Research Article

Study on the Production Factors in the Process of Production and Properties of Fly Ash-Based Coarse Aggregates

K. N. Shivaprasad¹ and Bibhuti Bhusan Das²

¹Department of Civil Engineering, JSS Science and Technology University, Mysuru 570006, India
²Department of Civil Engineering, National Institute of Technology Karnataka, Surathkal, Mangalore 575025, India

Correspondence should be addressed to K. N. Shivaprasad; shivaprasad.god@gmail.com

Received 19 April 2021; Revised 30 July 2021; Accepted 19 August 2021; Published 2 September 2021

1. Introduction

The statistic depicts global concrete production is approximately 5.3 billion cubic meters per year [1]. Typically, ordinary concrete contains about 70–80% aggregate, 12% cement, and 8% mixing water by mass [2]. On the other hand, the use of aggregates in the construction of aggregates is enormous. In the year 2019, global demand for construction aggregates was more than 51.7 billion tonnes, which is estimated to grow 5.2% annually. In India alone, it is predicted that consumption of aggregates is more than 5 billion metric tonnes in the year 2020 [3]. At present, the consumption rate of natural aggregates in global level has reached an alarming level. Hence, there is a necessity of producing an alternative and sustainable material which could replace the natural aggregates in concrete.

Many researchers have reported on the aggregates production using fly ash with suitable binding materials through artificial process [4]. In the production process, it is noted that different techniques are available such as agglomeration, expansion (bloating), pressing and crushing, etc., [4–6]. However, it is observed that the pelletization process is well developed agglomeration technique for producing artificial aggregates [4, 7–9]. However, the adoption of pelletization process in producing the artificial aggregates is still not being adopted widely by the construction industry and hence the production cost of artificial aggregates is found to be high as compared to the cost of natural aggregates.

For artificial fly ash aggregates it has been reported that production and properties of the aggregates mainly depend on the raw materials, size of the particles in the raw materials, type of binder, specific surface area, the wettability of particles, and production process involved [4, 9–14]. However, researchers reported that the engineering properties of produced fly ash aggregates are mainly influenced by the type and composition of binder used in the production process along with the dosage of the binder [12–14].
From the literature it is to be noted that the production process can be controlled in a better way with a disc type pelletizer as compared to other types of pelletizers such as drum or cone pelletizers [4, 11]. Furthermore, it is reported by the researchers that, in the pelletization process, different factors such as water content during pelletization, the angle of pelletizing disc, speed of pelletizing disc, and duration of the pelletization are the most influencing factors that affect the production process of aggregates [4, 11, 12]. The produced aggregates are subjected to different hardening methods such as sintering, normal water curing, cold bonding, steam curing, and autoclaving [4, 8, 10, 12–14].

The alkali activator solution, which acts as an activator in the geopolymerisation process, plays an important role in the surface hydrolysis of the raw material particles [15]. The alkaline solution with different types [15–19], concentrations [16–24], raw material to solution ratio [17, 25–27], and curing regime [15, 23, 24, 27, 28] has a significant influence in the geopolymerisation process. However, there are a limited number of studies reported in the literature on the utilization of alkaline solutions for the production of artificial fly ash aggregates, whereas the factors responsible for fly ash aggregates production through pelletization process, combined with the factors of geopolymerisation, are very much essential to understand the efficient and effective production.

To investigate the combined effect of geopolymerisation and pelletization factors on the properties of artificial fly ash aggregates, an experimental study is very much essential which could be carried out with the help of design of experiments. Various optimization techniques are available such as factorial designs [11, 29–33], central composites [34–36], response surface methodology [11, 35, 36], and Taguchi method [11, 37, 38]. Taguchi’s experimental design method is one of the best optimization methods defined by Genichi Taguchi which allows experimental trial runs to a small number and also to identify the influence of factors selected [11, 29]. Considering all the factors mentioned above, this experimental investigation was carried out to determine the combined effect of geopolymerisation and pelletization factors in the sustainable production of artificial aggregates using Taguchi’s experimental design method followed by grey relational analysis.

The production of the artificial aggregates is having different methods as per requirements or the end use in the products, whereas many researchers reported on the process with different raw materials as well as the different binders for the production of artificial aggregates. The present study is concentrated on the production process by pelletization technique and alkaline solution content and on characteristics of produced coarse aggregate simultaneously.

2. Materials and Methodology

2.1. Materials. Locally available fly ash was used in the production of artificial fly ash aggregate. The fly ash had a specific gravity of 2.20 and a specific surface area of 260.30 m²/kg. The chemical compositions are presented in Table 1 and the particle size distribution of fly ash analysed in the laboratory is presented in Figure 1. As per IS 3812 (Part 1) 2013 classification [39], fly ash has been classified as class F type. The laboratory grade sodium silicate solution (Na2SiO3) with alkali ratio (SiO2/Na2O) of 3.3 (8.0% Na2O, 26.5% SiO2, 65.5% H2O by mass) and sodium hydroxide (NaOH) flakes of 98% purity were used to prepare the alkaline solution.

2.2. Experimental Programme. The production of artificial aggregates is significantly affected by several factors such as type of alkali content and its dosage, raw material and its composition, and also the process of pelletization. In the present investigation, the raw material is fly ash and alkaline solution. To study the relative influence of several factors in the production process and aggregates properties, the following experimental programme was carried out.

The most influencing factors related to alkali content in geopolymerisation process and the factors related to geopolymerisation were identified as Na2O content, SiO2/Na2O ratio, water content, and curing methods [22–24, 26]. An increase of Na2O content and SiO2/Na2O ratio in alkaline solution will lead to higher level of binding property in the geopolymer [22–26]. The initial trial mixes were carried out with different composition of Na2O content from 3% to 7% (percentage of the mass of fly ash), water content from 18% to 22% (percentage of the mass of fly ash), and SiO2/Na2O ratio from 0.3 to 0.5. This alkaline solution was then sprayed to the pelletization disc. It was observed that, with increase in Na2O content (from 3 to 7%) and SiO2/Na2O ratio (from 0.3 to 0.5) with constant water content (21%), the alkaline solution was found to be highly viscous. This can be attributed to high content of solids in the solution [19, 40]. Hence, in the present study alkaline solution composition is restricted to 4 to 6% of Na2O content along with the varying SiO2/Na2O ratio from 0.3 to 0.5 and water content from 19% to 21%.

