Effect of molarity of sodium hydroxide and molar ratio of alkaline activator solution on the strength development of geopolymer concrete

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Abstract. In the current study, effect of SiO\textsubscript{2}/Na\textsubscript{2}O ratio in Sodium silicate (Na\textsubscript{2}SiO\textsubscript{3}) solution, Na\textsubscript{2}SiO\textsubscript{3}/NaOH ratio and molarity of NaOH on the compressive strength of geopolymer concrete. A geopolymer mix design is formulated with various mixes are casted with alkali activator solution (AAS) / fly ash (FA) =0.5 and constant fly ash content. The molar ratio of SiO\textsubscript{2}/Na\textsubscript{2}O in Na\textsubscript{2}SiO\textsubscript{3} solution is altered from 1.50 to 3.00 for different ratios of Na\textsubscript{2}SiO\textsubscript{3}/NaOH (2.0, 2.5 and 3.0) and also for various molarities of NaOH (8M,10M,12M,14M,16M and 18M) are studied for their synergetic effect on the compressive strength of geopolymer concrete. Results highlighted that the 16M NaOH yields high compressive strength when SiO\textsubscript{2}/Na\textsubscript{2}O in Na\textsubscript{2}SiO\textsubscript{3} solution is around 2.00 to 2.40 and Na\textsubscript{2}SiO\textsubscript{3}/NaOH=2.5.

1 Introduction

Geopolymer is a new development in the world of concrete in which cement is totally replaced by pozzolanic materials like fly ash, ground granulated blast furnace slag and activated by highly alkaline solutions to act as a binder in the concrete mix [1,2,3]. For the selection of suitable ingredients of geopolymer concrete to achieve desire strength at required workability, an experimental investigation has been carried out for the gradation of geopolymer concrete and a mix design procedure is proposed on the basis of quantity and fineness of fly ash, quantity of water, grading of fine aggregate, fine to total aggregate ratio [4,5,6,7,8,9,10].

2 Sodium hydroxide (NaOH) solution

Various molarities of NaOH are considered for study are 8M,10M,12M,14M,16M and 18M. The quantity of NaOH flakes to be mixed in distilled water is estimated based on the molarity. The molecular weight of NaOH is 40 which is determined in the lab, so for example to prepare 10M NaOH, sodium hydroxide flakes of 400 gram (10x40) were dissolved in one litre of deionized water then the total volume of the NaOH solution becomes 1.10 litres or 1100 ml. It was observed that for one gram of NaOH flake added to one litre water, the increase in volume of total solution is 0.25 ml. So, 400 grams added to one litre of deionized water will increase the total volume by 400 x 0.25=100 ml which means to prepare one litre volume of NaOH solution, NaOH flakes to be added to one litre deionized water is (400/1000) x 100=364 grams. Hence, the molarity of NaOH solution is reduced to 9.1 M (364/40) instead of 10 M.

| Molarity | NaOH flakes to be added to make NaOH solution (grams) | Molarity of NaOH solution |
|----------|------------------------------------------------------|--------------------------|
| 8M       | 296                                                  | 7.4M                     |
| 10M      | 364                                                  | 9.1M                     |
| 12M      | 429                                                  | 10.7M                    |
| 14M      | 491                                                  | 12.3M                    |
| 16M      | 552                                                  | 13.8M                    |
| 18M      | 610                                                  | 15.3M                    |

3 Sodium silicate (Na\textsubscript{2}SiO\textsubscript{3}) solution

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Factory prepared Sodium silicate solution with various compositions of SiO$_2$/Na$_2$O from 1.50 to 3.0 are procured. Sodium silicate solution has nearly 50-57% of water. Sodium silicate solution is added to sodium hydroxide solution before 30 to 60 min of mixing of concrete.

### 4 Mix Design

Mix design and component proportioning in alkali-activated concrete appear to be complicated due to the numerous factors involved. As a result, there is currently no standard mix design technique for alkali-activated binders concrete. Following the standards provided in IS 10262:2009, the basic mix proportions are determined. Maximum cement content provision given in the IS 456 code is adopted to arrive at following mix proportions.

