Influence of granite waste aggregate on properties of binary blend self-compacting concrete

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Abstract. This study explores the feasibility of granite waste aggregate (GWA) as a partial replacement of natural fine aggregate (NFA) in binary blend self-compacting concrete (SCC) prepared with fly ash. Total of nine SCC mixtures were prepared wherein one was Ordinary Portland cement (OPC) based control SCC mixture and remaining were fly ash based binary blend SCC mixtures which included the various percentages of GWA. Fresh properties tests such as slump flow, T\(_{500}\), V-funnel, J-ring, L-box, U-box, segregation resistance, bleeding, fresh density, and loss of slump flow (with time) were conducted. Compressive strength and percentage of permeable voids were evaluated in the hardened state. All the SCC mixtures exhibited sufficient flowability, passing ability, and resistance to segregation. Besides, all the binary blend SCC mixtures exhibited lower fresh density and bleeding, and better residual slump (up to 50% of GWA) compared to the OPC based control SCC mixture. Binary blend SCC mixture incorporating up to 40% GWA provided higher compressive strength than binary blend control SCC mixture. The findings of this study encourage the utilization of GWA in the development of binary blend SCC mixtures with satisfactory workability characteristics as a replacement of NFA.

Keywords: fly ash; granite waste aggregate; self-compacting concrete; fresh properties; bleeding; loss in slump flow; compressive strength

1. Introduction

The massive amount of different industrial wastes, for example, glass waste, waste foundry sand, granite and marble waste, and ceramic waste, are continuously generated with the growth in industrialization. These industrial wastes have created land and air pollution, and also created difficulties for producers in waste handling. The sustainable disposal of these waste materials is needed to find out. On the other hand, the construction industry is one of the larger consumers of natural resources such as cement and fine aggregate (or river sand). Massive utilization of natural resources has created a burden on the environment (Aslani \textit{et al.} 2018). Various investigations have been conducted by researchers in order to produce sustainable construction products by substituting natural resources with industrial wastes (Lenka and Panda 2017, Bisht and Ramana 2018, Gupta \textit{et al.} 2018, Jain \textit{et al.} 2018, Siddique \textit{et al.} 2018, Benyamina \textit{et al.} 2019, Choudhary \textit{et al.} 2020, Choudhary \textit{et al.} 2020, Gupta \textit{et al.} 2020, Jain \textit{et al.} 2020). The substitution of natural resources with industrial wastes will resolve both the issue mentioned above i.e., preserve the natural resources and solve the waste handling problems as well.

Granite waste is the residue of granite cutting industry, which is produced in huge quantity during the extraction and transformation process of granite blocks. India is the world’s third largest production country of granite blocks after China and Brazil, with a production amount of 45-55 million sqm per year (WNSA 2014). Mendoza \textit{et al.} (2014) stated that about 25% amount of granite blocks generates as a granite waste in the sawing process. To solve the waste disposal problem of granite waste, researchers have found the feasibility of granite waste in the normally vibrated concrete (NVC) as a cement and natural fine aggregate (NFA) replacement (Binici \textit{et al.} 2008, Elmoaty 2013, Vijayalakshmi \textit{et al.} 2013, Ghannam \textit{et al.} 2016, Singh \textit{et al.} 2016, Singh \textit{et al.} 2017, Mashaly \textit{et al.} 2018, Ghorbani \textit{et al.} 2019). Lower workability of granite concrete compared to that of plain concrete was observed by most of the researchers (Binici \textit{et al.} 2008, Vijayalakshmi \textit{et al.} 2013). Singh \textit{et al.} (2017) detected 45.45% reduction in workability on replacing 70% granite industry by-product with sand in NVC. Though, most of the researchers found the increment in strength on the incorporation of granite waste in concrete. Vijayalakshmi \textit{et al.} (2013) found the minor increment in the compressive strength of about 1% on the replacement of up to 25% of river sand with granite powder in NVC, and they observed the highest strength at 10% replacement level of granite powder. Ghannam \textit{et al.} (2016) observed the increment in the compressive strength up to 37% on the incorporation of up to 20% of granite powder in NVC as a sand replacement. Singh \textit{et al.} (2016)
carried out a review on NVC incorporating granite waste and suggested that it can be effectively used as an NFA replacement in the production of NVC.

Limited works have been done in the past for the incorporation of granite waste in SCC. The feasibility of granite waste in self-compacting concrete (SCC) has been investigated by earlier researchers (El Yamany et al. 2014, Sadek et al. 2016), as an inert filler or mineral additive by weight of cement. Ho et al. (2002) studied the effect of inert fillers such as granite and limestone powder on fresh properties of SCC and reported that SCC comprising granite powder required higher superplasticizer dosages in comparison to SCC comprising limestone powder. Karmegam et al. (2014) noticed up to 5.84% increment in the compressive strength on the replacement of up to 20% of cement with granite sawing waste in SCC.

Researchers have also used other types of stone waste as an NFA replacement in SCC and found the satisfactory fresh and compressive strength properties of SCC. Hameed et al. (2012) observed the improvement in fresh properties on the utilization of crusher rock dust and marble powder as an NFA replacement in SCC. Another study done by Hameed et al. (2012) reported that compressive strength increased on the utilization of crusher rock dust and marble powder as an NFA replacement in SCC. Sua-iam and Makul (2013) observed the satisfactory fresh properties on the incorporation of up to 20% of limestone powder in SCC as an NFA replacement. They also reported that compressive strength increased on the incorporation of up to 10% of limestone powder. Rai et al. (2016) reported that the fresh properties were found to be consistent at 30% replacement of fine aggregate by quarry waste. They also reported that compressive strength increased on the incorporation of up to 40% of quarry waste. Skender et al. (2019) revealed that the incorporation of limestone in SCC as a replacement of NFA led to a decrease in fresh properties results. However, they reported an increase in compressive strength at 15% content of NFA.

