Mix Design Processing for Self Compacting Geopolymer Mortar

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Abstract

The mortar flow and flow speed of self-compacting geopolymer mortar (SCGM) were determined by considering the various influencing parameters for the normal self-compacting mortar (SCM) and geopolymer mortar (GM). The test results showed that the effect of volume of water to volume of powder on the relative flow area (Gm) and relative flow speed (Rm) was different compared to normal SCM due to the high viscosity of matrix. The flow properties of SCGM were analyzed in terms of volume of water to volume of powder ratio, and superplasticizer to powder ratio, powder to sand ratio, viscosity of alkaline liquid and the water to geopolymer solid ratio. According to the analysis, flow prediction models for SCGM were formulated based on the parameters of both physical and chemical point of view. Moreover, a mix design of SCGM including a flow chart and mathematical expression was also proposed. This indicates that the typical volume ratio of SCGM was similar to SCM considering the volume of alkaline liquid with water in SCGM was equivalent to the volume of water in SCM.

1. Introduction

Self-compacting concrete (SCC) is a concrete that can be compacted under its own weight without any external vibration. The concept of self-compacting concrete (SCC) was first proposed by Okamura in 1986 to control the quality of concrete which should be independent of the quality of construction work. Then, the prototype was first developed by Ozawa and Maekawa at the University of Tokyo (Okamura et al. 1993; Okamura and Ozawa 1996; Maekawa and Ozawa 1999; Okamura and Ouchi 2003). It was recognized as a high performance concrete due to its high durability, passing ability, and flowability (Okamura and Ouchi 2003), further, homogeneity, resistance to segregation were also highly recognized later (Benabed et al. 2012). In general, to examine the mechanism of self-compacting concrete (SCC) a deep understanding of the rheological properties of self-compacting mortar (SCM) is mandatory (Mayhoub et al. 2021). The relative flow area and relative flow speed are the initial parameters to investigate the flow properties of SCC (Okamura and Ouchi 2003). It was investigated that the volume of water to volume of powder ratio (Vw/Vp) and superplasticizer to powder ratio (Sp/P) are two important parameters that govern the relative flow speed and relative flow area of SCC together with the sand to powder ratio.

The first attempt to develop an environment friendly concrete named geopolymer concrete (GPC) was made by Davidovits in 1979 (Davidovits 2013). The amorphous to semi-crystalline three dimensional aluminium silicate based structures were named geopolymer (Davidovits 1994). The main constituents of GPC include a binder, coarse aggregate, fine aggregate, and alkaline activators (Hardjito and Rangan 2005). Most of the previous studies were carried out determine the short and long-term mechanical properties of normal GPC. One of the main challenges in the field viability of GPC is its lower workability due to the higher viscosity of alkaline activators (Nematollahi and Sanjayan 2014; Fang et al. 2018; Parveen et al. 2018) . Ghafoor et al. (2021) showed that without the addition of any superplasticizer, the workability of GPC could be reduced by up to 5 mm. Nguyen et al. (2020) mentioned that preparing an optimum mix design for GPC with consideration of workability and other mechanical properties is a big challenge. The influencing parameters which affect the fresh mechanical properties of GPC were determined as water to geopolymer solid ratio (W/GPS) and alkaline activator to binder ratio (Hardjito and Rangan 2005; Aliabdo et al. 2016; Elyamany et al. 2018). Tao and Pan (2019) concluded that the research efforts to make a flowable GPC are very scarce and the innovation of a superplasticizer for making cost effective GPC is also mandatory for practical application. In addition, self-compacting geopolymer concrete (SCGC) is a revolutionary concept in the construction industry to keep the people away from the compaction work on the material including highly concentrated alkaline liquid. Therefore, to propose a rational mix design of SCGC by controlling the mix proportions is a major challenge as no research is available so far regarding the influencing

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The main objective of this study is to investigate the flow properties of SCGM and provide a rational mix design by determining the influencing parameters. Moreover, effect of volume of water to volume of powder ratio (Vw/Vp), superplasticizer to powder ratio (Sp/P), powder to sand ratio (FA/S), viscosity of alkaline liquid and water to geopolymer solid ratio (W/GPS) was investigated. A flow chart and mathematical expression for rational mix design processing are also proposed in this study based on the experimental test results. Figure 1 summarizes the comparison of constituent materials and volume-based and weight-based expressions of SCM and SCGM.

### 2. Preparation of experimental study

#### 2.1 Materials

##### 2.1.1 Fly ash

The locally available fly ash (FA) from coal power plants in Japan was used. The chemical composition of FA is shown in Table 1. The FA was classified as class F based on the chemical composition of SiO₂, Al₂O₃, and CaO (ASTM 2014). The physical properties of FA are shown in Table 2.

##### 2.1.2 Sand

The locally available silica sand was used as a fine aggregate. Due to uniform rounded particle size configuration, it gives advantage in flowability as shown in Fig. 2. Moreover, the advantage of usage of silica sand is high purity of silica which is a backbone of geopolymerization reaction. The chemical composition of silica sand is shown in Table 3. The physical properties of silica sand are also presented in Table 4. The density of silica sand is generally less than natural sand.