- **Fly Ash = 450 kg/m$^3$**
- **Alkali Activator solution (AAS) / Fly ash =0.5**
- **Na$_2$SiO$_3$/NaOH ratios adopted are 2.0, 2.5 and 3.0**

### 5 Effect of SiO$_2$/Na$_2$O ratio in Sodium silicate (Na$_2$SiO$_3$) solution

In this section, the effect of SiO$_2$/Na$_2$O ratio on the compressive strength of various geopolymer concrete specimens developed using various molarity of NaOH and molar ratios is studied. Molar ratio is defined as ratio of Na$_2$SiO$_3$/NaOH in Alkaline Activator solution. Alkaline Activator solution (AAS) / Fly ash ratio is maintained constant at 0.5. Compressive strengths of various geopolymer concrete specimens developed using various molarity of NaOH and molar ratios are presented in tables 2-4.

**Table 2.** Compressive strengths of geopolymer concrete mixes developed using various molarities of NaOH and Na$_2$SiO$_3$/NaOH ratio=2.0 for different SiO$_2$/Na$_2$O ratios

| SiO$_2$/Na$_2$O | Na$_2$SiO$_3$/NaOH=2.0 | Compressive Strength (MPa) |
|----------------|-------------------------|-----------------------------|
|                | NaOH Molarity           | 8M  | 10M  | 12M  | 14M  | 16M  | 18M  |
| 1.50           | 3.74                    | 4.08 | 4.26 | 4.35 | 5.75 | 4.89 |
| 1.60           | 4.22                    | 4.60 | 4.81 | 4.91 | 6.49 | 5.51 |
| 1.70           | 5.71                    | 6.22 | 6.50 | 6.64 | 8.78 | 7.46 |
| 1.80           | 10.98                   | 11.97| 12.51| 12.78| 16.89| 14.35|
| 1.90           | 13.18                   | 14.37| 15.02| 15.34| 20.27| 17.23|
| 2.00           | 22.42                   | 22.24| 23.26| 23.74| 31.38| 26.68|
| 2.10           | 24.41                   | 22.23| 23.25| 23.74| 31.38| 26.67|
| 2.20           | 19.87                   | 21.65| 22.64| 23.11| 30.55| 25.97|
| 2.30           | 19.38                   | 21.10| 22.06| 22.53| 29.78| 25.32|
| 2.40           | 17.75                   | 19.34| 20.22| 20.64| 27.29| 23.19|
| 2.50           | 11.05                   | 12.04| 12.58| 12.85| 16.98| 14.44|
| 2.60           | 9.42                    | 10.26| 10.73| 10.95| 14.48| 12.31|
| 2.70           | 7.92                    | 8.63 | 9.02 | 9.21 | 12.18| 10.35|
| 2.80           | 6.82                    | 7.43 | 7.77 | 7.94 | 10.49| 8.91 |
| 2.90           | 4.80                    | 5.23 | 5.47 | 5.58 | 7.38 | 6.28 |
| 3.00           | 4.64                    | 5.06 | 5.29 | 5.40 | 7.14 | 6.06 |
**Fig. 1.** Compressive strengths of geopolymer concrete mixes made with Na$_2$SiO$_3$/NaOH ratio 2.0 for various SiO$_2$/Na$_2$O ratios of Na$_2$SiO$_3$ and molarities of NaOH

Table 3. Compressive strengths of geopolymer concrete mixes developed using various molarities of NaOH and Na$_2$SiO$_3$/NaOH ratio=2.5 for different SiO$_2$/Na$_2$O ratios

| SiO$_2$/Na$_2$O | Compressive Strength (MPa) Na$_2$SiO$_3$/NaOH=2.5 |
|----------------|-----------------------------------------------|
|                | NaOH Molarity                                |
|                | 8M    | 10M   | 12M   | 14M   | 16M   | 18M   |
| 1.50           | 4.68  | 5.10  | 5.33  | 5.44  | 7.19  | 6.11  |
| 1.60           | 5.28  | 5.75  | 6.01  | 6.14  | 8.11  | 6.89  |
| 1.70           | 7.14  | 7.77  | 8.13  | 8.30  | 10.97 | 9.32  |
| 1.80           | 13.73 | 14.96 | 15.64 | 15.97 | 21.11 | 17.94 |
| 1.90           | 16.48 | 17.96 | 18.77 | 19.17 | 25.34 | 21.54 |
| 2.00           | 25.52 | 27.80 | 29.07 | 29.68 | 39.23 | 33.35 |
| 2.10           | 25.51 | 27.79 | 29.06 | 29.67 | 39.22 | 33.34 |
| 2.20           | 24.84 | 27.06 | 28.30 | 28.89 | 38.19 | 32.46 |
| 2.30           | 24.22 | 26.38 | 27.58 | 28.16 | 37.23 | 31.65 |
| 2.40           | 22.19 | 24.17 | 25.27 | 25.80 | 34.11 | 28.99 |
| 2.50           | 13.81 | 15.05 | 15.73 | 16.06 | 21.23 | 18.05 |
| 2.60           | 11.77 | 12.83 | 13.41 | 13.69 | 18.10 | 15.39 |
| 2.70           | 9.90  | 10.79 | 11.28 | 11.51 | 15.22 | 12.94 |
| 2.80           | 8.53  | 9.29  | 9.71  | 9.92  | 13.11 | 11.14 |
| 2.90           | 6.00  | 6.54  | 6.84  | 6.98  | 9.23  | 7.85  |
| 3.00           | 5.80  | 6.32  | 6.61  | 6.75  | 8.92  | 7.58  |
Fig. 2. Compressive strengths of geopolymcer concrete mixes made with Na$_2$SiO$_3$/NaOH ratio 2.5 for various SiO$_2$/Na$_2$O ratios of Na$_2$SiO$_3$ and molarities of NaOH.