Self-compacting concrete (SCC) is the advanced form of normally vibrated concrete (NVC) which has progressively been accepted, at the construction site, all over the world. SCC has several benefits over NVC, though the cost of SCC production is very high because it consists of higher cement content (EFNARC 2005, Mohamed and Tayeb 2019). Several studies (Zhao et al. 2015, Dadsetan and Bai 2017, Djelloul et al. 2018) are available in which researchers have partially replaced cement with the sustainable and economical powder materials like fly ash and ground granulated blast furnace slag etc. The utilization of these powder materials will not only reduce the cost of SCC but also enhance the fresh and hardened characteristics (Zhao et al. 2015). Furthermore, the behaviour of SCC in the fresh state is very sensitive, which must maintain homogeneity (i.e., stability) of the mixtures along with flowability or deformability. However, there is a strong possibility of instability (i.e., segregation and bleeding) together with favourable workability characteristics (Ren et al. 2019). Higher segregation (loss of uniformity of mixture) and bleeding (separation of water from the mixture) affects the mechanical and durability characteristics of concrete (Bartos 2013). Bleeding is more destructive if excessive water entrap within the concrete matrix, which can extensively impair the bond between the binder paste and the aggregate (Panesar and Shindman 2012). Moreover, higher bleeding lowers the plastic shrinkage cracking (Gokce and Andic-Cakir 2019). Contrary to this, when rapid drying circumstances are present, minor bleeding can hinder the finishing work on concrete surfaces (Wilson and Kosmatka 2011). Therefore, some amount of bleeding is tolerable in concrete (Wainwright and Ait-Aider 1995, Topcu and Elgun 2004). Due to the problems mentioned above associated with segregation and bleeding, it is necessary to evaluate the segregation and bleeding characteristics of the concrete mixture in the fresh state. Also, segregation resistance and bleeding attributes are evenly requisite for successful SCC mixture, apart from the better filling and passing ability (Ren et al. 2019). It is also well conceded that for superior construction products, the concrete mixture should have sufficient workability characteristics at the time of placing (Erdogdu et al. 2011). This criterion is essential for ready-mix concrete because sometimes, the concrete mixture is required to be delivered at the far location from the mixing plant. During transportation to far distance, workability of the concrete mixture is significantly reduced due to the possible reasons such as longer delivery time, loss of mixing water, failure of the truck mixer and jamming of traffic (Soroka and Ravina 1998). Loss of workability with time can be generally compensated by the application of vibration; however, this is unfeasible for SCC (Felekoglu and Sarikahya 2008). Therefore, time-dependent workability testing of an SCC mixture needs to be investigated in detail.

The past studies revealed that the use of granite waste in NVC as cement and NFA replacement had been a feasible option. Earlier, the authors of this study also found the appreciable feasibility of granite waste as an NFA replacement in the production of SCC (Jain et al. 2019, Jain et al. 2019a). Few researchers had explored the potential of granite waste in SCC, remarkably, as an alternative of NFA. Hence, this investigation has been carried out to explore the utilization of granite waste aggregate (GWA) in the development of economical fly ash based SCC as an alternative to NFA. The present study has mainly been done to evaluate the effect of GWA on fresh state properties of binary blend SCC. The results were also compared with Ordinary Portland cement (OPC) based concrete mixture. Several tests in the fresh state of SCC such as slump flow, T500, V-funnel, J-ring, L-box, U-box, segregation resistance, bleeding and fresh density were conducted. Slump flow loss of SCC mixtures with time, in the fresh state, was also evaluated. Whereas, compressive strength and percentage of permeable voids, in the hardened state of SCC, was evaluated.

2. Experimental program

2.1 Materials

Ordinary Portland cement (OPC) of 43 grade and fly ash of class-F were used in this investigation as a binder. Their
Influence of granite waste aggregate on properties of binary blend self-compacting concrete

Table 1 Physical properties and elemental composition of the binder

<table>
<thead>
<tr>
<th>Physical properties</th>
<th>Cement</th>
<th>Fly ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consistency (%)</td>
<td>27</td>
<td>-</td>
</tr>
<tr>
<td>Initial setting time (minutes)</td>
<td>120</td>
<td>-</td>
</tr>
<tr>
<td>Final setting time (minutes)</td>
<td>241</td>
<td>-</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>3.16</td>
<td>2.28</td>
</tr>
<tr>
<td>Soundness (mm)</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Residue retained on 90µ sieve (%)</td>
<td>1.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Residue retained on 45µ sieve (%)</td>
<td>52.33</td>
<td>4.66</td>
</tr>
<tr>
<td>Specific surface area (m²/kg)</td>
<td>297</td>
<td>353</td>
</tr>
<tr>
<td>Compressive strength (MPa)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7 days</td>
<td>34.5</td>
<td>-</td>
</tr>
<tr>
<td>28 days</td>
<td>45.8</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2 Physical properties and elemental composition of aggregates

<table>
<thead>
<tr>
<th>Physical properties</th>
<th>NFA</th>
<th>GWA</th>
<th>Coarse aggregate (10 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fineness modulus</td>
<td>2.50</td>
<td>1.40</td>
<td>5.99</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>2.64</td>
<td>2.57</td>
<td>2.71</td>
</tr>
<tr>
<td>Water absorption (%)</td>
<td>1.00</td>
<td>4.49</td>
<td>0.40</td>
</tr>
<tr>
<td>Crushing value (%)</td>
<td>-</td>
<td>-</td>
<td>24.46</td>
</tr>
<tr>
<td>Impact value (%)</td>
<td>-</td>
<td>-</td>
<td>24.72</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Element (symbol; %)</th>
<th>NFA</th>
<th>GWA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen (O)</td>
<td>44.21</td>
<td>51.53</td>
</tr>
<tr>
<td>Calcium (Ca)</td>
<td>34.93</td>
<td>2.06</td>
</tr>
<tr>
<td>Silicon (Si)</td>
<td>19.00</td>
<td>25.15</td>
</tr>
<tr>
<td>Aluminium (Al)</td>
<td>1.88</td>
<td>14.29</td>
</tr>
<tr>
<td>Iron (Fe)</td>
<td>1.23</td>
<td>1.68</td>
</tr>
<tr>
<td>Magnesium (Mg)</td>
<td>0.58</td>
<td>0.35</td>
</tr>
<tr>
<td>Sodium (Na)</td>
<td>0.12</td>
<td>-</td>
</tr>
<tr>
<td>Potassium (K)</td>
<td>0.23</td>
<td>2.52</td>
</tr>
<tr>
<td>Carbon (C)</td>
<td>-</td>
<td>7.12</td>
</tr>
<tr>
<td>Sulphur (S)</td>
<td>0.05</td>
<td>-</td>
</tr>
<tr>
<td>LOI (%)</td>
<td>3.97</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Fig. 1 Microstructure of fly ash

