Design of self-cured geopolymer concrete using Taguchi approach

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Abstract: Geopolymer concrete is the most suitable alternative to conventional concrete. It needs high-temperature curing to achieve better mechanical and durability properties, which is not possible on many Indian construction sites. Therefore, this research explores the effect of Variables like the quantity of aluminosilicate material (ASM), the ratio between Alkaline solution to the quantity of aluminosilicate material (AL/ASM), sodium silicate and sodium hydroxide ratio (SS/SH), and molarity of sodium hydroxide (SH) on the compressive strength and water absorption of Self-Cured Geopolymer Concrete (SCGC). The aforementioned properties have been optimized using the Taguchi approach and non-destructive testing (NDT) has also been performed on SCGC specimens. Along with the experimental work, a mathematical model was also developed using multiple regression analysis for predicting the compressive strength and water absorption of SCGC specimens. SCGC has been developed in an environment where temperature and humidity are not controlled. The experimental results inform that the specimen with ASM of 450 kg/m^3, AL/ASM ratio of 0.45, SS/SH ratio of 1.5, and molarity of SH 12M provides maximum compressive strength and minimum water absorption. The pattern of the Signal-to-noise ratio (S/N) curve of the NDT is alike to that of the destructive tests (DT). The findings predicted by the polynomial regression equations are identical to the experimental results compared to the linear regression equation. It has also been found that SCGC of M25 grade can be developed without controlling temperature and humidity.

Keywords: Geopolymer, non-destructive testing (NDT), outdoor curing, mathematical model, Taguchi Approach.

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Abbreviations

GGBFS	Granulated Blast Furnace Slag	GC	Geopolymer Concrete
OPC	Ordinary Portland Cement	ACGC	Ambient Cured Geopolymer Concrete
SCGC	Self-cured Geopolymer Concrete	CC	Conventional Concrete
SS	Sodium Silicate	FA	Fly Ash
SH	Sodium Hydroxide	AL	Alkaline Liquid
ASM	Quantity of alumino-silicate source materials	UPV	Ultrasonic Pulse Velocity
DT	Destructive Testing	NDT	Non-Destructive Testing

1. INTRODUCTION

The construction industry in India is the second-largest natural resources consumption sector after the agricultural sector, and it will transcend the agricultural sector before 2022. The key ingredient of the construction industry is OPC, which consumes heat for burning the limestone at 1400-1600 ^{0}C and emits 7% of the total production of greenhouse gas in the country, in the atmosphere[1]. India is a well-known reserve of limestone, but it will drain out in 2060. With the rapidly growing construction industry, the per capita demand for cement will go beyond 200 kg/person, with that cement production also increasing by 4-7% from current production in 2050 [2]. Besides, different types of by-products like ashes from thermal power plants, slags from the iron and steel industry, metakaolin, rice husk ash, clay, cement kiln dust, etc., from other industries are also rapidly evolving with urbanization. The dumping or disposal technique of these by-products is a serious concern for researchers. Therefore, the requisition for time encourages the researchers to discover some sustainable substitute to cement that can meet the demand for cement, reduce the production of greenhouse gases, and also properties of concrete with those materials are comparable or better than that of the CC. To conquer with aforementioned issues authors [3]–[8] are discussed the utility of by-products from industry and agriculture as partial replacement of concrete constituents and concluded that these by-products can be used as the constituents of the concrete. But still, geopolymer specimen is obtaining more attention compared to the CC, because geopolymer specimen completely replaces OPC by aforementioned by-products and reduce the CO_2 emission by approximately 9% [3].

Geopolymer was initially invented by V.D. Glukhovsky in 1957 but further, coined by J. Davidovits in 1978 [1], [4]. It is one among the inorganic polymers synthesized by rich alumino-silicate industrial or agricultural by-products viz. metakaolin, FA, silica fume, Rice Husk Ash, Blast furnace slag, corex slag, etc., and polymerized by the alkaline solution of hydroxide and silicates (primarily sodium or potassium) in the availability of high-temperature curing [5], [9], which possess zeolite like structure but demonstrating an amorphous microstructure [10]. The formation of geopolymer composites reduced the need for energy by 15% and the production of CO_2 by 70% (approximately) compared to the production of OPC composites [7], [11]. GC exhibited higher strength [10], [12], [13], better resistance to alkaline and acidic environment [1], [14], and superior thermal resistivity [9], [15] compared to CC. Reference [10], [16] informed that geopolymer has the potential to achieve more than 100 MPa compressive strength.

Among all by-products, mostly low calcium FA is utilized to develop geopolymer composites because of its physical and chemical characteristics along with the easy and economically availability of material [6], [7]. Reference [13] made an effort to developed the geopolymer mixture incorporated with FA using Taguchi's approach, which can be used in the seawater environment, and achieved more than 60 MPa compressive strength with the ratio of AL/ASM and SS/SH 0.30 and 2.5, respectively, when specimens were cured for 24 h at 75 ^{0}C. Researchers also reported that flexural and split tensile strength were much greater than that of the CC, but the modulus of elasticity, water absorption, drying shrinkage, and expansion has been less than that of the CC. Reference [17] reported the ratio of AL/ASM has not shown any effect on the compressive strength whereas, the ratio of SS/SH, molarities of SH, and the curing temperature has shown a positive impact on the mechanical properties up to a certain extent. Reference [18] developed geopolymer concrete using metakaolin and OPC as binder materials and found that increasing the OPC content enhanced the mix's strength. Similarly, reference [19] demonstrated that replacing 20% FA with OPC increased the compressive strength of GC by roughly 58%. Reference [20] informed that recycled coarse aggregates harm the GC properties, but these results were preferably good compared to the CC. Reference [4] used the approach of Taguchi, to find the compressive strength and water absorption of GC by incorporating OPC as an alternative to FA. After completing the experimental and analytical work, researchers achieved 64.39 MPa compressive strength and 3.04% water absorption after 7 days with the inclusion of 20% OPC as a substitute for FA. Researchers also developed a mathematical model with a high degree coefficient of determination to evaluate compressive strength and water absorption.