Furthermore, factors related to pelletization process such as the angle of pelleting disc, speed of pelleting disc, water content, and duration of the pelletization were identified [4, 7, 11]. The angle and speed of pelleting disc were varied from 35° to 55° with every 10° interval and 30 to 50 RPM with every 10 RPM interval, respectively. It is also observed from

2.1. Significance of the Study. The natural aggregates consumption is increasing rapidly because of the faster rate of infrastructure development worldwide. However, the mining of natural aggregates is creating a serious environmental imbalance. In the present situation, the challenge before the world is to have innovative and less carbon footprint materials for the construction industry. Hence, there is a need for an alternate material that can substitute the natural aggregate. Using artificial methods to produce substitute materials from industrial waste or byproducts will solve the disposal problem and at the same time, it is going to save natural resources. The use of artificially produced fly ash aggregate will gain significant importance for infrastructure development which can replace the naturally available materials.
the literature, for the formation of pellets, a minimum of 10 to 15 minutes is needed [7] and 12 to 18 minutes were selected with an interval variation of 3 minutes in the present study.

Although water content is a factor where both geopolymerisation and pelletization are getting affected, in the present study it was restricted; 19 to 21% of water content (\% is with respect to mass of fly ash) was selected based on the previous study [41]. The water added in the preparation of sodium hydroxide solution and water present in the sodium silicate solution together reference as the water content in the alkaline solution.

After the production of aggregates, it is subjected to different curing conditions as follows: (i) curing at ambient temperature (28 ± 2°C), (ii) heat curing at 80°C for 24 hours [15, 23, 24, 27, 42], and (iii) solution curing for 30 minutes [10] which will improve the properties of aggregates.

2.3. Design of Experiments with Taguchi’s Orthogonal Array. Experimental design was carried out using Taguchi’s orthogonal array. This orthogonal array was identified based on the factors and the levels which influence the most as described in the previous section and the same is presented in Table 2. In this phase the pelletization factors are allied with geopolymerisation factors and were investigated as the combined effect. The same was carried out with L27 (3^7) Taguchi orthogonal array to study the engineering properties of the artificial aggregates. The essential variables for each experimental trial run are labelled from TMC 1 to TMC 27 and they are presented in Table 3.

In the second phase, the response index for individual factor was analysed with the help of Minitab software to evaluate the response indices for all the selected factors from the experimental test results. Further, grey relational analysis of a statistical approach was analysed to understand the effect of combined factors from their responses all together in the production of sustainable aggregates.

2.4. Alkaline Solution Preparation. The required quantity of sodium hydroxide (NaOH) flakes was dissolved in normal tap water to prepare NaOH solution. The alkaline solution was prepared by mixing both NaOH solution and Na_2SiO_3 solution such that required proportions of Na_2O content (\%), water content (\%), and SiO_2/Na_2O ratio are maintained as per each trial mix provided in Table 3. With required proportion as specified in Table 3, alkaline solution is prepared and preserved in a closed container and allowed to cool, before using it in the production process.

2.5. Sustainable Aggregates Production. A laboratory scale disc pelletizer was used in this study [41, 42]. Pelletization was carried out in the following steps:

(i) The required proportion of alkaline solution was prepared
(ii) The necessary adjustment was made to the pelletizer
(iii) Weighed fly ash was transferred to the pelletizing disc
(iv) Required alkali solution was sprayed to the disc pelletizer directly within first three minutes during the pelletization process

2.6. Curing of Aggregates. In the present investigation artificially produced fly ash (APFA) aggregates were subjected to different curing conditions as per experimental programme and the details of each curing condition are as follows:

Ambient curing (A): the APFA aggregates through the pelletization process are kept at a temperature of 28 ± 2°C and relative humidity of 80% and were characterised at 14, 28, and 56 days.

Heat curing (H): the APFA aggregates through the pelletization process are allowed to set for 24 hours in ambient temperature conditions. After that, fly ash aggregates are subjected to a temperature of 80°C for 24
hours. Further, these aggregates are kept in ambient temperature conditions and were characterised at 14, 28, and 56 days.

Solution curing (S): the APFA aggregates through the pelletization process are first allowed to set for 24 hours in ambient temperature conditions. After that, fly ash aggregates are dipped in sodium silicate solution for 30 minutes. Further, these fly ash aggregates are kept in ambient temperature conditions and were characterised at 14, 28, and 56 days.

2.7. Testing on Aggregates. The pelletization efficiency in the aggregate production is calculated using equation (1). The particle size distribution in the production was determined using standard set of sieves (IS 383–2016) [43]:

$$\text{efficiency of pelletization} = \frac{\text{weight retained on the IS sieve no. 480}}{\text{total weight of materials used}} \times 100.$$

### Table 2: Different individual factors and their values considered in the study.

| Factors               | L1   | L2   | L3   |
|-----------------------|------|------|------|
| Na$_2$O content (%)   | 4    | 5    | 6    |
| SiO$_2$/Na$_2$O ratio | 0.3  | 0.4  | 0.5  |
| Water content (%)     | 19   | 20   | 21   |
| Speed of pelletizing disc (RPM) | 30   | 40   | 50   |
| Angle of pelletizing disc (°)  | 35   | 45   | 55   |
| Duration of pelletization (minutes) | 12   | 15   | 18   |
| Curing regime         | A    | H    | S    |

L: level; A: ambient temperature; H: heat cured; S: solution cured.

### Table 3: Combined factors and values used in the production trial runs.

| Trial runs | Na$_2$O content | SiO$_2$/Na$_2$O ratio | Water content | Speed of pelletizing disc | Angle of pelletizing disc | Duration of pelletization | Curing regime |
|------------|-----------------|-----------------------|---------------|--------------------------|--------------------------|--------------------------|---------------|
| TMC 1      | 4               | 0.3                   | 19            | 30                       | 35                       | 12                       | A             |
| TMC 2      | 4               | 0.3                   | 19            | 30                       | 45                       | 15                       | H             |
| TMC 3      | 4               | 0.3                   | 19            | 30                       | 55                       | 18                       | S             |
| TMC 4      | 4               | 0.4                   | 20            | 40                       | 35                       | 12                       | A             |
| TMC 5      | 4               | 0.4                   | 20            | 40                       | 45                       | 15                       | H             |
| TMC 6      | 4               | 0.4                   | 20            | 40                       | 55                       | 18                       | S             |
| TMC 7      | 4               | 0.5                   | 21            | 50                       | 35                       | 12                       | A             |
| TMC 8      | 4               | 0.5                   | 21            | 50                       | 45                       | 15                       | H             |
| TMC 9      | 4               | 0.5                   | 21            | 50                       | 55                       | 18                       | S             |
| TMC 10     | 5               | 0.3                   | 20            | 50                       | 35                       | 15                       | S             |
| TMC 11     | 5               | 0.3                   | 20            | 50                       | 45                       | 18                       | A             |
| TMC 12     | 5               | 0.3                   | 20            | 50                       | 55                       | 12                       | H             |
| TMC 13     | 5               | 0.4                   | 21            | 30                       | 35                       | 15                       | S             |
| TMC 14     | 5               | 0.4                   | 21            | 30                       | 45                       | 18                       | A             |
| TMC 15     | 5               | 0.4                   | 21            | 30                       | 55                       | 12                       | H             |
| TMC 16     | 5               | 0.5                   | 19            | 40                       | 35                       | 15                       | S             |
| TMC 17     | 5               | 0.5                   | 19            | 40                       | 45                       | 18                       | A             |
| TMC 18     | 5               | 0.5                   | 19            | 40                       | 55                       | 12                       | H             |
| TMC 19     | 6               | 0.3                   | 21            | 40                       | 35                       | 18                       | S             |
| TMC 20     | 6               | 0.3                   | 21            | 40                       | 45                       | 12                       | S             |
| TMC 21     | 6               | 0.3                   | 21            | 40                       | 55                       | 15                       | A             |
| TMC 22     | 6               | 0.4                   | 19            | 50                       | 35                       | 18                       | H             |
| TMC 23     | 6               | 0.4                   | 19            | 50                       | 45                       | 12                       | S             |
| TMC 24     | 6               | 0.4                   | 19            | 50                       | 55                       | 15                       | A             |
| TMC 25     | 6               | 0.5                   | 20            | 30                       | 35                       | 18                       | H             |
| TMC 26     | 6               | 0.5                   | 20            | 30                       | 45                       | 12                       | S             |
| TMC 27     | 6               | 0.5                   | 20            | 30                       | 55                       | 15                       | A             |
The APFA aggregates were assessed for basic engineering properties such as water absorption, aggregate impact value, and aggregate crushing value as per IS 2386 [44, 45]. Crushing strength of individual pellet was estimated using a compression testing machine (ring type unconfined compression test apparatus) and crushing strength (σ) of fly ash aggregate was calculated from the following equation [7]:

