Effects of the Sole or Combined Use of Chemical Admixtures on Properties of Self-Compacting Concrete

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Abstract

Chemical additives are very important in determining the behavioral characteristics of self-compacting concrete. For this reason, determining the building materials that make up the chemical structure of self-compacting concrete and the interactions of these materials is of great importance. The present study pertains to the effects of the use of different chemical admixtures (high-range water-reducing, i.e., superplasticizer, hydration accelerating, air-entraining, shrinkage reducing, and hydration heat reducing admixtures) on the fresh and hardened properties of self-compacting concrete. The influence of using a single one or a hybrid combination of the air-entraining, hydration-accelerating, heat-reducing, and shrinkage-reducing admixtures on the mechanical properties of fresh and hardened SCC was investigated through a set of tests. For this purpose, sixteen different SCC mixtures with different combinations of chemical additives were prepared and tested. The properties of fresh concrete were examined as well as the compressive and tensile strengths of the mixtures. SCC mixtures with shrinkage-reducing admixtures were evaluated in terms of shrinkage development. The effect of the use of admixtures was found to be more pronounced on the early-age concrete strength. The use of any type of additive in addition to the shrinkage reducing admixture increased the speed of flow of fresh concrete.

1. Introduction

Modern civil engineering applications require the economy and speed of construction. In certain types of concrete structures, for instance, bridges, the use of precast concrete members facilitate the construction by reducing the required labor and construction time. Nonetheless, the cast-in-place concrete construction is more preferable in a great majority of the structural systems [1-2], including the buildings, since the monolithic nature of the beam-column connections in this type of construction increases the degree of static indeterminacy of the overall structure and enables the redistribution of forces in the case of any structural damage. The seismic design provisions encourage the cast-in-place concrete construction due to the higher ductility provided by this type as compared to precast concrete and structural steel construction. These higher degrees of ductility can only be achieved by proper amounts and detailing of reinforcement in the bearing members of the structural system and the beam-column joints. The proper seismic detailing of reinforcement usually results in highly congested beam-column joint regions. Prolonged vibration duration for proper placement of concrete in these congested regions not only impairs the detailing, i.e., bar spacing and concrete cover, of the reinforcement but also can result in the segregation of fresh concrete. To overcome these difficulties, a new type of concrete, namely the Self-compacting concrete (SCC), is gaining popularity among designers and engineers. SCC is capable of flowing throughout the form under its own weight without any need for internal and external mechanical vibration. The use of SCC, particularly in concrete construction with highly congested reinforcement, not only contributes to the speed and economy of the construction but also provides homogeneity and uniformity of concrete throughout the whole structure. Due to its highly-flowable nature, SCC is effective in achieving good compaction and eliminating the undesired bleeding and segregation of concrete.

Self-compacting concrete (SCC) fill formworks without the need for external consolidation [3]. SCC is mostly characterized by its remarkable workability in the fresh properties [4-5]. Researchers have defined SCC in almost the same terms as a highly flowable concrete that should meet the requirements of flowability, passing ability, and segregation resistance [6-7]. The widespread practice is to narrow down the coarse aggregate content, limit the maximum size and use lower water/powder ratios together with superplasticizers (SP) [8-9] to produce self-compatibility in SCC.

Despite its various superiorities over conventional concrete (CC), SCC has a major disadvantage, the higher shrinkage rate and vulnerability to early-age shrinkage cracking, which has been studied vastly in the literature [10-12]. The higher amount and rate of shrinkage of SCC compared to CC is mainly caused by its higher paste volume, lower aggregate content, and lower bleeding capacity than CC. The presence of shrinkage cracks in concrete structures creates durability and serviceability concerns. Chemical additives, such as Shrinkage Reducing Admixtures (SRA), offer an effective solution for reducing the number and extent of shrinkage cracks in concrete members, particularly if the members are cast with SCC [13-15]. In addition to SRA, various types of chemical additives are used in SCC to attain desired properties in the fresh and hardened properties. For instance, superplasticizers are utilized to increase the particle dispersion and to give essential properties of filling, passing, and segregation resistance [16] of SCC when needed. SCC has higher fine particle content than CC, which, in turn, affects the flow properties of this concrete type. Superplasticizers serve as a dispersant, improve flow characteristics and the performance of the hardened fresh paste [17].