### Table 1 Chemical composition results of raw fly ash using x ray fluorescence (XRF).

| Constituents | Al₂O₃ | SiO₂ | CaO | Fe₂O₃ | Na₂O | SO₃ | K₂O | TiO₂ | MgO | FeO |
|--------------|-------|------|-----|-------|------|-----|-----|------|-----|-----|
| %            | 31.07 | 57.24| 1.86| 3.27  | 0.76 | 0.27| 1.32| 0.97 | 2.04| 0.78|

### Table 2 Physical properties of raw fly ash.

| Description                  | Test value |
|-----------------------------|------------|
| Color                       | Grey       |
| Particle density             | 2.31 g/cm³ |
| Fineness (Surface area)      | 4610 cm²/g |
| Loss of Ignition             | Less than 1.5 |

#### Fig. 1 Comparison of SCM and SCGM in this study.

#### Fig. 2 Particle size distribution curve of silica sand.
2.1.3 Alkaline activators
The NaOH and Na$_2$SiO$_3$ solution were used as an alkaline activator. The NaOH and Na$_2$SiO$_3$ alkaline activators were obtained from commercially available manufacturers. The NaOH content was used in the pellet form for the preparation of different molarity solutions based on the variation of solid content (Hardjito and Rangan 2005). The chemical composition of the Na$_2$SiO$_3$ solution is shown in Table 5. The viscosity of the Na$_2$SiO$_3$ solution was 0.13 pascal second at 20°C, measured by biaxial cylindrical rotational viscometer.

2.1.4 Superplasticizer
A locally available polyaryl ether (PAE) based superplasticizer was used. The main components and physical properties of the superplasticizer are shown in Table 6.

2.2 Mix proportions
The constituents for the preparation of SCGM include fly ash, silica sand, NaOH solution, Na$_2$SiO$_3$ solution, water, and superplasticizer. Initial trials were carried out to select the optimum range of extra water and superplasticizer. The additional extra water within the range of 5%-15% and a superplasticizer of 2%-6% by weight of fly ash were selected. The NaOH concentrations of 8 M, 12 M, and 16 M and Na$_2$SiO$_3$/ NaOH ratios of 1.5 and 2.5 were chosen based on a literature review of normal GPC. The alkaline activator to fly ash ratio (AA/FA) was kept constant at 0.6 based on some initial trial results. In most of the SCGM mixes, the fly ash to sand ratio was kept constant as 1 ratio 2. However, to investigate the effect of variation of fly ash to sand ratio on fresh mechanical properties of SCGM; the ratio was varied to 1 ratio 1.7 and 1 ratio 1.5 in comparison to 1 ratio 2.

Total nineteen (19) SCGM mixes were prepared from F1-0.5-16-2.5-I-285 to F19-0.5-16-1.5-I-285 to investigate the effect of influencing parameters on the fresh mechanical properties of SCGM. The speed of the mortar mixer was varied from low to high speed in a range of 160 rpm (slow speed) to 300 rpm (handheld high speed) to investigate its effect on the rheological properties of SCGM. The mix details of 19 SCGM mixes for 1 m$^3$ volume are presented in Table 7. The mixes were designated based on fly ash to sand ratio, NaOH molarity, sodium silicate to sodium hydroxide ratio, mixing order and mixing speed (Table 7). For example, mix F1-0.5-16-2.5-I-285 represents SCGM mix prepared with fly ash to sand ratio 0.5, NaOH molarity 16 M, sodium silicate to sodium hydroxide ratio 2.5, mixing order I and at mixing speed of 285 rpm. The mixing order type I, II and III will be explained in detail later in section 3.7.

2.3 Mixing, casting, and testing of specimens
The alkaline activator solutions comprised of NaOH and Na$_2$SiO$_3$ were prepared one day before casting to normalize the temperature and reactivity of NaOH particles. The mixing time was kept constant at 5 minutes for each SCGM mix. The fly ash and silica sand were dry mixed for one minute at normal speed. The dry mixing was followed by mixing with an alkaline solution at high speed for one minute. Then additional water was added, and mixing continued for one more minute. Lastly, a superplasticizer was added, and the mixing was continuing for another two minutes. The volume for one batch mixing is 1.18 liters (0.00118 m$^3$). This volume was calculated based on the volume of mini-V funnel and volume of 6 mini cylinder of diameter of 50 mm with height of 100 mm.

The fresh SCGM flow area was measured using the mini slump cone apparatus as per the European Federation of National Associations Representing for Concrete (EFNARC) guidelines (BIBM et al. 2005). To measure the flow speed of the SCGM mix, a mini-V funnel apparatus was used as per EFNARC guidelines as shown in Fig. 3. The various stages in the development of SCGM are shown in Fig. 4.
3. Fresh mechanical properties of SCGM

3.1 Comparison of flow and speed of SCGM with normal SCM

The measured mortar flow and flow time of SCGM mixes are presented in Table 8. According to previous research (Okamura and Ouchi 2003), the relative flow area (Gm) and relative flow speed (Rm) for normal self compacting mortar can be calculated as below.

$$G_m = \frac{d_1 \cdot d_2 - d_0^2}{d_0^2}$$  \hspace{1cm} (1)

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Table 7 Mix details of self-compacting geopolymer mortar (SCGM) mixes for 1 m³.

