Performance of Alkali-Activated Aerated Concrete using Class C Fly Ash

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Abstract. This paper focuses on the factors influencing the properties of alkali-activated aerated paste and mortar with high calcium fly ash as the source material, by comparing oven and ambient curing conditions. Design of experiments with response surface methodology is used to study the influence of each of the parameters on the properties of alkali-activated paste and mortar. To achieve a stable pore formation with aeration cooled liquid alkaline solution with a temperature below 15°C is used. The influence of each of the factor and their interaction effects on properties such as density, compressive strength and absorption of water were studied. For a constant dry density, the compressive strength achieved by ambient curing is higher compared to oven curing i.e. for a density of 900 kg/m³ the compressive strength with ambient curing is 4.5MPa while for oven curing it is 2.75MPa. But less water absorption is observed for oven curing compared to ambient curing. While the water absorption achieved was lower for oven curing it was higher for ambient curing resulting in not less than 10%.

1. Introduction
Alkali activation in concrete helped in the production of construction material along with the use of industrial by-products which helped in the reduction of carbon emission. It also helps in generating revenue with the use of fly ash along with the conservation of landfill space [1]. The physical and chemical characteristics of fly ash are governed by the method of production and source of the coal being used [2][3][4]. Alkali-activated aerated concrete using class F fly ash has been studied in detail while much on alkali-activated aerated concrete with class C fly ash is not reported. Studies by [5] using a foaming agent in class C alkali activation showed a comparison of curing condition and it was observed that room temperature curing resulted in increased porosity and water absorption compared to oven-cured samples. Most of the studies used curing ranged from ambient to 90°C. Alkali activation with aeration process in most of the studies has shown fast aeration [6][7] due to the reaction between alkali solution and aluminium powder resulting in rapid release of hydrogen [8]. Hence by varying the mix proportions on alkaline activated aerated paste and mortar with controlled aeration, a systematic study is carried out.

2. Materials and methods
The elemental composition of class C fly ash according to ASTM C618-12a [9] is presented in table 1. Using Blaine’s air permeability test, fineness value of fly ash is determined to be 390 m²/kg. Two mixes chosen for each curing type are alkali-activated paste and alkali-activated mortar. In the case of paste, it is 100% fly ash while in case of mortar; sand passing through 300 µm is used in the ratio of 1:1 measured in weight basis.
Table 1. Elemental composition of Class C fly ash.

| Elements   | CaO   | SiO₂  | MgO  | Al₂O₃ | Fe₂O₃ | SO₃   | K₂O  | Na₂O  | Others |
|------------|-------|-------|------|-------|-------|-------|------|-------|--------|
| Composition mass (%) | 13.76 | 39.89 | 2.28 | 31.46 | 6.17  | 3.19  | 0.12 | 0.59  | 2.54   |

Commercially available C50 aluminium powder (Al powder) was used as an aerating agent. Trials were conducted and it showed that there was no aeration with Al powder dosage below 0.1 % and further, when increased beyond 0.2 % the mix settled down with the inability to hold the mix. For a chosen range of Al powder and molarity of sodium hydroxide (NaOH), the liquid alkaline to ash ratio (La/ash ratio) was 0.6 to 0.65 for paste and 0.8 to 1.0 for mortar. When the liquid content is increased more than 0.65 for paste and 1.0 for mortar, the pores formed gets collapsed due to escape of the gas from the mix. The ranges of each of the varying parameters used for the alkali-activated aerated paste and mortar is shown in table 2.

Table 2. Parameters and its ranges.

| Parameters                          | Alkali-activated aerated paste | Alkali-activated aerated mortar |
|-------------------------------------|--------------------------------|--------------------------------|
| Al powder dosages                   | 0.1 – 0.2 %                    | 0.1 – 0.2 %                    |
| La/ash ratio                        | 0.6 – 0.65                     | 0.8 – 1.0                      |
| NaOH                                | 6 – 12 M                       | 6 – 12 M                       |
| NaSi / NaOH ratio                   | 1 – 2                          | 1 – 2                          |
| Oven curing temperature             | 60 – 90°C                      | 60 – 90°C                      |
| Ambient curing temperature          | 27 ± 5°C                       | 27 ± 5°C                       |

The alkaline solution is prepared using NaOH pellets and sodium silicate (NaSi) solutions. First, NaOH of required concentration was prepared and left for dissolution which dissipates the heat evolved. After 24hrs, with the prepared NaOH solution, NaSi solution was mixed in the required ratio and left undisturbed for 12hrs until the solution reaches room temperature. This prepared solution is used as an activator in the polymerisation process.