Accelerators constitute another important class of additives and they are commonly used to alter the kinetics and mechanism of hydration. The use of accelerators results in a reduction in setting times and an increase in the rate of mechanical strength development [18-19]. Air-entraining admixtures provide the required artificial air-void system to compensate for the volume extension from the freezing water in cementitious composites and ensure proper resistance to freezing and thawing [20]. The stabilization of micro air voids is also ensured by the use of these additives [21]. Proper air-entrainment, with appropriate volume and spacing factor, will dramatically improve the durability of concrete exposed to moisture during cycles of freezing and thawing. Additionally, hydration heat reducing admixtures are commonly employed in various types of concrete. In particular, the formation of thermal cracks, originating from the significant amount of hydration heat, necessitates the use of this type of admixtures in mass concrete, including but not limited to the water treatment plants and dams. These admixtures not only reduce the hydration heat of cement but also decrease the thermal stress by relaxing the restraining stress during the drop of temperature with expansive energy maintenance [22].

Although the effects of each of these admixtures on the properties of SCC in the fresh and hardened properties have been subject to studies in the literature. There is an obvious dearth of research on the effects of the different hybrid combinations of chemical admixtures on the properties of SCC. In this regard, this study aimed at filling this knowledge gap in the literature by determining the optimal combination of hybrid chemical admixtures in the proposed SCC mixtures ensuring the significant fresh and hardened properties of self-compacting concrete. In the present study, the influence of using a single

one or a combination of the air-entraining, hydration-accelerating, heat-reducing, and shrinkage-reducing admixtures on the mechanical properties of fresh and hardened SCC was investigated through a set of tests. For this purpose, sixteen different SCC mixtures with different combinations of chemical additives were prepared and tested. Various tests were conducted on fresh and hardened concrete mixtures, which yielded significant conclusions.

2. Experimental Program

2.1 Materials

The concrete mixes contained Ordinary Portland cement (OPC), fine aggregate in the form of crushed sand, coarse aggregate in the form of crushed stone, stone dust as powder material, and five different types of admixtures (superplasticizer, air-entraining, hydration-accelerating, heat-reducing, and shrinkage-reducing admixtures). The water-to-binder ratio of all concrete mixtures was set to 0.40.

CEM I 42.5 R, i.e., ASTM Type I, Portland cement that complied with the EN 197-1 standard[23]was used in this study. The chemical composition, physical and mechanical properties of the cement are shown in **Table 1**.

Table 1 Chemical composition, physical and mechanical properties of Portland cement.

Chemical composition (%)	Portland cement
SiO ₂	21.02
Al ₂ O ₃	5.93
Fe ₂ O ₃	3.22
CaO	61.84
MgO	1.55
Na ₂ O	0.39
K ₂ O	0.92
SO ₃	3.27
Loss on ignition	3.74
Insoluble residue	1.41
Physical and mechanical properties	
Specific gravity	3.05
Volumetric Expansion (Le-Chatelier) (mm)	0.5
Specific Surface Area (cm ² /g)	3870
Initiation of Setting (min.)	175
Completion of Setting (min.)	225
Compressive Strength (2days, MPa)	30.7
Compressive Strength (7days, MPa)	44.4
Compressive Strength (28days, MPa)	51.8

Crushed stone as coarse, crushed sand as fine aggregate, and stone dust, used in the concrete mixtures, had specific gravity values of 2.69, 2.66, and 2.65 g/cm³, respectively, and water absorption percentages of 0.6, 0.7, and 1.0, respectively. The sieve analysis results of the aggregates are given in **Table 2** and the gradation curves are illustrated in **Fig. 1**.

Table 2. Sieve analysis of the aggregates.