\[
\sigma = \frac{2.8 \times P}{\pi \times x^2},
\]

where \(P\) represents the failure load on the pellet and \(x\) is the size of pellets.

3. Experimental Results

Sustainable aggregates are artificially produced as explained in aggregate production section with trial runs as described in experimental program and they were evaluated for their production efficiency, particle size distribution, and engineering properties.

The experimental results were obtained at end of 14, 28, and 56 days; however, for the sake of brevity only 56 days’ results are discussed in the subsequent sections.

3.1. Efficiency and the Particle Size Distribution of the Aggregate. The pelletization efficiency of the produced aggregates with respect to water content was estimated using equation (1) and it is presented in Figure 2. It can be observed from Figure 2 that the efficiency is increased from 77.96% to 96.41% as water content increased from 19 to 21%.

The distribution of aggregates size in the production of fly ash aggregates with respect to different water content used is compared with nominal size of 20 mm graded aggregates as per IS 383–2016 [43] and presented in Figure 3. From Figure 3, it is observed that production of aggregates has a significant influence on the particle size distribution in production process. However, the APFA aggregates particle size distribution is within the limits of IS 383–2016 standards [43].

3.2. Specific Gravity and Bulk Density. The APFA aggregates which are subjected to different curing conditions were assessed for specific gravity, bulk density, and percentage of voids. The average value of apparent specific gravity, saturated surface dry specific gravity, loose and compacted bulk density of aggregates, and percentage of voids for different fly ash aggregates subjected to curing conditions are presented in Table 4.

3.3. Aggregates Impact Value. The response indices are determined from the experimental test results and the response index relationship for aggregate impact value with combined factors is presented in Figure 4. From Figure 4, it can be observed that, with increase in \(Na_2O\) content from 4% to 6%, aggregate impact value is improved from 27.88% to 22.78% at 56 days. Similarly increase in \(SiO_2/Na_2O\) ratio from 0.3 to 0.4 has improved the aggregate impact value from 26.71% to 25.47%, further increase of \(SiO_2/Na_2O\) ratio from 0.4 to 0.5 has marginal effect, and heat curing of artificially produced aggregates has significantly improved the aggregate impact value 23.69% when compared to aggregate impact values of 28.74% and 25.58% for ambient cured and solution cured aggregates at 56 days. The aggregate impact value gets marginally improved from 25.83% to 24.98% at 56 days with an increase in water content from 19% to 20%; further increase in the water content from 20% to 21% was found to have an adversarial effect on the aggregates impact value that decreased from 24.98% to 27.21% at 56 days. It is also noted from Figure 4 that the aggregates impact value has marginally improved from 25.93% to 25.59% due to the increase in the speed of pelletizing disc from 30 RPM to 50 RPM. Further increase in the angle of pelletizing disc from 35° to 55° and duration of pelletization of 12 to 18 minutes has shown the negligible improve on the aggregate impact values from 26.04% to 25.96% and 26.08% to 26.25% at 56 days, respectively.

3.4. Aggregate Crushing Value. The experimental test results are used to determine the response indices and the response index relationship for aggregate crushing value with combined factors is presented in Figure 5. From Figure 5, it can be observed that, with the geopolymerisation factors such as \(Na_2O\) content increase from 4% to 6%, aggregate crushing value is improved from 27.21% to 23.92% at 56 days. Similarly, increase in \(SiO_2/Na_2O\) ratio from 0.3 to 0.5 has marginally improved the aggregate crushing value from 26.72% to 25.33% at 56 days. It is also observed that heat curing and solution curing of aggregates have significantly improved the aggregate crushing value of 23.37% and 25.34%, respectively, at 56 days when compared to the aggregates crushing value 28.72% at 56 days of ambient cured fly ash aggregates. Aggregates crushing value has declined from 25.13% to 26.35% at 56 days due to increase in the water content in the trial mixes. However, from Figure 5, response indices of pelletization factors indicate that the duration of pelletization of 12 to 18 minutes has improved the aggregates crushing value from 26.62% to 24.17% at 56 days. Further, increase in speed of pelletizing disc from 30 RPM to 50 RPM and angle of pelletizing disc from 35° to 55° has negligible improvement on the aggregate crushing value from 26.01% to 25.93% and 25.93% to 25.98%, respectively, at 56 days.

3.5. Crushing Strength of Individual Pellets. The response indices are calculated from the experimental test results and the response index relationship for the crushing strength of individual pellets with combined factors is presented in Figure 6. From Figure 6, it can be observed that, with the geopolymerisation factors such as the \(Na_2O\) content increase from 4% to 6%, crushing strength of individual pellets is improved from 3.04 MPa to 3.79 MPa at 56 days. Similarly, increase of \(SiO_2/Na_2O\) ratio from 0.3 to 0.5 has improved the crushing strength of individual pellets from 3.24 MPa to 3.57 MPa at 56 days and heat curing has significantly improved the pellets crushing strength value to 3.81 MPa when
compared to crushing strength of individual pellets values 3.08 MPa and 3.28 MPa of ambient cured and solution cured aggregates at 56 days. Aggregate crushing strength of individual pellets has declined from 3.50 MPa to 3.21 MPa at 56 days with increase in the water content from 19% to 21%.