Most research work has been carried out by utilizing high-temperature curing to activate the polymerization reaction, which is problematic for cast-in-situ work. Some studies have also attempted to developed ACGC, by introducing calcium content by GGBFS [11], [21], alccofine [22], metakaolin [10], [18], OPC [23], nano-SiO_2 [24], etc. Reference [19], [25] reported that ambient curing curtails the cost and energy required for the heat curing process. Reference [11] concluded that replacing GGBFS with 10% rice husk ash or 15% silica fume might improve the strength of ACGC even more. Reference [22] considered FA and alccofine as ASM, to develop ACGC and reported that the highest strength Variables were achieved with 400 kg/m^3 FA and 16 M SH and also formed a dense structure. With the introduction of GGBFS and OPC as the partial replacement of the FA, ACGC properties have been improved but workability reduced [26]. Minimum water absorption for ambient cured geopolymer mortar has been obtained by the addition of nano-silica, the reason is that incorporation of nano-SiO_2 formed dense microstructure, which decreased water absorption and voids of the GC [27]. To build an FA-GGBS based self-cured geopolymer mortar (cured at the temperature of 30 ± 2 °C and relative humidity of 65 ± 5% for 24 h), reference [16] used natural sugars such as molasses, palm jaggery, and honey, as well as terminalia chebula as bio-additives. Researchers found that adding bio-additives resulted in the formation of a compact and dense microstructure, which increased compressive strength by 18–36%. Reference [28] concluded that granulated blast furnace slag sand might be used in place of river sand in geopolymer concrete and achieve similar or better results. In general, to achieve higher strength and superior durability for ambient cured geopolymer specimen required 10–12 M of SH, AL/ASM ratio 0.35–0.5, and the ratio between SS/SH 1.5–2.5 [25]. M. Klima et al. [9] found that There is still a need to investigate the durability and overall performance of GC over the long term. Although geopolymers are gaining traction in the construction industry, important obstacles remain, including the necessity for strong activators and a high/ambient curing temperature. This prevents India from fully utilizing geopolymer in construction projects [18], [29].

Nowadays, NDT has also been started on hardened concrete along with DT because sometimes DT becomes complicated in the existing concrete structures. The prime focus of the NDT is to check the adequacy or integrity of the existing structures. NDT is mainly performed in two ways, without damaging structure's surfaces like UPV, rebound hammer, etc., and partially damaging the old and new structures like the core test, pull out test, etc. Reference [28] established an equation for estimating compressive strength from UPV and discovered that UPV and GC compressive strength have a strong relationship, and might be used for calculating the compressive strength of GC. Reference [30] carry out the UPV test on the ACGC comprises different FA materials, bottom ash, and GGBFS, and researchers reported that the UPV test has the capability to estimate the compressive strength with less than 2MPa error. The NDT has also been performed by S. Naskar and A.K. Chakraborty [31], and they informed that Indian standards may also be suitable for GC after some modifications.

The fresh and hardened properties of geopolymer specimens were persuaded by the numerous substances such as ASM [32], [33], the ratio between alkaline solution and ASM (AL/ASM) [13], [34], Molarity (M) of SH [19], [35], [36], heat curing temperature and duration [16], curing method [37], the ratio between SS/SH [10], [34], the addition of water, superplasticizer [38], etc. Conducting an investigation, to understand the effect of the entire variable might be complicated. The current research objective is to develop SCGC in an environment where temperature and humidity are not controlled. Using the Taguchi approach, the ideal combination of ASH, SH molarity, SS/SH ratio, and AL/ASM ratio was obtained to yield maximum compressive strength and minimum water absorption.

To the authors' best information, none of the publications addressed the NDT on the SCGC specimens. Therefore, in this study, NDT has also been performed on the SCGC to find the internal quality of GC. In addition to the experimental work, a mathematical model has also been created by using multiple regression to predict compressive strength and water absorption of the SCGC specimens.

2. EXPERIMENTAL DETAILS

2.1 Characteristic of self–cured geopolymer concrete materials

SCGC was synthesized by FA, alkaline solution of SH and SS, fine aggregate, and coarse aggregate. Class FA as stipulated in IS 3812 (Part 1): 2013 [39] (acquired from Dirk India Private Limited, Nasik, India with product name Pozzocrete 60) was used as ASM. The specific surface area and the specific gravity of FA were 368 m^2/kg and 2.33, respectively, and roughly 16.37% material was retained on a 45μ sieve. The chemical properties of the FA have been presented in **Table 1** (provided by the supplier).

A hazy white colour and 11.5 pH thick liquid, obtained from Kiran Global Chems Ltd., Tamilnadu, India, was used as SS (supplied with name Geopolymer Activator Part-B) solution. The specific gravity of SS was 1.5 at 25^{0}C. The combination of potable water and 99.68% pure caustic soda flex was used to achieve the desired molarity of SH. The properties of the alkaline solution have been presented in **Table 2** (provided by the supplier). Sand elicited from Godavari River was used as fine aggregate with 1.21% water absorption and 2.6 specific gravity, whereas crushed 4.75–20 mm nominal size aggregates with water absorption 0.4% and specific gravity 2.8 was selected as coarse aggregates.

Table 1. Chemical properties of Fly ash.

Constituents	Test Result (% by weight)
Loss on Ignition	1.13
SiO_2+Al_2O_3+Fe_2O_3	92.73
Na_2O	0.55
SO_3	0.80
MgO	2.17
SiO_2	59.57
Al_2O_3	26.13
Fe_2O_3	7.03
CaO	0.05

Table 2 Properties of alkaline solution.

