Factors affecting the Characteristics of Self-Compacting Geopolymer Concrete

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Abstract: The aim of this research was investigation the effect of sodium hydroxide (SH) concentration and the ratio of sodium silicate (SS) to sodium hydroxide (SS/SH) on the fresh and hardened characteristics of fly ash (FA) related self-compacting geopolymer concretes (SCGC) containing recycled coarse aggregate (RCA). In addition to the influence of both curing time and temperatures on the compressive strength of SCGC specimens was also evaluated. Therefore, SCGC mixes with various SS/SH ratios (1.5, 2.0, 2.5 and 3.0) and three varies SH concentrations (8M, 10M, and 12M) were designed. Six SCGC mixes containing 100\% RCA were prepared. Both SH and SS solutions are used as alkaline activators. Fresh properties were evaluated according to the EFNARC specification. Although compressive strength was utilized to indicate the effect of the SH concentration and (SS/SH) ratio on the characteristics of SCGC specimens. The results of the experiments revealed that the ratio of SS/SH and the concentration of SH have a major influence on the efficiency of (SCGC). The optimum SS/SH ratio was 2.5. Furthermore, the research revealed that SCGC mixtures containing RCA conformed to the fresh properties limitations according to the EFNARC requirements for SCC. Moreover, the optimum oven curing time and temperature were 24 hr and 75°C respectively.

Keywords: SH concentration, SS/SH ratio, Curing time, Temperature, Self-compacting Geopolymer Concrete, Fresh and Hardened characteristics.

1. Introduction

Concrete is considered the most widely utilized material in the world after water due to its stability and facilitate of use in production different structural shapes, low relative cost, and availability of raw materials. The massive production of concrete structures, as well as the large production of cement that goes with it, has a undesirable influence on the climate \cite{1}. It is well known that same amount of CO\textsubscript{2} is produced for every amount of the cement production, and raw materials about 1.6 tons are required \cite{2}. As a result, global greenhouse gas emissions are expected to be around 1.65 billion tons \cite{1,2}. Geopolymer technology has recently been mentioned as the desire to replace conventional concrete (OPC) without the use of cement \cite{3}. Furthermore, when environmental issues are taken into account,
the excessive use of cement is undesirable. Mineral fillers or by-product cementitious materials like silica fume, GGBFS, and FA were utilized by the researchers. These materials are used to improve the workability and mechanical performance of concrete while also lowering the cost [4–8]. GGBFS and FA contribute to the performance of concrete, in addition to the economy and environmentally sustainable materials [9–11].

Furthermore, the removal of an old house or its natural destruction, as well as the landfilling of trash destructed products, creates a significant environmental issue. Recycling the destructed materials, on the other hand, eliminates the problem of landfilling and allows for the recovery of certain valuable materials. In the concrete industry, using demolition waste as a source of aggregate is becoming increasingly common. Environmental concerns, abiotic degradation of renewable aggregate supplies, and preventing waste landfilling due to dumping are the key factors for greater exposure to recycling waste materials [12–14]. In structural concrete applications, high-quality recycled aggregate has been manufactured and used. This topic has gotten a lot of coverage, with studies concentrating on both recycled fine and coarse aggregates. The researchers performed the first research on the behavior of concrete applied to recycled aggregate from various sources in 1977 [15], thus keeping the w/c ratio stable. As stated previously, the compressive strength of standard concrete is just 20% higher than that of concrete containing recycled aggregate.

Self-compacting concrete (SCC) is a new type of concrete that can consolidate without needing any external or internal mechanical vibration into the narrow and deep sections, heavily reinforced to fill the formwork [16]. Also, the resistance to segregation and facility of uniformity without loss of stability is one of the most significant interests in practicing SCC. Researchers have dealt significantly with the characteristics of SCC since the 1990s when it was used in the structure industry [12,17]. Self-compacting concrete (SCC) is a new kind of concrete that can consolidate by its own weight into narrow and deep sections, heavily strengthened to fill the formwork without the use of external or internal mechanical vibration [16]. Furthermore, one of the most significant interests in practicing SCC is the resistance to segregation and the desire to maintain uniformity without losing cohesion. After its use in the structure industry in the 1990s, researchers have focused on the behavior of SCC [17,18]. These experiments aim to evaluate the properties of SCGC including RCA with different SH concentrations.