It can be also understood from Figure 6 that pelletization factors response indices indicate a trivial improvement in pellets crushing strength from 3.36 MPa to 3.49 MPa due to the increase in the duration of pelletization from 12 to 18 minutes. However, increase in the angle of pelletizing disc from 35° to 55° and speed of pelletizing disc from 30 RPM to 50 RPM has shown the negligible improvement on the pellets crushing strength from 3.38 MPa to 3.39 MPa and 3.39 MPa to 3.41 MPa, respectively, at 56 days.

3.6. Water Absorption. The experimental test results are used to determine the response indices and the response index relationship for water absorption with combined factors is presented in Figure 7. From Figure 7, it is found that, with geopolymerisation factors such as Na₂O content from 4% to 6%, water absorption value improved from 11.37% to 9.04% and with increase in SiO₂/Na₂O ratio from 0.3 to 0.5 the water absorption also reduced from 10.91% to 9.92% at 56 days. It is also observed that solution curing of artificially produced aggregates has significantly reduced the water absorption value to 8.42% when compared to water absorption values of 10.58% and 12.44% for ambient cured and heat cured aggregates at 56 days. However, increase in speed of pelletizing disc from 30 RPM to 50 RPM and change in the angle of pelletizing disc from 35° to 55° have improved the water absorption of aggregates marginally from 10.47% to 9.82% and 10.76% to 10.26%, respectively, at 56 days. It is observed that duration of pelletization of 12 to 18 minutes has the water absorption values of 10.42% to 10.68% which has negligible effect on water absorption of aggregates.

4. Grey Relational Analysis

Sahoo et al. have presented the advantages of grey relational analysis in categorizing the most influencing parameters with respect to the material properties [46]. In this investigation, experimental test results on the APFA aggregates were considered as responses and grey relational analysis was carried out as follows.

4.1. Determination of Grey Relational Generations. The aggregate properties results such as aggregate impact value, aggregate crushing value, crushing strength of individual pellets, and water absorption are considered as responses for the grey relational analysis. In this analysis, standardization of responses is carried out such that the lower the obtained value for the produced aggregates the better for aggregate impact value, aggregate crushing value, and water absorption, whereas the higher value obtained is better for crushing strength of individual pellets of APFA aggregates. Grey relational generation was obtained with the experimental values to scale of 0–1 and it was calculated using equation (3). Computed grey relational generations on the responses are presented in Tables 5–7 at different curing ages.

$$x_i = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)}$$ (3)

where $x_i(k) =$ value after the GRG; $\min y_i(k) =$ smallest value of $y_i(k)$ for the $k^{th}$ response; and $\max y_i(k) =$ largest value of $y_i(k)$ for the $k^{th}$ response.

4.2. Assessment of Grey Relational Coefficients and Grey Relational Grades. The assessment of Grey relational
Figure 4: Response index relationship for aggregate impact value with combined factors.
Figure 5: Response index relationship for aggregate crushing value with combined factors.
Figure 6: Response index relationship for crushing strength of individual pellets with combined factors.
Figure 7: Response index relationship for water absorption with combined factors.
| Runs   | Aggregate impact value | Aggregate relational generations | Water absorption | Aggregate crushing value | Crushing strength of pellets | Aggregate relational coefficients | Grey relational grade \( (\gamma_i) \) | Water absorption |
|-------|------------------------|---------------------------------|----------------|--------------------------|----------------------------|---------------------------------|-------------------|----------------|
| TMC 1 | 0.000                  | 0.36                            | 0.100          | 0.129                    | 1.000                      | 0.964                           | 0.900             | 0.871          |
| TMC 2 | 0.516                  | 0.514                           | 0.508          | 0.235                    | 0.484                      | 0.486                           | 0.492             | 0.765          |
| TMC 3 | 0.236                  | 0.197                           | 0.198          | 0.412                    | 0.764                      | 0.803                           | 0.802             | 0.588          |
| TMC 4 | 0.164                  | 0.032                           | 0.000          | 0.329                    | 0.836                      | 0.968                           | 1.000             | 0.671          |
| TMC 5 | 0.695                  | 0.538                           | 0.321          | 0.165                    | 0.305                      | 0.462                           | 0.679             | 0.835          |
| TMC 6 | 0.390                  | 0.321                           | 0.136          | 0.388                    | 0.610                      | 0.679                           | 0.864             | 0.612          |
| TMC 7 | 0.072                  | 0.000                           | 0.060          | 0.588                    | 0.928                      | 1.000                           | 0.940             | 0.412          |
| TMC 8 | 0.478                  | 0.442                           | 0.345          | 0.200                    | 0.522                      | 0.558                           | 0.655             | 0.800          |
| TMC 9 | 0.129                  | 0.149                           | 0.169          | 0.729                    | 0.871                      | 0.851                           | 0.831             | 0.271          |
| TMC 10| 0.346                  | 0.245                           | 0.079          | 0.588                    | 0.654                      | 0.755                           | 0.921             | 0.412          |
| TMC 11| 0.179                  | 0.052                           | 0.097          | 0.353                    | 0.821                      | 0.948                           | 0.903             | 0.647          |
| TMC 12| 0.689                  | 0.586                           | 0.612          | 0.153                    | 0.311                      | 0.414                           | 0.388             | 0.847          |
| TMC 13| 0.094                  | 0.213                           | 0.174          | 0.600                    | 0.906                      | 0.787                           | 0.826             | 0.400          |
| TMC 14| 0.138                  | 0.036                           | 0.129          | 0.471                    | 0.862                      | 0.964                           | 0.871             | 0.529          |
| TMC 15| 0.519                  | 0.510                           | 0.429          | 0.000                    | 0.481                      | 0.490                           | 0.571             | 1.000          |
| TMC 16| 0.336                  | 0.522                           | 0.204          | 0.647                    | 0.664                      | 0.478                           | 0.796             | 0.353          |
| TMC 17| 0.239                  | 0.209                           | 0.160          | 0.376                    | 0.761                      | 0.791                           | 0.840             | 0.624          |
| TMC 18| 0.519                  | 0.470                           | 0.483          | 0.247                    | 0.481                      | 0.530                           | 0.517             | 0.753          |
| TMC 19| 0.717                  | 0.795                           | 0.597          | 0.329                    | 0.283                      | 0.205                           | 0.403             | 0.671          |
| TMC 20| 0.396                  | 0.165                           | 0.177          | 0.612                    | 0.604                      | 0.835                           | 0.823             | 0.388          |
| TMC 21| 0.305                  | 0.261                           | 0.166          | 0.447                    | 0.695                      | 0.739                           | 0.834             | 0.553          |
| TMC 22| 1.000                  | 1.000                           | 0.605          | 0.388                    | 0.000                      | 0.395                           | 0.612             | 1.000          |
| TMC 23| 0.594                  | 0.333                           | 0.496          | 0.824                    | 0.406                      | 0.667                           | 0.504             | 0.176          |
| TMC 24| 0.381                  | 0.205                           | 0.194          | 0.788                    | 0.619                      | 0.795                           | 0.806             | 0.212          |
| TMC 25| 0.925                  | 0.871                           | 1.000          | 0.235                    | 0.075                      | 0.129                           | 0.000             | 0.765          |
| TMC 26| 0.462                  | 0.305                           | 0.273          | 1.000                    | 0.538                      | 0.695                           | 0.727             | 0.000          |
| TMC 27| 0.355                  | 0.036                           | 0.285          | 0.753                    | 0.645                      | 0.964                           | 0.715             | 0.247          |
| Runs  | Grey relational generations | Δoi  | Grey relational coefficients | Water absorption | Grey relational grade (yi) |
|-------|-----------------------------|------|-----------------------------|----------------|--------------------------|
| TMC 1 | 0.132                       | 0.058| 0.092                       | 0.167          | 0.868                    |
| TMC 2 | 0.431                       | 0.602| 0.475                       | 0.117          | 0.569                    |
| TMC 3 | 0.268                       | 0.394| 0.239                       | 0.333          | 0.732                    |
| TMC 4 | 0.000                       | 0.149| 0.000                       | 0.222          | 1.000                    |
| TMC 5 | 0.637                       | 0.593| 0.309                       | 0.000          | 0.363                    |
| TMC 6 | 0.298                       | 0.473| 0.088                       | 0.346          | 0.702                    |
| TMC 7 | 0.275                       | 0.000| 0.095                       | 0.407          | 0.725                    |
| TMC 8 | 0.420                       | 0.485| 0.283                       | 0.080          | 0.380                    |
| TMC 9 | 0.108                       | 0.382| 0.176                       | 0.525          | 0.892                    |
| TMC 10| 0.403                       | 0.340| 0.114                       | 0.630          | 0.597                    |
| TMC 11| 0.098                       | 0.041| 0.266                       | 0.469          | 0.902                    |
| TMC 12| 0.671                       | 0.618| 0.554                       | 0.154          | 0.329                    |
| TMC 13| 0.183                       | 0.485| 0.258                       | 0.451          | 0.817                    |
| TMC 14| 0.251                       | 0.100| 0.033                       | 0.346          | 0.749                    |
| TMC 15| 0.468                       | 0.622| 0.540                       | 0.006          | 0.532                    |
| TMC 16| 0.498                       | 0.602| 0.190                       | 0.525          | 0.502                    |
| TMC 17| 0.149                       | 0.207| 0.193                       | 0.290          | 0.851                    |
| TMC 18| 0.414                       | 0.618| 0.423                       | 0.136          | 0.586                    |
| TMC 19| 0.569                       | 0.813| 0.499                       | 0.160          | 0.431                    |
| TMC 20| 0.424                       | 0.515| 0.115                       | 0.660          | 0.576                    |
| TMC 21| 0.386                       | 0.573| 0.188                       | 0.432          | 0.614                    |
| TMC 22| 1.000                       | 0.946| 0.613                       | 0.358          | 0.000                    |
| TMC 23| 0.786                       | 0.701| 0.495                       | 0.920          | 0.214                    |
| TMC 24| 0.600                       | 0.295| 0.153                       | 0.654          | 0.400                    |
| TMC 25| 0.851                       | 1.000| 1.000                       | 0.235          | 0.149                    |
| TMC 26| 0.736                       | 0.432| 0.364                       | 1.000          | 0.264                    |
| TMC 27| 0.525                       | 0.299| 0.351                       | 0.821          | 0.475                    |
Table 7: Grey relational generation, grey relational coefficients, and grey relational grade for different trial runs at 56 days.