| Mix ID     | Fly ash (kg/m³) | Sand (kg/m³) | NaOH (kg/m³) | NaOH (kg/m³) | Na₂SiO₃ (kg/m³) | Extra Water (kg/m³) | Super plasticizer (kg/m³) | Mixing order | Mixer speed | rpm |
|------------|-----------------|--------------|--------------|--------------|-----------------|-------------------|------------------------|--------------|-------------|-----|
| F1-0.5-16-2.5-I-285 | 545           | 1089         | 16           | 93           | 233             | 82                | 22                     | I            | 285         |     |
| F2-0.5-8.0-2.5-I-285 | 545           | 1089         | 8            | 93           | 233             | 55                | 22                     | I            | 285         |     |
| F3-0.5-12-2.5-I-285 | 545           | 1089         | 12           | 93           | 233             | 55                | 22                     | I            | 285         |     |
| F4-0.5-8.0-1.5-I-285 | 545           | 1089         | 8            | 131          | 196             | 27                | 22                     | I            | 285         |     |
| F5-0.5-16-2.5-I-285 | 545           | 1089         | 16           | 93           | 233             | 55                | 22                     | I            | 285         |     |
| F6-0.5-16-2.5-I-300 | 545           | 1089         | 16           | 93           | 233             | 27                | 22                     | I            | 300*        |     |
| F7-0.5-16-2.5-I-160 | 545           | 1089         | 16           | 93           | 233             | 27                | 22                     | I            | 160         |     |
| F8-0.5-8.0-1.5-I-285 | 545           | 1089         | 8            | 131          | 196             | 82                | 44                     | I            | 285         |     |
| F9-0.5-8.0-1.5-I-285 | 545           | 1089         | 8            | 131          | 196             | 55                | 33                     | I            | 285         |     |
| F10-0.5-8.0-1.5-I-285 | 545          | 1089         | 8            | 131          | 196             | 27                | 22                     | I            | 285         |     |
| F11-0.5-16-2.5-I-285 | 545           | 1089         | 16           | 93           | 233             | 55                | 11                     | I            | 285         |     |
| F12-0.5-16-2.5-I-285 | 545           | 1089         | 16           | 93           | 233             | 55                | 22                     | I            | 285         |     |
| F13-0.5-8.0-2.5-I-285 | 545          | 1002         | 16           | 101          | 253             | 59                | 24                     | I            | 285         |     |
| F14-0.66-16-2.5-I-285 | 635           | 952          | 16           | 109          | 272             | 64                | 25                     | I            | 285         |     |
| F15-0.5-16-2.5-I-285 | 545           | 1089         | 16           | 93           | 233             | 27                | 22                     | I            | 285         |     |
| F16-0.5-16-2.5-I-285 | 545           | 1089         | 16           | 93           | 233             | 27                | 22                     | II           | 285         |     |
| F17-0.5-16-2.5-III-285 | 545         | 1089         | 16           | 93           | 233             | 27                | 22                     | III          | 285         |     |
| F18-0.5-12-1.5-I-285 | 545           | 1089         | 12           | 131          | 196             | 27                | 22                     | I            | 285         |     |
| F19-0.5-16-1.5-I-285 | 545           | 1089         | 16           | 131          | 196             | 27                | 22                     | I            | 285         |     |

* handheld mixer.

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Fig. 4 Different stages for preparation of SCGM mix: (a) SCGM paste with addition of alkaline activator, (b) SCGM paste after addition of water, (c) SCGM paste with superplasticizer, (d) Flow spread of SCGM.
where \( \text{d}_1, \text{d}_2 \) are measured flow diameter, \( \text{d}_0 \) is flow cone diameter, \( t \) is measured time (sec) for the mortar to flow through the funnel.

The relationship between relative flow area (\( G_m \)) and relative flow speed (\( R_m \)) for SCGM is presented in Fig. 5. The effect of variation of relative flow area (\( G_m \)) and relative flow speed (\( R_m \)) based on the variation of volume of water to volume of powder (Vw/Vp) ratio and superplasticizer to powder (Sp/P) ratio is exhibited in Figs. 6(a) and 6(b) respectively. The range of relative flow area (\( G_m \)) and relative flow speed (\( R_m \)) normal SCM is also highlighted in Fig. 5 (Nepomuceno and Oliveira 2008). Interestingly, the boundary of self-compacting geopolymer (SCGM) did not fall in the range of SCM as shown in Fig. 5. This difference was due to the lower speed of SCGM due to the higher viscosity of the alkaline liquid solution (Ghafoor et al. 2021). The recommended values for the \( G_m \) and \( R_m \) normal SCM were within the range of 5.0-6.5 and 1.00-1.65 respectively, as presented in Fig. 5 (Okamura and Ouchi 2003; Nepomuceno and Oliveira 2008).