Although a few articles have been published related to self-compacting geopolymer concrete (SCGC), there has been no or minimal study on recycled coarse aggregates (RCA). The objective of this research is to clarify the impact of different SH concentrations and various ratios of SS/SH on the characteristics of SCGC. Therefore, six SCGC mixes with a constant alkaline/binder (a/b) ratio of 0.45 and a binder amount of 450 kg/m³ were designed. The workability and flow ability of SCGC mixes were investigated. Furthermore, the Mechanical performance of SCGC was also evaluated.

2. Experimental work

2.1 Materials

The binder materials in this sample were Class F Fly ash (FA) according to ASTM C618. Table 1 illustrates the properties of FA. Coarse aggregate was obtained from recycled aggregate from a locally destroyed reinforced shear wall building in Erbil, Iraq (CAg) with a maximum size of 16mm. Locally available river sand was utilized as fine aggregate (FAg) with a maximum size of 4mm as illustrated in Figure 1. The physical properties of aggregates were presented in Table 2. Sulphonated naphthalene was utilized as a superplasticizer (SP) with dark brown color and specific gravity of 1.16. The alkal activator was used as a mixture of SS and SH solutions. The elements ratio of commercially available SS (SiO₂: 29.4, water: 55.9 %, and Na₂O: 13.7 %, by mass and the specific gravity was 1.41. The purity of the SH was between 97 and 98 %. The concentration of SH solution was designated as 8, 10, and 12 to clarify the influence of SH concentration on the characteristics of SCGC. As well as the influence of (SS/SH) ratios on the performance of SCGC. Figure 2 shows the preparation process for the production of RCA.
Figure 1. Particle size distribution of aggregates.

Table 1. The properties of FA.

| Component | CaO | SiO₂ | Al₂O₃ | Fe₂O₃ | MgO | SO₃ | K₂O | Na₂O | LOI | SG | BF (m²/kg) |
|------------|-----|------|-------|-------|-----|-----|-----|------|-----|----|------------|
| FA (%)     | 1.59| 62.34| 21.13 | 7.16  | 2.39| 0.11| 3.38| 0.37 | 1.57| 2.29| 378        |
| LOI: Loss on ignition; SG: Specific gravity; BF: Blain fineness |

Table 2. The physical characteristics of aggregates.

| Aggregate | Specific gravity | Fineness modulus | Absorption (%) |
|-----------|------------------|------------------|----------------|
| Sand      | 2.6              | 2.6              | 1.05           |
| RCA       | 2.55             | 6                | 3.9            |

Figure 2. Preparation of RCA
2.2 Proportions of mixes

The components of SCGC mixes were illustrated in Table 3. Six mixes of SCGC were produced. SCGC mixes were created using four different ratios of SS/SH (1.5, 2, 2.5, and 3) and three different SH concentrations (8, 10, and 12). The alkaline/binder (a/b) ratio was kept constant (0.45). The superplasticizer was also kept constant (7%). Table 2 illustrates the mixes of SCGC utilized in this research.

Table 3. Mix proportions of SCGC.

| Mixtures | SS/SH ratio | SH concentration | FA (kg/m³) | Cag (kg/m³) | Fag (kg/m³) | SS (kg/m³) | SH (kg/m³) | W (kg/m³) |
|----------|-------------|------------------|------------|-------------|-------------|------------|------------|-----------|
| M1-SH8-S1.5 | 1.5         | 8                | 450        | 835         | 850         | 90         | 57         | 42        |
| M2-SH10-S1.5 | 1.5        | 10               | 450        | 835         | 850         | 90         | 57         | 42        |
| M3-SH12-S1.5 | 1.5        | 12               | 450        | 835         | 850         | 90         | 57         | 42        |
| M4-SH12-S2.0 | 2           | 12               | 450        | 835         | 850         | 118        | 57         | 42        |
| M5-SH12-S2.5 | 2.5         | 12               | 450        | 835         | 850         | 142.5      | 57         | 42        |
| M6-SH12-S3.0 | 3           | 12               | 450        | 835         | 850         | 171        | 57         | 42        |

SS: Sodium silicate, SHM: The concentration of sodium Hydroxide, SH: Sodium hydroxide, FAg: Fine aggregate, CAg: Coarse aggregate, FA: Fly ash, W: water.

2.3 Mixing procedure

The materials used for the production of SCGC mixes were shown in Figure 3. The alkaline solutions were prepared according to the concentration needed for this study before the mix preparation for about 24 hrs. SH has a molecular weight of 40 g/mol. Therefore, the SH concentration was prepared as follows: 8 SHM: 320 grams of solid SH per liter of water, 10 SHM: 400 grams of solid SH per liter of water, and 12 SHM: 480 grams of solid SH per liter of water The SH solution was allowed to cool for 4 hours at room temperature. The SS solution was then combined in different amounts with the SH solution (1.5, 2, 2.5, and 3). The procedure started with combining dry fly ash with saturated surface dry (SSD) aggregates in a rotary drum mixer for about 45 sec. After that, the alkaline solution was added for 1 minute. After that, the extra water-incorporated SP were mixed for an additional 1 minute. After that, the mixture was given a 200-second rest. The fresh properties testing was evaluated and the cubic molds were filled with SCGC mixture to evaluate the mechanical properties [1,19].