| Runs | Grey relational generations | Grey relational coefficients | Grey relational grade (yi) |
|------|----------------------------|----------------------------|--------------------------|
|      | Aggregate impact value | Aggregate crushing value | Crushing strength of pellets | Water absorption | Aggregate impact value | Aggregate crushing value | Crushing strength of pellets | Water absorption | Aggregate impact value | Aggregate crushing value | Crushing strength of pellets | Water absorption | Grey relational grade (yi) |
| TMC 1 | 0.106 | 0.032 | 0.000 | 0.163 | 0.894 | 0.968 | 1.000 | 0.837 | 0.359 | 0.341 | 0.333 | 0.374 | 0.374 | 0.352 |
| TMC 2 | 0.413 | 0.498 | 0.511 | 0.068 | 0.587 | 0.502 | 0.489 | 0.932 | 0.460 | 0.499 | 0.506 | 0.349 | 0.453 |
| TMC 3 | 0.364 | 0.330 | 0.155 | 0.524 | 0.636 | 0.670 | 0.845 | 0.476 | 0.440 | 0.427 | 0.372 | 0.512 | 0.438 |
| TMC 4 | 0.099 | 0.045 | 0.055 | 0.143 | 0.901 | 0.955 | 0.945 | 0.857 | 0.357 | 0.344 | 0.346 | 0.368 | 0.354 |
| TMC 5 | 0.650 | 0.575 | 0.202 | 0.000 | 0.350 | 0.425 | 0.798 | 1.000 | 0.588 | 0.540 | 0.385 | 0.333 | 0.462 |
| TMC 6 | 0.459 | 0.516 | 0.147 | 0.537 | 0.541 | 0.484 | 0.853 | 0.463 | 0.480 | 0.508 | 0.370 | 0.519 | 0.469 |
| TMC 7 | 0.173 | 0.000 | 0.048 | 0.469 | 0.827 | 1.000 | 0.952 | 0.531 | 0.377 | 0.333 | 0.344 | 0.485 | 0.385 |
| TMC 8 | 0.470 | 0.543 | 0.242 | 0.129 | 0.330 | 0.457 | 0.758 | 0.871 | 0.485 | 0.522 | 0.397 | 0.365 | 0.442 |
| TMC 9 | 0.205 | 0.385 | 0.229 | 0.701 | 0.795 | 0.615 | 0.711 | 0.299 | 0.386 | 0.448 | 0.394 | 0.626 | 0.463 |
| TMC 10 | 0.438 | 0.271 | 0.106 | 0.735 | 0.562 | 0.729 | 0.894 | 0.265 | 0.471 | 0.407 | 0.359 | 0.653 | 0.472 |
| TMC 11 | 0.152 | 0.109 | 0.167 | 0.367 | 0.848 | 0.891 | 0.833 | 0.633 | 0.371 | 0.359 | 0.375 | 0.441 | 0.387 |
| TMC 12 | 0.657 | 0.525 | 0.526 | 0.129 | 0.343 | 0.475 | 0.474 | 0.871 | 0.593 | 0.513 | 0.513 | 0.365 | 0.496 |
| TMC 13 | 0.191 | 0.448 | 0.266 | 0.524 | 0.809 | 0.552 | 0.734 | 0.476 | 0.382 | 0.475 | 0.405 | 0.512 | 0.444 |
| TMC 14 | 0.304 | 0.122 | 0.150 | 0.313 | 0.696 | 0.878 | 0.850 | 0.687 | 0.418 | 0.363 | 0.370 | 0.421 | 0.393 |
| TMC 15 | 0.470 | 0.566 | 0.430 | 0.054 | 0.530 | 0.434 | 0.570 | 0.946 | 0.485 | 0.535 | 0.467 | 0.346 | 0.458 |
| TMC 16 | 0.611 | 0.787 | 0.310 | 0.578 | 0.389 | 0.213 | 0.690 | 0.422 | 0.563 | 0.702 | 0.420 | 0.542 | 0.557 |
| TMC 17 | 0.000 | 0.308 | 0.302 | 0.265 | 1.000 | 0.692 | 0.698 | 0.735 | 0.333 | 0.419 | 0.417 | 0.405 | 0.394 |
| TMC 18 | 0.449 | 0.525 | 0.467 | 0.177 | 0.551 | 0.475 | 0.533 | 0.823 | 0.476 | 0.513 | 0.484 | 0.378 | 0.463 |
| TMC 19 | 0.611 | 0.842 | 0.479 | 0.095 | 0.389 | 0.158 | 0.521 | 0.905 | 0.563 | 0.759 | 0.490 | 0.356 | 0.542 |
| TMC 20 | 0.562 | 0.371 | 0.220 | 0.810 | 0.438 | 0.629 | 0.780 | 0.190 | 0.533 | 0.443 | 0.390 | 0.724 | 0.523 |
| TMC 21 | 0.378 | 0.348 | 0.183 | 0.401 | 0.622 | 0.652 | 0.817 | 0.599 | 0.446 | 0.434 | 0.380 | 0.455 | 0.429 |
| TMC 22 | 1.000 | 1.000 | 0.653 | 0.449 | 0.000 | 0.000 | 0.000 | 0.347 | 0.551 | 1.000 | 1.000 | 0.590 | 0.476 | 0.766 |
| TMC 23 | 0.724 | 0.729 | 0.606 | 0.939 | 0.276 | 0.271 | 0.394 | 0.061 | 0.645 | 0.648 | 0.559 | 0.891 | 0.686 |
| TMC 24 | 0.576 | 0.407 | 0.307 | 0.707 | 0.424 | 0.593 | 0.693 | 0.293 | 0.541 | 0.458 | 0.419 | 0.631 | 0.512 |
| TMC 25 | 0.880 | 0.977 | 1.000 | 0.320 | 0.120 | 0.023 | 0.000 | 0.680 | 0.806 | 0.957 | 1.000 | 0.424 | 0.797 |
| TMC 26 | 0.845 | 0.611 | 0.462 | 1.000 | 0.155 | 0.389 | 0.538 | 0.000 | 0.763 | 0.562 | 0.482 | 1.000 | 0.702 |
| TMC 27 | 0.604 | 0.321 | 0.529 | 0.864 | 0.396 | 0.679 | 0.471 | 0.136 | 0.558 | 0.424 | 0.515 | 0.786 | 0.571 |
coefficients (GRC) plays a vital role in grey relational analysis, which correlates the desired and actual obtained results. The GRC was calculated by using equation (4) and computed GRC are presented in Tables 5–7 with respect to different trial runs at different curing ages.