Constituents	Test Result
Properties of Sodium silicate	
Specific Gravity	1.52 at 25 ^{0}C
Water content (%)	53
Na_2O (%)	14–17
SiO_2 (%)	31–34
Boiling Point (^{0}C)	105
Properties of Sodium hydroxide	
Na_2Co_2 (%)	0.28
NaCl (Ppm)	290
Ni (Ppm)	1.2
Fe (Ppm)	3.2

2.2 *Determination of optimum mixture for self–cured geopolymer concrete*

To attain maximum compressive strength and least water absorption (without performing the unnecessary repetitive experiments) Taguchi approach was selected to ascertain the optimum mixture of SCGC. Four main variables that highly influence the compressive strength and water absorption such as ASM (350, 400, and 450 kg/m^3), AL/ASM ratio (0.35, 0.45, and 0.55), SS/SH ratio (1.5, 2.0, and 2.5) and molarity of SH (10, 12, and 14 M) were taken into account for the mix design shown in **Table 3**. An L-9 orthogonal array (3^4) was developed using Minitab 18 software to perform Taguchi analysis.

For mixed design calculation of SCGC, no such standards specifications are existing [6], [25], whereas researchers [40], [41] provide few guidelines to complete mix design calculation in addition to the IS 10262:2009 [42]. **Table 4** shows the mix proportion in each specimen. After performing many trials, it was found that to construct workable SCGC, there was neither a need for any additional water nor any superplasticizer.

2.3 Self–cured geopolymer concrete specimen preparation and testing

The solution of SS and SH was used as the alkaline solution and it has been recommended by [16], [41] that alkaline solution should be prepared, 24 hours before blending with dry materials because an exothermic reaction begins when combining SH flakes with water and SH solution with SS; therefore, it should be cool before adding with the other ingredients. R. Anuradha et al. [41] suggested that to prepare 1 kg solution of 10, 12, and 14 M SH, 314, 361, and 404 gram SH flakes were mixed with 686, 639 and 596-gram water, respectively.

Table 3**.** Variables and Grades considered for the Taguchi experiment design.

Variables	Grade 1	Grade 2	Grade 3
ASM (kg/m^3)	350	400	450
AL/ASM	0.35	0.45	0.55
SS/SH	1.5	2.0	2.5
Molarity of SH (M)	10	12	14

Table 4. Design mix proportions for SCGC trail mixes.

Mix	ASM (kg/m^3)	AL/ ASM	SS/ SH	SH (M)	Coarse Aggregates (kg/m^3)	Fine Aggregates (kg/m^3)
M-1	350	0.35	1.5	10	1295.37	701.66
M-2	350	0.45	2.0	12	1256.59	680.65
M-3	350	0.55	2.5	14	1217.88	659.68
M-4	400	0.35	2.0	14	1239.20	671.24
M-5	400	0.45	2.5	10	1194.82	647.20
M-6	400	0.55	1.5	12	1148.06	621.87
M-7	450	0.35	2.5	12	1182.99	640.78
M-8	450	0.45	1.5	14	1130.76	612.50
M-9	450	0.55	2.0	10	1081.12	585.61

To make SCGC specimens, saturated surface dry aggregates were first thoroughly mixed with FA for 5–7 minutes. After mixing, the required quantity of premixed AL was added gradually with dry materials and the blending continued for 4–5 minutes. Once a homogeneous mix was obtained, the workability of fresh homogenized SCGC mixtures was calculated using a slump cone test [43]; then, moulds were cast and compacted for one minute using a table vibrator for removing the present air voids. It has been found that specimens were too soft for demoulding after 24 h of casting because of the slow setting of GC in the ambient condition [44] therefore, all specimens were stripped on the third day of casting and stored outside the laboratory (no direct contact with sunlight) for the 28 days of curing.

Compressive strength, water absorption, UPV, and rebound hammer tests on the 150 mm size cubes SCGC specimens have been done according to standard test procedures [45], [46], [47], and [48], respectively. Before performing the DT, NDT was performed using Schmidt rebound hammers and Pundit ultrasonic pulse velocity. The compressive strength tests on SCGC cubes were executed by a semi-automatic digital compression testing machine with a 2000 k N capacity. For the measurement of water absorption, samples were kept in the oven for 48 h at 100^0C and allowed to cool at room temperature for 24 hours, then samples were submerged in water after taking weight. The initial and final water absorption has been calculated after immersing specimens in water for 30 min and 48 h, respectively. The water absorption was be determined with the help of weight before and after immersing in water and calculated in percentages

3. Experimental results and discussions

3.1 Optimization of key variables for self–cured geopolymer concrete

To optimize (according to the Taguchi approach the considered key variables of SCGC specimens', compressive strength and water absorption have been pursued as a dependent variable. The Taguchi approach takes into account the Signal–to–Noise ratio (S/N) for optimization. S/N ratio is divided into three different categories; those are as follows:

a) Larger is better:

$$\frac{S}{N} = -10\ \log_{10}(\text{mean of sum squares of reciprocal of measured data})$$

b) Nominal is best:

$$\frac{S}{N} = 10\ \log_{10}\left(\frac{\text{Square of mean}}{\text{Variance}}\right)$$

c) Smaller is better:

$$\frac{S}{N} = -10\ \log_{10}(\text{mean of the sum of squares of measure data})$$

In this study, for the optimization of compressive strength and water absorption, larger is better, and smaller is better category has opted. **Table 5** and **Figure 1** shows the compressive strength of the SCGC specimen calculated using DT and NDT, whereas **Table 5** and **Figure 2** exhibited the initial and final water absorption of the SCGC specimen. The workability of all SCGC specimens has been found between 75–100 mm. Maximum compressive strength and minimum water absorption have been achieved by M-8 with the 450 kg/m^3 ASM, 0.45 AL/ASM ratio, 1.5 the ratio of SS/SH, and 14 M molarity of SH. The density of all SCGC specimens is between 2426.07–2503.91 kg/m^3 (shown in **Table 5**), which is approximately equal to CC.