Cumulative percentage passing through the sieve				
Sieve (mm)	Stone dust (45%)	Crushed sand (35%)	Crushed Stone (20%)	Mixture (100%)
31.5	100.0	100.0	100.0	100
20.0	100.0	100.0	100.0	100
16	100.0	100.0	60.0	92
11.2	100.0	94.7	25.5	83
8	100.0	61.1	6.3	68
4	94.7	13.8	4.1	48
2	74.7	8.2	4.1	37
1	60.3	7.1	4.1	30
0.5	48.1	6.4	4.1	25
0.25	34.5	5.5	4.1	18
0.150	22.4	4.6	4.1	13
0.063	16.5	3.5	2.3	9

Five different types of chemical additives (superplasticizer, air-entraining, hydration-accelerating, heat-reducing, and shrinkage-reducing) were used in the concrete mixtures. The producers and product names of these additives are presented in **Table 3**, together with the percentage limits recommended by the producers and the percentages adopted in the present study.

Table 3. Chemical additives.

Admixture	Producer and Product Name	Recommended Percentage	Adopted Percentage
Superplasticizer	BASF Master Glenium 51 (Polycarboxylic Ether Based)	0.7 – 0.9	0.8
Hydration-Accelerating	BASF Master Set AC 326B (Calcium Nitrate Salt Based)	1.0 – 2.5	1.5
Air-Entraining	Sika AER	0.03 – 0.15	0.1
Shrinkage-Reducing	Grace Eclipse Floor	0.6 – 1.8	1.3
Hydration-Heat Reducing	Grace Daratard 77	0.2 – 1.5	0.8

2.2 Specimens and methodology

A total of sixteen concrete mixtures were prepared in the present study and the fresh and hardened concrete properties of these mixtures were determined. The mixtures were symbolized according to their chemical additives as shown in **Table 4**. The letter or group of letters “*S*”, “*HA*”, “*AE*”, and “*HR*” denote the presence of shrinkage-reducing, hardening-accelerating, air-entraining, and heat-reducing admixtures in the specimens. The letter “*R*”, on the other hand, symbolizes the plain (reference) specimens. All of the mixes, including the reference one, contained a superplasticizer to ensure the flowability of concrete, which differentiates SCC from CC.

Table 4. Specimen notations.

Specimen Notation	Additive
R	None
S	Only SRA
HA	Only Hardening Accelerator
AE	Only Air Entraining
HR	Only Heat Reducing
S+HA	SRA and Hardening Accelerator
S+AE	SRA and Air Entraining
S+HR	SRA and Heat Reducing
HA+AE	Hardening Accelerator and Air Entraining
HA+HR	Hardening Accelerator and Heat Reducing
HR+AE	Heat Reducing and Air Entraining
S+HA+HR	SRA, Hardening Accelerator and Heat Reducing
S+AE+HR	SRA, Air Entraining, and Heat Reducing
S+AE+HA	SRA, Air Entraining, and Hardening Accelerator
HA+AE+HR	Hardening Accelerator, Air Entraining, and Heat Reducing
S+AE+HA+HR	All Admixtures

The flow table (slump flow), unit volume weight, air content, V-funnel, L- and U-box tests were conducted to determine the properties of fresh concrete. Furthermore, the compressive strength values at the second

and 28th day and the splitting tensile strength at the 28th day were determined based on the EN 12390-3 [24] and EN 12390-6 [25] standards to identify the properties of the hardened concrete. In the uniaxial compression tests, 150×150×150 mm cube specimens were tested with a loading rate of 0.6 MPa/s. In the split cylinder tests, on the other hand, 100×200 mm cylinders were loaded at a speed of 0.06 MPa/s in the transverse direction. For each concrete mixture, a total of three compression and three split cylinder tests were conducted and the mean values of the three tests were adopted to compensate for the inherent variations in the material properties of specimens from the same batch. Specimens for drying and negative shrinkage were cured in water for 2, 7, 28, 90, 180 days, and for wetting-drying shrinkage, specimens were subjected to initial water curing for 28 days followed by wetting-drying cycles in Na₂SO₄ solution with a concentration of 10% until the completion of 60, 90, 135 and 180 days of complete curing periods on which they were failed. The microstructure of the samples was examined using scanning electron microscopy (SEM). For carrying out the microstructure surface examination, specimens were implemented gold coating. The specimens were explored by SEM. For the microstructure surface examination analysis, Quanta 450 FEG scanning electron microscopy (SEM) was used.