The developer of SCC Okamura proposed that to achieve the best flowable condition for SCC, SCM relative flow area (\( G_m \)) and relative flow speed (\( R_m \)) should be 5 and 1, respectively. In general, in SCGM to achieve an \( R_m \) of 1, the minimum \( G_m \) value should be 7, which is about 40% higher in comparison to normal SCM (Okamura and Ouchi 2003). The SCGM relative flow

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R_m = \frac{10}{t}
\]

Table 8 Test results of self-compacting geopolymer mortar (SCGM) mixes.

| Mix ID | Flow | Flow Time | Vw/Vp | Sp/P | FA/S | W/GPS | Viscosity of AA | NaO2/SiO2 | H2O/NaO2 |
|--------|------|-----------|-------|------|------|-------|-----------------|------------|-----------|
| F1-0.5-16-2.5-I-285 | 320 | 5.5 | 1.13 | 4 | 0.50 | 0.388 | 0.16 | 0.169 | 14.25 |
| F2-0.5-8.0-2.5-I-285 | 315 | 6 | 1.08 | 4 | 0.50 | 0.383 | 0.07 | 0.136 | 16.86 |
| F3-0.5-12-2.5-I-285 | 283 | 10 | 1.04 | 4 | 0.50 | 0.365 | 0.11 | 0.154 | 14.47 |
| F4-0.5-8.0-1.5-I-285 | 305 | 7 | 0.99 | 4 | 0.50 | 0.355 | 0.07 | 0.147 | 14.89 |
| F5-0.5-16-2.5-I-285 | 275 | 13 | 1.01 | 4 | 0.50 | 0.349 | 0.16 | 0.169 | 12.84 |
| F6-0.5-16-2.5-I-300 | 225 | 36 | 0.89 | 4 | 0.50 | 0.308 | 0.16 | 0.169 | 11.44 |
| F7-0.5-16-2.5-I-160 | 210 | 60 | 0.89 | 4 | 0.50 | 0.308 | 0.16 | 0.169 | 11.44 |
| F8-0.5-8.0-1.5-I-285 | 345 | - | 1.23 | 8 | 0.50 | 0.437 | 0.07 | 0.147 | 18.23 |
| F9-0.5-8.0-1.5-I-285 | 325 | - | 1.11 | 6 | 0.50 | 0.396 | 0.07 | 0.147 | 16.56 |
| F10-0.5-8.0-1.5-I-285 | 305 | - | 0.99 | 4 | 0.50 | 0.355 | 0.07 | 0.147 | 14.89 |
| F11-0.5-16-2.5-I-285 | 270 | 17 | 1.01 | 2 | 0.50 | 0.349 | 0.16 | 0.169 | 12.84 |
| F12-0.5-16-2.5-I-285 | 280 | - | 1.01 | 4 | 0.50 | 0.349 | 0.16 | 0.169 | 12.84 |
| F13-0.5-16-2.5-I-285 | 310 | - | 1.01 | 4 | 0.59 | 0.349 | 0.16 | 0.154 | 14.48 |
| F14-0.66-16-2.5-I-285 | 318 | - | 1.01 | 4 | 0.67 | 0.349 | 0.16 | 0.145 | 15.54 |
| F15-0.5-16-2.5-I-285 | 270 | - | 0.89 | 4 | 0.50 | 0.308 | 0.16 | 0.169 | 11.44 |
| F16-0.5-16-2.5-II-285 | 250 | - | 0.89 | 4 | 0.50 | 0.308 | 0.16 | 0.169 | 11.44 |
| F17-0.5-16-2.5-III-285 | N/A | - | 0.89 | 4 | 0.50 | 0.308 | 0.16 | 0.169 | 11.44 |
| F18-0.5-12-1.5-I-285 | N/A | - | 0.89 | 4 | 0.50 | 0.329 | 0.11 | 0.195 | 10.36 |
| F19-0.5-16-1.5-I-285 | N/A | - | 0.94 | 4 | 0.50 | 0.308 | 0.16 | 0.173 | 12.13 |

Fig. 5 Relationship between relative flow area (\( G_m \)) and relative flow speed (\( R_m \)) of SCGM and comparison with normal SCM.
area ($G_m$) and relative flow speed ($R_m$) were within the range of 7-9 and 1-1.8 respectively, as highlighted in Fig. 5. It was observed that due to the higher viscosity of SCGM paste no segregation was observed except for mix F1-0.5-16-2.5-I-285 and F2-0.5-8.0-2.5-I-285, where due to high-water content some water was separated out.

The effect of the volume of water to volume powder ratio ($V_w/V_p$) on relative flow area ($G_m$) and relative flow speed ($R_m$) was investigated while keeping the superplasticizer to powder ratio ($S_p/P$) constant at 4% as shown in Fig. 6. The relationship between $G_m$ and $R_m$ for SCM can be expressed by equation (3) in accordance with $V_w/V_p$ under the constant $S_p/P$ (Ouchi et al. 1997).

$$R_m = A \cdot G_m^{0.4}$$

where, $A$ is a function of $V_w/V_p$ (in this study; $A=3.5(V_w/V_p)-2.25$). Further, it was noted that the ratio of $G_m$ to $R_m$ for SCM is almost constant with the variation of $V_w/V_p$ under the constant $S_p/P$ (Okamura and Ouchi 2003). In comparison to normal SCM, the trend was quite different for SCGM, with an increase in the $V_w/V_p$, the $G_m$ of SCGM was increased continuously, however, the increase in $R_m$ was not much significant, as shown in Fig. 6. Okamura and Ouchi (2003) concluded that for normal SCM the increase in $V_w/V_p$ significantly increases the relative flow speed ($R_m$), whereas the increase in $S_p/P$ increased the relative flow area ($G_m$) as shown in Figs. 6(a) and 6(b), respectively. Moreover, for SCGM, the increase in $G_m$ and $R_m$ with the increase in $V_w/V_p$ was not linear as shown in Fig. 6(b). This could be due to the higher viscosity of the alkaline solution, due to which the effect of water on increasing $G_m$ and $R_m$ was less significant compared to normal SCM.