ANOVA (95% of confidence Grade) has been performed (using Minitab 18) on the obtained experimental results, to determine the percentage contribution of considered Variables. ANOVA results for compressive strength (**Figure 3**) informed the ASM has the highest contribution (47.14%) while the other key Variables, AL/ASM ratio, SS/SH ratio, and molarity of SH have contributed 30.94%, 8.02%, and 13.90%, respectively. Reference [18], [19] also observed that, in comparison to the other variables, ASM has a major impact on the strength of GC. Likewise, for water absorption (**Figure 3**) molarity of SH has the highest participation (56.39%), whereas the remaining variable such as the ASM, AL/ASM ratio and SS/SH ratio have contributed 33.96%, 7.73%, and 1.92%, respectively. It was also found from **Table 5** that M-1 specimen with the 350 kg/m^3 ASM, 0.35 AL/ASM ratio, 1.5 SS/SH ratio, and 10 M molarity of SH achieved a very small amount of compressive strength (11.95 MPa), therefore this specimen cannot be suggested for any other construction work

4.1.1 Effect of quantity of aluminosilicate material

The ASM was the most significant contributing variable for compressive strength and the second most significant variable for water absorption. The S/N curve for compressive strength (**Figure 4**) indicates that compressive strength continually increases from 350 kg/m^3 to 450 kg/m^3 with an increase in ASM quantity. The mean compressive strength of specimens having the ASM 350 kg/m^3 was 17.29 MPa and this value increased by 46.76% and 52.17% for specimens having the ASM 400 kg/m^3 and 450 kg/m^3, respectively

S/N curve for water absorption (**Figure 5**) explains water absorption was gradually decreased with the increase of the ASM from 350 kg/m^3 to 450 kg/m^3. Minimum water absorption has been achieved by specimen having ASM 450 kg/m^3. The mean water absorption for specimens containing 350 kg/m^3 ASM was 3.33% and it decreases by 2.80% and 4.60% for specimens containing ASM 400 kg/m^3 and 450 kg/m^3, respectively. This can be attributed to the fact that increasing the amount of ASM may lead to the formation of a dense structure and a strong bond with aggregates, a decrease in water absorption and an increase in compressive strength.

Table 5: Experimental test results of self–cured geopolymer concrete trail mixes.

Mix	**Density (kg/m^3)**	**Compressive strength (MPa)**		**UPV (km/sec)**	**Water absorption (%)**	
		DT	**NDT**		**Initial**	**Final**
M-1	2426.07	11.95	10.70	4.14	1.52	3.42
M-2	2469.74	20.99	18.22	4.42	1.23	3.23
M-3	2436.33	18.92	16.62	4.11	1.48	3.35
M-4	2439.22	20.84	17.94	4.19	1.24	3.21
M-5	2476.89	23.54	21.46	4.37	1.43	3.33
M-6	2486.89	31.73	27.72	4.85	1.16	3.18
M-7	2458.67	22.30	19.34	4.24	1.35	3.11
M-8	2503.11	32.33	28.00	4.93	1.12	3.09
M-9	2491.56	24.30	21.54	4.73	1.27	3.34

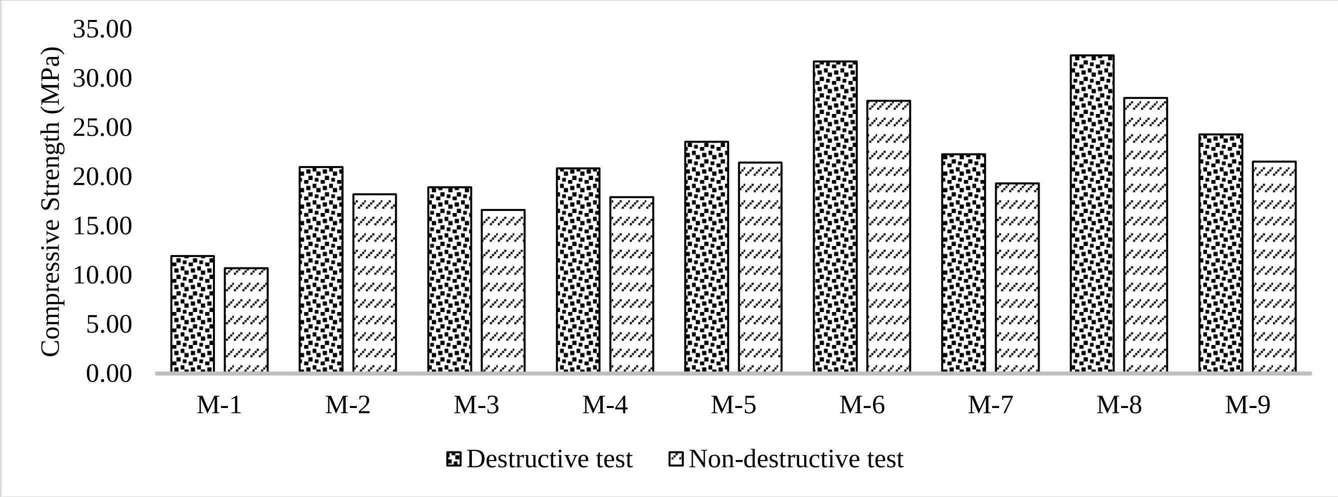

Figure 1: Compressive strength of SCGC trial mixes.