3. Research Findings

3.1 Fresh properties

The results of unit weight, air content, slump flow, V- funnel, U-box, and L-box tests are presented in **Table 5**. The aim is to compare the passing capability, filling capability, and segregation resistance of different SCC mixtures based on EFNARC [26].

Table 5. Properties of fresh concrete mixtures.

Mixtures	Unit weight (kg/m^3)	Air content (%)	Slump flow (mm)	V-funnel (second)	U-box (mm)	L-box (mm/mm)
Reference (R)	2401	2.0	700	12	60	0.9
S	2350	2.1	650	13	50	0.86
HA	2396	2.5	710	11	40	0.91
AE	2345	4.0	660	14	50	0.85
HR	2345	2.3	640	13	50	0.86
S+HA	2380	2.4	640	12	70	0.91
S+AE	2365	4.1	720	10	40	0.92
S+HR	2375	2.0	690	11	50	0.86
HA+AE	2350	3.6	700	11	50	0.92
HA+HR	2370	2.5	685	11	40	0.93
HR+AE	2370	4.3	720	11	50	0.93
S+HA+HR	2379	2.4	690	11	40	0.88
S+AE+HR	2360	3.9	720	14	70	0.90
S+AE+HA	2360	4.0	725	13	60	0.93
HA+AE+HR	2364	4.2	720	14	70	0.92
S+AE+HA+HR	2365	3.7	715	13	60	0.91

3.1.1 Unit weight

The unit weight values are also illustrated in **Fig. 2** for the sake of comparison. The effect of chemical admixtures on the settlement of SCC can be clearly grasped from this **Fig 2**. Accordingly, the addition of solely AE or HR to the mixture resulted in a decrease of 2.33% in unit weight as compared to the base (reference) mixture. The unit weight of the SCC mixture with only shrinkage reducer (S) was 2.12% lower than the reference value. Among the mixes with only one type of admixture, specimen HA had the highest unit weight value, which was almost equal to the respective value of the plain specimen.

If it is compared the mixes with more than one type of additive, the simultaneous use of HA and AE (HA+AE) resulted in the greatest decrease (2.12%) in unit weight. SCC with S+HR, S+HA+HR, and S+HA had closer unit weights to the reference mixture, which were only 1.08, 0.92, and 0.88% smaller than the reference value, respectively. The unit weights of specimens S+AE+HA and S+AE+HR were about 1.71% smaller than the reference value, while the specimen HA+AE+HR had a 1.54% lower unit weight compared

to the plain mixture. The use of S+AE or S+AE+HA+HR decreased the unit weight by 1.50%, yet the use of HA+HR or HR+AE by 1.29% compared to the base specimen.

In general, the mixes with HA had higher unit weight values than the ones without HA. In other words, the hardening-accelerating additive has a slight or no influence on the unit weight. The use of HR and AE yields a slight decrease in the unit weight of SCC when used alone or with other chemical additives. This is because air-entraining (AE) admixture typically plays a critical role in reducing the surface tension at the water-air interface and protects concrete against freezing and thawing damage by inducing an air content of approximately 6% in the mixture [27-32]. Increasing the air content generally reduces the unit weight and the concrete strength [32].

3.1.2 Air content

The air content values of the mixtures are shown in **Fig. 3** for comparison. These values ranged between 2 and 4.3%. The air contents of the mixtures with air-entraining (AE) additive ranged from 3.6 to 4.3%, implying the major contribution of this additive to the air content as expected. The air content of fresh SCC with no additive was 2%, while this content increased to 4% in the sole presence of AE. The air content increased further to 4.1 and 4.3% when AE was used together with S and HR, respectively. The air content of HA+AE remained below the respective value of mixture AE. To be more specific, the inclusion of shrinkage-reducing (S) and heat-reducing (HR) additive in addition to AE contributed to the air content, while the inclusion of hydration-accelerating (HA) admixture had a reverse effect. All of the mixtures with two or three more additives in addition to AE had air contents in the vicinity of the mixture with only AE (4%). The low unit weights of the mixtures with AE can be attributed to the high air contents of these mixtures.

