A Review on characterization and application of fly ash cenosphere

T Gupta¹ and P S Bokare²

¹ OP Jindal University Raigarh, India
² OP Jindal University, Raigarh, India

*Corresponding author’s e-mail address: tulika.gupta@opju.ac.in

Abstract. The Fly Ash Cenospheres (FAC) or alumino-silicate is one of the most valuable by-products of fly ash generated by coal thermal power plants. It is an industrial by-product of high commercial value. It is found that FAC is hollow spherical microspheres having sizes varying 5-500 µm and chemically inert particles and make them an ideal material to replace fine aggregate from cement concrete. This study presents a systematic review of observational studies on the properties and application of FAC. Different industries use FACs due to their unique properties such as hollow spherical shape and lightweight, less specific gravity, high compressive strength, high thermal resistance, and acoustic insulation, etc. The addition of FAC to concrete has found to reduce the density of concrete without compromising the strength. Other properties such as compressive strength, flexural strength, toughness, ductility, micro-structure, etc are also documented in this study. The gap in the literature is identified and reported at the end of the research report.

1. Introduction

The Fly Ash Cenosphere (FAC) or aluminosilicate is the by-product of coal fly ash emerging as a waste product of thermal power generation plants. The FAC is a value-added product, having many applications in industries as well as in construction. FAC is hollow, lightweight, spherical in shape, having a specific gravity less than water [1]. A general view of FAC is presented in figure 1.

![General view of FAC](image)

**Figure 1.** General view of FAC [2].
The FAC is recovered from the Fly Ash by the Dry Separation and Wet Separation method. A combination of these methods is generally used for the recovery of FAC from fly ash. A brief description of the recovery methods is presented in the next section.

1.1 Recovery Methods of FAC

(a) Dry Separation Process
It comprises fluidized bed separation followed by screening and pneumatic separation in a free-fall air chamber. The mechanical activator assists the fluidised bed separation to prevent agglomeration. This reduces the portion of material that requires further treatment. The FAC is then, individually subjected to pneumatic separation [3].

(b) Wet Separation Process:
This the most widely accepted and used method for the separation of the FAC from fly ash. Wet separation is carried out by using the liquid medium and based on the density difference between floaters and the liquid [4]. The FAC is light in weight as compared to liquid. Due to this, the FAC floats on the liquid. The wet separation method is popularly known as the “Sink and Float” method.

1.2 Properties of FAC
Various researchers have reported the properties of FAC as lightweight, with high compressive strength, low thermal conductivity, hollow, etc. Therefore, the FAC is an ideal additive to the concrete to reduce the unit weight without compromising the strength of concrete. Typical properties of FAC are presented in Table 1.

| Sr. No | Property of FAC                  | Value                                  |
|--------|----------------------------------|----------------------------------------|
| 1      | Size                             | 0.005 mm to 0.035 mm                   |
| 2      | Mean Diameter                    | 0.117 mm                               |
| 3      | Compressive Strength             | 7.38 MPa                               |
| 4      | Composition                      | Silica, Alumina, Ferrous (Approx. 90%) |
| 5      | Electrical Resistance            | $R = 2.26 \times 10^8 \, \Omega$       |
| 6      | Mass Loss at 1000 C              | Negligible                             |
| 7      | Wall Thickness                   | 10% of Diameter                        |

These properties (presented in Table 1) of FAC render it as an ideal application in replacement of fine aggregate in concrete, replacement of cement in concrete, acoustics, synthetic foam, paints, plaster, etc. In addition, the chemically inert nature of FAC is useful in many applications since it is chemically inert in nature.

The chemical characteristics (item no 4 of Table 1) indicate that the FAC is rich in silica, alumina, and ferrous. These constituents impart the physical properties to FAC which are highly useful as commercial application.

Though various researchers studied and reported the properties of FAC, they have used Fly Ash originated from different sources of coals, for studying the properties of FAC. Hence there is a large variation in reported properties of FAC. Another, these efforts are not documented in one place to provide the overall scenario of the characteristics and application of FAC. This report, therefore, summarizes the available research reports on the properties of FAC.

This paper is divided into three major sections dealing with methods of separation of FAC, characterization of FAC, and application of FAC followed by conclusions and the selected references.
2. Methods of Separation of FAC

The FAC is obtained by use of two methods, the dry separation method and the wet separation method. The wet separation method is popularly used by researchers. This section presents a brief account of the observations that are put forward by the researchers, world over, on both the separation methods.

2.1 Dry Separation Method

In the dry separation method, the researchers reported two types of separation methods. The first one uses the sieving by appropriate aperture sieve for physical separation of FAC from fly ash. In the second one, the centrifuge is used for the physical separation of FAC from fly ash. A typical flow diagram for dry separation is presented in figure 2.

![Figure 2. Typical flow diagram of dry separation process [3].](image)

Author [3] carried out the dry separation method for FAC and further tried the wet separation using a fluidized bed. They recovered the FAC exceeding 81%. Author reported a 66% recovery of FAC using the dry separation method [6]. They tried the same sample separation by the wet method and resulted in a recovery of 80%.