elemental compositions and physical properties are presented in Table 1. Scanning electron microscopic (SEM) image of fly ash is shown in Fig. 1, which indicates the smooth and spherical morphology of fly ash. River sand of 4.75 mm maximum size and basalt-based stone of 10 mm maximum size conforming to BIS: 383 (2016) were used as fine and coarse aggregates. Granite waste aggregate (GWA) of maximum 4.75 mm size in wet condition was procured from the locally situated industrial area. It was used in the dried condition, as shown in Fig. 2. The particle size distribution of natural fine aggregate (NFA) and GWA are shown in Fig. 3, which indicates that particles of GWA are finer than NFA particles. The physical properties of all aggregates are presented in Table 2. SEM images of NFA and GWA are shown in Figs. 4(a) and (b), respectively, which indicate that GWA particles have rough and angular morphology as compared to the smooth and granular morphology of NFA particles. The elemental compositions of NFA and GWA are presented in Table 2. Figs. 5(a) and (b) show the XRD patterns of NFA and GWA respectively. Quartz is the primary phase in NFA, whereas, quartz, albite, and microcline are the primary phases in GWA. A polycarboxylate ether (PCE) based superplasticizer (SP) of
Total nine SCC mixtures, as given in Table 3, were made by keeping constant effective water to binder ratio (w/b) of 0.35 and fixed binder content of 548.53 kg/m³. Out of the nine SCC mixtures, one mixture (mix no. A0) was prepared with 100% OPC binder labelled as OPC based control SCC mixture, one mixture (mix no. A1) was prepared with partial replacement (by weight) of 30% cement with fly ash labelled as fly ash based binary blend control SCC mixture (without GWA), and remaining (mix no. A2-A8) were fly ash based binary blends SCC mixtures (with GWA). Mix no. A2-A8 had a constant proportion of cement and fly ash as of mix no. A1, in which NFA was partially replaced (by weight) with GWA in varying percentages of 20% to 60%. The amount of fly ash was kept constant at 30% since beyond this percentage of fly ash significant reduction in strength was observed during trial work. Earlier researchers (Mohamed 2011, Uysal and Sumer 2011, Leung et al. 2016, Ardalan et al. 2017) also recommended the incorporation of fly ash up to 35% as a cement replacement in the concrete mixtures. Total aggregates content was kept fixed at an amount of 1654.8 kg/m³. Extra water was added, for compensating the water absorption of aggregates, at the time of mixing. The dosage of SP was varied for attaining the target slump flow in the range of 750±30 mm.

### Table 3 Details of SCC mix proportions (kg/m³)

<table>
<thead>
<tr>
<th>Mix no.</th>
<th>Cement (kg/m³)</th>
<th>Fly ash (kg/m³)</th>
<th>NFA</th>
<th>GWA (%)</th>
<th>GWA Coarse aggregate (kg/m³)</th>
<th>Water* (kg/m³)</th>
<th>SP dosage (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A0</td>
<td>548.53</td>
<td>-</td>
<td>968.35</td>
<td>-</td>
<td>-</td>
<td>698.17</td>
<td>204.47</td>
</tr>
<tr>
<td>A1</td>
<td>383.97</td>
<td>164.56</td>
<td>968.35</td>
<td>0</td>
<td>698.17</td>
<td>204.47</td>
<td>0.82</td>
</tr>
<tr>
<td>A2</td>
<td>383.97</td>
<td>164.56</td>
<td>774.68</td>
<td>20</td>
<td>193.67</td>
<td>698.17</td>
<td>211.23</td>
</tr>
<tr>
<td>A3</td>
<td>383.97</td>
<td>164.56</td>
<td>726.26</td>
<td>25</td>
<td>242.09</td>
<td>698.17</td>
<td>212.92</td>
</tr>
<tr>
<td>A4</td>
<td>383.97</td>
<td>164.56</td>
<td>677.85</td>
<td>30</td>
<td>290.51</td>
<td>698.17</td>
<td>214.60</td>
</tr>
<tr>
<td>A5</td>
<td>383.97</td>
<td>164.56</td>
<td>629.43</td>
<td>35</td>
<td>338.92</td>
<td>698.17</td>
<td>216.29</td>
</tr>
<tr>
<td>A6</td>
<td>383.97</td>
<td>164.56</td>
<td>581.01</td>
<td>40</td>
<td>387.34</td>
<td>698.17</td>
<td>217.98</td>
</tr>
<tr>
<td>A7</td>
<td>383.97</td>
<td>164.56</td>
<td>484.18</td>
<td>50</td>
<td>484.18</td>
<td>698.17</td>
<td>221.36</td>
</tr>
<tr>
<td>A8</td>
<td>383.97</td>
<td>164.56</td>
<td>383.97</td>
<td>60</td>
<td>581.01</td>
<td>698.17</td>
<td>224.74</td>
</tr>
</tbody>
</table>

*Effective water was 191.99 kg/m³ in each mix.

### 2.3 Mixing and casting

Rotary drum mixer was used for mixing the ingredients of SCC. Aggregates, cement and fly ash were first added into the mixer and thereafter mixed them thoroughly for one minute in the mixer. Three-quarters of water was then poured into the mixer and mixed with the raw materials for two minutes. Subsequently, remaining water along with admixture was poured and mixed for another two to three minutes. The mixer was then kept in stable condition for one minute for the activation of admixture. Thereafter, mixing was carried out for an extra one to two minutes. Before casting of test samples, fresh properties tests of SCC were performed. All the casted specimens were then left for one day in moulds at room temperature and following day stripped and placed in water for curing till the age of testing.

### 2.4 Testing procedure

The effect of GWA on the fresh state of fly ash based binary blend SCC mixtures was evaluated by workability tests such as slump flow, T<sub>500</sub>, V-funnel, J-ring, L-box, U-box and sieve segregation resistance as per the EFNARC standards (EFNARC 2002, EFNARC 2005). Slump flow, T<sub>500</sub> time and V-funnel time were conducted to measure the filling ability of concrete. Slump flow was evaluated as the average of the diameter of spread concrete in two perpendicular directions. T<sub>500</sub> time was noted when concrete mixture reached the 500 mm diameter of spread concrete during the slump flow test. V-funnel time (at T<sub>10sec</sub> and T<sub>3min</sub>) was noted when concrete mixture entirely flowed out through funnel after opening the bottom gate of V-funnel apparatus. V-funnel time (T<sub>3min</sub>) was evaluated to check the segregation of SCC mixtures. For satisfactory resistance to segregation of an SCC mixture, V-funnel time (T<sub>3min</sub>) should not be exceeded by initial V-funnel time (T<sub>10sec</sub>) plus 3 sec (EFNARC 2002).

J-ring, L-box and U-box tests were conducted to measure the passing ability of concrete. J-ring step height was measured as the difference in height level of concrete at inside and outside of J-ring bar. J-ring flow diameter and T<sub>500</sub> time were also recorded during the J-ring test. L-box height ratio (H₂/H₁) was recorded by taking the ratio of the height of concrete (H₂) at the endpoint of horizontal section
Table 4 Approval criteria for SCC (EFNARC 2002, EFNARC 2005)