The air contents of mixtures without AE were close to the respective reference (base) values, which are 2.1, 2.3, 2.5, and 2% for mixtures with only S, only HR, only HA, and both S and HA, respectively.

3.1.3 Slump flow

The slump flow diameters of the mixtures in **Table 5** are also depicted in **Fig. 4** for comparison. While the flow diameter of the base SCC specimen was 700 mm, the flow diameters of the S+AE+HA, HA+AE+HR, and S+AE mixtures were measured as 725, 720, and 720 mm, respectively. The minimum flow diameter was measured as 640 mm in HR and S+HA series. Although the AE mixture had a smaller flow diameter (660 mm) than the reference, the flow diameters of all mixtures containing other chemicals in addition to AE exceeded the reference value.

For instance, the flow diameter of S+AE+HA exceeded the base value by 3.57%, while the flow diameters of S+AE, HR+AE, HA+AE+HR, and S+AE+HR were 2.85% greater than the reference value. Similarly, the

respective value of the S+AE+HA+HR mixture was 2.14 % greater than the flow diameter of the reference mixture. In other words, the addition of one, two, or three admixtures to SCC in addition to AE has a positive influence on the flowability. Parallel to this finding, the previous studies reported that the slump increases by approximately 100 mm per 1% air [33].

The flow diameters of HA, S+HR, S+HA+HR were 1.42% above the reference value. The flow diameters of HR+AE, AE, S, HR, and S+HA series were 2.14, 5.72, 7.14%, 8.57, 8.57%, respectively, below the base value.

3.1.4 V-funnel

The V-funnel flow times of the mixtures, given in **Table 5**, are depicted in **Fig. 5**.

Minimum flow time among the mixtures was recorded as 10 seconds in S+AE, while SCC with HA, HA+AE, HA+HR, HR+AE, S+HR, and S+HA+HR series had flow times of 11 s, which is 8.33% smaller than the respective value of the base specimen. To be more specific, the addition of only HA or binary combinations of the admixtures decreased the flow time, i.e., increased the flowability, of SCC. Among the binary combinations of admixtures, only the S+HA mixture had an identical flow time (12 seconds) to the base mixture. Furthermore, among the mixtures with a single additive, only the mixture with HA was more flowable than the plain mixture.

The addition of only AE, HA+AE+HR, and S+AE+HR increased the flow time to 14 seconds, i.e., by 16.67%, while the addition of only S, only HR, S+AE+HA, and S+AE+HA+HR increased this time to 13 seconds, i.e., by 8.33%, compared to the base specimen. Except for the mixture S+HA+HR, the combinations of admixtures composed of three or four chemicals had higher flow times, i.e., less flowability, as compared to the reference mixture. When all results are examined, the flow time values are close to each other, implying that the combination of chemical additives does not exhibit negative effects on the flow time of SCC.

3.1.5 U-box

Next, the U-box passing values of the fresh mixtures, given in **Table 5**, are illustrated in **Fig. 6** for comparison. U-box test is based on the measurement of filling a second chamber by passing through concrete reinforcement. The passing values indicate the difference between the levels of two compartments of the U-box apparatus and the flowability increases as this value approaches zero, meaning that the second compartment is filled to the same level as the first one.

In the presence of a single admixture and binary combinations of admixtures, the passing values remained below the base value (60 mm). The fresh properties of SCC mixtures with only HA, HA+HR, S+AE, and S+HA+HR had 40 mm passing values. The fresh properties of SCC mixtures with only AE, only S, only HR, HA+AE, HR+AE, and S+HR had 50 mm and the mixtures with HA+AE+HR and S+AE+HR had 70 mm passing values. Similar to the findings from the V-funnel test, the addition of HA, the binary

combinations including HA (except for S+HA), and the ternary S+HA+HR combination increased the flowability of concrete mixture, i.e., decreased the passing value. The hydration-accelerating admixture contributes to the flowability of SCC when used alone in the mixture or combination with the other admixtures.