2.1. Studies on controlled pore formation
There observed a fast formation of hydrogen gas from the initial trial mix study of alkali-activated aerated paste. This is due to the sudden aeration process due to the reaction of Al powder with the alkaline solution. To control this sudden formation of aeration, different methods were studied namely; (a) Lowering the concentration of the NaOH solution below 6M (controlled the rate of aeration but resulted in very low compressive strength), (b) Superplasticiser as retarders (Enhances the mixing process but could not control the faster aeration), (c) Alkaline solution stored at low temperature (Could control the fast aeration process without disturbing the formation of pores). Hence, the required reaction rate was attained by lowering the temperature of the alkaline solution. The alkali-activated paste was prepared by mixing an alkaline solution having a temperature of 15°C with class C fly ash for about 2 minutes which resulted in aeration up to 10 minutes.

2.2. Experimental procedure
In the experimental study with an increased number of parameters, ‘Design of Experiments’ was used separately for alkali-activated paste and mortar using Response Surface Methodology. In case of temperature curing 50 sets and for ambient curing 40 sets of pre-set experiments were conducted separately for each combination of mixes with alkali-activated paste and mortar. Fly ash, Al powder and pulverised sand (in case of mortar) were dry mixed and then alkaline solution at a lower temperature of 15°C was used. This was mixed thoroughly for about 1-2 minutes and samples were cast. For measuring the variation in fresh density a graduated glass beaker of 250 ml was taken and is initially filled up to 2 cm graduation scale and the variation in density is measured up to 15 minutes at an interval of 5 minutes concerning the rate of aeration. Six cubes (IS 4031 – Part 6) were cast to determine the dry density, compressive strength and for water absorption. 3 cubes were cast separately, for each set of the designed experiment. The surfaces of the cubes were levelled after 12hrs and prepared for curing. In case of oven
curing the samples were cured for 24 hours at pre-set temperature and for ambient curing the cubes were stored at room temperature for 28 days. The variation in properties observed in both the curing conditions for alkali-activated paste and mortar are analysed statistically using Statistical Analysis Software [11] with a quadratic response surface model and the influence of varying factors and their interaction effects on the properties were studied.

3. Results and discussions

3.1. Workability

Figure 1 shows the measured flowability of alkali-activated paste and alkali-activated mortar using the flow table test. It is observed that workability is mainly influenced by La/ash ratio in both the alkali-activated paste and mortar irrespective of the NaSi/NaOH ratio and NaOH concentration. Increase in La/ash ratio makes the mix more workable while the increase in molarity reduces the workability. This reduction in workability with the increase in molarity is due to an increase in viscosity of the alkaline solution which decreases the ability of the mortar to flow [12]. Further lowering of the La/ash ratio resulted in a stiff mix regardless of the variation in NaSi/NaOH ratio and NaOH concentration.

![Figure 1. Variation in workability for alkali-activated aerated Class C flyash.](image)

3.2. Fresh density

The fresh density of alkali-activated paste and mortar was measured for each combination of designed experiments. It is observed that reduction in fresh density was substantial up to 10 minutes, which
indicates that aeration is complete almost within 10 minutes from the time of samples being cast in the mould. It is also evident from figure 2 that Al powder dosage and La/ash ratio influenced the fresh density rather than other parameters.

3.3. Dry density

Figure 3 illustrates the difference in dry density of alkali-activated aerated paste for both the oven curing and ambient curing condition. From figure 3(a) it is witnessed that the density increases linearly with increase in the concentration of NaOH for a given range of NaSi/NaOH ratio and Al powder dosage. In the case of oven cured samples, the polymerisation is enhanced which increases the density with increase in temperature. Further, with lower NaSi/NaOH ratio resulted in gradual variation in density, whereas when the NaSi/NaOH ratio was increased, only marginal variation in density is observed. Moreover, for a given molarity when the La/ash ratio increases the workability increases which results in reduced density. In the case of ambient curing, it is observed that there is a significant increase in density with increase in molarity for a given NaSi/NaOH ratio and lower dosage of Al powder. Whereas, for the increased dosage of Al powder and NaSi/NaOH ratio, La/ash ratio greater than 0.63, resulted in very marginal density variation. It is evident that for a constant NaSi/NaOH ratio and Al powder dosage, ambient curing shows higher density compared to oven curing in the alkali-activated aerated paste. The trend observed in alkali-activated aerated mortar is similar to that of the alkali-activated aerated paste.

