International Journal of Advanced Structural Engineering (2022) 12 : 661–670

ORIGINAL RESEARCH

Assessing the effects of self-consolidating concrete components on workability to compensate the negative impacts resulted by temperature and time

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Abstract

Compared to other concrete types, the self-compacting concrete (SCC) offers a higher workability. Accordingly, the SCC performance is highly affected by the ambient temperature and extended transportation time. In previous studies, the effect of constituents on SCC at various time and temperature was only studied after the concrete temperature reached the normal range. Nonetheless, in the present research, it is tried to reduce the negative impacts of changing temperature and time by using cement, limestone powder, and chemical admixtures without considering temperature constraints for concrete. In this research, SCC samples temperature were selected for different seasonal conditions. Therefore, once the concrete temperature reached the ambient temperature, slump flow, T50, VSI, J-ring, and rheology tests were conducted on a total of 21 different concrete mixtures with water to cement ratio of 0.4. According to the results, application of retarding admixture and increased cement dosage contributed to improved workability and rheological behavior. On the other hand, an increase in the limestone powder dosage, rather than cement, was seen to impose a larger contribution to increased passing ability of SCC through rebars, but since the concrete containing limestone powder exhibited larger slump losses, one should increase the dosage of cement or retarding admixture to retain the concrete workability. Generally, it was found that the temperature and concrete mixture composition effectively control performance characteristics of the SCC. Therefore, it is recommended to keep the concrete from being overheated as it can otherwise lead to the acceleration of cement hydration and hence decreased workability.

Keywords: Temperature, Cement, Limestone powder, Viscosity-modifying agent, Retarding admixture

Introduction

Self-compacting concrete (SCC) is a special type of concrete that can be spread over the target to fill in the mold and encompass the reinforcement without any mechanical compaction. In the recent past, thanks to its super homogeneity and easy placement, SCC has been increasingly used in structures with sensitive architectural designs where compact reinforcements are required [1-5].

The term rheology refers to material deformation and flow. Recognition of the rheological behavior of SCC helps select the concrete material and undertake the mixture design properly. Numerous effects of admixtures as well as basic constituents of fresh concrete (e.g., water, Air-entrained admixture, superplasticizer, and silica fume) on the concrete rheology have been demonstrated required [6].

In SCC mixtures, mineral powders exhibit desirable properties that improve the fresh and consolidated mixture properties. The mineral powders are used to reduce the consumption of Portland cement and achieve target properties for the concrete mixtures. Application of pumice powder for improving rheological properties of SCC has been reportedly fruitful [7-9]. Effect of silica fume on the rheological characteristics is pretty complicated. At a dosage of 3 – 5%, it tends to reduce the yield stress and plastic viscosity. However, as the dosage increases to 5 – 10%, the silica fume ends up increasing the yield strength and plastic viscosity [10-13]. In addition to mineral powders, retarders can be used to cope with the effects of high temperatures and to prevent problems when there are inevitable lags between mixing time and concrete casting. Retarders are used in different conditions that require extended setting time and delayed cement hydration, such as foundations of a large building, dams, oil and gas wells, bridge piers and roller compacted concrete [14-

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16]. The effectiveness of a retarder depends on the C_3A dosage in Portland cement which can increase the setting time. Of course, if retarder is used more than the permitted-level, it can completely prevent concrete set. In recent years, some studies were conducted on the setting time of concrete using a type of retarder to improve the concrete's quality, maintain workability and control cement hydration. In these studies, the effects retarders and their optimal amounts were studied on a concrete mixture [17-20].

Investigation of workability and rheology of the concrete is necessary to avoid any blockage in the concrete placement pipelines and ensure proper passage of the concrete through the rebars. Upon a change to rheological properties of the concrete, it is important to consider the concrete pump pressure, pipe length, and water absorption capacity of the aggregate [21]. Rheological properties of the fresh mixture impose large contributions to mixing, pumping, and even consolidation properties of the SCC [22, 23]. Workability and rheological properties of the concrete change over time and in the course of the pumping stage [24-27].

Design and development of rheological properties of SCC is an important topic in the concrete technology. Proper choices of particle size distribution for aggregates, cement type, and chemical admixtures are known to fundamentally affect this topic. Most of the published methods for SCC design have been focused on optimization of particle size distribution and cement content for optimizing the flow and stability of the paste, mortar, and fresh concrete [28]. Traditionally, compatibility of the cement with the superplasticizer has been tested on the cement paste. Therefore, it can be stipulated that the design and development of SCC has been based on rheological experimentation of the cement paste. However, effects of various parameters on the rheology of the cement paste and fresh concrete are not always that explicit [29]. On the other hand, the mortar has been proposed as a model for predicting rheological properties of SCC as functions of time and temperature. According to the literature, rheological properties of the mortar are well correlated to those of the fresh SCC [30].

Researchers have shown that the measured diameter of the slump flow is inversely associated with the yield stress. Measured T50 values in the slump flow tests are proportional to the plastic viscosity. Effects of aggregate and particle type on rheological properties of the concrete mixture have been considered many researchers. Increased dosage of sand in the aggregate in the range of 35 – 55% leads to a reduction in the yield stress (increased slump flow) coupled with a simultaneous increase in the plastic viscosity (i.e., longer T50 values). In the meantime, a further increase in the gravel dosage in the range of 50 – 60% tends to reduce the slump flow by about 10 cm while increasing the T50 by about 1 second [31-35].