Figure 3. (a) SH solution, (b) SH flakes, (c) Sodium silicate, (d) Fly ash, (e) Fine aggregate, (f) Superplasticizer, (g) Recycled coarse aggregate.
3. Tests Procedures

All fresh properties tests are carried following the EFNARC, 2005 [20]. A responsive test used to characterize the flow-ability of the mixture in free flow situations is the slump flow value. EFNARC classify the standard slump flow into three categories, each of which defines the purposes for which SCC is used. On the other hand, these experiments cannot determine direct viscosity; this test determines the rate of flow in terms of viscosity. Moreover, V-funnel flow test was evaluated through the time calculated via the V-shaped funnel, which is the elapsed time almost mixed flow through the V-funnel opening. The L-box and J-Ring measure the fresh concrete's capability to flow through narrow gaps and confined spaces, such as areas with congested reinforcement, without losing homogeneity or consistency.

3.1 The fresh properties tests of SCGCs

All fresh properties tests are carried out in accordance with the EFNARC committee's European specification for SCC development [20]. A responsive test used to characterize the flow-ability of fresh mix in free flow situations is the slump flow value. As a result, it was recommended that all SCC mixes be specified. EFNARC classifies the standard slump flow into three categories, each of which defines the purposes for which SCC is used. Table 3 displays the standard application areas as well as the higher and lower limits for these classes. The viscosity of the SCC is determined by the flow time of a V-funnel. These experiments, on the other hand, cannot determine direct viscosity; instead, this test determines the rate of flow in terms of viscosity. The elapsed time nearly mix flow through the V-funnel opening is the time evaluated through the V-shaped funnel. The passing-ability of fresh concrete to go through narrow gaps like places of crowded reinforcement without lack of homogeneity or segregation is evaluated via the use of J-Ring and L-box measures. Table 5 shows the results of the current study's L-box height ratios.

3.2 Curing condition of the SCGC specimens

The specimens were left at room temperature for 24 hours before curing. The SCGC was then subjected to oven curing for 24 and 48 hours at temperatures of (60, 75, 85, and 90) °C. According to previous study, the optimum temperature for curing is 75°C. The specimens were left at lab until the time of hardened test. A hydraulic measurement device with a 2000 kN capacity was utilized to measure the compressive strength of the hardened SCGC by EN 12390-3 2001, as seen in Figure 4 [21]. Three identical 100 mm cubes were used to measure each mix.

4. Experimental work results

The influence of various SH concentrations and SS/SH ratios on the fresh characteristics of SCGC containing 100% RCA was studied, and the outcomes were presented in Table 4 and Figure 5. According to the findings, the SH concentration had a significant effect on the fresh characteristics of
SCGC. On the other hand, the passing ability tests were greatly influenced. Moreover, the ratio of SS/SH had a great influence on the viscosity activity of SCGC mixes (V-Funnel).

**Table 4.** The influence of the different concentration and SS/SH ratios on the fresh properties.

| Mixtures     | SS/SH | SH concentration | Slump flow (mm) | V-funnel flow time (sec) | Segregation resistance ratio | J-Ring (mm) | L-Box ratio |
|--------------|-------|------------------|-----------------|--------------------------|-------------------------------|-------------|-------------|
| M1-SH8-S1.5  | 1.5   | 8                | 752             | 9.1                      | 9.2                           | 741         | 1           |
| M2-SH10-S1.5 | 1.5   | 10               | 741             | 10.1                     | 10.5                          | 723         | 0.94        |
| M3-SH12-S1.5 | 1.5   | 12               | 712             | 11.9                     | 12.0                          | 702         | 0.92        |
| M4-SH12-S2.0 | 2     | 12               | 701             | 12.2                     | 11.9                          | 696         | 0.89        |
| M5-SH12-S2.5 | 2.5   | 12               | 703             | 13.7                     | 13.6                          | 692         | 0.84        |
| M6-SH12-S3.0 | 3     | 12               | 672             | 14.6                     | 14.5                          | 641         | 0.83        |

