Fly Ash: An Alternative Material for Filling Mining Voids

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Abstract

This paper describes the results obtained from laboratory studies for utilization of fly ash in mine filling applications. It discusses the results obtained from material characterization study to select the best material out of seven different samples studied.

1. Introduction

Slurries commonly refer to mixture of settling particles and some certain liquid such as water. The transport of slurries by hydraulic pipelines is widespread in the minerals, metallurgy, water, and some other industrial applications to carry the raw materials and their products to the designated places. Similarly, fly ash can be transported most economically over great distances using a hydraulic slurry pipeline. Notwithstanding the good technical results achieved by fly ash slurry technologies, technical areas, which deserve further development work, still exist. Design data for slurry pipeline systems are usually obtained using pilot plant studies. The primary aim of this work was to investigate the rheological properties of concentrated fly ash slurries by using rheological instruments with a view to transport the material smoothly and economically (by reducing drag friction) to mine site area to fill worked out empty voids. Fine fly ash slurry may be described as a colloidal system in which the solids are dispersed through the liquid. Because of the high surface charge to mass ratio of fly ashes, van der Waals attractive forces and electrostatic repulsive forces dominate particle interactions. It is the sum of these two forces between particles that determine the nature of the slurry rheology. The net particle interactions can be strongly repulsive, where the particles remain dispersed, so that the fluid exhibits Newtonian flow characteristics. The rheological properties of fine fly ash slurries can be manipulated by altering the concentration of solids and by controlling the electrostatic repulsive forces between the particles. The electrostatic repulsive forces can be increased or decreased by manipulating the pH and the ionic content in the suspending medium. Increasing the repulsive forces with the addition of a dispersing agent may break down the structure and reduce or eliminate non-Newtonian flow behavior. Alternatively, the net interaction between particles can be strongly attractive so that a floc structure will be created. Flocs can form networks which cause the slurry to exhibit non-Newtonian flow characteristics. This structure can resist shear distortion giving the fluid a yield stress. With the addition of small amounts of specific chemical reagents it is possible to manipulate particle-particle interactions between fly ash particles in the
slurry. Variations in flow behavior including elimination of yield stress are associated with these changes. Almost all pipelines in the world today are transporting material in the turbulent flow regime using a critical velocity to keep the particles in suspension. Laminar flow attracts sedimentation and blockage of the pipelines. Therefore, rheological characterization is essential before designing any pipeline system. The engineering properties of a material are dependent to a large extent on the composition of material. There exists wide variation in the composition of fly ash depending on coal types, types of furnace, temperature, collection technique etc. Some of the results of the current investigation and their corresponding analysis have been presented in this paper.

2. Characterization of ingredients
The primary aim of this investigation was to develop fly ash based composite materials suitable for mine filling applications. So a detailed analysis of the constituent materials was first carried out to select the best material out of seven different sources for further study with respect to its flow and in-place strength characteristics. The results of the material characterization study are reported here as given below.

3.0. Results and discussion
3.1. Physical properties
Physical properties help in classifying the coal ashes for engineering purposes and some are related to engineering properties. The fly ash was collected in dry state and was in loose stage. Its average water content was less than 1%. The fly ash used had a powdery structure with medium to dark grey colour indicating low lime content (Meyers et al. 1976). The measured physical properties of seven fly ash samples are reported in Table 4.2.1.

3.1.1. Specific gravity
Specific gravity is an important physical property for evaluating geotechnical applications. A series of tests were conducted to determine the specific gravity (G) values of the fly ash samples, and the average values of G are reported in Table 4.2.1. These values ranged from 2.20 to 2.27, indicating some variation among ash sources. The specific gravity of F1 is lower as compared to other ash sources i.e. 2.20 which are due to high percentage of fine particles. As reported by Kim et al. (2005), the variation in G values is attributable to two factors: (1) chemical composition, and (2) presence of hollow fly ash particles or particles with porous or vesicular textures. Different amounts of hollow particles present in fly ash caused a variation in apparent specific gravity. The apparent specific gravity is also affected by the porosity of its particles. This variation may also be due to trapped micro bubbles of air in ash particles (Trivedi and Singh, 2004). Guo et al. (1996) examined the chemical compositions of hollow and solid fly ash particles
separately, and the data revealed that hollow-particle fly ash had significantly lower iron content (4.5%) than solid particle fly ash (25%).

