014).

3.7. *Correlations between the tests*

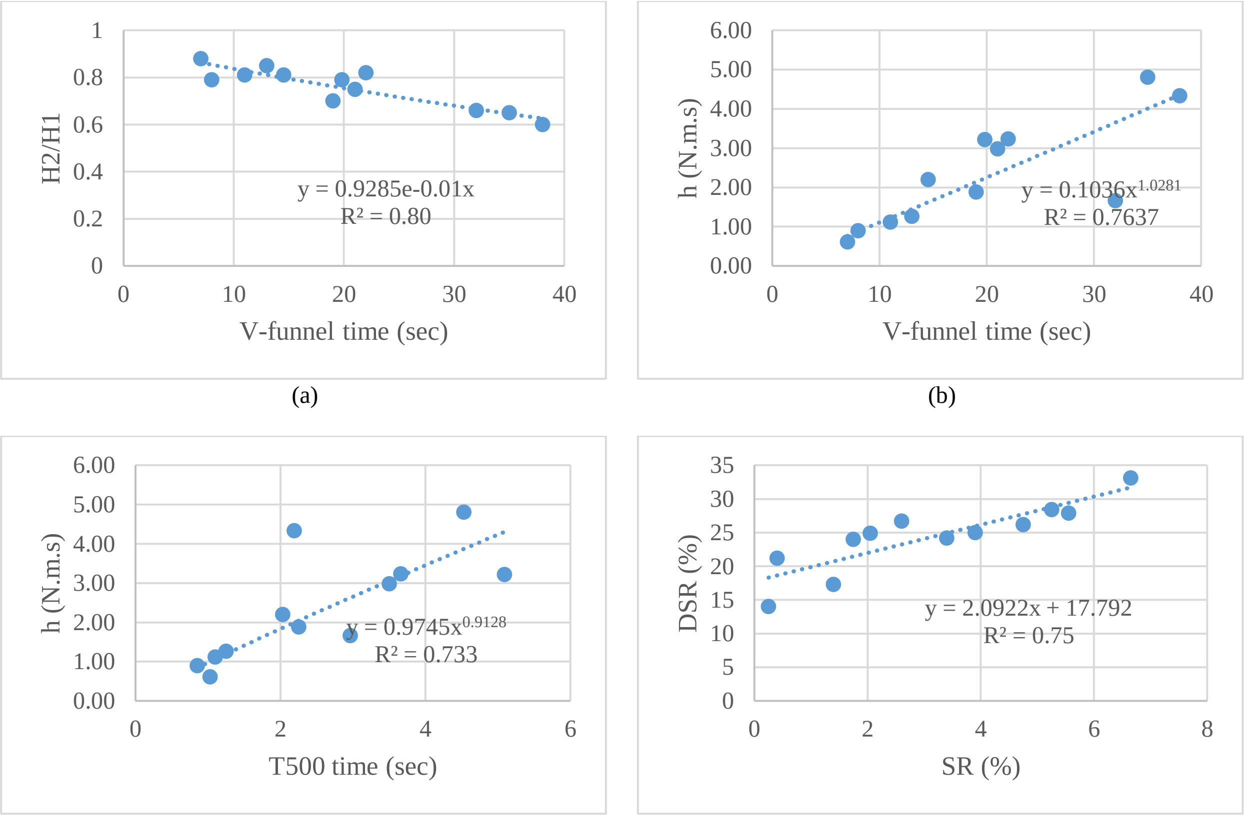
It is possible to find relations between the results of several tests performed on SCC. For example, slump flow diameter and V-funnel (or T500) time, which are easy and cheap to measure, can represent the yield stress and plastic viscosity, respectively, which are truly measured by expensive rheometers (Kamal H. Khayat et al., 2004; Tregger, Gregori, Ferrara, & Shah, 2012). Segregation tests can be related to V-funnel and L-box tests (Kamal H. Khayat et al., 2004) since aggregate blocking at the V- funnel orifice or at the gaps between the reinforcing bars of L-box can indicate segregation. Even the slump flow test can be used to evaluate the dynamic segregation (Tregger et al., 2012).

Accordingly, the test results of this study were matched with each other to investigate their possible correlations as explained below:

Figure 6a shows that the V-funnel and L-box test results have a strong relation with R2 of 0.80. This was expected since both tests are involved in the flow of SCC through a narrow spacing.

It is known from the literature (Bartos, Sonebi, & Tamimi, 2002; EFNARC, 2005; Saleh Ahari, Erdem, & Ramyar, 2015) that viscosity can be estimated by V-funnel and T500 test. This information was verified in Figure 6b and 6c. The relatively high R2 values can be attributed to the fact that both V-funnel and T500 tests are based on the measurement of the flow speed, although the former is the flow through a narrow space and the latter is unconfined flow.