4.1 J-Ring and slump flow tests

Table 4 and Figure 5 illustrate the flow-ability values of SCGC mixes. Slump flow and J-Ring test values for SCGC mixes were ranged between 672 to 752 mm for the slump flow and 641 to 741 mm for J-Ring test. It was concluded that the mixes designed with higher SH concentration had a low slump flow. The lower slump flow was seen for the mix designed with 12 SH concentration. The J-ring test values were also reduced with an increase in SH concentration. However, all mixes were conforming to the EFNARC, 2005 [20]. For slump flow, all SCGC mixes were in the range class 2 slump flow (SF2). The previous researchers reported similar results [22,23]. Normal aggregates were used in SCGC analysis [24]. It was also indicated that the J-Ring and slump flow test decreases with the high concentration of SH and higher viscosity [25,26]. As a result, the influence of the SH concentration on the flow-ability of SCGCs including RCA is comparable to SCGCs including natural aggregates.

The influence of the ratio of SS/SH on the slump flow of SCGC mixes is indicated in Table 4. It was noted that the SS/SH value has a significant impact on slump flow and J-Ring values. A considerable decrease in the values of J-Ring and slump flow was illustrated with an increase in the value of SS/SH. The adhesiveness of the alkaline solution is increased with higher SS content increases [8,27].

4.2 V-Funnel test

The time measured for the V-funnel test are tabulated in Table 4. The SCGC mixtures had v-funnel times ranging from 9.1 sec to 14.6 sec. It was noted that all V-funnel values less than 25 sec and in the range of EFNARC, 2005 [20]. Table 4 reveals that increasing the SH concentration from 8 to 12 SHM increased the time of V-funnel from 9.1 to 11.9 sec. The previous researchers investigated that the time of V-funnel was observed to change slightly when the concentration of SH was increased from 8 to 12 [28]. The viscosity of the solution increases as the concentration of SH increases.

Table 4 indicates that once the SS/SH value reaches 3.0, the SS/SH value has no influence on the V-funnel time, because the trend line of the increasing time of flow were rapidly increases. The high values of the ratio of the SS/SH (3.0) increased the viscosity of the mix. As a result, it can be concluded that the influence is minimal up to a ratio of SS/SH (2.5); In addition, the influence of the ratio 3 has a substantial influence on the values of V-funnel.

4.3 L-box test

The values of passing-ability (L-box) is presented in Table 4. The findings show that all SCGC mixes accepted with EFNARC’s L-box ratio requirements, regardless of SH concentration or the ratio of SS/SH. The high ratio of L-box decreased dramatically with the high concentration of SH solution as observed in Table 4. The L-Box values were between 1 to 0.92 for the concentration of SH between 8 to 12 respectively. The previous researchers studied three various concentrations of SH solution (8SHM, 10SHM, and 12SHM) in SCGC mixtures including natural aggregate and the L-Box test results
were nearly similar [25]. The effect of the values of SS/SH on the passing ability of SCGC was more significant. It was noted that a significant reduction in the L-Box values was observed with a high ratio of SS/SH. As the ratio of SS/SH changed from 1.5 to 3.0, the ratio of L-Box decreased from 0.92 to 0.83.

Figure 5. Effect of SH concentration and SS/SH ratio on slump flow and J-Ring

4.4 Segregation resistance test

Table 4 illustrates the values of segregation resistance. In general, it has been shown that the segregation resistance of SCGC mixtures was limited with the high concentration of SH and high values of SS/SH. However, the SH concentration had more effects than the ratio of SS/SH. Furthermore, the segregation resistance for all mixes was acceptable within the EFNARC 2005, specifications (5-15%). The segregation resistance test values decline from 13.5 % to 10.5 % for the SH concentration 8SHM to 12SHM respectively. Since the SH reacts with the water during the process of geopolymerization, resulting in less segregation with high viscosity, the mixes have a high resistance to segregation.

Moreover, the segregation resistance was less affected by the ratio of SS/SH after the ratio of (2.5). Also, the sodium silicate solution increased the adhesiveness of the mix decreases the segregation resistance for SCGC mixes. SH concentration and SS/SH ratio decreases the slump flow value and L-Box ratio of the blend while increasing plastic viscosity. Mixes containing a higher concentration of SH and SS/SH ratio became more cohesive and viscous, and the flow-ability and fluidity of SCGC mixes declined as the ratio of SH concentration increased and increased the resistance to bleeding and segregation. According to the EFNARC 2005, all mixes examined were in the VS2/VF2 class. The mixes had good segregation resistance and/or free of bleeding in addition to low formwork pressure. On the other hand, it was deducted that the setting time of the mixtures improved with the higher
concentration of SH and SS/SH ratio. The minimum setting time was observed through the use of 8 SHM and SS/SH ratio of 1.5.