The recommended range of SCM flowability and flow time was in between 250-300 mm and 2-10 seconds, respectively (Belaidi et al. 2016). For normal SCM, flow time was quite less, even at lower flowability in comparison to SCGM, as shown in Fig. 7. The difference in flow time was about 82% for the same flowability of 283 mm as shown in Fig. 7. The GPM with flowability greater than 250 mm is considered as highly flowable geopolymer mortar (Ishak et al. 2019). Overall, test
results concluded that the relative flow area \((G_m)\) and relative flow speed \((R_m)\) of SCGM were not proportional like normal SCM due to the higher viscosity of the alkaline solution.

3.2 Effect of water to powder volume ratio on flow properties

The effect of water to powder volume ratio \((V_{w}/V_p)\) on the flowability of SCGM was firstly examined. The volume of water \((V_w)\) contains both extra water and water in the alkaline liquid. The \(V_{w}/V_p\) versus flow shows almost linear relationship as shown in Fig. 8, despite of the concentration of alkaline liquid. For instance, the mix F1-0.5-16-2.5-I-285, F2-0.5-8.0-2.5-I-285 and F3-0.5-12-2.5-I-285 contained 16M, 8M and 12M of NaOH solution respectively, however, mix F1-0.5-16-2.5-I-285 had higher \(V_{w}/V_p\) and larger flow area due to much amount of extra water in comparison to mix F2-0.5-8.0-2.5-I-285 and F3-0.5-12-2.5-I-285. The mix F8-0.5-8.0-1.5-1-I-285, F9-0.5-8.0-1.5-I-285 and F10-0.5-8.0-1.5-I-285 contained same 8M NaOH solution. However, for mix F8-0.5-8.0-1.5-1-I-285, F9-0.5-8.0-1.5-I-285 and F10-0.5-8.0-1.5-I-285 had \(V_{w}/V_p\) of 1.23, 1.11 and 0.99 because of the difference of the amount of extra water. Then, the flow area follows the order of \(V_{w}/V_p\). Overall, results concluded that \(V_{w}/V_p\), which is significantly affected by the amount of extra water, is the one of the governing parameters as same as the case of normal SCM.

3.3 Effect of superplasticizer to powder ratio

The effect of superplasticizer to powder ratio \((S_{p}/P)\) was also examined as shown in Fig. 9. The flowability was almost proportionally increased from 270 mm to 345 mm about only 27% with an increase in the superplasticizer to powder ratio \((S_{p}/P)\) from 2% to 8%. In contrast, for normal SCM, a very small increase in superplasticizer percentage, resulted in a significant increase in flowability in the relatively lower viscous mortar as highlighted in Fig. 9.

Considering the effect of water on increasing the flow properties of SCGM as shown in Fig. 8, the superplasticizer was not so sensitive. This implies that the liquid viscosity had more significant effect on the flowability of SCGM rather than the dispersibility of powder.

3.4 Effect of powder to sand ratio

The effect of the powder (only fly ash in this study) to sand ratio \((FA/S)\) on the flow properties of SCGM was investigated as shown in Fig. 10. It was investigated that with an increase in fly ash to sand ratio, the flowability of SCGM was clearly increased. The increase of flowability of SCGM was from 280 mm to 318 mm, about 13% with...
an increase in the fly ash to sand ratio from 0.50 to 0.67. However, the effect of variation of fly ash to sand ratio on the flowability of SCGM was not as significant as normal SCM based on the variation of cement to sand ratio (Ban and Ramli 2010). This might be because of high flow properties of fly ash particles and uniform configuration of silica sand particles, which resulted in a limited effect.

### 3.5 Effect of viscosity of alkaline liquid on flow properties

Considering the difference of flow and flow speed between SCGM and normal SCM in 3.1, the effect of viscosity of alkaline liquid was further studied. According to our measurement, the viscosity of Na₂SiO₃ solution with 8 M NaOH solution was about 0.07 pascal second, with 12 M NaOH solution was about 0.11 pascal second and with 16 M NaOH solution was about 0.16 pascal second. These were obviously high comparing with the general viscosity of water; 0.001 pascal second at 20°C.

The effect of alkaline liquid viscosity on the flow is shown in Fig. 11 for the same fly ash to sand ratio but different extra water volume of 30 kg/m³, 60 kg/m³ and 90 kg/m³. It is clear that the decrease of alkaline liquid viscosity gives the increase of flow. In addition, the extra water works well especially for the mix proportion with denser alkaline solution.

### 3.6 Effect of water to geopolymer solid ratio on flow properties

The W/GPS versus flow is shown in Fig. 12. The geopolymer solid (GPS) is a summation of fly ash and the solids of NaOH, Na₂O, SiO₂ in the solution, even though...
the NaOH, Na$_2$O and SiO$_2$ perform as part of liquid at the time of mixing. Thus, the W/GPS is available to consider the effect of extra water together with the alkaline liquid viscosity among the mixes with same fly ash volume. The proportional relationship was found, as same as the normal GPC (Li et al. 2017). With an increase in the W/GPS ratio from 0.308 to 0.437, the flowability of SCGM was increased from 225 mm to 345 mm, about 53% in Fig. 12. This is because with increase in geopolymer solid ratio (fly ash, NaOH(solids), Na$_2$SiO$_3$) the alkaline activator concentration inside SCGM matrix increased which ultimately resulted in increase in the viscosity of system.