Rheological behavior of fresh concrete is affected by temperature. This introduces a major problem in SCC. Even small changes in the temperature cause significant loss of flow properties. Accordingly, one should note that the temperature is an important factor as far as the rheology is concerned. Variations of concrete mixture yield stress and plastic viscosity with temperature indicate a cement-associated uncertain trend. Therefore, acknowledging the important role of temperature in the cement hydration and rheology of SCC, it must be carefully accounted for in our analysis [36, 37].

According to ACI 238 [38] and the research by Łukowski [39], an increase in temperature tends to improve the yield stress growth rate while reducing the plastic viscosity growth rate. Temperature-sensitivity of rheological properties is usually sourced from the mixture design of SCC.

Ideal ambient temperature for concrete placement is 20 - 23°C. A too high ambient temperature tends to cause such problems as increased cement hydration and water evaporation. Cement hydration is known to be controlled by temperature, cement content, and application of admixtures. An increase in cement hydration and water evaporation can not only deteriorate the concrete freshness but also adversely affect the strength and durability of consolidated concrete [40-42].

Test results have shown that the samples at higher temperatures exhibit lower 7-day and 28-day compressive strengths than similar samples at lower temperatures. Such problems can be alleviated by using chemical admixtures and adjusting cement type, water to powder ratio, and other constituents of the concrete. Given the important role of temperature in determining the composition of SCC (e.g., superplasticizer, cement dosage, viscosity-modifying agent, and limestone powder dosage) and estimating the resultant changes to the rheology, it must be considered carefully [43-45].

Effect of temperature on a mixture with a high water to powder ratio (including cement and limestone powder) differs from that on a mixture with a low water to powder ratio. At lower temperatures, a powder-rich mixture exhibits good performance while the same mixture may render brittle at higher temperatures. In general, powder type SCC accelerates the setting time significantly. This can be linked to the reduced water to powder ratio coupled with the use of limestone filler that is known to contribute to faster setting time. Therefore, the powder-rich SCC can be seen as the best choice for short transportation and rapid construction site progress [46-49].

In previous research works, the common practice was to reduce the concrete temperature to normal range followed by investigating the effects of SCC components at different times and ambient temperatures. Moreover, there is still no report on the comparison of different components of SCC on its performance (e.g., effect of retarding admixture compared to other components of the SCC). In this research, first, workability tests were performed to qualitatively compare the effects of cement, limestone powder, viscosity-modifying agent, and retarding admixture on the fresh SCC mixtures without taking the temperature considerations. Next, a rheometer was utilized to investigate rheological parameters of SCC mixtures.

2. Experimental program

2-1- Materials

Portland cement, Type II, and limestone powder with the gravities of 3150 and 2610 kg/m^3, respectively were used in SCC mixtures. The chemical composition of Portland cement and limestone powder are presented in Table 1. The aggregates used were gravel, coarse sand and fine sand with the maximum sizes of 12.5, 4.75, and 2.36 mm, respectively. The physical characteristics of the aggregates are shown in Table 2 and the aggregate grading curve is indicated in Fig. 1.

In this research, we used polycarboxylate superplasticizer (PC), viscosity-modifying agent (VMA), and retarding admixture with specific weights of 1030, 1500, and 1180 kg/m^3, respectively. The cement-superplasticizer compatibility test was performed through mini slump test where slump loss was measured at 0, 15, and 30 min. Specifications of the four tested mixtures and the obtained values of mini slump are reported in Table 3 and Figure 2, respectively.

Table 1. Chemical composition of Portland cement and limestone powder

Chemical composition	Portland Cement	Limestone Powder
SiO2	20.74	2.80
Al2O3	4.90	0.35
Fe2O3	3.50	0.50
MgO	1.20	1.80
CaO	62.95	51.22
SO3	3.00	1.24
Loss on ignition (LOI)	1.56	42.06
Insoluble residue	0.74	2.80

Table 2. Physical characteristics of aggregates

Aggregate type	Density (Kg/m^3)	SSD Humidity (%)
Gravel	2570	2.944
Coarse Sand	2700	3.230
Fine Sand	2750	3.075

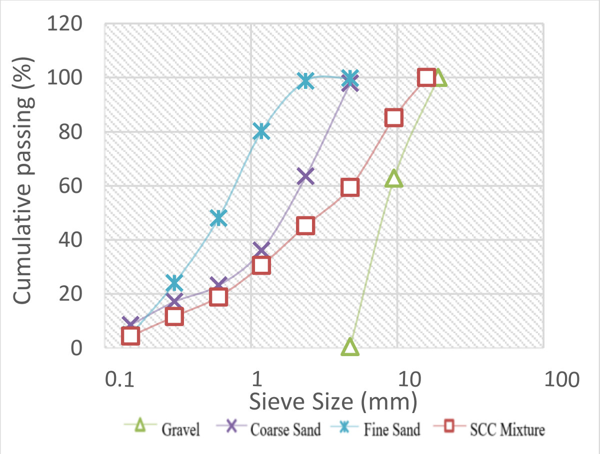


Fig. 1. Aggregates grading curves

Table 3. Mixture proportions for cement-superplasticizer compatibility test

Mixture ID	Cement (gr)	Limestone Powder (gr)	water (ml)	PC (cc)	Cement to Powder ratio	Coarse Sand (gr)	Fine Sand (gr)
S1	1000	0	250	3	-	0	0
S2	737	263	250	5	2.8	0	0
S3	600	150	250	5	4	969.5	484.7
S4	450	150	180	5	3	969.5	484.7