3.1.6 U-box

The highest L-box passing ratio values were found to belong to SCC specimens with HA+HR, HR+AE, and S+AE+HA as 93%. The passing ratios of SCC specimens, with HA+AE, S+AE, and HA+AE+HE, were measured as 92%, while the respective values of specimens with HA, S+HA, and S+AE+HA+HR were 91%. The passing ratio of SCC without additive (base) and with S+AE+HR was measured as 90% and the related values of S+HA+HR, S, HR, and S+HR specimens as 88, 86, 86, and 86%, respectively.

Accordingly, the SCC specimens with HA+HR, HR+AE, and S+AE+HA have a more homogeneous structure compared to other SCC mixtures and the flow was observed to be continuous throughout the horizontal chamber in these mixtures. When all results are examined, all values are close to each other. The combination of chemical additives did not show a major negative effect on the flow time of SCC. Similar to the results from the U-box test, the L-box test indicated that the combinations with air-entraining and hydration-accelerating admixtures create more flowable mixtures of SCC.

In general, the use of chemical additives, especially the hardening-accelerating, air-entraining, and hydration heat-reducing admixtures, and their binary combinations improve the flow properties of the SCC. Similar to the positive contribution of hydration accelerators on workability, SCC mixtures with air-entraining admixture show superior passing ability. When the air-entraining admixture is not used, large, entrapped pores are irregularly distributed in the SCC and this irregular distribution reduces the workability. But the pore size decreases, and the distribution of pores is enhanced with the inclusion of air-entraining admixture, and thus increasing workability [34]. Similar results were attained in the L-box test (**Fig. 7**). This test is applied to measure the flowability of SCC through reinforcing bars. In the test, the criterion of the passing ratio to exceed 0.8 is sought [26].

3.2 Hardened properties

The 2-day and 28-day compressive strength and 28-day splitting tensile strength test results were also explored in the present study and the values are given in **Table 6**.

Table 6. Properties of hardened properties of SCC.

Mixtures	2-Day Compressive Strength(MPa)	28-Day Compressive Strength(MPa)	28-Day Splitting Tensile Strength(MPa)
Reference (R)	44.5	63.5	4.2
S	42.0	60.5	4.0
HA	45.5	62.0	3.9
AE	41.0	57.0	3.6
HR	34.0	59.5	4.1
S+HA	43.0	62.0	3.9
S+AE	40.5	58.5	3.8
S+HR	35.5	59.5	3.9
HA+AE	41.5	59.0	3.8
HA+HR	36.5	59.0	3.9
HR+AE	27.0	57.5	3.7
S+HA+HR	38.0	59.5	4.1
S+AE+HR	37.0	59.0	3.9
S+AE+HA	41.5	60.0	3.8
HA+AE+HR	37.5	57.5	3.8
S+AE+HA+HR	39.0	60.0	4.0

3.2.1 Compressive strength

The compressive strength test results of different SCC mixtures are shown in **Fig. 8**.

The 2-day compressive strength values of the specimens ranged between 27.0 and 45.5 MPa. The 28-day compressive strength, on the other hand, varied between 57.0 and 63.5 MPa. In plain words, the variation in compressive strength decreased significantly at 28 days. As expected, the hydration-accelerating (HA) additive had a positive influence on the early-age compressive strength. To be more specific, the strength of the mixture HA exceeded the related strength of the base mixture by 2.25%, while the 28-day strength of HA remained below the base value. This situation has shown that the hardening accelerator contributes to strength at an early age as shown in the literature [27,28]. The other specimens with a single additive had 2- and 28-day compressive strength values below the plain mixture. The lowest 2-day compressive strength value among the mixtures with a single additive was measured in mixture HR,

whose 2-day strength was 23.59 % smaller than the base value. The lowest 28-day strength value, on the other hand, was measured in mixture AE.