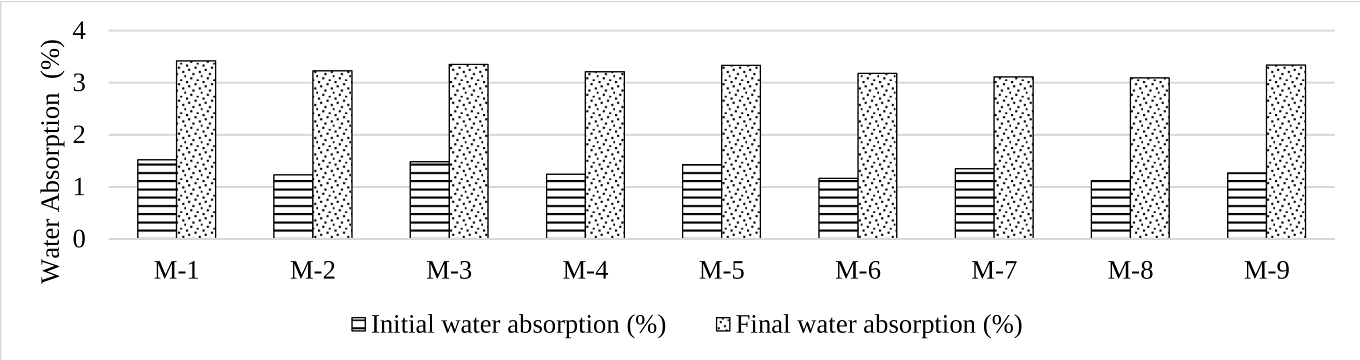

Figure 2: Initial and final Water absorption of SCGC trial mixes

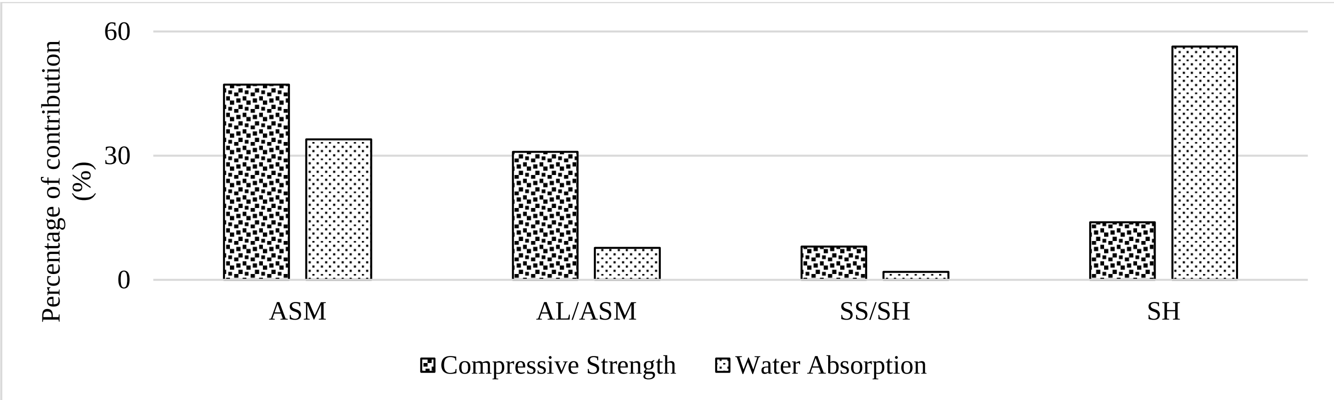

Figure 3: Percentage of the contribution of considered Variables in Compressive Strength and Water Absorption.

4.1.2 Effect of molarity of sodium hydroxide

The molarity of SH was the most significant variable for water absorption and the third most significant variable for compressive strength compared to the other factors. It was observed from the findings (**Figure 4** and **Figure 5**) that with the increase in the molarity of SH from 10M to 12M, the water absorption of SCGC specimen decreases whereas, the compressive strength increases. However, this behaviour becomes reverse beyond the 12M. Similar trends were also obtained by M.N.S. Hadi et al. [34], whereas, A. Mehta et al. [4] found 15M as optimum molarity of SH, which may be due to the high-temperature curing and OPC inclusion in GC.

The mean water absorption for 10M specimens was 3.36% and it was decreased by 5.65% and 4.36% for 12M specimens and 14M specimens, respectively. The mean compressive strength for 10M specimens was 16.61 MPa and it was increased by 25.45% and 20.57% for 12M specimens and 14M specimens, respectively. The main purpose of SH in geopolymer is leaching of alumina and silica in early stages and enhancing geopolymerization reaction, which promotes achieving a higher compressive strength [25], [34]. This could be attributed that more hydroxide ions (after 12M) developed in the early stage may decelerate the geopolymerization reaction, therefore the behaviour of the molarity of SH becomes reverse after 12M. It was also reported by [25] that the leaching and geopolymerization process is slower at room temperature, causing the development of less strength compared to oven and steam curing.

4.1.3 Effect of the alkaline solution to the aluminosilicate source materials

The AL/ASM has the potential to influence the compressive strength and water absorption of SCGC specimens. The effect of the AL/ASM ratio on GC was not reported by all researchers as identical. Some findings have shown that a higher AL/ASM ratio promote compressive strength [38], [41], while other studies reported the reverse effect on the compressive strength [13], [34]. It can be noticed from **Figure 4** that the compressive strength of SCGC specimens increases with the increase of AL/ASM ratio 0.35 to 0.45, while **Figure 5** shows that the water absorption of the SCGC specimen decreases with the increase of AL/ASM from 0.35 to 0.45, however, the effect reversed after the AL/ASM ratio 0.45.

It was observed based on the experimental results that the mean of the compressive strength for the AL/ASM ratio 0.35 was 15.30 MPa, while the mean was increased 39.51% and 36.05% for the AL/ASM ratio 0.45 and 0.55, respectively. The mean water absorption for the AL/ASM ratio 0.35 was 3.25%, while the mean was decreased by 0.92% for the AL/ASM ratio 0.45 and increased by 1.33% for the AL/ASM ratio 0.55, respectively. This could be attributed that, the higher AL/ASM ratio has a higher alkaline activator which increases the SiO_2/Al_2O_3 ratio and enhances the properties of SCGC specimens by the formation of strong Si–O–Si bonds [38] but after a certain limit, higher AL/ASM ratio slowdown the geopolymerization reaction because of the availability of the excess water [34] reverse the effect.

4.1.4 Effect of sodium silicate to sodium hydroxide ratio

The ratio between SS/SH is another important influencing factor to affects the properties of SCGC specimens. It has been observed that the SS/SH ratio has the least percentage contribution for the development of compressive strength and water absorption of SCGC specimens. Maximum compressive strength and minimum water absorption have been achieved with the SS/SH ratio of 1.5 as shown in **Figure 4** and **Figure 5**. It was also found that with the rise of the SS/SH ratio from 1.5 to 2.5, compressive strength is steadily declining, whereas water absorption is consistently increasing.