5. Mechanical properties of SCGC
The results indicated that the SH concentration and the ratio of SS/SH improved the compressive strength of the SCGC specimens with high concentration of SH and ratio of SS/SH. The compressive strength of the concentrations 10 and 8 was almost identical. However, as seen in Figure 6a and Table 5, the optimum concentration of SH for SCGC was 12 similar to the outcomes investigated by earlier researchers.

Table 5. Influence of the different concentration and SS/SH ratios on the compressive strength.

| Mixtures     | SS/SH | SH concentration | CS (MPa) |
|--------------|-------|------------------|----------|
| Influence of SH concentration |       |                  |          |
| M1-SH8-S1.5  | 1.5   | 8                | 24.1     |
| M2-SH10-S1.5 | 1.5   | 10               | 24.4     |
| M3-SH12-S1.5 | 1.5   | 12               | 26.4     |
| Influence of SS/SH ratio |       |                  |          |
| M4-SH12-S2.0 | 2     | 12               | 32.3     |
| M5-SH12-S2.5 | 2.5   | 12               | 35.8     |
| M6-SH12-S3.0 | 3     | 12               | 35.4     |

As indicated in Figure 6b, the compressive intensity of the SCGC specimens was improved with the high ratio of SS/SH up to 2.5, then slightly decreased when the ratio (3) was utilized. According to the findings, the ideal ratio of SS/SH as 2.5. The optimal ratio of SS/SH, according to the previous researcher, is 2.5.

**Figure 6. Compressive strength of SCGC mixtures.**
The optimum mix was M5-SH12-S2.5 with SH concentration 12 and SS/SH ratio 2.5. The curing time and Temperature was studied for M5. Figure 7 illustrates the compressive strength values of SCGC specimens used in this study. The results showed that the strength of SCGC specimens oven-cured for 24 hr was significantly higher than that of specimen oven-cured for 48 hr. The perfect curing time in the oven was 24 hr. This may be due to the early water evaporation in the mixes, which induces more evaporation and micro cracks after 48 hours of curing. The increased curing temperature causes the OH ions to break down the Si-O and Al-O, and increasing the polarization phase and resulting in a coarser and porous SCGC microstructure [29].

![Compressive strength of SCGC mixtures](image)

**Figure 7.** Compressive strength of SCGC mixtures.

Figure 8 shows the specimens cured at 24 and specimen cured at 48 hours. Due to the evaporation process, the specimen cured at 48 hours has micro cracks and micro pores on the surface. Furthermore, as the age of the test progressed, the compressive strength of SCGC was improved. The compressive strength of SCGC measured at 28 days was more than the compressive strength of specimens tested at 7 days. Furthermore, the compressive strength values for the specimens cured at 75, 85, and 90°C were very similar. As a result, the SCGC's optimum curing time was 24 hours at 75°C.
a. Specimen cured for 24 hrs.  
b. Specimen cured for 48 hrs.

Figure 8. Specimen cured for (a) 24 hrs, specimen cured at 48 hrs.

6. Conclusion

The conclusions established from the study's findings are as follow:

- The results showed that the adhesiveness of the mix are significantly influenced by the SH concentration. The flow-ability was also decreased with an increase in the SH concentration.
- The results of the fresh mix are inversely proportional to the amount of SH solution present.
- The ratio of SS/SH (2.5) was stated to be the best to meet the requirements of EFNARC 2005, particularly for the segregation resistance and flow-ability tests.
- SH concentration and SS/SH ratio decreases the slump flow value and L-Box ratio of the blend while increasing plastic viscosity. Mixes containing a higher concentration of SH and SS/SH ratio became more cohesive and viscous, and the flow-ability and fluidity of SCGC mixes declined as the ratio of SH concentration increased and increased the resistance to bleeding and segregation.
- According to the EFNARC 2005, all mixes examined were in the VS2/VF2 class. The mixes had good segregation resistance and/or free of bleeding in addition to low formwork pressure.
- On the other hand, it was deducted that the setting time of the mixtures improved with the higher concentration of SH and SS/SH ratio.
- The optimum SS/SH ratio was 2.5 and the optimum SH concentration was 12.
- The optimum oven curing time and temperature were 24 hr and 75 °C respectively.
- The research revealed that SCGC mixtures containing RCA conformed to the fresh properties limitations according to the EFNARC 2005, requirements for SCC.

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