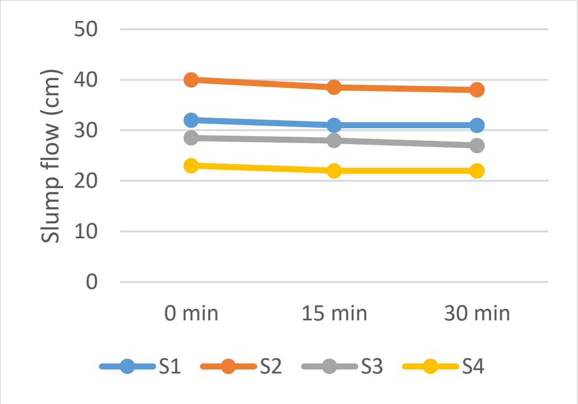


Fig. 2. Mini slump values obtained upon cement-superplasticizer compatibility test

2-2- Mix proportions

Overall, 21 mixture proportions with water to cement ratio of 0.4 were made as presented in Table 4. In this research, 15 mixture proportions were designed to identify the pros and cons of increasing cement and limestone powder dosages. Also, 6 mixture proportions were designed containing various percentages of retarding admixtures based on SCC rheology properties. These mixture proportions had a target slump of 700±10 mm; they were compared with their corresponding temperatures among the first three mixtures (control mixtures).

Table 4. SCC mixture proportions

Mixture ID	Portland Cement (kg/m^3)	Limestone Powder (kg/m^3)	Gravel (kg/m^3)	Coarse Sand (kg/m^3)	Fine Sand (kg/m^3)	PC (% of cement)	VMA (% of cement)	Retarder (% of cement)	Ambient Temperature (˚C)
C 380 - L	380	-	744	372	744	0.64	0.6	-	11.8
C 380 - N	380	-	744	372	744	0.68	0.6	-	20.6
C 380 - H	380	-	744	372	744	0.71	0.6	-	30.7
C 420 - L	420	-	713	356	713	0.59	0.6	-	10.2
C 420 - N	420	-	713	356	713	0.62	0.6	-	20.3
C 420 - H	420	-	713	356	713	0.67	0.6	-	30.2
C 460 - L	460	-	681	341	681	0.55	0.6	-	10.5
C 460 - N	460	-	681	341	681	0.56	0.6	-	21.4
C 460 - H	460	-	681	341	681	0.63	0.6	-	30.1
LP 100 - L	380	100	724	362	724	0.69	-	-	10.7
LP 100 - N	380	100	724	362	724	0.73	-	-	20.8
LP 100 - H	380	100	724	362	724	0.78	-	-	31.1
LP 50 - L	380	50	704	352	704	0.67	0.3	-	11.4
LP 50 - N	380	50	704	352	704	0.7	0.3	-	21.3
LP 50 - H	380	50	704	352	704	0.75	0.3	-	30.3
RA 3% - L	380	-	744	372	744	0.64	0.6	0.3	10.5
RA 3% - N	380	-	744	372	744	0.68	0.6	0.3	21.2
RA 3% - H	380	-	744	372	744	0.71	0.6	0.3	30.4
RA 6% - L	380	-	744	372	744	0.64	0.6	0.6	11.1
RA 6% - N	380	-	744	372	744	0.68	0.6	0.6	20.6
RA 6% - H	380	-	744	372	744	0.71	0.6	0.6	30.9

2-3- Mixing methods

In this paper, three ambient temperature ranges of low (10-12°C), normal (20-22°C), and high temperature (30-31°C) were considered. All materials including aggregate, cement, and limestone powder were placed in the environment condition in order for the fresh concrete reaching the ambient temperature. Initially, sand and gravel with one-third volume of water were mixed in the mixer for one minute. Then, the cementitious materials accompanied by a third of water and super-plasticizer were added to the mixture and the mixing process was continued for 3 minutes. Afterward, the remaining part of water (one-third of volume) and VMA (if it was considered) were added to the mixture. In this step, retarding admixture (if it was considered) was added to the mixture every one minute for 3 times; accordingly, it took 3 minutes. Then, the mixing process was stopped for 3 minutes. Finally, the mixing process was continued for 2 more minutes.

2-4- Test methods

2-4-1 Workability tests

Slump flow, T50, and stability index tests were performed according to ASTM C1611 (Figure 3) [50]. In the slump flow test, average diameter of the concrete spread circle is used as an indicator of the concrete flowability. Moreover, the time taken for the concrete to reach the 50-cm spread circle (T50) provides a measure of the concrete viscosity. In the slump flow test, once the concrete reached an stable appearance, it is subjected to a visual inspection and followed by assigning a visual stability index (VSI).

In this research, all studied mixtures exhibited VSIs of 0 or 1.