The mean compressive strength of specimens having an SS/SH ratio of 1.5 was 21.11 MPa and it decreases by 12.99% and 14.79% for specimens having SS/SH ratios of 2.0 and 2.5, respectively. It was also observed that the mean water absorption of specimens having an SS/SH ratio of 1.5 was 3.23% and it increases by 0.93% and 1.03% for specimens having SS/SH ratio 2.0 and 2.5, respectively. The alteration of the SS/SH ratio did not much significantly influence the 28 days compressive strength and water absorption of SCGC specimens (**Figure 4** and **Figure 5**). This could be attributed to the fact that the observed tendency of SCGC specimens is due to the excessive silicates, which hinders the formation of sodium aluminosilicate hydrate gels by occluding the polymerization reaction [49].

From the above discussion, it can be concluded that the optimum value of the considered key Variables such as the ASM, the ratio between AL/ASM, SS/SH ratio, and molarity of SH were 450 kg/m^3, 0.45, 1.5, and 12M, respectively. A new specimen (M-10) has been prepared using the optimum value of considered variables to achieve maximum compressive strength and minimum water absorption and found that the M-10 specimen achieved 33.18 MPa compressive strength, whereas, initial and final water absorption was 1.08% and 3.05%, respectively, which were better than all other specimens.

4.2 Non-destructive tests on the self–cured geopolymer concrete

NDT is performed to access the mechanical and durability properties of the existing structures without impairing their utility and performance. In the present time, this method is adopted to check the internal quality of concrete without destructing the specimens. The UPV test has been performed to assess the discontinuity such as micro-crack, crack depth, and deterioration of concrete, in between the travel path of ultrasonic wave [12]. **Table 5** shows, The UPV for all specimens was more than 3.5 km/sec which points out the uniformity and homogeneity of the specimens. From the results, it was found that the concrete quality grading of all the samples was good, while, M-6, M-8 and M-9 were in excellent quality grading as per [47]. The rebound hammer test has been used to calculate the compressive strength of concrete without damaging it. The results of compressive strength obtained by rebound hammer were almost equal to that of the DT (**Table 5** and **Figure 1**).

The results presented in **Figure 6** and **Figure 7** show, the S/N curve pattern for NDT was approximately similar to the S/N curve for the compressive strength and water absorption (**Figure 4** and **Figure 5**). The S/N curves

(**Figure 6**) illustrates that with the increase in the ASM from 350 kg/m^3 to 450 kg/m^3, the UPV continuously increases, which informs the formation of a dense microstructure. The effect of the ASM on UPV also enlightens the reduction of the voids and cracks present in the concrete. However, UPV and compressive strength obtained by rebound hammer decrease with the increase of the SS/SH ratio. This can be attributed to the fact that excessive silicates also impede the travel of UPV, such that it reduces compressive strength by occluding the geopolymerization reaction. While with the increase in AL/ASM ratio and the molarity of SH, initially increases the compressive strength obtained by rebound hammer and UPV and then decreases, similar to the S/N curve for compressive strength and water absorption. The reduction of UPV after AL/ASM ratio 0.45, authenticates the availability of the more alkaline solution, which have a negative effect on the mechanical and durability properties of SCGC specimens.

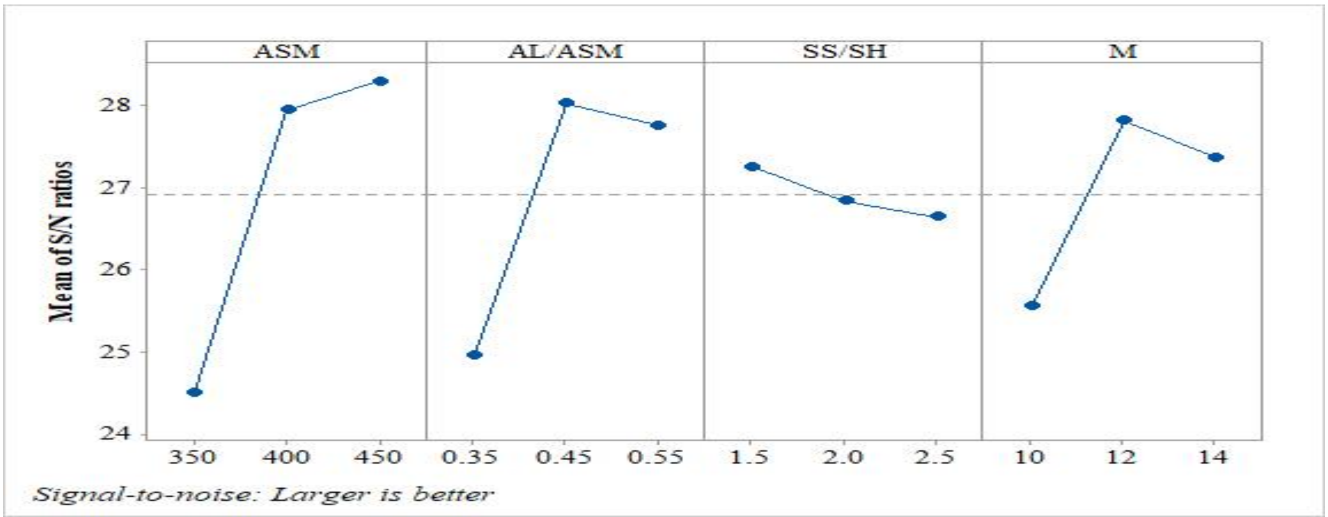

Figure 4: Signal-to-noise ratio curve for compressive strength.