2.2 Wet Separation Method

Author reported that the most efficient separation method of FAC is wet separation [7]. They tried to recover the FAC in two plants of air classifier with 90% and 81% recovery, respectively. The difference in yields is reported due to different sources of coal. Table 2 presents a summary of the FAC yield reported by various authors.

| Sr. No. | Author                     | % of FAC Obtained |
|---------|----------------------------|-------------------|
| 1       | Wrona et al. (2020) [3]    | 81                |
| 2       | Acar et al. (2016) [7]     | 81                |
| 3       | Petrus et al. (2011) [6]   | 80                |
| 4       | Hajima et al. (2010) [8]   | 66                |

Table 2 indicates that the yield of FAC is similar in both, dry and the wet separation method.

3. Characterization of FAC

This section presents the review of research reports published by researchers on the characterization of FAC collected from the fly ash by using different methods of separation. The various authors investigated the properties of FAC by collecting samples from different coal-based power plants. On reviewing various research reports, the characteristics of FAC can be categorized as:

(i) Chemical and Mineralogical Characteristics
(ii) Morphological Characteristics
(iii) Physical Characteristics
The following discussion presents the summary of reports on these characteristics.

3.1 Chemical and Mineralogical Characteristics

The FAC primarily contains silica and alumina [5, 9-22]. Various techniques such as X-Ray Diffraction Analysis (XRD), Scanning Electron Microscopy (SEM), X-Ray Fluorescence (XRF), etc. are used by researchers to determine various characteristics of FAC [2, 4, 5, 9-12, 14, 15, 19, 21, 23, 25-29].

Author used XRF and XRD to evaluate the characteristics of FAC [30]. Table 3 presents the gist of characteristics reported by them.

### Table 3. Chemical composition of FAC [30].

| Country | SiO₂ | Al₂O₃ | Fe₂O₃ | CaO | SO₃ | Na₂O | K₂O | P₂O₅ | TiO₂ | MgO |
|---------|------|-------|-------|-----|-----|------|-----|------|------|-----|
| India   | 50-60| 25-35 | 2-8   | 1-6 | 0-1 | 0-1  | 1-3 | 0-1  | 1-5  | 0-1 |
| China   | 40-65| 15-35 | 2-8   | 1-6 | 0-1 | 0-2  | 1-3 | 0-1  | 1-5  | 0-1 |
| Australia | 45-60 | 25-30 | 5-10 | 1-6 | 0-1 | 0-1  | 0-3 | 0-1  | 1-5  | 0-1 |
| USA     | 30-60| 25-35 | 2-15  | 1-15| 0-1 | 0-4  | 0-4 | 0-1  | 1-5  | 0-1 |

Note: All figures are in %

Table 3 indicates that FAC mostly contains SiO₂ followed by Al₂O₃ irrespective of occurrence and location. The highest % of SiO₂ and Al₂O₃ in FAC is observed in India and China followed by Australia and the USA. The difference in the concentration of SiO₂ and Al₂O₃ can be contributed to the composition of coal in respective countries.

Adesina 2020 [31] reviewed various research efforts on mineralogical characteristics of the FAC as presented in Table 4.

### Table 4. Chemical composition of FAC.

| Sr. No | Authors                  | SiO₂ | Al₂O₃ | Fe₂O₃ | CaO | SO₃ | Na₂O | K₂O | P₂O₅ | TiO₂ | MgO |
|--------|--------------------------|------|-------|-------|-----|-----|------|-----|------|------|-----|
| 1      | Wang et al. 2011 [32]    | 62.2 | 29.7  | 3.5   | 0.9 | 1.7 | -    |     |      |      |     |
| 2      | Sarkar et al. 2008 [33]  | 54.6 | 36.9  | 1.8   | 0.39| 2.8 | 0.3  |     |      |      |     |
| 3      | Ngu et al. 2007 [33]     | 62.4 | 26.2  | 0.9   | 0.03| 0.3 | 1.3  |     |      |      |     |
| 4      | Li et al. 2013 [24]      | 53.5 | 31.5  | 5.5   | 2.0 | 2.4 | 0.8  |     |      |      |     |
| 5      | Zhao et al. 2010 [35]    | 56.0 | 26.0  | 7.0   | 4.7 | 3.2 | 0.5  |     |      |      |     |
| 6      | Fomenko et al. 2016 [36]| 56.3 | 25.1  | 9.6   | 1.35| 2.9 | 0.8  |     |      |      |     |
| 7      | Kolay and Bhusal 2014 [10]| 52.5 | 30.0  | 7.5   | 1.15| 2.0 | -    |     |      |      |     |
| 8      | Wang et al. 2013 [13]    | 62.3 | 19.9  | 5.9   | 1.5 | -   | -    |     |      |      |     |
| 9      | Blanco et al. 2000 [37]  | 56.0 | 25.0  | 6.9   | 4.2 | 3.4 | 2.2  |     |      |      |     |
| 10     | Wang et al. 2012 [26]    | 58.1 | 32.0  | 3.7   | 0.9 | 3.1 | 0.8  |     |      |      |     |
| 11     | Hanif et al. 2017 [39]   | 73.1 | 16.7  | 2.0   | 1.06| 3.9 | 2.4  |     |      |      |     |
| 12     | Xu et al. 2015 [9]       | 61.0 | 32.1  | 3.1   | 0.71| 1.7 | 3.1  |     |      |      |     |
| 13     | Kannan et al. 2016 [40]  | 65.0 | 36.0  | 3.0   | 0.5 | -   | -    |     |      |      |     |
| 14     | Chen et al. 2016 [41]    | 58.0 | 35.0  | 1.5   | 1.9 | 0.3 | 0.7  |     |      |      |     |
| 15     | Liu et al. 2017 [18]     | 57.4 | 31.9  | 2.3   | 0.44| 1.4 | 0.54 |     |      |      |     |
| 17     | Chen et al. 2019 [43]    | 58.9 | 27.2  | 5.4   | 0.99| 4.18| -    |     |      |      |     |
| 18     | Patel et al. 2020 [44]   | 56.2 | 33.4  | 2.8   | 1.46| -   | -    |     |      |      |     |
| 19     | Kolay and Singh 2001 [1] | 52.3 | 30.1  | 7.5   | 1.15| 1.98| 0.02 |     |      |      |     |
| 20     | Xi et al. 2020 [45]      | 59.8 | 32.3  | 2.2   | 0.24| 0.52| 0.33 |     |      |      |     |
Table 4 indicates that the mineralogy of FAC is dominated by SiO$_2$ and Al$_2$O$_3$ followed by Fe$_2$O$_3$. These mineral components impart much-desired properties such as smooth surface, inertness, chemical stability, and lightweight to FAC.