3.1.2. Specific surface area and bulk density

The specific surface area of the fly ash samples varies between 0.187 m²/g and 1.24 m²/g and the bulk density of the fly ash samples ranged between 1.60 g/cm³ and 1.99 g/cm³ (Table 4.2.1). Though there is little difference in values, comparatively, the average specific gravity and bulk density of fly ashes were found to be less than that of river bed sand. The F₁ fly ash is having less specific gravity and more specific surface area compared to others which would also facilitate possible surface modification by chemical additives for smooth flow in the pipelines. A larger specific surface area of fly ash will make the fly ash particles more easily grafted by the surfactant, making it more suitable to be modified. The high specific surface area of fly ash will also result in a strong adsorptive capacity of fly ash to surfactant suspensions.

3.1.3. Porosity and moisture content

The porosity of the bulk fly ash samples varied between 9.135% and 34.2% and the moisture content varied between 0.15 % - 0.8% (Table 4.2.1). The presence of pores in fly ash may influence the eventual chemical state of the adsorbed vapour by shielding material contained in pores from photochemical degradation (Schure et al., 1985).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>F₁</th>
<th>F₂</th>
<th>F₃</th>
<th>F₄</th>
<th>F₅</th>
<th>F₆</th>
<th>F₇</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colour</td>
<td>Gray</td>
<td>Gray</td>
<td>Gray</td>
<td>Dark gray</td>
<td>Light gray</td>
<td>Light gray</td>
<td>Light gray</td>
</tr>
<tr>
<td>Specific gravity (G)</td>
<td>2.20</td>
<td>2.23</td>
<td>2.27</td>
<td>2.25</td>
<td>2.26</td>
<td>2.24</td>
<td>2.21</td>
</tr>
<tr>
<td>Bulk density (ρ), g/cm³</td>
<td>1.75</td>
<td>1.6</td>
<td>1.67</td>
<td>1.89</td>
<td>1.95</td>
<td>1.99</td>
<td>1.80</td>
</tr>
<tr>
<td>Porosity (φ), %</td>
<td>20.5</td>
<td>34.2</td>
<td>15.7</td>
<td>19.6</td>
<td>20.732</td>
<td>9.135</td>
<td>18.55</td>
</tr>
<tr>
<td>Moisture content, %</td>
<td>0.20</td>
<td>0.8</td>
<td>0.25</td>
<td>0.15</td>
<td>0.398</td>
<td>0.22</td>
<td>0.401</td>
</tr>
<tr>
<td>Specific surface area, m²/g</td>
<td>1.24</td>
<td>0.185</td>
<td>0.458</td>
<td>0.187</td>
<td>0.408</td>
<td>0.428</td>
<td>0.395</td>
</tr>
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<td>Particle size analysis</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D(4,3), µm</td>
<td>171.61</td>
<td>14.27</td>
<td>48.204</td>
<td>91.26</td>
<td>48.214</td>
<td>59.79</td>
<td>65.608</td>
</tr>
<tr>
<td>D(3,2), µm</td>
<td>8.5</td>
<td>5.04</td>
<td>13.105</td>
<td>32.05</td>
<td>13.115</td>
<td>14.003</td>
<td>15.175</td>
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<tr>
<td>D₉₀</td>
<td>988.5</td>
<td>30.831</td>
<td>113.727</td>
<td>187.61</td>
<td>113.757</td>
<td>144.133</td>
<td>158.144</td>
</tr>
<tr>
<td>D₅₀</td>
<td>11.2</td>
<td>8.367</td>
<td>29.972</td>
<td>74.573</td>
<td>29.871</td>
<td>39.375</td>
<td>43.47</td>
</tr>
<tr>
<td>Coefficient of uniformity, C_u</td>
<td>6.3</td>
<td>1.15</td>
<td>1.12</td>
<td>0.70</td>
<td>1.13</td>
<td>1.09</td>
<td>1.07</td>
</tr>
</tbody>
</table>
3.1.4. Grain size analysis

The grain size distribution of fly ashes is very important factor for their use as pozzolans as it influences the behaviour. It provides information related to particle size- whether coarse grained or fine grained and their gradation, etc. The particle sizes of seven fly ash samples exhibit wide variations (Figures 1-3), with F4 being the coarsest and F2 the finest fly ash. The results of particle size analysis of the fly ash samples are also summarized in Table 4.2.1. The grain size distributions for the fly ash samples indicated that the fly ash samples consist of sand-sized (<4.75 mm), silt-sized (0.075-0.002 mm), and clay-sized (<0.002 mm) particles. The sample from F1 (ETPS) exhibits a near normal distribution of fines and coarse fractions. Almost 90% of the particles are less than 50 µm which confirms to the ASTM (D 2487-06, 2006). Fly ashes from other six sources though possess fine sizes; the percentage is less than that of F1.