\[
\xi_i(k) = \frac{\Delta_{\text{min}} + \psi \Delta_{\text{max}}}{\Delta_{\text{min}} + \psi \Delta_{\text{max}}} \tag{4}
\]

where \(\Delta_{\text{min}} = \|x_0(k) - x_i(k)\|\) is the difference of the absolute value between \(x_0(k)\) and \(x_i(k)\) and \(\Delta_{\text{max}}\) and \(\Delta_{\text{min}}\) = maximum and minimum values of the absolute differences of all comparing sequences, respectively. \(\psi\) is a distinguishing coefficient \((0 \leq \psi \leq 1)\) and in the present study, \(\psi = 0.5\) is taken.

The Grey relational grade (GRG) \(\gamma_i\) is calculated using equation (5) and presented in Tables 5–7 at various curing ages. If the Grey relational grade is higher it signifies a stronger relational degree between the investigated trial run and the ideal sequence.

\[
\gamma_i = \frac{1}{n} \sum_{k=1}^{n} AP(k) \xi_i(k) \tag{5}
\]

where \(n\) = number of process responses.

The GRC was computed for individual factors with respect to combined factors and the values of GRC are presented in Table 8. From Table 8, it is observed that the highest GRG among the geopolymerisation factors is 6% of Na₂O content (level 3) followed by curing regime–heat curing (level 2) and 0.5 of SiO₂/Na₂O ratio (level 3) and among the pelletization factors the highest GRG is observed for angle of pelletization disc (level 1) and followed by 18 minutes of duration of pelletization (level 3) and speed of pelletization disc at 50 RPM (level 3). Whereas water content is the important factor which plays important role in geopolymerisation and pelletization process, it is observed that higher GRG is observed for 20% of water content (level 2).

The level of significance of each individual factor is estimated through difference of maximum and minimum values. It is ranked according to the higher differences in the values of Grey relational grade and is presented in Table 8. From the table, based on the rank given in the grey relational analysis for the geopolymerisation factors, it clearly indicates that the curing regime and higher Na₂O content have major role in the aggregates production at early ages. However, the higher Na₂O content plays significant role in improving the engineering properties of the produced aggregates. Further, it is observed that curing regime rank is changed since solution curing of produced aggregates has improved overall engineering properties of aggregates at later ages. It is clear that, in the fly ash aggregate production with alkaline solution, Na₂O content, curing regime, and SiO₂/Na₂O ratio play major role in the rate of geopolymerisation of fly ash. Further, the GRG for factors of pelletization such as speed of pelletizing disc, angle of pelletizing disc, and duration of pelletization has relatively less influence as compared to the factors of geopolymerisation such as Na₂O content, SiO₂/Na₂O ratio, water content, and curing regime in the production of artificial aggregates. However, water content plays a prominent and dual role in geopolymerisation process and pelletization which acts as a medium in the process.