<table>
<thead>
<tr>
<th>Test</th>
<th>Class</th>
<th>Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slump flow (spreading diameter; mm)</td>
<td>SF1</td>
<td>550-650</td>
</tr>
<tr>
<td></td>
<td>SF2</td>
<td>660-750</td>
</tr>
<tr>
<td></td>
<td>SF3</td>
<td>760-850</td>
</tr>
<tr>
<td>T500 slump flow time (sec)</td>
<td>VS1</td>
<td>≤2</td>
</tr>
<tr>
<td></td>
<td>VS2</td>
<td>&gt;2</td>
</tr>
<tr>
<td>V-funnel time (sec)</td>
<td>VF1</td>
<td>≤8</td>
</tr>
<tr>
<td></td>
<td>VF2</td>
<td>9-25</td>
</tr>
<tr>
<td>L-box (passing ratio)</td>
<td>PA1 (for 2 bars)</td>
<td>≥0.80</td>
</tr>
<tr>
<td></td>
<td>PA2 (for 3 bars)</td>
<td>≥0.80</td>
</tr>
<tr>
<td>J-ring (step height; mm)</td>
<td></td>
<td>0-10</td>
</tr>
<tr>
<td>U-box (filling height; mm)</td>
<td></td>
<td>0-30</td>
</tr>
</tbody>
</table>

The performance of SCC incorporating GWA in the hardened state was evaluated by conducting a compressive strength test as per BIS: 516 (1959). Compressive strength test was conducted for 7 and 28 days cured specimens of 100×100×100 mm size. Percentage of permeable voids was also evaluated on 28 days cured specimens of 100×100×100 mm size. Percentage of permeable voids was expressed as the segregation ratio (%) of the weight of mortar fraction (passed by the 5 mm aperture sieve) to the weight of the original sample (poured onto the sieve having 5 mm aperture). The approval criteria for all the workability test of SCC is presented in Table 4.

Bleeding of each SCC mix in the fresh state was determined according to ASTM C232 (2014), while the density of freshly mixed SCC was determined according to ASTM C138 (2016).

The loss in slump flow with elapsed time, at 10 (initial slump flow), 20, 30, 45 and 60 minutes after the initial contact of water with the cement, was also examined in the fresh state in order to identify the influence of GWA on the workability retention capacity of SCC.

The performance of SCC incorporating GWA in the hardened state was evaluated by conducting a compressive strength test as per BIS: 516 (1959). Compressive strength test was conducted for 7 and 28 days cured specimens of 100×100×100 mm size. Percentage of permeable voids was also evaluated on 28 days cured specimens of 100×100×100 mm size, in the hardened state of SCC. The percentage of permeable voids were evaluated by Eq. (1) as per the guidelines of ASTM C642 (2013).

\[
\text{Percentage of permeable voids (\%) } = \frac{(C-A)}{(C-D)} \tag{1}
\]

where, \(A\) is the oven-dry weight of specimen, \(C\) is the saturated weight of specimen after immersion and boiling and \(D\) is the immersed apparent weight of specimen.

3. Result and discussion

3.1 Fresh state characteristics

3.1.1 SP dosage

The required SP dosage for attaining the target slump flow in the range of 750±30 mm is given in Fig. 6. It can be viewed from Fig. 6 that the SP dosage initially decreased, compared to the fly ash based binary blend control SCC mixture (mix no. A1), from 0.82 kg/m³ to 0.74 kg/m³ on increasing of replacement level of GWA from 0% to 25%, thereafter it increased. Moreover, SP dosage for mix no. A4 (i.e., 30% replacement level of GWA) was also lesser than the mix no. A1.

The lower SP dosage for up to 30% replacement level of GWA was due to the presence of free water, which developed the water coats on solid grains and ultimately supported the flowability of SCC mixture. The same phenomena was reported by Li and Kwan (2013), who studied the influence of water and paste film thickness on the rheology of the concrete matrix. It may also be noted that powder content increased on the increment of replacement of NFA with GWA as GWA had the lower size and low specific gravity compared to the NFA. This increased powder content dominated the flowability of the fly ash based binary blend SCC mixture incorporating GWA (up to 30% replacement level only). Beyond 30% replacement level of GWA, the rough and angular morphology of GWA (Fig. 3(b)) dominated the flowability of fly ash based binary blend SCC mixture and ultimately enhanced the requirement of SP dosage.

The SP dosages were less in all the flyash based binary blend SCC mixtures prepared with and without GWA (mix no. A1 to A8) as compared to the OPC based control SCC mixture (mix no. A0). This lower SP dosage for mix no. A1 to A8 has hinted that binary blend SCC mixture, even incorporating the higher content of GWA, can be produced at very low cost compared to that of conventional SCC. The dosage of SP significantly reduced from 2.61 kg/m³ to 0.82 kg/m³ on the replacement of 30% cement binder with fly ash binder. The reduction of SP dosages on the inclusion of fly ash can be well explained by the round and smooth morphology of fly ash particles (Fig. 1). This round and smooth morphology of fly ash particles reduced the inter-particle friction by the ball bearing action, which resulted in lowered SP dosages for binary blend SCC mixture.

3.1.2 Workability properties

All workability properties of SCC mixtures are given in Table 5. As stated earlier, the values of slump flow diameter (shown in Fig. 7) for all the SCC mixtures were maintained constant within the range of 750±30 mm. Mix no. A1-A8
were found in the slump flow class SF3 according to the European guidelines for SCC classification (EFNARC 2005) as given in Table 4 herein, while only mix no. A0 was found in slump flow class SF2. All the SCC mixtures, based on slump class, can be used for structures made with congested reinforcement and complex shapes (EFNARC 2005). However, it is normally difficult to achieve satisfactory segregation resistance for slump flow class SF3 mixtures (EFNARC 2005). Besides, the results of J-ring slump flow diameter (shown in Table 5 and Fig. 7) were found lesser than the slump flow diameter for all the SCC mixtures except mix no. A1, which indicated the reduction in filling and passing ability. The highest difference of 25 mm was observed between slump flow and J-ring slump flow diameter shown in Fig. 7 for binary blend SCC mixture incorporating 60% GWA and paste interface at a 60% substitution level of GWA. However, all the SCC mixtures were found in the category of no visible blocking (the difference between slump flow and J-ring slump flow diameter ≤25 mm) according to ASTM C1621 (2017).

### 3.1.2.1 T<sub>500</sub> and V-funnel time

The results of T<sub>500</sub>, T<sub>500J</sub>, V-funnel time (at T<sub>10sec</sub> and T<sub>Min</sub>) are given in Table 5 and Fig. 8. T<sub>500</sub> and V-funnel time (T<sub>10sec</sub>) indicate the flowability as well as the viscosity of SCC mixtures. It can be viewed from Table 5 and Fig. 8 that T<sub>500</sub> and V-funnel time (T<sub>10sec</sub>) initially slightly decreased, compared to the fly ash based binary blend control SCC mixture (mix no. A1), on the replacement of 20% and 25% NFA with GWA. Both the parameters then increased on the replacement of NFA beyond 25% with GWA. However, both the parameters were found lower for replacement of up to 30% of NFA with GWA (i.e., for mix no. A2-A4).