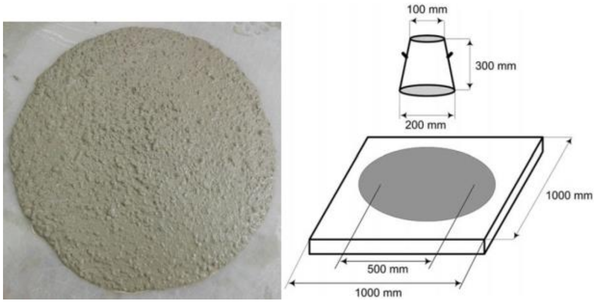
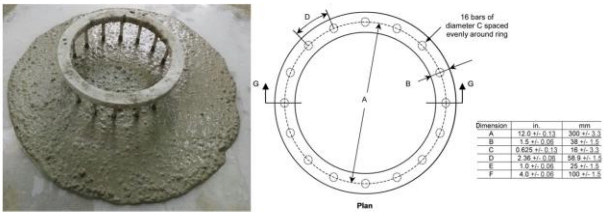


Fig. 3. Workability tests including slump flow, VSI, and T50

J-ring test was conducted according to ASTM C1621 [51]. This test simulates the passage of the concrete among the densely places reinforcements in the mold. Upon this test, ultimate spread circle diameter is compared to that in the slump flow test. Indeed, the difference between the average values of the restricted slump flow and unrestricted slump flow shows the degree to which the concrete can pass through the rebars. Noteworthily, in these two states, the slump flow measurement is conducted by averaging two orthogonal diameters of the concrete spread circle. A demonstration of the test is shown in Figure 4.



Dimension	in.	mm
A	12.0 +/- 0.13	300 +/- 3.3
B	1.5 +/- 0.06	38 +/- 1.5
C	0.625 +/- 0.13	16 +/- 3.3
D	2.36 +/- 0.06	58.9 +/- 1.5
E	1.0 +/- 0.06	25 +/- 1.5
F	4.0 +/- 0.06	100 +/- 1.5

Fig. 4. J-ring test

Table 5 lists admissible constraints for slump flow, T50, and J-ring tests on SCC according to ASTM C1611, ASTM C1621, and ACI 237-R, respectively.

Table 5. Standard limitations of SCC tests [50-52]

Test	Limitations		Notes
	ACI 237-R	ASTM	
Slump flow (mm)	450-760	480-740	ASTM C1611
T50 (sec)	2-5	-	ASTM C1611
J-ring (mm)	-	0-50	ASTM C1621

2-4-2 Rheology test

According to Figure 5, we used a rheometer device to measure rheological parameters. These included yield stress and plastic viscosity. The rheometer was composed of a wide-gap concentric cylinder, a rotating vane, a motor for providing torsional torque, and a computer system with a display. The cylinder was made to a height of 32 cm and a volume of 29 L. the vane was made up of a shaft to the end of which four rectangular blades were attached. The blades could be immersed into the concrete with the other end of the shaft fixed to the torsional motor to transmit the motor-generated torque to the sample in the cylinder. In order to determine the yield stress and plastic viscosity, the rotational speed of the blades was gradually increased from 0 to 0.7 rps in 30 s at a step size of 0.1 rps, so as to break the thixotropic structure; afterward, it was decelerated to 0. Average and maximum torque values as well as applied speed were recorded every 5 second and shown on the display of the rheometer after the test. The corresponding torque to the applied velocity values was depicted as two upward and downward curves equaling to yield stress that was depicted as the function of shear rate. The yield stress and plastic viscosity could then be obtained using Equations (1) and (2). In fact, comparing the Bingham's model to the measured values by the rheometer, it is evident that g and h are measured and calculated instead of τ_0 and μ [53]:

$$T = g + hN \tag{1}$$

$$\tau = \tau_0 + \mu\dot{\gamma} \tag{2}$$

Where T (Nm) is the torque resistance, N (rps) is the rotational speed, g (Nm) is the intercept of the T-N line with torque axis, and h (Nm.s) is the slope of the T-N line. From the above equations, it is clear that g and h correspond to τ_0 and μ. Therefore, once finished with obtaining g and h from the rheometer, Equations (3) and (4) were applied to these parameters to convert them into yield stress and plastic viscosity [53]:

$$\tau_0 = \frac{\left(\frac{1}{{R_1}^2} - \frac{1}{{R_2}^2}\right)}{\ln\left(\frac{R_2}{R_1}\right) 4\pi H}(g) \tag{3}$$

$$\mu = \frac{\left(\frac{1}{{R_1}^2} - \frac{1}{{R_2}^2}\right)}{8\pi^2 H}(h) \tag{4}$$

In equations 2, 3 and 4, τ_0 (pa), μ (pa.s), $\dot{\gamma}$ (s^{-1}) and τ (pa) are the yield stress, plastic viscosity, shear rate and shear stress, respectively. Moreover, R_1, R_2, and

H represent the vane radius, cylinder radius, and vane height, which are herein equal to 5, 15, and 12 cm, respectively.

Fig. 5. Rheometer device and tested sample

2-4-3 Compressive strength test on SCC

The compressive strength test was performed according to BS 1881 standard instruction [54]. Three 15 × 15 × 15-cm cubic samples of each mixture were cast for the compressive strength test and were tested 28 days after casting (Figure 6). The average strength of three samples was considered as the test results.

Fig. 6. Compressive strength test machine and concrete curing tank

3. Results and Discussions

3-1- Slump flow test

Results of the slump flow test are shown in Figure 7. According to the results, increasing the cement dosage from 380 to 460 kg/m^3 at different temperatures led to a slump loss in the range of 3 – 7 cm. In this respect, ACI238-1R instruction [38] recommends increasing the cement dosage in the constant ratio of water to cement.