Figure 2. Fresh density variation for Al powder dosage-0.1%, NaSi/NaOH ratio–1.

Figure 3. Dry density of alkali-activated paste for oven curing and ambient curing.
3.4. Compressive strength

The compressive strength of oven cured and air-cured samples of alkali-activated aerated paste and mortar are shown in figure 4. The lower La/ash ratio and higher NaOH concentration yielded in higher compressive strength for the chosen range of Al powder dosage. It is observed from the studies that there is a reduction in compressive strength with increase in NaSi/NaOH ratio from 1 to 2 with a reduction in density (i.e. 770 to 305 kg/m³). This reduction is due to the variation in silica content altering the pH of the alkaline solution [12].

![Figure 4. Compressive strength of oven cured and ambient cured samples of alkali-activated paste.](image-url)
From figure 4 it is observed that as the temperature of curing increases to 90°C the compressive strength increases for a given dosage of Al powder. The air-cured alkali-activated paste resulted in higher strength of 5.25 MPa compared to oven-cured strength of 3.8 MPa. Further, when the molarity of NaOH and Al powder dosage is being constant, an increase in NaSi/NaOH ratio ensured reduced compressive strength. Considering both the curing condition it is observed that for any chosen NaSi/NaOH ratio and dosage of Al powder, reduced La/ash ratio increased compressive strength.

*Figure 5. Compressive strength of oven cured and ambient cured samples of alkali-activated mortar.*
The strength of alkali-activated aerated mortar is higher compared to that of alkali-activated aerated paste for the chosen density. Further, with the increase in NaSi/NaOH ratio from 1 to 2, compressive strength decreased with mortar which is similar to oven-cured aerated paste. From figure 5 it is witnessed that for air curing there is an increase in compressive strength for the similar range of densities to that of the oven curing for the given range of Al powder.

3.5. Water absorption
Even though water absorption plays an essential role in designing the concrete, very few research papers discuss the water absorption properties of aerated concrete. It is observed that for a given Al powder dosage and temperature, the increase in NaSi/NaOH ratio resulted in an increase in water absorption with the corresponding decrease in dry density. Also, it is observed that as the curing temperature is raised, it resulted in reduced water absorption with an increase in density. An increase in dosage of Al powder resulted in very high water absorption irrespective of the effect of curing temperature. The range of water absorption obtained is very high compared to oven curing which may be due to increased interconnected pores with incomplete polymerisation.

![Figure 6. Water absorption for aerated alkali-activated mortar for Al dosage - 0.1%.(a) Temp - 70°C (b) Temp - 90°C (c) Temp - 27±5°C](image)

A similar observation as made in the alkali-activated aerated paste is observed from figure 6 for mortar, with reduced water absorption not exceeding 28%. Also, the reduction in water absorption of alkali-activated mortar with air curing is similar compared to the aerated paste. Whereas, it is seen that with an increase in NaSi/NaOH ratio, there is a marginal decrease in water absorption or is in a close-by range which is a reverse trend compared to alkali-activated aerated paste.
4. Conclusions
The factors influencing the properties of alkali-activated aerated paste and mortar with high calcium fly ash as the source material is studied at two different curing conditions, namely; ambient and oven curing.

i) Reduced alkaline solution temperature resulted in stable pore formation of alkali-activated aerated class C fly ash.

ii) For a given molarity and La/ash ratio, the density is increased in the range of 400–900 kg/m$^3$ for paste and 900–1650 kg/m$^3$ for mortar with an increase in temperature.

iii) In ambient curing, increase in NaSi/NaOH ratio there exists a wider range of density that could be achieved.

iv) As the strength range achieved in both types of curing condition yields almost the same range; hence low-temperature curing is suitable for Class C fly ash.

v) Ambient curing results in higher water absorption compared to oven curing by about 17 to 35% more for the chosen range of Al dosage.

vi) Presence of reduced calcium along with reduced Si/Al ratio might not be influencing the properties of high calcium fly ash alkali-activated aerated concrete. Thus the suitable addition of binder may enrich the properties along with improved Si/Al ratio.

5. References
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