The 2-day and 28-day compressive strength values of all mixtures with two, three, and four additives were smaller than the respective values of the plain mixture. For instance, the 2-day compressive strengths of HR+AE, S+HR, and S+AE+HR series were 39.33, 20.22, and 17.98% lower than the base value. Among the mixtures with more than one additive, the S+HA mixture had the highest 2- and 28-day strength values, which were much closer to the related values of the reference mixture. For brevity, chemical additives had negative effects on the compressive strength of SCC, and this negative influence was more pronounced in the early-age strength, particularly in the mixtures with no HA. The negative influence of additives on compressive strength decreased in time. Strikingly, the addition of air-entraining and/or heat-reducing chemicals reduced the early-age compressive strength up to 39.33%, while this reduction became more insignificant in the long term. The 28-day compressive strength values of SCC specimens with AE, HR+AE, HA+AE+HR, and S+AE were 10.24, 9.45, 9.45, and 7.87% smaller than that of the base specimen. The reason for AE to reduce the concrete strength stems from the fact that AE increases the entrapped air content in the mixture. With the increase in the air content, the compactness of SCC decreases, and its porosity increases, so the strength decreases. These results are consistent with the ones in the literature [32].

Recall that, with the addition of shrinkage reducing and hydration accelerating admixture SCC had the highest 2- and 28-day strength values. As can be seen in **Fig. 9**, this results in considerably depending on dense Calcium-Silicate-Hydrate (C-S-H) gel-forming. The forming C-S-H gel decreases the number of pores in the cementitious composites due to the filling effect of pores [38-43]. The morphological structure of C-S-H gel resembles a web-like structure from weak crystalline fibers. During the hydration process, Calcium-Silicate-Hydrate gels concentrate around the hydrated cement particles and cover all particles.

3.2.2 Splitting tensile strength

The 28-day splitting tensile strength test results explored in the present study and the results are shown in **Fig. 10**.

The lowest and highest 28-day splitting tensile strength results were obtained as 3.6 and 4.2 MPa, respectively. Similar to the compressive strengths, all of the mixtures had tensile strength values lower than the related value of the reference mixture. As in 28-day compressive strength, SCC specimens with AE and HR+AE had the lowest tensile strength values, which were 14.28 and 11.90%, respectively, smaller than the related strength of the plain mixture. In summary, the utilization of different combinations of chemical additives did not contribute to the compressive and tensile strength.

3.3 Effect of shrinkage reducing admixture on length changes of SCC

3.3.1 Negative shrinkage

Negative shrinkage developments of SCC with 1% SRA and control SCC specimens were shown in **Fig. 11**.

As shown in **Fig. 11**, at any age of water curing, specimens of SCC with 1% SRA exhibited higher negative shrinkage than the control specimen. It is thought that SRA addition forms an adverse pressure acting against the cohesion of the gel particles, that SRA affects the water absorbed, C-S-H gels and pores, and that it supports particles lift from each other possessing thickened the absorbed water layer because of the water absorbed by CSH gels [35].

3.3.2 Drying shrinkage

Drying shrinkage developments of SCC with 1% SRA and control SCC specimens were shown in **Fig. 12**.

Drying shrinkage increased until the end of 180 days of total curing for both SCC with 1% SRA and SCC control specimens. The control specimens showed higher drying shrinkage than that of SCC with 1% SRA specimens at the end of curing age. Research determines the effects of SRA on shrinkage as a complex mechanism [36]. It is usually believed that SRA helps decrease drying shrinkage by decreasing the surface tension [37]. SRA addition plays a key role in drying shrinkage and is particularly striking in decreasing it at the early ages.

3.3.3 Negative shrinkage due to W/D cycles in Na_2SO_4 solution

Negative shrinkage developments of SCC with 1% SRA and control SCC specimens after subjected to W/D cycles Na_2SO_4 solution were shown in **Fig. 13**.

According to **Fig. 13**, both SCC with 1% SRA and control SCC specimens illustrated increases in negative shrinkage that they expanded upon exposure to W/D cycles in sulfate suspension and the trend of expansion was continuous until the end of 180 days which was awaited because of the blended ingress of both water and sulfate ions (that lead to ettringite) causing expansion as inferred previously [15].