According to Figure 7, increased temperature and limestone powder dosage to 50 and then 100 kg/m^3 (LP 50 and LP 100, respectively) increased the slump loss by about 2 – 9 cm. This result is in agreement with the result of Schmidt et al. [46] that water to powder ratio reduction increased the slump loss. Therefore, powder type SCC is recommended for neither high-temperature applications nor long transportation times.

Another point to note on Figure 7 is that the SCC containing retarding admixture at 0.3% (RA 0.3%) could well control the slump loss while this effect was weaker when the retarding admixture dosage was increased to 0.6%. That is, an increase in the retarding admixture dosage may not necessarily contribute to reducing the slump loss.

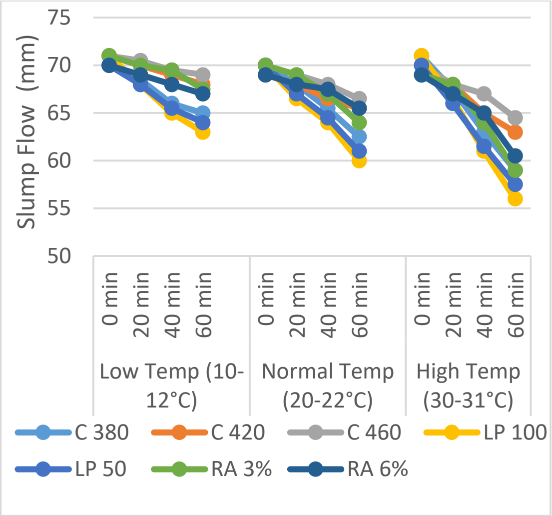


Fig. 7. Results of slump flow test for SCC mixtures

3-2- J-ring test

Passing ability of SCC mixtures through rebars was demonstrated by the J-ring test. As it is seen in Figure 8, the J-ring value increases with temperature, indicating some blockage. On the other hand, the reducing effect of increasing the limestone powder dosage on the J-ring was stronger than the effect of increasing the cement dosage. However, since concrete containing limestone powder exhibit higher slump losses, it is recommended to use C 420 and C 460 mixtures when the ambient temperature is high or transportation distance is long. This result is in agreement with Wallevik research [6].

On the other hand, as shown in Figure 8, comparing the mixtures containing a retarding admixture to the C 380 mixture, it was figured out that the retarding admixture increased the J-ring value, thereby limiting the passing ability of the SCC through the rebars. This result is consistent with those reported by Alsadey [55] who concluded that the use of a retarding admixture makes the workability reduction.

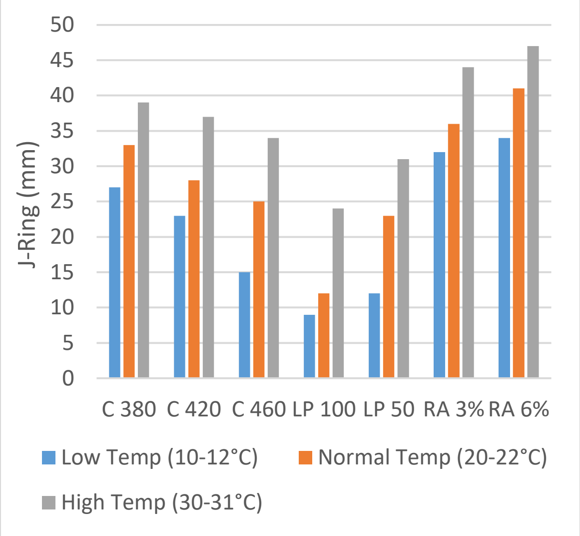


Fig. 8. Results of J-ring test for SCC mixtures

3-3- T50 test

At the other end of the spectrum, any increase in the limestone powder dosage lowers the T50 value, so that the LP 100 mixture exhibited the lowest T50 value. This can be attributed to the increase in superplasticizer dosage to achieve a slump flow of 700 mm. these findings are in agreement with those of Mueller and Wallevik [56] and Gesoğlu et al. [57]. Another important point on Figure 9 is the fact that the retarding admixture positively affects the T50 due to the reduce in workability.