The important manifestation of SiO$_2$ and Al$_2$O$_3$ concentration in FAC is its inertness and smooth surface structure. This characteristic also provides thermal stability above 1000°C.

Figure 3. XRD diffraction Spectra of FAC [5].

Author studied the mineralogical characteristics of FAC originated from coal fly ash of Talcher Super Thermal Power Station, Kanhia, Odisha [5]. The coal in this thermal power station originates from the Kaniha coal block of Mahanadi Coalfields Ltd. The XRD image of the FAC sample is presented in figure 3 and the details of constituents are presented in Table 5 this indicates that the mineralogical composition of FAC is dominated by SiO$_2$ and Al$_2$O$_3$ similar to that reported by some authors [30, 31].

Table 5. Chemical composition (wt. %) of the FAC sample compound [5].

| Compound | SiO$_2$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | Na$_2$O | K$_2$O | MgO | TiO$_2$ | P$_2$O$_5$ | LOI |
|----------|---------|-------------|-------------|--------|-------|-----|--------|-----------|-----|
| Percentage | 48.62 | 27.79 | 3.75 | 0.86 | 4.23 | 0.46 | 2.12 | 7.99 | 4.18 |

Similarly, many other authors studied the mineralogical composition of FAC and concluded that SiO$_2$ and Al$_2$O$_3$ are the principal components of FAC. Table 4 presents a summary of the mineralogical composition of FAC reported by various authors.
3.2 Physical Characteristics of FAC

Many authors [3, 6-8, 16, 51] reported that FACs are smooth and spherical in shape and have a diameter of 1 µm to 500 µm [4, 5, 10, 11, 14, 17, 19, 20, 48]. The researchers used scanned electron microscopy for ascertaining the physical properties of FAC.

The majority of researchers however reported that the size of FAC ranges from 45 µm to 600 µm [4, 52]. The shell thickness of FAC reported by the authors ranges from 1µm to 2 µm [52]. The bulk density is attributed as the principal character of FAC which makes FAC commercially useful [10, 11, 19, 21-24, 42, 47]. The bulk density of FAC varies from 0.25 g/cm³ to 0.7 g/cm³ which indicates that FAC is lighter than water.

Blanco et al. 2000 [37] however contradicted the observation of earlier researchers on the particle size of FAC. They reported the minimum particle size of 0.2 mm based on granulometric analysis of FAC. This contradictory observation is possibly due to the source of coal. The variation in morphological properties of FAC is attributed to the origin of coal from which the FAC is extracted.

Table 6 presents a summary of the morphological characteristics of FAC.