The lower T<sub>500</sub> and V-funnel time (T<sub>10sec</sub>) for mix no. A2-A4 (i.e., up to 30% replacement level of GWA) as compared to the mix no. A1 might be due to the effective lubrication between particles. It may also be noted that the incorporation of finer material (i.e., GWA up to 30%) in SCC might have improved the particle arrangement of powder skeleton and ultimately provided better lubrication between particles. Laskar and Talukdar (2008) also noticed the same behaviour for rice husk modified concrete mixtures. However, the greater T<sub>500</sub> and V-funnel time (T<sub>10sec</sub>) for mix no. A5-A8 may be because of the commencement of the domination of angular and rough morphology of GWA at higher replacement levels (especially for 50% and 60% GWA), which ultimately increased the inter-particle friction between particles.

On the other side, as compared to OPC based control SCC mixture (mix no. A0), fly ash based binary blend SCC mixtures (mix no. A1 to A7) prepared with the replacement of up to 50% of NFA with GWA exhibited lesser T<sub>500</sub> and V-funnel time (T<sub>10sec</sub>). This lower time was due to the smooth and spherical morphology of fly ash particles (Fig. 1) which mitigated the adverse effect of GWA on workability to some extent.

T<sub>500</sub> time for mix no. A1-A6 was less than 2 sec which falls in the viscosity class VS1 according to EFNARC standard (EFNARC 2005), whereas the same parameter for mix no. A0, A7 and A8 was higher than 2 sec which falls in the viscosity class VS2. Similarly, V-funnel time (T<sub>10sec</sub>) for mix no. A1-A6 were less than 8 sec which falls in the viscosity class VF1 according to EFNARC standard (EFNARC 2005), whereas V-funnel time (T<sub>10sec</sub>) for mix no. A0, A7 and A8 was higher than 8 sec which falls in the viscosity class VF2. Again, similar to SF3 slump flow class, VS1/VF1 viscosity class SCC mixtures exhibit the good filling ability and can be utilized for the structures having dense reinforcement, but SCC mixtures of these viscosity class generally exhibit the segregation and bleeding (EFNARC 2005).

Furthermore, the results of T<sub>500</sub> time were in line with the observations of T<sub>500J</sub> time. T<sub>500J</sub> time for all the SCC

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**Table 5** Fresh properties of self-compacting concrete mixtures

<table>
<thead>
<tr>
<th>Mix no.</th>
<th>Slump flow (T&lt;sub&gt;500&lt;/sub&gt;)</th>
<th>V-funnel (T&lt;sub&gt;500J&lt;/sub&gt;)</th>
<th>J-ring</th>
<th>L-box (H&lt;sub&gt;L&lt;/sub&gt;/H&lt;sub&gt;F&lt;/sub&gt;)</th>
<th>U-box (H&lt;sub&gt;U&lt;/sub&gt;/H&lt;sub&gt;F&lt;/sub&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A0</td>
<td>745</td>
<td>2.25</td>
<td>750</td>
<td>1.50</td>
<td>0.84</td>
</tr>
<tr>
<td>A1</td>
<td>770</td>
<td>1.54</td>
<td>770</td>
<td>1.57</td>
<td>0.88</td>
</tr>
<tr>
<td>A2</td>
<td>765</td>
<td>1.51</td>
<td>760</td>
<td>1.57</td>
<td>0.98</td>
</tr>
<tr>
<td>A3</td>
<td>765</td>
<td>1.46</td>
<td>757</td>
<td>1.54</td>
<td>0.98</td>
</tr>
<tr>
<td>A4</td>
<td>770</td>
<td>1.50</td>
<td>765</td>
<td>1.55</td>
<td>0.97</td>
</tr>
<tr>
<td>A5</td>
<td>755</td>
<td>1.65</td>
<td>745</td>
<td>1.84</td>
<td>0.97</td>
</tr>
<tr>
<td>A6</td>
<td>750</td>
<td>1.87</td>
<td>740</td>
<td>2.08</td>
<td>0.95</td>
</tr>
<tr>
<td>A7</td>
<td>755</td>
<td>2.15</td>
<td>740</td>
<td>2.48</td>
<td>0.91</td>
</tr>
<tr>
<td>A8</td>
<td>750</td>
<td>3.13</td>
<td>725</td>
<td>3.67</td>
<td>0.84</td>
</tr>
</tbody>
</table>

---

**Fig. 7** Effect of GWA on Slump flow and J-ring slump flow diameter of fly ash based binary blend SCC mixtures

**Fig. 8** Effect of GWA on T<sub>500</sub>, T<sub>500J</sub> and V-funnel time of fly ash based binary blend SCC mixtures.
mixtures was higher than $T_{500}$ time, which indicated the reduction in passing ability. However, the insignificant difference between $T_{500}$ and $T_{900}$ time was observed for all the developed SCC mixtures (except mix no. A8 containing 60% GWA). It can also be viewed from Fig. 8 that the results of V-funnel time ($T_{\text{min}}$) for mix no. A0-A8 were lower than the limitation (initial V-funnel time ($T_{\text{V-funnel}}$)+3 sec) established by EFNARC (EFNARC 2002). Hence, it was deduced that mix no. A0-A8 had enough resistance to segregation.

### 3.1.2.2 J-ring, U-box and L-box

The results of J-ring step height, U-box filling height, L-box height ratio are given in Table 5 and Fig. 9. J-ring step height and U-box filling height for fly ash based binary blend SCC mixtures (i.e., mix no. A2-A4) prepared with the replacement of up to 30% of NFA with GWA were nearly similar to fly ash based binary blend control SCC mixture (mix no. A1). J-ring step height and U-box filling height increased with the increment of GWA replacement beyond 30% for mix no. A5-A8 as compared to mix no. A1, which indicated the reduction in passing ability. Likewise, L-box height ratio ($H_2/H_1$) for replacement of up to 30% of NFA with GWA (i.e., for mix no. A2-A4) were similar to mix no. A1 and then decreased with the increment in replacement level of GWA beyond 30%. The reduction in passing ability beyond 30% replacement level of GWA may be due to the increase in inter-particle friction, which was related to the angular and rough texture of GWA.

Moreover, as compared to OPC based control SCC mixture (mix no. A0), the fly ash based SCC mixtures prepared with and without GWA (mix no. A1-A7) showed lower J-ring step height and U-box filling height, and higher L-box height ratio except mix no. A8. Passing ability will be better, if J-ring step height and U-box filling height will be lower than 10 mm and 30 mm respectively, and L-box height ratio will be higher than 0.80. Even though the reduction in passing ability beyond 30% replacement level of GWA was seen in the present study, the J-ring step height, U-box filling height, and L-box height ratio for all the SCC mixture ranged between 3.00-9.25 mm, 7-23 mm, and 0.84-0.98 respectively, which met the minimum requirement laid down by EFNARC standards for SCC mixture.