| SiO$_2$/Na$_2$O | Compressive Strength (MPa) | NaOH Molarity |
|----------------|---------------------------|---------------|
|                | Na$_2$SiO$_3$/NaOH=3.0    | 8M | 10M | 12M | 14M | 16M | 18M |
| 1.50           | 4.35                      | 4.64 | 4.80 | 5.06 | 6.69 | 5.68 |
| 1.60           | 4.91                      | 5.23 | 5.41 | 5.71 | 7.54 | 6.41 |
| 1.70           | 6.64                      | 7.07 | 7.32 | 7.72 | 10.20 | 8.67 |
| 1.80           | 12.77                     | 13.61 | 14.08 | 14.85 | 19.63 | 16.68 |
| 1.90           | 15.33                     | 16.34 | 16.89 | 17.83 | 23.57 | 20.03 |
| 2.00           | 23.73                     | 25.30 | 26.16 | 27.60 | 36.48 | 31.02 |
| 2.10           | 23.72                     | 25.29 | 26.15 | 27.59 | 36.47 | 31.01 |
| 2.20           | 23.10                     | 24.62 | 25.47 | 26.87 | 35.52 | 30.19 |
| 2.30           | 22.52                     | 24.01 | 24.82 | 26.19 | 34.62 | 29.43 |
| 2.40           | 20.64                     | 21.99 | 22.74 | 23.99 | 31.72 | 26.96 |
| 2.50           | 12.84                     | 13.70 | 14.16 | 14.94 | 19.74 | 16.79 |
| 2.60           | 10.95                     | 11.68 | 12.07 | 12.73 | 16.83 | 14.31 |
| 2.70           | 9.21                      | 9.82 | 10.15 | 10.70 | 14.15 | 12.03 |
| 2.80           | 7.93                      | 8.45 | 8.74 | 9.23 | 12.19 | 10.36 |
| 2.90           | 5.58                      | 5.95 | 6.16 | 6.49 | 8.58 | 7.30 |
| 3.00           | 5.39                      | 5.75 | 5.95 | 6.28 | 8.30 | 7.05 |
Based on the compressive strength attained, it was observed that for the optimum SiO₂/Na₂O in Sodium silicate should be between 2.00-2.40. From the current study SiO₂/Na₂O ratio of 2.0 found to give high compressive strength. Three molar ratios of Na₂SiO₃/NaOH are considered for the current study. Of which the molar ratio of Na₂SiO₃/NaOH =2.5 by mass yields high compressive strength so this molar ratio is recommended. Even the literature suggests similar results reported by other researchers. Therefore, sodium silicate solution with composition Na₂O = 16.37 %, SiO₂ = 34.35 % and H₂O = 49.28 % and Sodium hydroxide solution having 13.8 M concentration are chosen after various trials on the basis of cube compressive strength, whereas Alkaline Activator solution (AAS) / Fly ash ratio is maintained constant at 0.50 throughout the experiment on the basis of workability. Workability of geopolymer concrete was measured by flow table apparatus and cubes of 150 mm side were cast and tested for compressive strength after specified period of oven heating. The temperature of oven heating was maintained at 60 °C for 24 h duration and tested after one day of oven heating. It was observed that the results of workability and compressive strength are well match with the required degree of workability and compressive strength. So, proposed method is used to design of 30 MPa strength range geopolymer concrete.