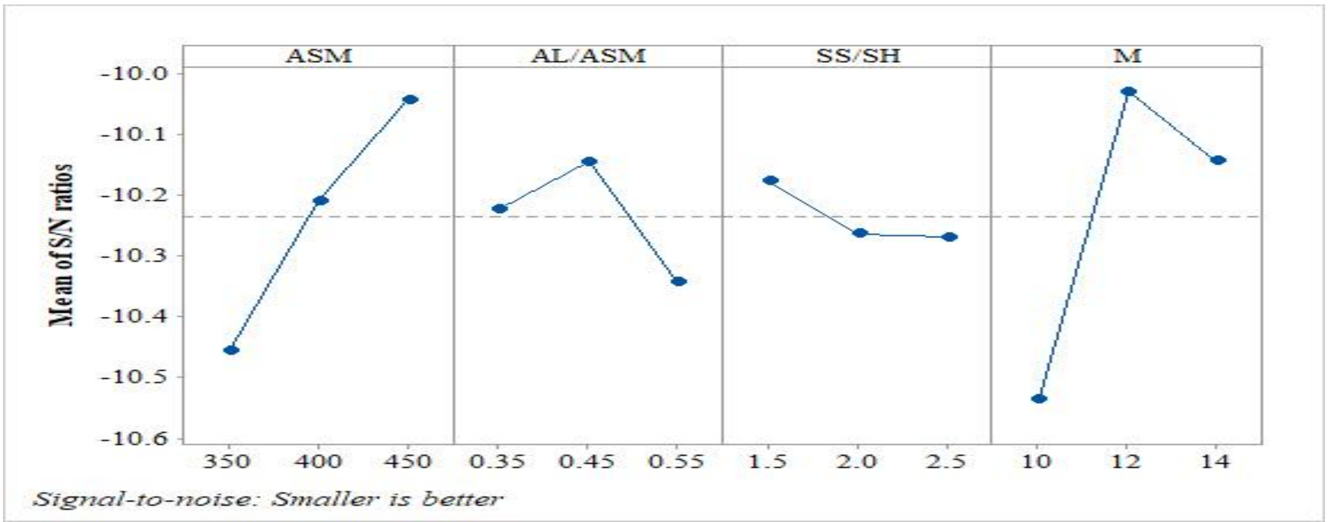

Figure 5: Signal-to-noise ratio curve for water absorption.

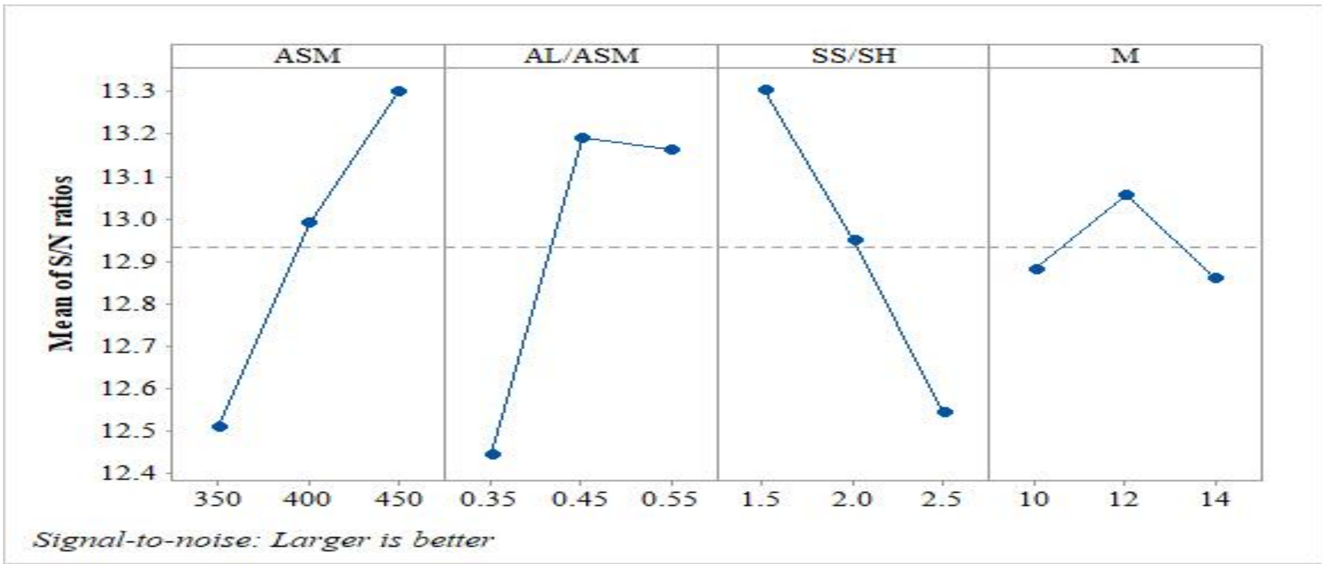

Figure 6: Signal-to-noise ratio curve for ultrasonic pulse velocity.

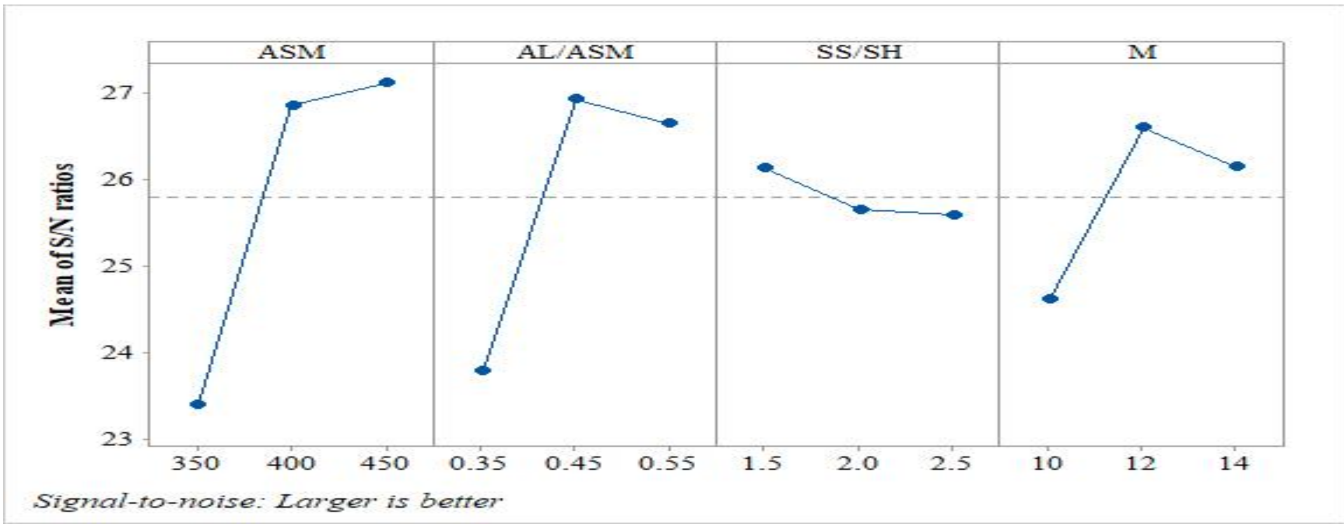

Figure 7: Signal-to-noise ratio curve for compressive strength obtained from the rebound hammer.