### 5. Discussion

The response indices of individual properties of aggregates from Figures 4 to 7 and combined effect in the grey relational analysis from Table 8 clearly show that higher Na₂O content, higher SiO₂/Na₂O ratio, and heat curing have significant
influence on the properties of APFA aggregates due to higher rate of geopolymerisation [15, 24]. Whereas the heat curing of aggregates increased the water absorption in the aggregates, solution curing has significantly improved water absorption in the aggregates which can be observed in the response indices in Figure 7, which corresponds to the higher degree of geopolymerisation of fly ash particles on the surface of the aggregates [10, 15, 24]. On the other hand, response indices of individual aggregates properties with different pelletization factors observed in Figures 4 to 7 and grey relational analysis from Table 8 clearly showed that the influence of the pelletization factors on the aggregate properties is negligible.

Further, it is observed that water content played an important role in the production process and to attain the necessary engineering properties of APFA aggregates due to following reasons. Firstly, in production stage, as the water content increases from 19% to 21%, the efficiency of production improved and particle size distribution of produced aggregates has marginally shifted towards coarser side. It is also observed from response indices of individual properties of aggregates from Figures 4 to 7 and combined effect in the grey relational analysis from Table 8 that an increase in water content from 19% to 21% has marginal and adverse effect on the properties of the APFA aggregates. In the geopolymerisation process of APFA aggregates, this water content may be used in early surface hydrolysis of fly ash particles or insufficient water for surface hydrolysis of fly ash which lead to less contribution to mechanical strength [17, 47, 48].

6. Conclusions

From this experimental study, it can be concluded that water content in alkaline solution plays a major role in the production process of the artificial aggregates and also to their engineering properties. Water content of 20% by mass of fly ash was found to be essential for the suitable production of artificial aggregates. It is observed that engineering properties of produced aggregates are very much sensitive to the factors of the geopolymerisation such as Na2O content, SiO2/Na2O ratio, and curing regime. The most vital factors such as Na2O content and heat curing improved the engineering properties at an early age attributed to the faster rate of degree of polymerisation. However, solution curing of produced aggregates has improved overall engineering properties of aggregates at later ages due to continuous geopolymerisation process, since the aggregates have absorbed sodium silicate solution during the curing period and that contributes to engineering properties at later ages. Further, statistically designed experiments showed that geopolymerisation factors have significantly influenced the engineering properties of the APFA aggregates as compared to the pelletization factors.

Data Availability

The experimental data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Authors’ Contributions

The manuscript has been read and approved by all authors.

References

[1] A. Hasanbeigi, L. Price, and E. Lin, “Emerging energy-efficiency and CO2 emission-reduction technologies for cement and concrete production: a technical review,” Renewable and Sustainable Energy Reviews, vol. 16, no. 8, pp. 6220–6238, 2012.
[2] P. K. Mehta, “Greening of the concrete industry for sustainable development,” Concrete International, vol. 24, no. 7, pp. 23–28, 2002.
[3] Freedonia, World Construction Aggregates – Industry Study with Forecasts for 2019 and 2024, The Freedonia Group, Cleveland, OH, USA, 2019.
[4] G. Baykal and A. G. Döven, “Utilization of fly ash by pelletization process; theory, application areas and research results,” Resources, Conservation and Recycling, vol. 30, no. 1, pp. 59–77, 2000.
[5] J. L. Clarke, Structural Lightweight Aggregate concrete, pp. 7–12, CRC Press; Taylor & Francis Group, Boca Raton, FL, US, 2014 Apr 21.
[6] C. Gunasekara, S. Setunge, D. W. Law, N. Willis, and T. Burt, “Engineering properties of geopolymer aggregate concrete,” Journal of Materials in Civil Engineering, vol. 30, no. 11, Article ID 04018299, 2018 Aug 30.
[7] P. Gomathi and A. Sivakumar, “Characterization on the strength properties of pelletized fly ash aggregate,” ARPN Journal of Engineering and Applied Sciences, vol. 7, no. 11, pp. 1523–1532, 2012.
[8] P. Priyadharshini, G. Mohan Ganesh, and A. S. Santhi, “Experimental study on cold bonded fly ash aggregates,” International Journal of Civil and Structural Engineering, vol. 2, no. 2, pp. 493–501, 2011.
[9] K. Ramamurthy and K. I. Harikrishnan, “Influence of binders on properties of sintered fly ash aggregate,” Cement and Concrete Composites, vol. 28, no. 1, pp. 33–38, 2006.
[10] M. Gesoglu, T. Ozturan, and E. Guneyisi, “Effects of fly ash properties on characteristics of cold-bonded fly ash lightweight aggregates,” Construction and Building Materials, vol. 21, no. 9, pp. 1869–1878, 2007.
[11] K. I. Harikrishnan and K. Ramamurthy, “Influence of pelletization process on the properties of fly ash aggregates,” Waste Management, vol. 26, no. 8, pp. 846–852, 2006.
[12] P. Gomathi and A. Sivakumar, “Fly ash based lightweight aggregates incorporating clay binders,” Indian Journal of Engineering and Materials Sciences, vol. 21, no. 2, pp. 227–232, 2014.
[13] N. U. Kockal and T. Ozturan, “Characteristics of lightweight fly ash aggregates produced with different binders and heat treatments,” Cement and Concrete Composites, vol. 33, no. 1, pp. 61–67, 2011.
[14] R. Manikandan and K. Ramamurthy, “Effect of curing method on characteristics of cold bonded fly ash aggregates,” Cement and Concrete Composites, vol. 30, no. 9, pp. 848–853, 2008.
[15] B. V. Rangan, D. Hardjito, E. W. Steenie, and M. J. S. Dody, “Studies on fly ash-based geopolymer concrete,” Proceedings...
Advances in Civil Engineering

of the World Congress Geopolymer, Saint Quentin, France, vol. 28, pp. 133–137, 2005.

[16] J. Davidovits, "Geopolymers and geopolymeric materials," Journal of Thermal Analysis, vol. 35, no. 2, pp. 429–441, 1989.

[17] D. Khale and R. Chaudhary, "Mechanism of geo-polymerization and factors influencing its development: a review," Journal of Materials Science, vol. 42, no. 3, pp. 729–746, 2007.

[18] M. Komjjenovic, Z. Bascarevic, and V. Bradic, "Mechanical and microstructural properties of alkali-activated fly ash geopolymers," Journal of Hazardous Materials, vol. 181, no. 1, pp. 35–42, 2010.

[19] H. Y. Leong, D. E. L. Ong, J. G. Sanjayan, and A. Nazari, "The effect of different Na 2 O and K 2 O ratios of alkali activator on compressive strength of fly ash-based geopolymer," Construction and Building Materials, vol. 106, pp. 500–511, 2016 Mar 1.

[20] D. Hardjito, C. C. Chua, and H. L. Carrie, "Strength and setting times of low calcium fly ash-based geopolymer mortar," Modern Applied Science, vol. 2, no. 3–5, 2008.

[21] U. Rattanasak and P. Chindaprasirt, "Influence of NaOH solution on the synthesis of fly ash geopolymer," Minerals Engineering, vol. 22, no. 12, pp. 1073–1078, 2009.