The effect of the water to binder ratio (w/b) on normal SCM flowability is similar to the water to geopolymer solid ratio (W/GPS) effect on SCGM as shown in Fig. 10 (Domone 2007; Leemann and Winnefeld 2007; Gupta et al. 2021).

However, with an increase in water to geopolymer solid ratio from 0.308 to 0.388, the flow time was decreased from 36 s to 5.5 s about 554% as shown in Fig. 13. The flow time of normal SCM was significantly low in comparison to SCGM even at lower water to binder ratio (w/b) as shown in Fig. 13.

It was also observed that Na$_2$O molar ratio was also important governing parameter which controls the reaction mechanism during geopolymerization. The mix of F18-0.5-12-1.5-I-285 and F19-0.5-16-1.5-I-285 having Na$_2$SiO$_3$/NaOH ratio of 1.5 immediately hardened, which had a Na$_2$O/SiO$_2$ molar ratio within the range of 0.173-0.195 and H$_2$O/Na$_2$O molar ratio within range of 10.362-12.125. This might be because with increase in excessive OH$^-$ concentration, chances of early precipitation and dissolution increased due to which setting time of geopolymer also decreased sharply (Ghafoor et al. 2021).

### 3.7 Effect of mixer order and mixing speed

The mixing order for these three mixes is mentioned in Table 9. In this study, a superplasticizer was added always at the last step to increase the rheological properties of the mortar (Dils et al. 2012). The effect of the mixing order on the flowability of SCGM is shown in Fig. 14. It was observed that mixing time and pattern clearly influenced on flow property of SCGM by different mechanisms with the higher viscosity of the alkaline liquid. The flow of order type I, II, II was 270 mm, 250 mm and 0 mm, respectively. The mix F17-0.5-16-2.5-III-285 immediately hardened due to the immediate reaction of fly ash with the alkaline activator,
ultimately resulting in early precipitation (Ghafoor et al. 2021). The physical appearance of SCGM paste after mixing with alkaline activators for mix F15-0.5-16-2.5-I-285, F16-0.5-16-2.5-II-285, and F17-0.5-16-2.5-III-285 is presented in Fig. 15.

The effect of mixer speed on the flowability of SCGM was determined as shown in Fig. 16. It was observed that with a change in the mixer speed, the rheological properties of SCGM were also changed. It was physically observed that with increase in mixer speed the flow spread became circular in comparison to low-speed mixer as shown in Fig. 16. The mixes F6-0.5-16-2.5-I-300, F7-0.5-16-2.5-I-160 and F15-0.5-16-2.5-I-285 were prepared using 300 rpm handheld mixer, a fixed mixer with 160 rpm low-speed mode, the same mixer with 285 rpm high speed mode, respectively. The mixing speed influences the flowability of SCGM in comparison to mixing order as shown in Fig. 16. The increase in mixing speed from 160 rpm (F7-0.5-16-2.5-I-160) to 285 rpm (F15-0.5-16-2.5-I-285) ultimately resulted in increase in the flowability from 210 mm to 270 mm about 29%. This is because at lower speed, the lumps of SCGM were not entirely broken due to higher viscosity of matrix, as shown in Figs. 17 (a) and 17(b). The normal SCC rheological properties were also changed with the increase in mixing speed and required a longer mixing time at high speed for uniform composition (Dils et al. 2012;
Joshi 2020). However, the highest mixing speed 300 rpm using hand mixer could not fully break lump as shown in Fig. 17 (a). This suggested that the flowability of SCGM obtained from the mixing with a handheld mixer depends on the worker’s expertise.

4. Discussion of the results

4.1 Regression model for mortar flow and flow time

4.1.1 Flowability prediction from physical point of view

The design regression models for SCGM were developed using multiple regression analysis. The first design model was based on the physical point of view at the mixing. The parameter is $V_w/V_p$, $Sp/P$ (%), FA/S and viscosity of alkaline liquid ($\nu_a$) at the mixing. The regression model was developed based on the test results of 13 SCGM mixes that were cast in the same condition as presented in Table 8. A regression model was developed to predict the flow of self-compacting geopolymer mortar ($F_{ph}$) is formulated as given in Eq. (4). The coefficient of determination ($R^2$) for Eq. (4) is 0.857.

\[
F_{ph} = 169 \left( \frac{V_w}{V_p} \right) + 1.72 (Sp/P) + 297 \left( \frac{FA}{S} \right) - 0.317 (\nu_a)
\] (4)

The viscosity of alkaline liquid was explicitly formulated as negative coefficient in Eq. (4). Then, Eq. (4) verified that the effect of superplasticizer is relatively small for SCGM. The comparison of actual and predicted SCGM flow results were shown in Fig. 18(a).