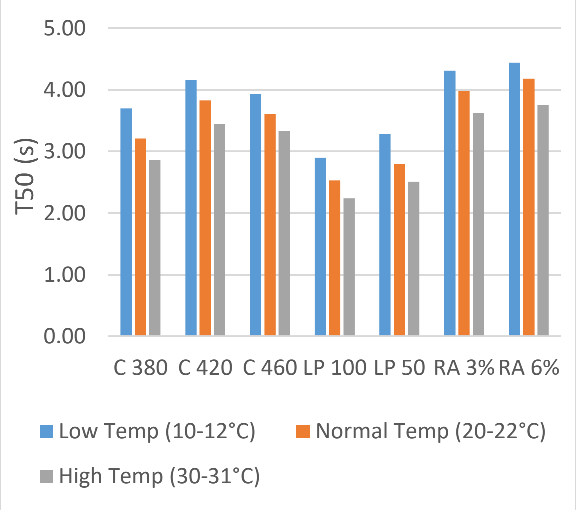


Fig. 9. Results of T50 tests on SCC mixtures

3-4- Rheology test

Measured values of yield stress and plastic viscosity of SCC mixtures are shown in Figures 10 and 11, respectively. With increasing the cement dosage at different temperatures, reduced values of yield stress were seen. For example, C 420 and C 460 concrete mixtures exhibited 7 and 14 MPa lower yield stresses than the C 380 mixture, respectively, which matched well with the report by Wallevik [6]. It is to be noticed that increasing cement has increased the growth rate of yield stress during the time in spite of the initial yield stress. That is, at an elevated temperature, C 420 (at 40 and 60 min) and C 460 (at 60 min) mixtures showed higher yield stresses than C 380 mixture. Focusing on the plastic viscosity, an increase in cement dosage from 380 and 420 to 480 kg/m^3 lowered the plastic viscosity. This result is in agreement with Wallevik research [6]. In the meantime, increasing the cement dosage from 380 to 420 kg/m^3 rather increased the plastic viscosity. This implies that the optimal cement dosage is 420-kg/m^3. Another important point is that increasing cement and reducing temperature increases the viscosity growth rate. Accordingly, at a low temperature, the C 460 mixture demonstrated a higher plastic viscosity than C 380 mixture at 60 min.

According to Figure 10, at zero time, the yield stress decreases by 10 – 20 Pa with increasing the limestone powder dosage. Moreover, at all times but the zero time, the difference in yield stress among different mixtures increases with temperature. For instance, with increasing the limestone powder dosage from 50 to 100 kg/m^3, the yield stress difference was found to increase by 4, 15, and 26 Pa at 20-min, 40-min, and 60-min times, respectively. On the other hand, as shown in Figure 11, the plastic viscosity decreases with increasing the limestone powder dosage. This indicates that adding the viscosity-modifying agent (VMA) imposes a better effect onto the plastic viscosity. This finding is in compliance with the EFNARC guideline [58] where VMA have been acknowledged as a key element of SCC.

Results of rheological studies on different mixtures containing retarding admixture are shown in Figures 10 and 11. Generally, yield stress in all time and higher temperatures in concretes containing retarding admixture are so close to the yield stress of the control sample (C 380). This shows that one must keep the temperature from increasing when using a retarding admixture. Moreover, according to Figure 10, the retarding admixture imposed an adverse effect on the yield stress initially. In this respect, at zero time, the yield stress of the mixtures containing retarding admixture at 0.3 and 0.6% increased by 10 and 17 Pa, respectively, compared to the C 380 mixtures. Based on previous studies [55, 59], an increase in the dosage of retarding admixture tends to reduce the initial slump and slump loss rate; this is while the slump flow loss tends to increase the yield stress in turn [60]. This justifies the results of the present study considering the slump flow. On the other hand, since retarding admixtures tend to retard the growth of yield stress with time, at the time of 40 min, the mixture with retarding admixture exhibited a lower yield stress than the C 380 mixture. The lower temperature leads to raise this difference. Another important point is that as retarding admixtures are first increased the yield stress and reduce the yield stress rate, they increase the plastic viscosity and reduce the plastic viscosity rate during the time. The decrease in the rate of yield stress over time for SCC containing retarding admixture became evident at 40 min. This is while reducing the plastic viscosity growth rate for SCC containing retarding admixture was seen after 60 minutes. Hence, concrete containing retarding admixture can improve rheology at the time of greater than 40 minutes.