| Sr. No. | References                     | Size (µm) | Shell Thickness (µm) | Mean Diameter (µm) | Wall Thickness (µm) |
|---------|--------------------------------|-----------|----------------------|--------------------|--------------------|
| 1       | Yoriya et al. 2020 [16]        | 45 - 220  | -0.7 - 21.6          | 25.9 - 229.2       | 0.7 - 21.6         |
| 2       | Petrus et al. 2020 [51]        | 2 - 200*  | 2 - 30*              | 1 - 10             | NA                 |
| 3       | Yoriya et al. 2019 [4]         | 5 - 500   | 2 - 30*              | < 100              | 2 - 30             |
| 4       | Sarkar et al. 2007 [33]        | 20.72 -   | 2 - 30*              | 112.56             | 2.072 -            |
| 5       | Beddu et al. 2018 [17]         | 6.91 - 149.6 | 2 - 30*        | 6.91 - 149.6       | 0.691 -           |
| 6       | Ranjbar and Kuenzel 2017 [19]  | 5 - 500*  | 1 - 18              | 20 - 300           | 1 - 18             |
| 7       | Liu et al. 2017 [42]           | 10 - 200  | 2 - 30*              | 10 - 200           | 0.1 - 20           |
| 8       | Zyrkowski et al. 2016 [16]     | 5 - 500*  | 10 - 100             | 20 - 80            | < 25               |
| 9       | Fomenko et al. 2015 [11]       | 10 - 200  | 5 - 35               | 47 - 225           | 2.4 - 12.7         |
| 10      | Xu et al. 2015 [9]             | 5 - 500*  | 2 - 30*              | 94                 | 0.5 - 50           |
| 11      | Kolay and Bhusal 2014 [10]     | 2 - 250   | 10 - 20              | NA                 | 20                 |
| 12      | Joseph et al. 2013 [14]        | 5 - 500*  | 1 - 20               | 0.8 - 80           | 1 - 20             |
| 13      | Li et al. 2012 [25]            | 63 - 250  | 2 - 10               | 10 - 200           | 1 - 3              |
| 14      | Wang et al. 2012 [53]          | 5 - 500*  | 2 - 30*              | 10 - 200*          | 0.5 - 50           |
| 15      | Chávez-Valdez et al. 2011 [48]| 17        | 2 - 30 *             | 10 - 200 *         | 0.17               |
| 16      | Fomenko et al. 2011 [54]       | 5 – 500*  | 2.5 – 8.2            | 59 - 143           | 2 - 5              |
| 17      | Anshiṣ et al. 2010 [49]        | 120 - 325 | 1.5 - 16             | 50 - 350           | 2 - 16.2           |
| 18      | Ngu et al. 2007 [34]           | 45 - 150  | 1 - 35               | 10 - 200*          | 2 - 26             |
| 19      | Anshiṣ et al. 2005 [55]        | 500       | 3 - 5                | 10 - 200*          | 50                 |
| 20      | Vereshchagina et al. 2004 [56]| 10 - 500  | 2 - 30*              | 10 - 200*          | 1 - 50             |
| 21      | Vassilev et al. 2004 [52]      | 20 - 600  | 2 - 30*              | 10 - 200*          | NA                 |
| 22      | Kolay and Singh 2001 [1]       | 40 - 140  | 2 - 30*              | 10 - 200           | 0.4 - 14           |

Note: * Approximate values are written. NA — Not Available.

The properties presented in Table 6 are evaluated by researchers using various techniques SEM, XRD, etc. A glimpse of the summary of properties of FAC indicates that the particle size of FAC falls in the range of nano size. The inertness of FAC coupled with its low density and nano-size makes it an ideal material for the replacement of fine aggregate from concrete. Another, the shell thickness, and the smooth surface of FAC make it an ideal candidate for use as a roller bearing in concrete improves the workability.
4 Application of FAC

One of the objectives of the study is to embark upon the application of FAC in replacing cement and aggregate from concrete. There have been several studies that have investigated the effect of the addition of FAC in cement concrete as a replacement of fine aggregate/cement [40, 57-59]. The major advantage of replacing fine aggregate/cement is the reduction in the unit weight of concrete without compromising the strength of concrete. Many research attempts are directed towards the replacement of fine aggregate/cement in concrete by FAC mainly because of the reduction in the unit weight of concrete without compromising the strength.

Another important characteristic of FAC is its inert nature and nanoparticle size making it an ideal replacement of fine aggregate/cement. Therefore, a number of research reports are available on the effect of replacement of fine aggregate/cement from concrete. Few researchers have also tried other applications of FAC such as synthetic in foam and composite material.

This section deals with the application of FAC in the following areas:
4.1 Replacement of cement
4.2 Replacement of fine aggregate
4.3 Uses as a composite material

4.1 Replacement of cement by FAC from Concrete:

The FAC originates from the fly ash as described in the preceding paragraph. It is, therefore, obvious that the FAC possesses that properties like fly ash. The FAC possesses pozzolanic and cementitious properties of fly ash which are very useful for the replacement of cement from concrete. Other properties such as bulk density, particle size, and surface area help in accelerating the hydration process of cement. The hollow FAC particles carry water which helps in the internal curing of concrete thereby reducing shrinkage cracks in concrete [18].

Author utilized FAC in combination with silica fumes as a replacement of cement in mortar and reported that the mechanical strength of mortar reduced with an increase in replacement percentage of FAC [40, 58]. However, the authors have not reported the optimum percentage of replacement of FAC where the mechanical strength will not fall below the desired value. While some authors [38, 40] reported that the loss in strength due to the addition of FAC can be compensated by using silica fume. One of the important draws back of the addition of FAC to cement mortar for plaster is that it increases the porosity which may increase seepage.

Author investigate and reported that though the addition of FAC may improve the strength of cement paste initially, over the period the strength decreases [39]. The increased pozzolanic activity due to the addition of FAC plays an important role in the reduction of strength over the period. They have reported that 10% replacement of FAC by weight is an optimum replacement of FAC. The increase in porosity is reported by the authors due to the addition of FAC. The higher percentage of FAC addition adversely affected the durability of concrete.