Increased water-to-cement ratios in Portland cement concrete produce a reduction in strength development, as does an excess OH concentration of 18M in the geopolymer mix. Furthermore, a higher concentration of NaOH solution may cause the polymerization process to be disrupted. It was discovered that increasing the leaching out of Si⁴⁺ and Al³⁺ ions from fly ash particles enhances the sodium aluminosilicate hydrate (N-A-S-H) gel.
gel, resulting in high strength, at a concentration of 16M NaOH.

7 Conclusions

Based on the results obtained the following are conclusions drawn:

1. In the present study alkaline activator solution (AAS) / fly ash (FA) =0.5 and constant fly ash content are adopted
2. The optimum molar ratio of SiO$_2$/Na$_2$O in Na$_2$SiO$_3$ solution is found to be around 2.00 to 2.40
3. The optimum Na$_2$SiO$_3$/NaOH is found to be 2.5
4. The optimum molarity for NaOH is found to be 16M to achieve a strength of range 20-30 MPa.

References

1. Srinivas, T, Abhignya. G and Ramana Rao. N.V, A Review on Geopolymer RCC Beams made with Recycled Coarse Aggregate, E3S Web of Conferences, ICMED, 10-12 July 2020, India (2020).
2. T. Srinivas, S. V. Srinidhi and N.V. Ramana Rao, A Review on Flexural Behavior of RCC Beams Made with Geopolymer Concrete, E3S Web of Conferences, ICMED, 10-12 July 2020, India (2020).
3. T. Srinivas , P. Bhavana, and N. V. Ramana Rao, Effect of Manufactured Sand on Flexural Behavior of Geopolymer RCC Beams: A review, E3S Web of Conferences, ICMED, 10-12 July 2020, India (2020).
4. B. J. Varghese and P. B. Bobba, " 2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES), 2016, pp. 1-5
5. T. Srinivas and N.V.Ramana Rao, IJCET, Volume 10, 510 (2019).
6. K. Sai Gopi, Dr. T. Srinivas and S. P. Raju V, E3S Web of Conferences ICMED 184, 01084GRIET, 28-29 February, https://doi.org/10.1051/e3sconf/2020184011084(2020)
7. Jagannadha Kumar, M.V., Jagannadha Rao, K., Dean Kumar, B., Srinivasa Reddy, V., Int. J. of Civil Eng. and Tech., 9(7), pp. 1133-1141 (2018)
8. M. Kavitha, P. B. Bobba and D. Prasad, 2016 IEEE 7th Power India International Conference (PICON), 2016, pp. 1-6
9. Ganta, J.K., Seshagiri Rao, M.V., Mousavi, S.S., Srinivasa Reddy, V., Bhojaraju, C., Structures 28, pp. 956-972 (2020)
10. Naidu, K.S.S.T., Rao, M.V.S., Reddy, V.S., Int. J. of Innov. Tech. and Explor. Eng (JIITEE), 8(9 Special Issue 2), pp. 641-642 (2019)
11. Chandana Priya, C., Seshagiri Rao, M.V., Srinivasa Reddy, V., Int. J. of Civil Eng. and Tech., 9(11), pp. 2218-2225 (2018)
12. Srinivas Rao J, S K Tummala, Kuthuri N R, Indonesia Journal of Electrical Engg. & Computer Science, 21 (723), 2020
13. Satya Sai Trimurthy Naidu, K., Seshagiri Rao, M.V., Srinivasa Reddy, V., Int. J. of Civil Eng. and Tech., 9(11), pp. 2383-2393 (2018)
14. Supriya, Y., Srinivasa Reddy, V., Seshagiri Rao, M.V., Shrihari, S., Int. J. of Rec. Tech. and Engi., 8(3), pp. 5381-5385 (2019)
15. Kotkunde, N., Krishna, G., Shenoy, S.K., Gupta, A.K., Singh, S.K. International Journal of Material Forming, 10 (2), pp. 255-266 (2017)
16. Govardhan, D., Kumar, A.C.S., Murti, K.G.K., Madhusudhan Reddy, G. Materials and Design, 36, pp. 206-214. (2012)
17. K. Satyanarayana, A. V. Gopal, and P.B. Bobu, Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 228(1), 152 (2014)
18. Kumar, P., Singhal, A., Mehta, S., Mittal, A. Journal of Real-Time Image Processing, 11 (1), pp. 93-109. (2016)
19. Raghunadha Reddy, T., Vishnu Vardhan, B., Vijayapal Reddy, P. International Journal of Applied Engineering Research, 11 (5), pp. 3092-3102 (2016)
20. Hussaini, S.M., Krishna, G., Gupta, A.K., Singh, S.K. Journal of Manufacturing Processes, 18, pp. 151-158 (2015)