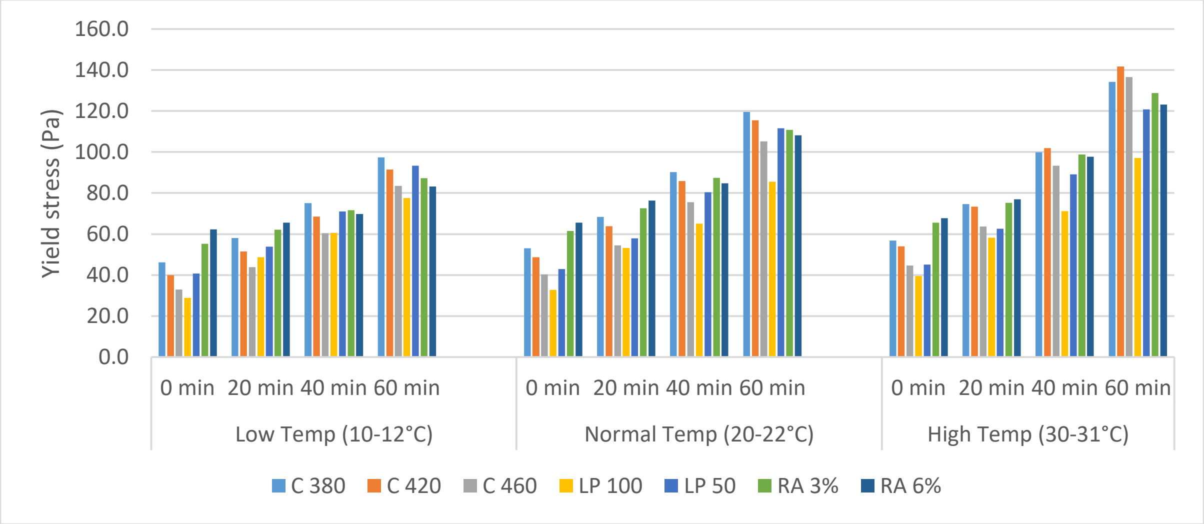


Fig. 10. Yield stress of SCC mixtures

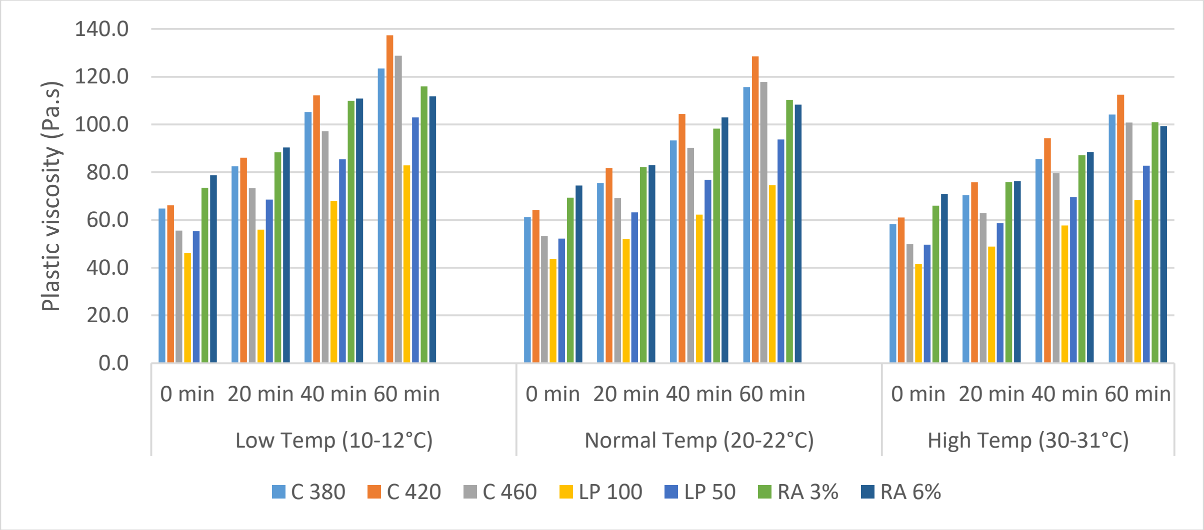


Fig. 11. Plastic viscosity of SCC mixtures

3-5- Concrete compressive strength test

Results of 28-day compressive strength tests are shown in Figure 12. With increasing the cement dosage of the mixtures, compressive strength of the sample was seen to improve by 4 – 10 MPa. In addition, for each 10°C decrease in temperature, the samples showed 3 – 5 MPa higher compressive strength. This was due to the fact that a lower temperature tends to provide for a longer time for adequate hydration of the cement [61].

On the other hand, according to Figure 12, with increasing the limestone powder dosage to 50 kg/m^3, the compressive strength increased by 4 MPa, but further increase in the limestone powder dosage to 100 kg/m^3 lowered the SCC compressive strength to 2 MPa below that of the concrete mixture enriched with the limestone powder at 50 kg/m^3. According to Li et al. [62, 63], increasing the limestone powder dosage up to 10% of cement weight maximize the compressive strength. Therefore, the obtained result is logical.

Another point to note on Figure 12 is that, upon increasing the retarding admixture dosage to 0.3 or 0.6%, the 28-day compressive strength decreased by 2 – 5 MPa. This is due to the fact that the retarding admixture limits the strength growth rate. This finding is in agreement with the research by Alsadey [55].

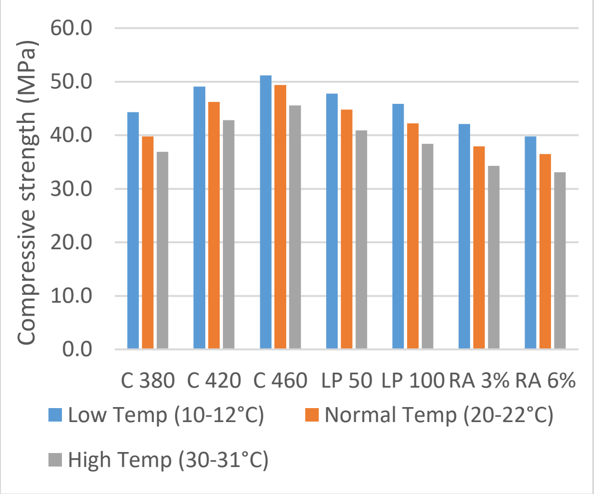


Fig. 12. Results of 28-day compressive strength of SCC mixtures

4. Statistical analysis

The results from the performance characteristics of SCC, including tests of slump flow, J-ring, T50, compressive strength, and rheology were statistically analyzed by means of the analysis of variance (ANOVA). This was done through two-factor analysis at a confidence level of 95% to investigate the significance of the effects of mixture composition and temperature on performance characteristics of SCC mixtures using SPSS software. For the purpose of ANOVA, first, data normality was checked with the Kolmogorov – Smirnov test, followed by conducting the analysis on normal data. Results of the effect of mixture composition and temperature on the performance of the SCC are summarized in Table 6. In this respect, the H_0 assumption implied that agent variable (independent) imposes no significant effect on the response variable, while the rejection of this hypothesis confirmed the H_1 assumption implying that the agent variable significantly affects the response variable. This has been expressed in Equation (5):

$$H_0 : \mu_1 = \mu_2 = \ldots = \mu_k$$
$$H_1 : \exists i, j \; s.t \; u_i \neq u_j \; (i, j = 1, 2, \ldots) \tag{5}$$

According to the results of ANOVA regarding the effects of temperature and mixture composition on performance characteristics of SCC, we generally found p-values below 0.05, indicating that the temperature and mixture composition impose significant effects on the results of all conducted tests, including the slump flow and rheology. The mixture composition, however, was found to impose stronger effects in the J-ring, T50, compressive strength, and plastic viscosity tests. This was evident from the partial eta squared values (93.6, 90.7, 91.1, and 89.5 for the mixture composition) obtained upon the ANOVA. Therefore, in these tests, improving the mixture composition by means of cement or retarding admixture would lead to better outcomes. This was while the temperature, rather than the mixture composition, was the most effective factor in the slump flow and yield stress tests, as shown by the variance values of 94.2 and 90.7.