Here author reported that the FAC is an ideal material for the replacement of cement to some extent [60]. However, the increased proportion of FAC reported the loss of strength of concrete. Author [37] experimented with a filling of gaps using microfilters in concrete using FAC. They reported that when the optimum gaps are filled with FAC paste, the thermal conductivity of the concrete sample improves with a simultaneous reduction in the mechanical strength of concrete. They further reported that the acoustic behaviour of concrete with FAC similar to that without FAC.

This work suggested the addition of Silica fume to improve the performance of concrete and reported compressive strength, tensile strength, flexural strength, fracture mechanism, and toughness of concrete resulting from the addition of FAC. Some investigations [61] concluded that the use of the FAC as a nanofiller increased the porosity because of their spherical nature [38]. Also, it seems that the addition of the FAC in cement paste reduces the density of concrete and makes it lightweight concrete. The lightweight concrete made up of FAC will help for improving the thermal conductivity and be used as a noise barrier [37].
4.2 Replacement of fine aggregate by FAC from Concrete

Many authors extensively reported the use of FAC as a partial replacement of fine aggregate. This has two objectives first as a nanofiller and second as a replacement of fine aggregate. The particle size distribution of fine aggregate and FAC is presented in figure 4.

![Figure 4](image_url)

**Figure 4.** Fineness modulus of fine aggregate and FAC.

The particle size distribution of FAC and fine aggregate indicate that both have similar particle size distribution hence can be used as a replacement of each other. The effect of replacement of fine aggregate by FAC on concrete is studied by many researchers and have reported that the replacement affects the following properties of concrete.

1. Mechanical strength.
2. Workability.
3. Bulk density.
4. Surface Finish.
5. Porosity.
6. Thermal Conductivity.

Some investigations conducted by authors [46, 58] reported that the mechanical strength of concrete remains at the desired level even after the addition of FAC. However, the volume of pores in concrete has been found to increase due to the addition of FAC. This may adversely affect the permeability of concrete. Research [62] reported that the addition of FAC in any form in concrete adversely affects the hydration hence the addition of FAC to the tune of 5 to 10% is only advisable in concrete. Author [63] reported that though the addition of FCA as replacement of prime aggregate initially increased the mechanical strength, the further addition of FAC reduces the mechanical strength due to poor inter-particle bonding between cement and FAC. They suggested only a low volume of FAC replacement in concrete.

Investigation by author [58] reported various replacement proportions such as 33%, 67%, and 100% of fine aggregate by FAC. Results of concrete produced after the replacement of fine aggregate by FAC indicate that the compressive strength decreased as the percentage replacement of FAC was increased [58]. Results of a similar experiment are reported by some other authors Satpathy et al. 2019 wherein they combined the use of FAC with Sintered Fly Ash (SFA) as a replacement of fine aggregate. Satpathy et al. 2019 reported that the optimum proportion of FAC and SFA is 50% and 75% respectively for achieving desired mechanical properties [57]. Author [64] reported that the addition of micro-size FAC in lightweight concrete reduced the ductility and thermal conductivity of concrete.
Figure 5. Variation in density with % replacement of (a) cement (b) fine aggregate with FAC.

Figure 5 and figure 6 presents the variation in compressive strength with percentage replacement of fine aggregate and cement by FAC reported by various authors. It is seen from the figure 5 that the compressive strength and density reduce with an increase in the percentage of replacement. This is reported by almost all researchers. However, no author has reported the globally optimize percentage replacement of fine aggregate/cement with FAC which will give desired mechanical strength and bulk density. However, a higher proportion of addition of FAC decreases the strength and density on one hand and increases the porosity (seepage) on the other hand. This needs to be investigated in detail.

Figure 6. Variation in compressive strength with % replacement of (a) cement (b) fine aggregate with FAC.

The FAC can also be used in many other forms in composite materials. The properties of FAC such as particle size, spherical shape, inertness, etc make it an ideal material to be used as a composite
material. Various authors [65, 66] reported the use of FAC with polyethylene and zinc. Author [32] reported geo-polymeric use as metakaolin (MK)-based slurry. Few authors reported the research on silane treatment of FAC to be incorporated in thermoplastic high-density polyethylene. Some literature studied the effect of the FAC coated with nickel and ZSM-5 to form magnetic ZSM-5/Ni/Fly [66] ash hollow spheres and characterized by SEM, XRD, nitrogen adsorption, and vibrating sample magnetometer.

The summary of research efforts reporting the replacement of cement and fine aggregate by FAC is presented in Table 7.

Table 7. Summary of Results of Replacement of Fine Aggregates and Cement by FAC.