4.1.2 Flowability prediction from chemical point of view

The second design model was developed from the chemical point of view to find out the flow of SCGM as a function of water to geopolymer solid (W/GPS) ratio, Na$_2$O/SiO$_2$ molar ratio, and H$_2$O/Na$_2$O molar ratio. The analysis was conducted based on the results of 13 mixes as shown in 4.1.1. A regression model was developed to predict the flow of self-compacting geopolymer mortar ($F_{cm}$) is formulated as given in Eq. (5). The coefficient of determination ($R^2$) for Eq. (5) is 0.875.

\[
F_{cm} = -3.00(T) + 325
\] (5)

The comparison of actual and predicted SCGM flow results were shown in Fig. 18(b).

4.1.3 Flowability prediction from flow passing speed

Similarly, another model was developed to predict the flow of self-compacting geopolymer mortar ($F_{SCGM}$) as a function of flow time ($T$) is given in Eq. (6). This model was developed based on the test results of SCGM mixes (F1-0.5-16-2.5-I-285, F2-0.5-8.0-2.5-I-285, F3-0.5-12-2.5-I-285, F4-0.5-8.0-1.5-I-285, F5-0.5-16-2.5-I-285, F6-0.5-16-2.5-I-300) as tabulated in Table 8.

\[
F_{SCGM} = -3.00(T) + 325
\] (6)

The coefficient of determination ($R^2$) for Eq. (6) is 0.917. The maximum difference between actual and predicted flow was about 4.26% which was within ±15% as shown in Fig. 19. For Eq. (6) standard error and mean absolute error were about 11.33% and 8.17%, respectively.

4.2 Mix Design Processing

The mix design flow of self-compacting geopolymer mortar (SCGM) is shown in Fig. 20. This flow chart should be applied for the conditions, mixing speed more than 285 rpm and mixing time more than 300 seconds. First, mix design parameter set 1 relating to the weight ratio of AA/FA, P/S, and target air contents in the volume are set as 0.60, 0.50, and $V_{air}$ respectively. Second, mix design parameter set 2 relating weight ratio Sp/P, W/P and W/GPS are determined as k, l, m by the engineer based on the priority. Through the process, we can have 5 conditional expressions in addition to the condition 1m$^3$ of total volume. Third, the concentrations of alkali activators $r_X$, $r_{Y1}$, $r_{Y2}$ are determined to calculate the densities of each component of mix material.

\[
\text{Fig. 18 Relationship between actual and predicted flow of SCGM: (a) using Eq. (4), (b) using Eq. (5).}
\]
\[ V_p + V_s + V_a + V_{SP} + V_x + V_{air} = 1.0 \]  
(7)

\[ AA = \frac{0.6 \cdot SH + SS}{P} = 0.6 \quad \therefore -0.6P + SH + SS = 0 \]  
(8)

\[ \frac{P}{S} = 0.5 \quad \therefore P - 0.5S = 0 \]  
(9)

\[ \frac{Sp}{P} = k \quad \therefore -kP + Sp = 0 \]  
(10)

\[ \frac{W_c}{P} = l \quad \therefore -lP + W_c = 0 \]  
(11)

\[ W_{GPS} = m \left( \frac{W_{cm} + (1 - r_1)SH + (1 - (r_1 + r_2))(1 - m)SS}{P + r_5SH + (r_1 + r_2)SS} \right) = m \]

\[ \therefore -mP + W_{cm} + (1 - r_5 - mr_5)SH + \left( 1 - (r_1 + r_2) - m(r_1 + r_2) \right)SS = 0 \]  
(12)

Fig. 19 Relationship between actual and predicted flow of SCGM using Eq. (6).

Fig. 20 Flow chart for mix design processing of SCGM.

**Design of Self Compacting GP mortar mix**

Set Mix parameter set 1

Choose Priority

Workability

Set Mix parameter set 2

3rd Chemical compositions

Solve D-matrix (*)

Check the requirements
\( \frac{Na_2O}{SiO_2} \leq 0.16 \)
\( H_2O/Na_2O \geq 14 \)

Satisfy

Trial mixing
Check the flow

Satisfy

Flow ≥ 285mm
Flow Passing Time ≤ 10 s

For the conditions:
- Mixing speed ≥ 285rpm
- Mixing Time ≥ 300s
Fourth, the weight conditions expressed in the equation from (8) to (12) are transformed to the volumetric conditions using material densities, then, the volumetric mix proportion for 1m³ is determined by solving the design matrix (D-matrix) as below:

\[ [D][V] = [A] \]  
\[ [V] = [D]^{-1}[A] \]  
\[ \begin{bmatrix} V_x \\ V_y \\ V_w \\ V_a \\ V_r \\ V_f \end{bmatrix} = \begin{bmatrix} D_{11} & D_{12} & D_{13} & D_{14} & D_{15} & D_{16} \\ D_{21} & D_{22} & D_{23} & D_{24} & D_{25} & D_{26} \\ D_{31} & D_{32} & D_{33} & D_{34} & D_{35} & D_{36} \\ D_{41} & D_{42} & D_{43} & D_{44} & D_{45} & D_{46} \\ D_{51} & D_{52} & D_{53} & D_{54} & D_{55} & D_{56} \\ D_{61} & D_{62} & D_{63} & D_{64} & D_{65} & D_{66} \end{bmatrix} \begin{bmatrix} 1.0 - V_x \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \]  

where

\[ D_{11} = D_{12} = D_{13} = D_{14} = D_{15} = D_{16} = 1.0 \]
\[ D_{21} = -0.6\rho_p, \quad D_{23} = \rho_x, \quad D_{26} = \rho_y \]
\[ D_{31} = \rho_p, \quad D_{32} = -0.5\rho_p \]
\[ D_{41} = -k\rho_p, \quad D_{44} = \rho_{sp} \]
\[ D_{51} = -m\rho_p, \quad D_{53} = \rho_w, \quad D_{55} = \left(1 - r_x (1 + m)\right)\rho_p, \]
\[ D_{61} = \left(1 - (r_y + r_z) (1 + m)\right)\rho_f \]