### 3.1.3 Segregation resistance

The results of segregation resistance in terms of segregation ratio (%) are given in Fig. 10. Segregation ratio for all the SCC mixtures varied between 7.20-10.18%. The segregation ratio increased with the increase in replacement level of GWA up to 30% (i.e., for mix no. A2-A5), thereafter it decreased beyond the 35% replacement level of GWA (i.e., for mix no. A6-A8). However, mix no. A6-A8 (containing 40-60% GWA respectively) also exhibited higher segregation ratio than mix no. A1.

The higher segregation ratio for mix no. A2-A8 was due to the higher water absorption capacity of GWA. Similar variations had been observed by Kou and Poon (2009), who utilized the recycled fine aggregate (up to 100%) as an alternative to NFA in the development of SCC. Furthermore, substantial viscosity (i.e., higher $T_{500}$ and V-funnel time) has been observed in the present study (section 3.1.2) for the higher replacement levels of GWA, which can be the possible reason behind the slight decrement in segregation ratio for mix no. A6-A8 (beyond 35% replacement level of GWA). Sun and Young (2014) also reported that the substantial viscosity of the SCC mixture inhibits higher segregation. It may also be noted that the higher amount of GWA (specifically beyond 35%) tended to improve the segregation resistance but at the demise of flowability and passing ability (as seen during workability test).

On the other side, as compared to OPC based control SCC mixture (mix no. A0), all the fly ash based SCC mixtures prepared with and without GWA showed a higher segregation ratio. A higher segregation ratio might be related to the smooth surface of fly ash particles. Mohamed and Najm (2017) also reported that the substitution of a higher amount of cement with fly ash resulted in substantial segregation. An increase in segregation ratio was also observed by Zhao et al. (2015) on the increment of cement substitution with fly ash in SCC. A higher segregation ratio was observed by Ling et al. (2012) also on the utilization of recycled glass in SCC due to the smooth surface of the recycled glass.

However, European guideline for SCC (EFNARC 2002) recommends that for considerable resistance to segregation of an SCC mixture, segregation ratio should be between 0-15%. It may be noted that the aforementioned criteria for
segregation ratio, in the present study, was fulfilled by all the SCC mixtures. Furthermore, as stated previously, mix no. A1-A8 (binary blend SCC mixture containing 0-60% GWA) fell in slump flow class SF3 for which resistance to segregation is more difficult according to European guidelines for SCC (EFNARC 2002). However, based on the segregation resistance test, it can be declared that mix no. A1-A8 can be effectively used for the structure having dense reinforcement without the significant problem of segregation.

### 3.1.4 Bleeding

The results of the bleeding test are shown in Fig. 11. Bleeding for all the SCC mixtures varied between 1.11-2.23%. The bleeding (%) increased with increase in replacement level of GWA up to 35% (for mix no. A2-A5), thereafter it decreased beyond the 35% replacement level of GWA (for mix no. A6-A8). However, mix no. A6-A8 (containing 40-60% GWA respectively) also exhibited higher bleeding than mix no. A1.

The higher bleeding for mix no. A2-A8 (containing 20-60% GWA respectively) may be due to the free water, which was added in the concrete mixture during mixing (as described in section 2.2) for compensating higher water absorption of GWA aggregate. Similar behaviour was observed by Siddique et al. (2019), who replaced ceramic aggregate with NFA in the production of concrete mixture. However, the slight decrement in bleeding was seen for mix no. A6-A8 (beyond 35% replacement of GWA), even though water correction was applied for those mixtures too, which may be due to the trapping of water at the irregular and uneven surface of GWA within the concrete matrix. It may also be noted that the increment in fine content, due to the higher surface area of GWA, raised the viscosity of SCC mixture significantly beyond a certain level of GWA content (Jalal et al. 2015). This increment in viscosity resulted in a cohesive SCC mixture (for mix no. A6-A8) and ultimately resisted significant bleeding. An enhancement in viscosity (higher T_{50} and V-funnel time), observed in the present study (section 3.1.2) for higher replacement level of GWA, may also capture water in the concrete matrix instead of releasing free mixing water (Topçu and Elgun 2004). The lower bleeding for mix no. A6-A8 hints that the morphology of GWA particles (irregular and uneven surface, and higher specific surface area), in the present study, has been dominating the bleeding capacity of SCC mixture at higher replacement level of GWA (especially for 50% and 60% level).

On the other side, as compared to OPC based control SCC mixture (mix no. A0), the fly ash based SCC mixtures prepared with and without GWA (mix no. A1-A8) showed minor bleeding. This lesser bleeding in all fly ash based SCC mixtures may be due to the lower size of fly ash particles as compared to the cement particles (Olorunsogo 1998). The results of the bleeding test in the present study are in line with (Kim et al. 2014, Jalal et al. 2015), who utilized the fly ash for the production of SCC. However, some researchers (Lachemi et al. 2003, Sun and Young 2014) indicated that the utilization of fly ash in SCC as a replacement of cement increases bleeding due to the reduction in inter-particle friction, which is related to the smooth and spherical morphology of fly ash particles. Even though fly ash particles also have smooth and spherical morphology in the present study, but the lower size of fly ash particles may dominate the bleeding capacity. Moreover, the bleeding (%) for all SCC mixtures in the present study was within the limitation (0.1% to 2.5%) as suggested by Kosmatka et al. (2011). Hence, it can be deduced that the inclusion of GWA together with fly ash could restrain the significant bleeding and preserve the bleeding (%) within limitation also.

### 3.1.5 Loss of slump flow

The results of the slump flow diameter with time are shown in Fig. 12. At each time period, the percentage reduction of slump flow compared to initial slump flow for each SCC mixture is also given in Fig. 13. As expected, slump flow diameter decreased over time for all the SCC mixtures, which was mainly due to the occurrence of physical and chemical activities (like hydration of cement and evaporation of water) within the concrete matrix. The above mentioned physical and chemical activities were responsible for the reduction of flowability of the resulting concrete mixture by lowering the free water from the freshly mixed concrete. Comparison to fly ash based binary blend control SCC mixture (mix no. A1), the higher loss of slump flow with time was observed for fly ash based binary blend SCC mixture containing GWA (mix no. A2-A8). For example, mix no. A2 showed 0.00, 3.92, 11.76, 30.07 and 47.06% loss of slump flow, whereas mix no. A1 showed 0.00, 3.90, 10.39, 29.87 and 44.81% loss of slump flow at 10, 20, 30, 45 and 60 minutes respectively. This higher loss of slump flow for mix no. A2-A8 (containing GWA) might be attributed to the higher water absorption capacity of GWA. The loss of slump flow with time was also observed by Kou and Poon (2009), who utilized the fine recycled aggregate in SCC. The loss in workability generally depends on the moisture state of aggregate condition i.e. air dried aggregate, oven dried aggregate, and saturated surface dried aggregate (Poon et al. 2004). It was also reported by (Poon et al. 2004) that oven dried aggregate exhibited a substantial loss in slump with time followed by air dried and saturated surface dried aggregates. Likewise, in this study, the quicker loss of slump flow with time was observed because air dried aggregates were used in this study which reduced the availability of free water. Furthermore, at 20 minutes and even at the evolution of

![Fig. 11 Effect of GWA on bleeding of fly ash based binary blend SCC mixtures](image-url)
time periods, the loss of slump flow was more prominent for 50% and 60% replacement level of GWA due to the enhanced viscosity of SCC mixtures. However, at 20 minutes, the loss of slump flow for mix no. A1-A6 (containing 20-40% GWA respectively) was insignificant compared to the initial slump flow. This may be because of the low absorption of free water by aggregates at the initial time (i.e., up to 20 minutes). The results of this study, for loss of slump flow, are in agreement with the observation of Carro-Lopez et al. (2015), who replaced the NFA (0-100%) with the recycled fine aggregate in the production of SCC.