| Sr. No. | Reference | % Replacement | W/C Ratio | Density Kg/m³ | Compressive Strength (N/mm²) | Flexural Strength (N/mm²) | Split Tensile Strength (N/mm²) |
|---------|-----------|---------------|-----------|---------------|-----------------------------|--------------------------|-----------------------------|
| 1       | de Souza et al. 2019 [58] | 33 | 0.2 | 2134 | 40.5 | 46.1 | - | - |
|         |           | 67 |          | 1912 | 1650 | 58.87 | 10.80 | 31.49 |
|         |           | 100 |          | 1870 | 53.86 | 56.35 | 16.00 | 32.69 |
|         | Chen et al. 2019 [43]   | 0 |          | 1724 | 1477 | 50.06 | 11.59 | 33.89 |
|         |           | 10 | 0.32 | 1592 |          | 53.86 | 13.61 | 33.83 |
|         |           | 20 |          | 1477 |          | 50.06 | 11.59 | 33.89 |
|         |           | 30 |          | 2200 |          | 34.87 | 4.62 | 3.58 |
| 2       | Satpathy et al. 2019 [57] | 50 | NA | 1980 | 1870 | 18.75 | 3.38 | 2.68 |
|         |           | 75 |          | 1867 | 1769 | 20.47 | 3.73 | 2.86 |
|         |           | 100 |          | 1980 | 1867 | 18.75 | 3.38 | 2.68 |
|         |           | 30 |          | 1769 | 1612 | 20.47 | 3.73 | 2.86 |
| 3       | Hanif et al. 2017a [39] | 40 | 0.3 | 1506 | 1444 | 48.48 | 8.61 | 2.912 |
|         |           | 50 |          | 1444 | 1342 | 43.50 | 7.37 | 2.761 |
|         |           | 60 |          | 1342 | 1260 | 43.50 | 7.37 | 2.761 |
|         |           | 70 |          | 1260 |          | 30.38 | 5.38 | 1.656 |
| 4       | Hanif et al. 2017 [67]  | 10 |          | 1900 | 1700 | 60 | - | - |
|         |           | 20 | 0.3 | 1500 | 1700 | 60 | - | - |
|         |           | 30 |          | 1500 |          | 60 | - | - |
|         |           | 40 |          | 1500 |          | 60 | - | - |
|         |           | 50 |          | 1500 |          | 60 | - | - |
| 5       | Kannan et al. 2016 [40] | 10 |          | 1500 | 1500 | 55 | - | - |
|         |           | 15 |          | 1500 |          | 55 | - | - |
|         |           | 20 |          | 1500 |          | 55 | - | - |
|         |           | 25 |          | 1500 |          | 55 | - | - |
|         |           | 30 |          | 1500 |          | 55 | - | - |
| 6       | Patel et al. 2019 [46]  | 50 |          | 22.66 | 22.66 | - | - | - |
|         |           | 75 |          | 22.66 | 22.66 | - | - | - |
|         |           | 100 |         | 22.66 | 22.66 | - | - | - |

Results show that the sample contains a hollow structure with a magnetic property [66]. Author [68] investigated the effect of the addition of FAC to concrete on acoustic properties of concrete. They reported that due to the reduction in density of concrete the acoustic properties of concrete improved considerably. Author [69] reported that the fracture toughness of concrete increases by 200% due to the addition of FAC.
Table 8. Presents the summary of use of FAC as a composite material.

| Sr. No. | Author | % Addition of FAC | Observation Reported |
|---------|--------|-------------------|----------------------|
| 1       | Venkatesha et al. 2020 [70] | 0.5, 1, 1.5, 2 | Flexural strength and internal laminar shear strength increased with 1.5% FAC composite and constant 2% bamboo and glass hybrid epoxy. |
| 2       | Umashankar et al. 2018 [71] | 20, 30, 40, 50 | Optimum mix obtained at 30%, at this mix tensile strength, flexural strength, and impact strength recorded maximum. |
| 3       | Ashoka et al. 2018 [72] | 3, 6, 9 | Modulus of elasticity, yield stress, and hardness increases with an increase in FAC but a decrease in the elongation. |
| 4       | Rugele et al. 2017 [73] | 10, 30, 50, 60 | the composite material shows an increase in strength with the increase in firing temperature, and a decrease of mechanical reliability with a decrease in density, which is typical for porous materials. |
| 5       | Gupta and Kua 2020 [74] | 10, 20, 30, 40 | Design matrix mix of rice husk biochar, silica fume, and FAC 10 – 30% best mix as a replacement for cement. |
| 6       | Huang 2019 [43] | 0.1, 0.2, 0.3 | Lightweight toughness cement-based composites containing 20% FAC and 1% fibre volume have the best toughness and ductility. |

Table 8 indicates that the FAC can also be used in composite material successfully due to its unique characteristics such as lightweight, smooth surface finish, nanoparticle size, etc. Its inert nature contributes to its use as a composite material.

4.3 Miscellaneous
The FAC is utilized in many other ways such as phase change material [42], internal curing agent [18], nanofillers [75], etc. However, the distinguished properties of FAC make it the most suitable material for the replacement of fine aggregate and cement.

5. Results and Discussion
A closer look at the literature, reveals some gaps and shortcomings listed below. There is still a great deal of work to be done in the application of FAC in cement concrete.

1. While extensively reviewing the literature, it was found that no author evaluated the effect of the addition of FAC on the workability of concrete. Various tests to evaluate the workability of concrete, such as compaction factor, slump cone, and Vee — Bee can be used to access the effect of the addition of FAC on the workability of concrete.

2. The authors tried various percentages of replacement of FAC and have reported its effect on various properties of concrete. But there is no agreement on the optimum percentage of the addition of FAC to achieve optimum properties of concrete.