[22] A. M. Mustafa Al Bakri, H. Kamarudin, M. Bhnussain, A. R. Rafaiz, and Y. Zarina, "Effect of Na2SiO3/NaOH ratios and NaOH molarities on compressive strength of fly-ash-based geopolymer," ACI Materials Journal, vol. 109, no. 5, pp. 503–508, 2012.

[23] G. Görhan and G. Kürklü, "The influence of the NaOH solution on the properties of the fly ash-based geopolymer mortar cured at different temperatures," Composites Part B: Engineering, vol. 58, pp. 371–377, 2014.

[24] S. V. Patankar, Y. M. Ghugal, and S. S. Jamkar, "Effect of concentration of sodium hydroxide and degree of heat curing on fly ash-based geopolymer mortar," Indian Journal of Materials Science, vol. 2014, Article ID 938789, 6 pages, 2014.

[25] D. Hardjito, E. W. Steenie, M. J. S. Dody, and B. V. Rangan, "On the development of fly ash-based geopolymer concrete," ACI Materials Journal - American Concrete Institute, vol. 101, no. 6, pp. 467–472, 2004.

[26] A. Fernández-Jiménez and A. Palomo, "Composition and microstructure of alkali activated fly ash binder: effect of the activator," Cement and Concrete Research, vol. 35, no. 10, pp. 1984–1992, 2005.

[27] T. Rahmiati, K. A. Azizli, Z. Man, L. Ismail, and M. F. Nuruddin, "Effect of solid/liquid ratio during curing time fly ash based geopolymer on mechanical property," Materials Science Forum, vol. 803, pp. 120–124, 2014.

[28] D. L. Y. Kong, J. G. Sanjayan, and K. Sagoe-Crentsil, "Comparative performance of geopolymers made with metakaolin and fly ash after exposure to elevated temperatures," Cement and Concrete Research, vol. 37, no. 12, pp. 1583–1589, 2007.

[29] M. Cavazzuti, "Design of experiments," in Optimization Methods, pp. 13–42, Springer Berlin Heidelberg. Heidelberg, German, 2013.

[30] T. Krishnan and R. Purushothaman, "Optimization and influence of parameter affecting the compressive strength of geopolymer concrete containing recycled concrete aggregate: using full factorial design approach," IOP Conference Series: Earth and Environmental Science, vol. 80, no. 1, Article ID 012013, 2017 Jul.

[31] M. A. Mosaberpanah and O. Eren, "CO2–full factorial optimization of an ultra-high-performance concrete mix design," European Journal of Environmental and Civil Engineering, vol. 22, pp. 1–4, 2016 Jul 20.

[32] M. Sonobe, L. Svernova, and P. J. Bartos, "Factorial design of cement slurries containing limestone powder for self-consolidating slurry-infiltrated fiber concrete," Materials Journal, vol. 101, no. 2, pp. 136–145, 2004.

[33] K. A. Soudki, E. F. El-Salakawy, and N. B. Elkum, "Full factorial optimization of concrete mix design for hot climates," Journal of Materials in Civil Engineering, vol. 13, no. 6, pp. 427–433, 2001 Dec.

[34] N. U. Kockal and T. Ozturan, "Effects of lightweight fly ash aggregate properties on the behavior of lightweight concretes," Journal of Hazardous Materials, vol. 179, no. 1–3, pp. 954–965, 2010 Jul 15.

[35] G. Hanrahan and K. Lu, "Application of factorial and response surface methodology in modern experimental design and optimization," Critical Reviews in Analytical Chemistry, vol. 36, no. 3–4, pp. 141–151, 2006 Dec 1.

[36] V. Vasuki and K. Ramamurthy, "Identification of design parameters influencing manufacture and properties of cold-bonded pond ash aggregate," Materials and Design, vol. 54, pp. 264–278, 2014 Feb 1.

[37] M. Olivia and H. Nikrakz, "Properties of fly ash geopolymer concrete designed by Taguchi method," Materials and Design, vol. 36, pp. 191–198, 2012 Apr 1.

[38] L. Srinivasan, K. Mohammad Chand, T. Deepan Bharathi Kannan, P. Sathiya, and S. Biju, "Application of GRA and TOPSIS optimization techniques in GTA welding of ISCDV6 aerospace material," Transactions of the Indian Institute of Metals, vol. 71, no. 2, pp. 373–382, 2018 Feb 1.

[39] Bureau of Indian Standards, IS 3812 – Part 1, Specification for Pulverized Fuel Ash: For Use as Pozzolana in Cement, Cement Mortar and concrete, Bureau of Indian Standards, New Delhi, 2013.

[40] A. Wongsa, Y. Zaetang, V. Sata, and P. Chindaprasirt, "Properties of lightweight fly ash geopolymer concrete containing bottom ash as aggregates," Construction and Building Materials, vol. 111, pp. 637–643, 2016 May 15.

[41] K. N. Shivaprasad and B. B. Das, "Influence of alkali binder dosage on the efficiency of pelletization of aggregates from iron ore tailing and fly ash," International Journal of Engineering Research in Mechanical and Civil Engineering, vol. 2, no. 3, pp. 388–392, 2017.

[42] K. N. Shivaprasad and B. B. Das, "Effect of duration of heat curing on the artificially produced fly ash aggregates," in IOP Conference Series: Materials Science and Engineering, vol. 431, no. 9, IOP Publishing, Article ID 092013, 2018 October.

[43] Bureau of Indian Standards, IS 383, Coarse and fine Aggregates for concrete – Specification, Bureau of Indian Standards, New Delhi, 2016.

[44] Bureau of Indian Standards, IS 2386 – Part 3, Methods of Test for Aggregates for concrete: Specific Gravity, Density, Voids, Absorption and Bulking, Bureau of Indian Standards, New Delhi, 1963.

[45] Bureau of Indian Standards, IS 2386 – Part 4, Methods of Test for Aggregates for concrete, Mechanical properties Bureau of Indian Standards, New Delhi, 1963.

[46] S. Sahoo, B. B. Das, and S. Mustakim, "Acid, alkali, and chloride resistance of concrete composed of low-carbonated fly ash," Journal of Materials in Civil Engineering, vol. 29, no. 3, pp. 1–12, Article ID 04016242, 2016.

[47] B. Joseph and G. Mathew, "Influence of aggregate content on the behavior of fly ash based geopolymer concrete," Scientia Iranica, vol. 19, no. 5, pp. 1188–1194, 2012 Oct 1.
[48] L. Weng and K. Sagoe-Crentsil, "Dissolution processes, hydrolysis and condensation reactions during geopolymer synthesis: Part I-Low Si/Al ratio systems," Journal of Materials Science, vol. 42, no. 9, pp. 2997–3006, 2007 May 1.