4.3 Prediction of compressive strength and water absorption of self–cured geopolymer concrete

Based on the obtained experimental results, mathematical equations were developed to predict the compressive strength (indicated as CS) and water absorption (indicated as WA) of SCGC specimens, using linear (equation (1) and (3)) and polynomial regression (equation (2) and (4)). In the linear and polynomial equation, compressive strength and water absorption were considered as the dependent variable, whereas key Variables such as ASM (indicated as B), AL/ASM ratio (indicated as A), SS/SH ratio (indicated as S) and molarity of SH (indicated as M) were selected as the independent variables. The results obtained by the linear and polynomial regression model were compared with the experimental results. The obtained linear and polynomial regression equations for compressive strength and water absorption are shown in **Table 6**.

Based on the coefficient of determination (R^2) values from the regression analysis, it can be concluded that polynomial regression analysis provides the most reliable results for compressive strength and water absorption as compared to linear regression and is also verified from **Table 7**. For the M-10 specimen, equations 2 and 4 predicted compressive strength and water absorption as 33.09MPa and 3.12%, respectively whereas, the experimental results reported that compressive strength and water absorption as 33.18MPa and 3.05%, respectively. **Table 8** compares the compressive strength values obtained by several researchers (specimens were cured in ambient condition and used only FA as the ASM) with the predicted compressive strength values from equation 2. It observed that equation 2 values were very close to the experimental results. The authors could not find any research articles to compare the water absorption results with equation 4.

Table 6: Equation for predicting compressive strength and water absorption

Equation	R^2 Value	Equation No.
CS = 0.0902B + 33.1A - 3.75S + 1.025M -32.8	0.74	(1)
CS =1.233B + 388.3A - 26.44S + 19.18M - 0.001429B^2 - 394.7A^2 + 5.673S^2 - 0.7567M^2- 421	1	(2)
WA = 4.140 - 0.001533B + 0.217A + 0.0333S-0.0367M	0.68	(3)
WA = 10.13 - 0.006867B - 4.433A + 0.2467S - 0.7367M + 0.000007B^2 + 5.167A^2 - 0.05333S^2 + 0.02917M^2	1	(4)

Table 7. Comparison of experimental and predicted results of compressive strength (MPa) and water absorption (%) of self–cured geopolymer concrete specimens.

Mix	Compressive Strength (MPa)			Water Absorption (%)		
	Experimental	Predicted by equation 1	Predicted by equation 2	Experimental	Predicted by equation 3	Predicted by equation 4
M-1	11.95	14.98	11.79	3.42	3.36	3.47
M-2	20.99	18.47	20.81	3.23	3.33	3.28
M-3	18.92	21.95	18.73	3.35	3.29	3.40
M-4	20.84	21.72	20.63	3.21	3.16	3.27
M-5	23.54	19.05	23.35	3.33	3.34	3.39
M-6	31.73	28.16	31.53	3.18	3.26	3.24
M-7	22.30	22.30	22.08	3.11	3.17	3.18
M-8	32.33	31.41	32.10	3.09	3.08	3.16
M-9	24.30	28.75	24.09	3.34	3.27	3.41
M-10	33.18	29.36	33.09	3.05	3.16	3.12

Table 8. Validation of the polynomial regression equation for compressive strength.

Reference	ASM (kg/m^3)	AL/ASM	SS/SH	SH (M)	Compressive Strength (MPa)	
					Experimental	Predicted
[21]	400	0.45	2.5	14	≈ 25	27.43
[50]	500	0.456	2.5	12	20.24	23.29
[51]	425	0.35	2.5	10	22.08	17.45
				12	24.65	22.52
				14	25.73	21.53
[52]	394.3	0.4	2.5	12	22.18	25.22

5. Conclusions

The ASM, the ratio between AL/ASM, SS/SH ratio, and molarity of SH were considered as the influencing Variables for the compressive strength and water absorption of SCGC specimens and optimized by the Taguchi approach. NDT was also performed on the SCGC specimens, along with experimental work mathematical regression equations has also been developed to predict the compressive strength and water absorption. Based on the experimental work, major outcomes can be summarized as follows:

1) It might be possible to construct an M25 grade of SCGC, without controlling humidity and temperature.
2) The SCGC specimen with 450 kg/m^3 ASM, 0.45 AL/ASM ratio, 1.5 SS/SH ratio, and 12 M SH have achieved maximum compressive strength (33.18 MPa) and minimum water absorption (3.05%) at room temperature curing, therefore it was considered as the optimum content of the key Variables.
3) The ASM and molarity of SH were the most effective factor for the compressive strength (47.14%) and water absorption (56.39%), respectively.
4) The UPV for all the SCGC specimens were more than 3.5 km/sec, which enlighten the uniformity and homogeneity of the specimens.
5) The compressive strength obtained from the NDT and DT were quite similar to each other, which corroborated the utility of NDT of Indian standards with GC.
6) The experimental results were most identically predicted by polynomial regression equations compared to the linear regression equations because of the higher degree of determination.

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Declarations

The lead author of this research declares that no funding agencies are involved in the complete study and also there are no conflicts of interest. The authors state that the data confirming the results of this experimental work is included in the paper.

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