Fifth, the total amounts of chemicals are verified based on the required molar ratio of Na₂O/SiO₂ and H₂O/Na₂O. If either of both amounts does not satisfy the requirements, the engineer should go back to the third step, then change the concentration of solutions. Finally, the flow of the mortar is examined by trial mixing. If the flow does not satisfy the requirement, the weight of extra water can be simply increased in the second step.

Interestingly, the average mix proportion of SCGM in this study shows almost a similar volume balance of average mix of SCM (Okamura and Ouchi 2003) (Fig. 21). This suggests that the flowability of SCGM can be controlled by V_w/V_p and either V_w/V_p or V_w/V_s. However, the flow time of SCGM strongly depends on the viscosity governed by alkali liquid concentration r_x, r_y and r_z.

5. Conclusions

In this experimental work, nineteen (19) self-compacting geopolymer mortar (SCGM) mixes were cast to investigate the rheological properties with the variation of different influencing parameters. The following conclusions are drawn based on the experimental results presented in the paper.

1. The boundary limits of relative flow area (G_m) and relative flow speed (R_m) of SCGM and SCM were not similar. The relative flow speed (R_m) of SCGM was significantly lower than SCM.
2. The volume of water to volume of powder ratio (V_w/V_p) had a positive impact on flow area in comparison to the flow speed of SCGM. The trend of R_m and G_m based on the variation of V_w/V_p and Sp/P was different from normal SCM due to the high viscosity of matrix.
3. The flow properties of SCGM were analyzed in terms of V_w/V_p, Sp/P, FA/S, viscosity of alkaline liquid and the W/GPS. This analysis clarified that the parameters relating to viscosity of matrix have strong impact for SCGM. The notable effect of mixing order, mixing speed and type of mixer on the flow property of SCGM were demonstrated as well.
4. According to the analyses, flow prediction models for SCGM were formulated based on the parameters of both physical and chemical point of view. The predicted flow results of SCGM matched well with the corresponding experimental results. The predicted results of flowability were within 15% of the corresponding experimental results.
5. A flow chart and mathematical expression for rational mix design for SCGM with a certain strength are proposed. The calculated typical volume ratio of SCGM was similar to SCM considering the volume of alkaline liquid with water in SCGM was equivalent to the volume of water in SCM.
6. The properties of hardened material; compressive strength and microstructure, of these mixes will be shown in the subsequent paper in future.

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**Notation**

- $P$: Weight of powder per unit volume (in this study, powder consists of fly ash only) [kg/m$^3$]
- $S$: Weight of sand per unit volume [kg/m$^3$]
- $W$: Weight of mixing water per unit volume [kg/m$^3$]
- $SH$: Weight of NaOH solution per unit volume [kg/m$^3$]
- $SS$: Weight of Na$_2$SiO$_3$ solution per unit volume [kg/m$^3$]
- $Sp$: Weight of superplasticizer per unit volume [kg/m$^3$]
- $AA$: Weight of alkaline activators solution consists of NaOH and Na$_2$SiO$_3$ solution per unit volume [kg/m$^3$]
- $V_P$: Volume of powder (in this study, powder consists of fly ash only) [m$^3$]
- $V_S$: Volume of sand [m$^3$]
- $V_W$: Volume of mixing water [m$^3$]
- $V_{Sp}$: Volume of superplasticizer [m$^3$]
- $V_X$: Volume of NaOH solution at 20°C [m$^3$]
- $V_Y$: Volume of Na$_2$SiO$_3$ solution at 20°C [m$^3$]
- $V_{AA}$: Volume of alkaline liquid at 20°C, $V_{AA} = V_X + V_Y$
- $V_{air}$: Volume of air (generally, 0.01) [m$^3$]
- $r_X$: NaOH solid weight ratio in NaOH solution at 20°C (generally 8M:0.26, 12M:0.36, 16M:0.44)
- $r_{Y1}$: Na$_2$O weight ratio in Na$_2$SiO$_3$ solution at 20°C (in this study, 0.13)
- $r_{Y2}$: SiO$_2$ weight ratio in Na$_2$SiO$_3$ solution at 20°C (in this study, 0.30)
- $\rho_P$: Particle density of powder (in this study, 2310) [kg/m$^3$]
- $\rho_S$: Particle density of sand (in this study, 2330)[kg/m$^3$]
- $\rho_W$: Density of mixing water at 20°C (in this study, 1000)[kg/m$^3$]
- $\rho_{Sp}$: Density of superplasticizer at 20°C (in this study, 1040)[kg/m$^3$]
- $\rho_X$: Density of NaOH solution at 20°C (generally 8M: 1465) [kg/m$^3$]
- $\rho_Y$: Density of Na$_2$SiO$_3$ solution at 20°C (in this study, 1465) [kg/m$^3$]