3. The wear resistance of concrete after the addition of the FAC has been found very rarely mentioned [65].

4. The dynamic compressive strength of concrete and the fracture toughness are important properties of concrete required for the surface durability of rigid pavement. These properties of concrete are not probed by the researchers. The permeability is an important characteristic of concrete. The researchers have not probed the effect of the addition of the FAC on the permeability of concrete.
6. Conclusions
The work described above is carried out to document various characteristics of the FAC reported by authors all over the world. It briefly accounts for the application of FAC such as a replacement material of fine aggregate and cement. This report concisely documents the contribution of authors world over in the study of FAC and its various applications.

Researchers have reported various characteristics of the FAC such as size, pore size, shell thickness, density, and chemical configuration of the FAC. The researchers have used XRD, XRF, SEM, and EDS to study various aspects of FAC. Following conclusions can be drawn from the work reported by the researcher’s world over.

6.1 Characterization of FAC
Characteristics in brief:
(i) The particle size of the FAC was found to vary from 10 µm to 500 µm.
(ii) The average shell thickness of the FAC is reported as 10 to 20 µm.
(iii) The unit weight of the FAC was found to vary from 0.65 to 0.75 g/cm³.
(iv) The chemical composition of the FAC was reported as the sum of Al₂O₃, SiO₂, Fe₂O₃, CaO, MgO, MgCl₂, etc.
(v) The variation in characteristics of the FAC is mainly due to the origin of the FAC that is the origin of coal.

Though the researchers have reported different characteristics of FAC, there is wide variation in reporting the characteristics. Though this is attributed to the origin of coal fly ash, the use of different methods for characterization is also one of the reasons for the variation in reported characteristics. Hence it is required to decide a specific range for the characteristics which will encompass all the known sources of coal fly ash the world over.

6.2 Application of FAC
The FAC is found to have a wide range of applications in the replacement of fine aggregate and cement. The mechanical strength and density of the concrete are found to decrease with an increase in the percentage of FAC addition. However, the optimum percentage of FAC addition needs to be ascertained for achieving the desired mechanical strength and bulk density.

References
[1] Kolay P K and Singh D N 2001  *Cem. Concr. Res.* 31 539
[2] Danish A and Mosaberpahan M A 2020  *J. Mater. Sci.* 55 4539
[3] Wrona J, Zukowski W, Bradlo D and Czuprynśki P 2020  *Energies* 13 3576
[4] Yoriya S, Intana T and Tepsri P 2019  *Appl. Sci.* 9 3792
[5] Sen S 2014  Physical properties of cenosphere, PhD diss. NIT Raulkela, 2014.
[6] Petrus H, Hirajima T, Oosako Y, Nonaka M, Sasaki K and Ando T 2011  *Int. J. Miner. Process.* 98 15
[7] Acar I and Atalay M U 2016  *Fuel.* 180 97
[8] Hirajima T, Petrus HTBM, Oosako Y, Nonaka M, Sasaki K and Ando T 2010  *Int. J. Miner. Process.* 95 18
[9] Xu B, Ma H and Hu C 2015  *Mater. and Struc.* 18
[10] Kolay P K and Bhosal S 2014  *Fuel.* 117 118
[11] Fomenko E V et al. 2015  *Energy and Fuels.* 29 5390
[12] Żyrkowski M J 2014  *Report of UG work* 17 4
[13] Wang J Y, Chia K S, Liew J Y R and Zhang M H 2013  *Cem. Concr. Compos.* 43 39
[14] Joseph K V, Francis F, Chacko J, Das P and Hebbar G 2013  *Int. J. Eng. Res. Technol.* 2 18
[15] Li Y and Wu H 2012  *Energy and Fuels.* 26 130
[16] Yoriya S and Tepsri P 2020  *Appl. Sci.* 10 1
[17] Beddu S, Zainoodin M, Kamal N M, Mohamad D, Nabihah S and Nazri F M Green Design and Manuf. Adv. and Emer. App. AIP Conf. Proc. 2030 020259-1

[18] Liu F, Wang J, Qian X and Hollingsworth J 2017 Cem. Concr. Res. 95 39

[19] Ranjbar N and Kuenzel C 2017 Fuel. 207 1

[20] Zyrkowski M, Neto R C, Santos L F and Witkowski K 2016 Fuel. 174 49

[21] Luong D, Lehmhus D, Gupta N, Weise J and Bayoumi M 2016 Materials (Basel). 9 115

[22] Chandel V and Bhatia O S 2016 Int. J. Eng. Trends Technol. 29 133

[23] Yang B, Yang Y F and Gai G S 2013 Adv. Mater. Res. 826 215

[24] Li Y, Gao X and Wu H 2013 Energy Fuels. 27 8118151.