Segregation resistance should be examined for two different conditions of the fresh SCC. The segregation resistance of a stationary concrete (for example in a formwork) can be different from that of the same concrete which is in motion. While the former one is denoted by static segregation resistance, the latter is named as dynamic segregation. Although the static and dynamic segregation resistance are different from each other, the results found in this study correlated well, as seen in Figure 6d.



(a) (b)

(c) (d)

Figure 6. Correlation between different test results.

4. Conclusions

Effects of basic mix design parameters such as w/c, slump flow (or indirectly superplasticizer content), CA/TA, and D_{max} on the main characteristics of SCC were investigated by performing several tests. Within the investigated ranges for these variables, following general conclusions can be drawn:

1. Increasing the w/c decreased the superplasticizer demand for a given slump flow due to the fluidizing effect of more water in the mixtures. CA/TA and D_{max} decreased the superplasticizer demand and increased the flowability.
2. Torque plastic viscosity (h) and the results of the viscosity-indicating tests (T500 and V-funnel) were generally affected from the mix-design variables in the same way: Increasing the slump flow or w/c decreased the viscosity since higher superplasticizer content in such mixtures make a favourable effect on the speed of the flow. Similarly, increasing the CA/TA and D_{max} decreased the viscosity by reducing the aggregate surface area to be wetted by the paste, which made the paste more available for the SCC motion.
3. Both H2/H1 and L-box flow times were affected in the same manner from the mix design variables. As slump flow and w/c increased, H2/H1 and flow time results indicated better passing ability. Increase in CA/TA and D_{max} reduced the passing ability which can be understood from lower H2/H1 and higher L-box flow time. Higher content of coarse aggregates or bigger aggregates can cause more collision while passing through the reinforcing bars.
4. The effect of w/c were different on g and h while the other mix design variables (slump flow, CA/TA and D_{max}) showed similar effects on the individual values of these rheological parameters. The g values were lower when the slump flow was higher because the higher amount of superplasticizer in such mixtures provided better dispersion of cement particles and promoted the flow.

5. All of the stability tests (VSI, sieve segregation and DSST) were affected from the varied mix-design variables in the same way. For a given slump flow, increasing the w/c resulted in more stable mixtures due to their lower superplasticizer contents. Increasing the slump flow (or superplasticizer content), CA/TA and D_{max} disturbed the stability. Although the effect of design parameters on static and dynamic sieve segregation tests showed similar tendency, the effects on the dynamic segregation test was less pronounced.
6. In almost all of the test results, the effects of w/c and slump flow were more when compared to CA/TA and D_{max}.
7. The effects of each mix-design parameter on individual test results are summarized in Table 3.
8. Good correlations were obtained between i) V-funnel and L-box passing ratio (R^2=0.80), ii) V-funnel and h (R^2=0.76), iii) T500 and h (R^2=0.73), and iv) static and dynamic segregation (R^2=0.75) test results.

Table 3. Effect of each variable on the test results (I: Increases, D: Decreases) (Self elaboration)

Increasing values of	SP demand	T_{500}	VSI	Vf time	H2/H1	L-box time	g	h	SR	DSR
Slump flow	I	D	I	D	I	D	D	D	I	I
w/c	D	D	D	D	I	D	I	D	D	D
CA/TA	D	D	I	D	D	I	D	D	I	I
D_{max}	D	D	I	I	D	I	I	I	I	I

Author contributions: Mohammad Musa Alami: experimental investigation and data collection; Tahir Kemal Erdem: conceived the original idea, planned the experiments, critically revised the article. Both authors contributed to the development and writing of the article.

Funding: The authors received no financial support for this article.

Acknowledgments: The authors thank to the contribution of Prof. Kamal H. Khayat for the development of the DSSR test method.

Conflicts of interest: The authors declare that there is no conflict of interest for the article.

References

ACI 237 R. (2007). Self-consolidating concrete ACI 237 R. In *Mi, Usa*.

Aïssoun, B. M., Hwang, S. D., & Khayat, K. H. (2016). Influence of aggregate characteristics on workability of superworkable concrete. *Materials and Structures/Materiaux et Constructions*, *49*(1–2), 597–609. https://doi.org/10.1617/s11527-015-0522-9

Alami, M. M., Erdem, T. K., & Khayat, K. H. (2016). Development of a New Test Method to Evaluate Dynamic Stability of Self-Consolidating Concrete. *SCC2016-8th International RILEM Symposium on Self-Compacting Concrete*, 113–122. Washington D.C.