Table 6. ANOVA analysis for SCC tests results

Source of variation	Type III sum of squares	df	Mean square	F	P-value	Partial eta squared
(a) Slump Flow						
Corrected Model	758.857a	20	37.943	1397.895	0.000	0.998
Intercept	3129.143	1	3129.143	115284.211	0.000	1.000
temperature	372.286	2	186.143	6857.895	0.000	0.942
blend type	364.857	6	60.810	2240.351	0.000	0.874
temperature * blend	21.714	12	1.810	66.667	0.000	0.850
Error	1.140	42	0.027			
Total	3889.140	63				
Corrected Total	759.997	62				
(b) J-ring						
Corrected Model	6829.714a	20	341.486	908.897	0.000	0.998
Intercept	52462.286	1	52462.286	139633.460	0.000	1.000
temperature	2328.000	2	1164.000	3098.099	0.000	0.893

blend type	4367.714	6	727.952	1937.516	0.000	0.936
temperature * blend	134.000	12	11.167	29.721	0.000	0.805
Error	15.780	42	0.376			
Total	59307.780	63				
Corrected Total	6845.494	62				
(c) T50						
Corrected Model	23.861a	20	1.193	205.364	0.000	0.990
Intercept	754.488	1	754.488	129870.821	0.000	1.000
temperature	5.188	2	2.594	446.539	0.000	0.835
blend type	18.563	6	3.094	532.557	0.000	0.907
temperature * blend	0.110	12	0.009	1.572	0.137	0.310
Error	0.244	42	0.006			
Total	778.593	63				
Corrected Total	24.105	62				
(d) Compressive strength						
Corrected Model	1548.500a	20	77.425	106.270	0.000	0.981
Intercept	112903.000	1	112903.000	154964.902	0.000	1.000
temperature	497.977	2	248.989	341.749	0.000	0.842
blend type	1041.400	6	173.567	238.229	0.000	0.911
temperature * blend	9.123	12	0.760	1.043	0.430	0.230
Error	30.600	42	0.729			
Total	114482.100	63				
Corrected Total	1579.100	62				
(e) Yield stress						
Corrected Model	17180.214a	20	859.011	93.221	0.000	0.978
Intercept	215426.286	1	215426.286	23378.389	0.000	0.998
temperature	8711.866	2	4355.933	472.712	0.000	0.907
blend type	7236.014	6	1206.002	130.877	0.000	0.849
temperature * blend	1232.334	12	102.695	11.145	0.000	0.701
Error	387.020	42	9.215			
Total	232993.520	63				
Corrected Total	17567.234	62				
(f) Plastic viscosity						
Corrected Model	11991.071a	20	599.554	104.388	0.000	0.980
Intercept	133013.763	1	133013.763	23159.040	0.000	0.998
temperature	1845.997	2	922.998	160.703	0.000	0.814
blend type	9752.522	6	1625.420	283.002	0.000	0.895
temperature * blend	392.552	12	32.713	5.696	0.000	0.619
Error	241.227	42	5.743			
Total	145246.060	63				
Corrected Total	12232.297	62				

5. Conclusions

The main purpose of the present study is to compare the main components of SCC for compensating temperature- and time-induced negative impacts. In this research, SCC mixtures were evaluated through tests of slump flow, T50, J-ring, rheology, and compressive strength at different temperatures. Upon compiling and investigating the test results, the following conclusions can be drawn:

- Increasing the temperature results in an increase of slump loss, an increase of yield stress, and a reduction of plastic viscosity. This shows that increasing the temperature must be prevented.
- Application of retarding admixture and increasing the cement dosage lowers the slump loss. However, increased dosage of limestone powder tends to boost the slump loss, so that a powder-rich SCC tends to rapidly lose its workability at elevated temperatures. This implies that the limestone powder suits low-temperature applications and short transportations, but one should rather increase the cement dosage in SCC when high-temperature applications and long transportations are considered.
- Increasing the cement dosage to up to 420 kg/m^3 improved the rheology (i.e., lower yield stress coupled with higher plastic viscosity). This was while increasing the limestone powder dosage of SCC lowered both the yield stress and plastic viscosity. This shows that the plastic viscosity exhibits a better response to the cement dosage rather than the limestone powder dosage. On the other hand, focusing on the application of retarding admixture in the SCC, the concrete mix containing the retarding admixture exhibited better rheological properties than the control sample after 40 min. Moreover, at all times and high temperatures, rheological properties of the SCC containing retarding admixture were highly close to those of the control sample. This highlights that one should keep the temperature low when using a retarding admixture.
- The limestone powder positively affects the compressive strength of SCC. Indeed, increasing the limestone powder dosage to 50 kg/m^3 increases the compressive strength by about 4 MPa. Moreover, increased cement dosage coupled with reduced initial temperature of SCC can increase 28-day compressive strength of the samples. On the hand, with increasing the retarding admixture dosage to 0.6%, a drop of compressive strength is seen because the retarding admixture tends to retard the strength growth rate.

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