4. Conclusions

Sixteen different SCC mixtures with different combinations of chemical additives were prepared and tested. The effects of the use of a combination of different chemical additives (superplasticizer, air-entraining, hydration accelerating, heat reducing, and shrinkage reducing) in the concrete mixture on the properties of fresh and hardened properties of SCC were investigated. Various tests were conducted on fresh and hardened concrete mixtures, which yielded significant conclusions. The following conclusions were drawn from the experiments on fresh and hardened concrete:

- The hydration-accelerating additive was found to increase the unit weight of SCC when used together with the other additives, while the heat-reducing and air-entraining chemicals result in significant reductions in the unit weight of SCC when used alone or with other chemical additives. The mixtures containing hydration accelerator in addition to other chemicals had higher unit weight values than the mixtures with the same additive combination but without hydration accelerator.
- The use of shrinkage-reducing and heat-reducing additives in the mixture in addition to the air-entraining additive contributes to the air content, while the inclusion of hydration-accelerating admixture has an opposite effect. The low unit weights of the mixtures with air-entraining chemical stem from this increase in air content.
- The slump flow diameter of SCC can be enhanced when the air-entraining admixture is used in combination with two or three other chemicals. The increase in the air content has a major positive effect on the slump flow diameter, and hence the flowability of SCC, particularly when other chemicals are also present in the mixture.
- Based on the V-funnel test, the combinations of chemical additives do not have major effects on the flow time of SCC. The combinations of admixtures including the hydration-accelerating additive are more effective in decreasing the flow time and increasing the flowability of SCC, particularly when a hydration-accelerating chemical is used along with the shrinkage-reducing one.
- The combinations of chemical additives result in little or no change in the flow time of SCC. Nonetheless, the U-box and L-box tests indicated that the admixture combinations containing air-entraining and hydration-accelerating admixtures create more flowable SCC mixtures.
- The addition of chemical admixtures to SCC has negative effects on the compressive and tensile strength. The reduction in the compressive strength due to the addition of admixtures is more pronounced at an early age, and this reduction becomes less significant in the long term.
- Among different mixtures, the ones containing air-entraining and heat-reducing admixtures are subject to greater reductions in the compressive and splitting tensile strength. The hydration-accelerating chemical provides SCC with early-age compressive strength above the reference value, while the 28-day strength of the mixture with these additive drops below the respective value of the plain mixture.

Overall, it is shown that it was possible to use shrinkage reducing and hydration accelerating added SCC for the targeted level of the SCC properties. This combination was found to be effective in providing the highest enhancements, considering all fresh and hardened state properties simultaneously. In future works, the effect of all hybrid combinations of chemical admixture on the durability of SCC may investigate. The super-plasticizer, air-entraining, hydration accelerating, heat reducing, and shrinkage reducing were adopted within the scope of the present study. In future studies, the fresh and hardened properties of SCC can be investigated for the sole and combined use of other chemical additives.

Declarations

Conflict of interest

The authors declare no conflict of interest.

Ethical standards

The authors state that this article does not contain any studies with human participants or animals performed by any of the authors.

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Figures

Figure 1

Gradation curves of aggregates.

Figure 2

Unit weights of different SCC mixtures.

Figure 3

Air contents of the different SCC mixtures.

Figure 4

Slump flow values of the different SCC mixtures.

Figure 5

V-funnel flow times of the different SCC mixtures

Figure 6

U-box passing values of the different SCC mixtures.

Figure 7

L-box passing ratio of the different SCC mixtures.

Figure 8

Compressive strengths of the different SCC mixtures.

Figure 9

SEM images of the S+HA SCC mixtures.

Figure 10

Splitting tensile strengths of the different SCC mixtures.

Figure 11

Negative shrinkage developments of SCC with 1% SRA.

Figure 12

Drying shrinkage developments of SCC with 1% SRA.

Figure 13

Negative shrinkage developments of SCC with 1% SRA as a result of wetting-drying cycles in Na_2SO_4 solution.