Artigas, V. F., Positieri, M. J., Quintana, M. V., Oshiro, Á., & Cortez, R. (2021). Self-compacting mortars with mineral additions : perlite and lime- stone filler. *Revista de La Construcción*, *20*(3), 479–490.

Assaad, J., Khayat, K. H., & Daczko, J. (2004). Evaluation of static stability of self-consolidating concrete. *ACI Materials Journal*, *101*(3), 207–215. https://doi.org/10.14359/13116

Bartos, P. J. ., Sonebi, M., & Tamimi, A. . (2002). Workability and Rheology of Fresh Concrete: Compendium of Test. *RILEM Report - TC145 WSM*, (January 2002), 57–60.

Benaicha, M., Hafidi Alaoui, A., Jalbaud, O., & Burtschell, Y. (2019). Dosage effect of superplasticizer on self-compacting concrete: Correlation between rheology and strength. *Journal of Materials Research and Technology*, *8*(2), 2063–2069. https://doi.org/10.1016/j.jmrt.2019.01.015

Bouziani, 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. https://doi.org/10.1016/j.conbuildmat.2013.08.039

Bui, V. K., Montgomery, D., Hinczak, I., & Turner, K. (2002). Rapid testing method for segregation resistance of self-compacting concrete. *Cement and Concrete Research*, *32*(9), 1489–1496. https://doi.org/10.1016/S0008-8846(02)00811-6

Chia, K. S., & Zhang, M. H. (2004). Effect of chemical admixtures on rheological parameters and stability of fresh lightweight aggregate concrete. *Magazine of Concrete Research*, *56*(8), 465–473. https://doi.org/10.1680/macr.2004.56.8.465

Domone, P. L. (2006). Self-compacting concrete: An analysis of 11 years of case studies. *Cement and Concrete Composites*, *28*(2), 197–208. https://doi.org/10.1016/j.cemconcomp.2005.10.003

EFNARC. (2005). The European Guidelines for Self-Compacting Concrete. *The European Guidelines for Self Compacting Concrete*, (May), 63. Retrieved from http://www.efnarc.org/pdf/SCCGuidelinesMay2005.pdf

El-Chabib, H., & Nehdi, M. (2006). Effect of mixture design parameters on segregation of self-consolidating concrete. *ACI Materials Journal*, *103*(5), 374–383. https://doi.org/10.14359/18160

Erdem, T. K., Khayat, K. H., & Yahia, A. (2009). Correlating rheology of self-consolidating concrete to corresponding concrete-equivalent mortar. *ACI Materials Journal*, *106*(2), 154–160. https://doi.org/10.14359/56462

Esmaeilkhanian, B., Khayat, K. H., Yahia, A., & 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. https://doi.org/10.1016/j.cemconcomp.2014.03.001

Felekoğlu, B., Türkel, S., & Baradan, B. (2007). Effect of water/cement ratio on the fresh and hardened properties of self-compacting concrete. *Building and Environment*, *42*(4), 1795–1802. https://doi.org/10.1016/j.buildenv.2006.01.012

Ferraris, C., Larrard, F., & Martys, N. (2001). Fresh concrete rheology: recent developments. *Materials Science of Concrete*, *VI*, 215–241.

Hu, J., & Wang, K. (2011). Effect of coarse aggregate characteristics on concrete rheology. *Construction and Building Materials*, *25*(3), 1196–1204. https://doi.org/10.1016/j.conbuildmat.2010.09.035

Jiao, D., Shi, C., Yuan, Q., An, X., Liu, Y., & Li, H. (2017). Effect of constituents on rheological properties of fresh concrete-A review. *Cement and Concrete Composites*, *83*, 146–159. https://doi.org/10.1016/j.cemconcomp.2017.07.016

Khayat, K. H., Ghezal, A., & Hadriche, M. S. (2000). Utility of statistical models in proportioning self-consolidating concrete. *Materials and Structures/Materiaux et Constructions*, *33*(5), 338–344. https://doi.org/10.1007/bf02479705

Khayat, K H, Hu, C., & Laye, J. M. (2000). Influence of aggregate Grain-Size Distribution on Workability of Self-Consolidating Concrete. *International Symposium on High Performance Concrete - Workability, Strength and Durability*, *1*(May), 641–658.

Khayat, Kamal H., Assaad, J., & Daczko, J. (2004). Comparison of field-oriented test methods to assess dynamic stability of self-consolidating concrete. *ACI Materials Journal*, *101*(2), 168–176. https://doi.org/10.14359/13066

Kim, J. H., Noemi, N., & Shah, S. P. (2012). Effect of powder materials on the rheology and formwork pressure of self-consolidating concrete. *Cement and Concrete Composites*, *34*(6), 746–753. https://doi.org/10.1016/j.cemconcomp.2012.02.016

Koehler, E., & Fowler, D. (2004). Development of a Portable rheometer for fresh Portland cement concrete. *International Center of Aggregates Research*, 321. Retrieved from http://www.icar.utexas.edu/publications/105/105-3F.pdf

Koehler, E. P., & Fowler, D. W. (2007). *Final Report ICAR Project 108: Aggregates in Self-Consolidating Concrete*. 362.