On the other side, as compared to OPC based control SCC mixture (mix no. A0), the lesser loss of slump flow (shown in Fig. 13) with time was obtained for fly ash based binary blend SCC mixture (prepared with and without GWA except mix no. A8), which indicated the higher residual slump for fly ash based binary blend SCC mixture. This might be due to the slower hydration reactivity of fly ash as compared to cement in the given unit time which slowly used up the free mixing water from the concrete mixture (Erdogdu et al. 2011, Mehdipour et al. 2013). The spherical shape of fly ash particles might also be causing higher residual slump for fly ash based binary blend SCC mixture. Contrary to this, higher loss of slump flow with time was noticed by Erdogdu et al. (2011) and Ardalan et al. (2017) for fly ash based self-compacting mortar and SCC mixtures, respectively, as compared to control mixture. Erdogdu et al. (2011) reported that the lean paste content in fly ash based mixture was the reason behind the lower residual slump. However, based on the present study, it can be declared that fly ash based binary blend SCC mixtures incorporating up to 50% of fly ash particles may primarily be due to the lower specific gravity of fly ash as compared to OPC based control SCC mixture (mix no. A1), binary blend SCC mixtures prepared with GWA (mix no. A2-A8) exhibited lower fresh density. The lower fresh density may primarily be because of the lower specific gravity of GWA (2.57) as compared to the NFA (2.64). Furthermore, comparatively higher reduction in the fresh density was obtained for mix no. A7 and A8 (containing 50% and 60% GWA), respectively, as compared to the mix no. A1. This lower fresh density might be due to the trapping of water within the concrete matrix (as lower bleeding was seen in the present study), which formed the water bubbles or pockets. An enhanced viscosity, which trapped the water within the concrete matrix and not allowed to escape it from the surface, can also be the reason behind the higher reduction of fresh density for mix no. A7 and A8 (Felekoğlu, Türkel et al. 2007). The findings of this study for fresh density are in agreement with the observation of Carro-Lopez et al. (2015), who found the reduction in wet density of SCC mixtures on replacing NFA with recycled fine aggregate.

On the other side, as compared to the OPC based control SCC mixture (mix no. A0), all the fly ash based SCC mixtures prepared with and without GWA exhibited lower fresh density. This lower fresh density again may be primarily because of the lower specific gravity of fly ash (2.28) as compared to the cement (3.16). Lower wet density of fly ash based SCC mixtures was also observed by Zhao et al. (2015).

GWA exhibited higher residual slump (or higher workability retention capacity) than OPC based control SCC mixture. It can also be indicated that all the SCC mixtures (mix no. A0-A8) entirely lost their workability characteristics after 30 minutes. Hence, concrete mixtures could be categorized as vibrated concrete beyond 30 minutes. However, the reduction in loss of slump flow (or workability retention capacity) could be improved by using modified SP (Felekoğlu and Sarıkahya 2008). The workability retention capacity of the concrete mixture could also be improved by using saturated surface dry aggregate (Poon et al. 2004).
3.1.7 Summary of fresh properties

It can be seen from the results of fresh properties that all the developed SCC mixtures exhibited the adequate filling and passing ability along with sufficient segregation resistance and bleeding capacity and complied with EFNARC standards (EFNARC 2005). Furthermore, the incorporation of GWA up to 30% increased the filling and passing ability which might be due to the better lubrication between particles. Earlier, Hameed et al. (2012) also noticed that the utilization of crusher dust fine and marble powder as an NFA replacement in SCC improves the filling and passing ability. They reported that the increase in fine content increases the paste volume which supports the better lubrication of particles and ultimately causes improved filling and passing ability. However, the filling and passing ability of SCC mixtures (in the present study) decreased with the increment of GWA replacement beyond 30%. This may be because of the domination of angular and rough morphology of GWA at higher replacement levels (especially for 50% and 60% GWA). Moreover, once close packing was attained, any small increment in GWA concentration beyond the optimum level (i.e., GWA>30% in the present case) enhanced the viscosity of SCC mixtures by agglomerating the particles. The same phenomena was observed by Topcu et al. (2009), who studied the influence of marble waste on properties of SCC. The improvement in flowability was also observed by Sadek et al. (2016) on the inclusion of granite waste in SCC as a mineral additive. The adequate passing ability on the inclusion of granite waste in SCC as a cement replacement was also observed by Karmegam et al. (2014). Sua-iam and Makul (2013) also reported that the incorporation of up to 20% of limestone powder in SCC as an NFA replacement provides satisfactory fresh properties. They also reported that the incorporation of limestone fines improves the particle arrangement and increases lubricating paste volume which causes the better filling and passing ability of SCC.

Furthermore, the incorporation of GWA (especially for GWA>35%) reduced the segregation and bleeding to some extent, even after water correction was applied. It may be noted that the increment in fine content, due to the higher surface area of GWA, binds the excess water content and raises the viscosity of SCC mixture significantly beyond a certain level of GWA content (Jalal et al. 2015). This increment in viscosity resulted in a cohesive SCC mixture (for GWA>35%) and ultimately reduced segregation and bleeding but at the demise of filling and passing ability. Rai et al. (2016) also did not observe any segregation and bleeding on the incorporation of up to 30% of quarry waste in SCC as an NFA replacement. It can also be noted that incorporation of GWA increased the loss of slump flow which might be due the higher water absorption capacity of GWA. Earlier, Kou and Poon (2009) also observed the similar results for SCC containing fine recycled aggregate as a NFA replacement.

Moreover, the incorporation of fly ash increased the filling and passing ability and decreased the bleeding capacity and loss of slump flow. All the fly ash blended SCC, prepared with and without GWA (except 60% GWA content), exhibited better fresh properties than OPC based control SCC mixture. The incorporation of fly ash mitigated the adverse effect of GWA on fresh properties to some extent which might be due to the smooth and spherical morphology of fly ash particles (Fig. 1). Earlier, Tangchirapat et al. (2013) noticed the similar results for SCC made with fly ash and recycled aggregate.