[25] Li Y 2012 Curtin University 1 140

[26] Wang J Y, Zhang M H, Li W, Chia K S and Liew R J Y 2012 Cem. Concr. Res. 42 721

[27] Wang J, Dong S, Wang D, Yu X, Han B and Ou J 2019 J. Mater. Civ. Eng. 31 04019030

[28] Liu Z, Zhao K, Tang Y and Hu C 2019 Adv. Mater. Sci. Eng. 2019 1

[29] Petrus H T B M, Hirajima T, Oosako Y, Nonaka M, Sasaki K and Ando T 2011 Int. J. Miner. Process. 98 15

[30] Agrawal U S and Wanjari S P 2017 Mater. Today Proc. 4 9797

[31] Adesina A 2020 Dev Built Environ. 4 100029

[32] Wang M, Jia D, He P and Zhou Y 2011 Ceram. Int. 37 1661

[33] Sarkar A, Rano R, Mishra K K and Mazumder 2015 Taylor Fr. 30 271

[34] Ngui L N, Wu H and Zhang D K 2007 Energy and Fuels. 21 3437

[35] Zhao Y, Zhang J, Tian C, Li H, Shao X and Zheng C 2010 Energy and Fuels. 24 834

[36] Fomenko E V et al. 2016 Solid Fuel Chem. 50 238

[37] Blanco F, García P, Mateos and P Ayala J 2000 Cem. Concr. Res. 30 1715

[38] Hanif A, Parthasarathyp, Ma H, Fan T and Li Z 2017 Cem. Concr. Compos. 81 35

[39] Hanif A, Lu Z, Diao S, Zeng X and Li Z 2017 Constr. Build Mater. 140 139

[40] Kannan S K, Andal and Shanmugasundaram M 2016 Adv. Mater. Sci. Eng. 2016 1

[41] Li C and Qiao X 2016 Chem. Eng. J. 302 389

[42] Liu F, Wang J and Qian X 2017 Cem. Concr. Compos. 80 317

[43] Chen W and Huang Z 2019 Materials (Basel) 12 1

[44] Patel S K, Satpathy H P, Nayak A N and Mohanty C R 2020 J. Inst. Eng. Ser. A. 101 179

[45] Xi B et al. 2020 J. Clean Prod. 262 121274

[46] Patel S K, Majhi R K, Satpathy H P and Nayak A N 2019 Constr. Build Mater. 226 579

[47] Zyrkowski M, Neto R C, Santos L F and Witkowski K 2016 Fuel. 174 49

[48] Chávez-Valdez A, Arizmendi-Morquecho A, Vargas G, Almanza J M and Alvarez-Quintana J. 2011 Acta Mater. 59 2556

[49] Anshits N N, Mikhailova O A, Salanov A N and Anshits AG 2010 Fuel. 89 1849

[50] Sokol E and Volkova N 2000 Fuel Proc. Tech. 67 35

[51] Petrus H T B M et al. 2020 J. Environ. Chem. Eng. 8 104116

[52] Vassilev S V, Menendez R, Diaz-somoano M and Martinez-tarazona M R 2004 Fuel 83 585

[53] Wang B, Li Q, Wang W, Li Y and Zhai J 2011 Appl. Surf. Sci. 257 3473

[54] Fomenko E V, Anshits N N, Pankova M V, Solovyov L A and Anshits A G 2011 World Coal Ash Conf–May. 2011 9

[55] Anshits N N, Vereshchagina T A, Bayukov O A, Salanov A N and Anshits A G 2005 Glass Phy. Chem. 31 306

[56] Vereshchagina T A et al. 2004 Glass Phy. Chem. 30 247

[57] Satpathy H P, Patel S K and Nayak A N 2019 Constr. Build Mater. 202 636

[58] De Souza F B, Montedo O R K and Grassi R L E G P A 2019 Rev. Matéria 24 1

[59] Dhivyaa P, Minnalkodi G and Dhanalakshmi G 2018 IRJET 5 2010

[60] Shukla S, Seal S, Akesson J, Oder R, Carter R and Rahman Z 2001 App. Surf. Sci. 181 35

[61] Barbare N, Shukla A and Bose A 2003 Cem. Concr. Res. 33 1681

[62] Punidie I, Prantskevichene I, Kligis M and Kairite A G 2019 Refract. Ind. Ceram. 59 482
[63] Shukla A, Bose A, Wayne Lee K and McBride S P 2001 *J. Mater. Sci.* **37** 4217
[64] Zhou H and Brooks A L 2012 *Constr. Build Mater.* **198** 512
[65] Chand N, Sharma P and Fabim M 2010 *Mater. Sci. Eng. A.* **527** 5873
[66] Tao H, Yao J, Zhang L and Xu N 2009 *Mater. Lett.* **63** 203
[67] Hanif A, Lu Z, Diao S, Zeng X and Li Z 2017 *Constr. Build Mater.* **140** 139
[68] Tiwari V, Shukla A and Bose A 2004 *App. Acou.* **65** 263
[69] Cardoso R J and Shukla A 2002 *J. Mater. Sci.* **37** 603
[70] Venkatesha B K and Saravanan R 2020 *Int. J. Veh. Struct. Syst.* **12** 447
[71] Umashankar L V, Sasikumar T, Raghu Vikram M V, Reddy P T and Reddy S M 2018 *Int. J. Civ. Eng. Technol.* **9** 246
[72] Ashoka E, Sharanaprabhu C M, Krishnaraja G K and Kudari SK 2018 *AIP Conf Proc.* **2018** 1943
[73] Ruegele K, Lehmhus D, Hussainova I, Peculevica J, Lisnanskis M and Shishkin A 2017 *Materials (Basel).* **10** 1
[74] Gupta S and Kua H W 2020 *Constr Build Mater.* **253** 119083
[75] Hanif A, Lu Z and Li Z 2017 *Constr Build Mater.* **144** 37