Libre, N. A., Khoshnazar, R., & Shekarchi, M. (2010). Relationship between fluidity and stability of self-consolidating mortar incorporating chemical and mineral admixtures. *Construction and Building Materials*, *24*(7), 1262–1271. https://doi.org/10.1016/j.conbuildmat.2009.12.009

Long, W. J., Lemieux, G., Hwang, S. D., & Khayat, K. H. (2012). Statistical models to predict fresh and hardened properties of self-consolidating concrete. *Materials and Structures/Materiaux et Constructions*, *45*(7), 1035–1052. https://doi.org/10.1617/s11527-011-9815-9

Ma, K., Feng, J., Long, G., Xie, Y., & Chen, X. (2017). Improved mix design method of self-compacting concrete based on coarse aggregate average diameter and slump flow. *Construction and Building Materials*, *143*, 566–573. https://doi.org/10.1016/j.conbuildmat.2017.03.142

Okamura, H., & Ozawa, K. (1994). Self-compactable high performance concrete in Japan. *ACI International Workshop on High Performance Concrete*, 31–44.

Panesar, D. K., & Shindman, B. (2012). The effect of segregation on transport and durability properties of self consolidating concrete. *Cement and Concrete Research*, *42*(2), 252–264. https://doi.org/10.1016/j.cemconres.2011.09.011

Reinhardt, H. W., & Wüstholz, T. (2006). About the influence of the content and composition of the aggregates on the rheological behaviour of self-compacting concrete. *Materials and Structures/Materiaux et Constructions*, *39*(7), 683–693. https://doi.org/10.1617/s11527-006-9102-3

Saleh Ahari, R., Erdem, T. K., & Ramyar, K. (2015). Time-dependent rheological characteristics of self-consolidating concrete containing various mineral admixtures. *Construction and Building Materials*, *88*, 134–142. https://doi.org/10.1016/j.conbuildmat.2015.04.015

Shen, L., Jovein, H. B., & Wang, Q. (2016). Correlating aggregate properties and concrete rheology to dynamic segregation of self-consolidating concrete. *Journal of Materials in Civil Engineering*, *28*(1), 04015067.

Shen, L., Struble, L., & Lange, D. (2009). Modeling dynamic segregation of self-consolidating concrete. *ACI Materials Journal*, *106*(4), 375–380. https://doi.org/10.14359/56658

Silva, Y. F., Delvasto, S., Izquierdo, S., & Araya-Letelier, G. (2021). Short and long-term physical and mechanical characterization of self-compacting concrete made with masonry and concrete residue. *Construction and Building Materials*, *312*(October), 125382. https://doi.org/10.1016/j.conbuildmat.2021.125382

Struble, L., Szecsy, R., Lei, W.-G., & Sun, G.-K. (1998). Rheology of cement paste and concrete. *Cement, Concrete and Aggregates*, *20*(2), 269–277.

Tregger, N., Gregori, A., Ferrara, L., & Shah, S. (2012). Correlating dynamic segregation of self-consolidating concrete to the slump-flow test. *Construction and Building Materials*, *28*(1), 499–505. https://doi.org/10.1016/j.conbuildmat.2011.08.052

Valcuende, M., Jarque, C., & Parra, J. (2007). Homogeneidad de los hormigones autocompactantes Self-consolidating concrete homogeneity. *Materiales de Construcción*, *57*(287), 37–52.

Wong, H. H. C., & Kwan, A. K. H. (2008). Packing density of cementitious materials: Part 1-measurement using a wet packing method. *Materials and Structures/Materiaux et Constructions*, *41*(4), 689–701. https://doi.org/10.1617/s11527-007-9274-5

Yahia, A., Tanimura, M., & Shimoyama, Y. (2005). Rheological properties of highly flowable mortar containing limestone filler-effect of powder content and W/C ratio. *Cement and Concrete Research*, *35*(3), 532–539. https://doi.org/10.1016/j.cemconres.2004.05.008

Zhang, Z., Xiao, J., Zhang, Q., Han, K., Wang, J., & Hu, X. (2021). A state-of-the-art review on the stability of self-consolidating concrete. *Construction and Building Materials*, *268*, 121099. https://doi.org/10.1016/j.conbuildmat.2020.121099