3.2 Compressive strength and percentage of permeable voids

The results of 7 and 28 days compressive strength test for all SCC mixtures are presented in Fig. 15. The compressive strength for 7 and 28 days ranged from 20.97 MPa to 34.43 MPa and 32.63 MPa to 46.67 MPa respectively. An increment in compressive strength, as expected, was seen with the prolonging in curing period. As compared to OPC based control SCC mix (mix no. A0), all the fly ash based SCC mixtures prepared with and without GWA (mix no. A1-A8 except the mix no. A4) showed the
lower compressive strength for both curing periods. At 28 days curing period, only fly ash based SCC mixture incorporating 30% GWA (i.e., mix no. A4) showed higher compressive strength than mix no. A0, which could be due to the combined filler efficacy of GWA and fly ash. The results of the percentage of permeable voids (Fig. 16) also substantiate this claim as the lowest percentage of permeable voids was obtained for the same mix no. A4. Furthermore, the lower compressive strength for fly ash based SCC mixture was mainly due to the substantial replacement of cement with fly ash, which formed the lower hydration product (Jalal et al. 2015). However, loss in compressive strength reduced at the curing period of 28 days due to the slow hydration activity of fly ash, which indicated the effectiveness of fly ash at higher curing periods. For example, the 7 days compressive strength of mix no. A1 reduced by 23.91% compared to the mix no. A0, whereas the 28 days compressive strength of the similar mix reduced by 15.33%. The results are agreeing with Zhao et al. (2015) and Leung et al. (2016), who found improved compressive strength for SCC mixes prepared with fly ash at higher curing periods.

On the other hand, as compared to the fly ash based binary blend control SCC mixture (mix no. A1), an improvement in compressive strength was observed with the increase in replacement level of up to 30% of NFA by GWA and after that decrement was observed for the higher replacement. However, for 35% and 40% replacement level of GWA, the compressive strength was also higher compared to mix no. A1. The highest compressive strength was obtained for mix no. A4, whereas the lowest compressive strength was obtained for mix no. A8. The elevated strength up to 40% replacement level of GWA might be related to rough and irregular morphology of GWA particles (Fig. 4(b)), which made a good interlocking with cement paste. The filler efficacy of GWA also reduced the interconnected voids within the concrete matrix leading the development of enhanced strength. The higher strength of binary blend SCC mixes containing GWA might be due to the improved packing density resulting from the finer content of GWA (Sadek et al. 2016). However, it may also be noted that once sufficient packing was achieved (up to 30% GWA in the present case), any more increment in replacement level increased the voids within the concrete matrix instead of filling inter-particle space (Kwan and McKinley 2014). This increment in voids resulted in lesser compressive strength at higher GWA content. The percentage of permeable voids shown in Fig. 16 also substantiates this claim. Fig. 17 also indicates the inversely proportional relation between compressive strength and percentage of permeable voids where the increment in compressive strength value shows the decrease in the percentage voids. Similar pattern between void ratio and compressive strength for granite modified SCC was also obtained by Elyamany et al. (2014) on utilizing granite waste in the production of SCC as a mineral additive. It may also be noted that the deficit of binder content (related to the higher surface area of aggregate phase), at a higher replacement level of GWA, can also be a reason for reduction of strength. Furthermore, the entrapment of water within the concrete matrix for the higher replacement of GWA has been observed in the present study during the bleeding test, which formed voids on the hardening of concrete. Formation of many voids could be the reason for the significant reduction in compressive strength at 50 and 60% replacement level of GWA (for mix no. A7 and A8).

The similar trend for compressive strength was observed by earlier researchers (Vijayalakshmi et al. 2013, Ghannam et al. 2016, Singh et al. 2016, Singh et al. 2017) on the replacement of NFA by GWA in NVC. Likewise, other authors (Binici et al. 2008, Elmoaty 2013, Mashaly et al. 2018, Ghorbani et al. 2019) also found higher compressive strength on the inclusion of granite waste in NVC as a replacement of cement. Karmegam et al. (2014) and Sadek et al. (2016) also reported that granite powder improved the compressive strength of conventional SCC. Both Vijayalakshmi et al. (2013) and Ghannam et al. (2016) found the highest compressive strength at 10% substitution level of NFA with GWA in NVC. Singh et al. (2016) and Singh et al. (2017) found the highest compressive strength at 25% substitution level of NFA with GWA in NVC. Whereas, the highest compressive strength (in the present case) was seen at 30% substitution of NFA with GWA.

4. Conclusions

The present study was conducted to evaluate the effect of granite waste aggregate (GWA) as a partial replacement of natural fine aggregate (NFA) on fly ash based binary blend self-compacting concrete (SCC). Based on the results and discussion, this investigation allows us to interpret the following conclusion:

√ Incorporation of up to 30% GWA led to a decline in the required superplasticizer (SP) dosages for fly ash based binary blend SCC. Moreover, all the fly ash based binary blend SCC mixtures, prepared with and without GWA, exhibited lower requirement of SP dosages when compared to the Ordinary Portland cement (OPC) based control SCC mixture.

√ All the SCC mixtures exhibited enough filling ability and passing ability and satisfied the criteria laid down by EFNARC standards.

√ Segregation resistance of all the fly based binary blend SCC mixtures, prepared with and without GWA, was found higher as compared to the OPC based control SCC mixture. However, segregation resistance of all the SCC mixtures met the criteria laid down by EFNARC standards.

√ All the fly ash based binary blend SCC mixtures containing GWA exhibited higher bleeding when compared to the fly ash based control SCC mixture (prepared without GWA). However, bleeding of all the fly based binary blend SCC mixtures, prepared with and without GWA, was obtained lower as compared to the OPC based control SCC mixture and also within the satisfactory limit (0.1–2.5%) given by other researchers.

√ All the SCC mixtures showed significant loss of slump flow with time, especially beyond 20 minutes. However, fly ash based binary blend SCC mixtures incorporating
up to 50% GWA exhibited higher residual slump (or higher workability retention capacity) than OPC based control SCC mixture. Moreover, the workability retention capacity of SCC mixture could be improved by using suitable modified superplasticizer.

- The fresh density of all the fly based binary blend SCC mixtures, prepared with and without GWA, was obtained lower as compared to the OPC based control SCC mixture.
- Incorporation of up to 40% GWA led to the enhanced compressive strength of fly ash based binary blend SCC mixture.
- The deployment of two industrial wastes (i.e., fly ash and GWA) in the production of SCC would extensively promote sustainability in the construction industry together with enhanced characteristics.

Durability and microstructure characteristics can be considered for future work to evaluate the effect of GWA on the internal microstructure of developed SCC mixture.

Acknowledgments

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