3.1.5. Coefficient of uniformity

The coefficient of uniformity \( C_u = \frac{D_{60}}{D_{10}} \) affects the workability of the fly ash grains. The higher the coefficient of uniformity, the better is its adaptability to compaction and hence strength. The coefficient of uniformity of the seven samples varies from 0.70 to 6.3. The minimum value belongs to PTPS (F4) which has highest fraction of coarsest particles. The maximum value 6.3 was exhibited by ETPS (F1). This value is more than 6, thus the fly ash particles can be regarded as well graded (Sridharan and Prakash, 2007). Other fly ash specimens show \( C_u \) value less than 6. Hence the fly ash sample F1 is well graded compared with the other fly ash samples as per the classification and gradation of soils (ASTM International D 2487-06, 2006). Also, only the F1 fly ash sample depicted bi-modal particle size distribution thought to be the sum of two normal distributions. These materials are known to favour high densities of the consolidated mass because of their enhanced packing characteristics (Oberacker et al., 2001).

![Figure 4.1. Particle size distribution curve of fly ash sample F1](image)
The SEM photomicrographs depicted the presence of particles with different shapes namely, glassy solid spheres, hollow spheres (cenospheres), broken, sphere within another sphere (plerosphere), tubular, smooth porous grains and some other irregularly shaped particles (Figures 4 and 5). These particles affect the compaction behavior (Leonards and Bailey, 1982). The micrographs depict without any formation of cementitious compounds. It confirms that the fly ash used in this investigation has low calcium content. It compares favorably to those observed elsewhere (Baker and Laguros, 1985).
Table 3. Results of particle size analysis of fly ash samples

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Size range (%)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt; 1 µm</td>
<td>1 µm - 50 µm</td>
<td>&gt; 50 µm</td>
</tr>
<tr>
<td>F1</td>
<td>3.66</td>
<td>87.80</td>
<td>08.54</td>
</tr>
<tr>
<td>F2</td>
<td>2.77</td>
<td>92.73</td>
<td>04.50</td>
</tr>
<tr>
<td>F3</td>
<td>1.02</td>
<td>68.20</td>
<td>31.78</td>
</tr>
<tr>
<td>F4</td>
<td>0.10</td>
<td>34.37</td>
<td>65.53</td>
</tr>
<tr>
<td>F5</td>
<td>1.02</td>
<td>68.40</td>
<td>30.58</td>
</tr>
<tr>
<td>F6</td>
<td>0.97</td>
<td>58.07</td>
<td>40.93</td>
</tr>
<tr>
<td>F7</td>
<td>0.90</td>
<td>55.16</td>
<td>43.94</td>
</tr>
</tbody>
</table>

The fly ash investigated is predominantly fine grained and mostly composed of compact or hollow spheres of different sizes. Some other vitreous unshaped fragments also can be seen in the F7 fly ash sample. SEMs also show that the spheres in the F2 fly ash sample are more closely packed than those in the other samples; thus, F2 exhibits the lowest surface area and pore volume. Unlike other samples, F4 has many unshaped fragments that are ascribed to unburned char (Trivedi and Singh, 2004; Kim et al., 2005; Wang et al., 2008). Spherical particles make up most of the fly ash, especially in the finer fractions. These spheres are glassy and mostly transparent (Figures 4, F1, F2; and 5, F6), indicating complete melting of silicate minerals. The few opaque spheres (Figure 5, F7) are mostly composed of magnetite or other iron oxide particles (Fisher et al., 1978). The fly ash particles in F1 sample are similar in shape and form-
distinctly spherical shape which is considered to be ideal material for mine filling purposes (Canty and Everett, 2001). It is apparent that F1 fly ash has much superior particle morphology than the other fly ashes. Comparatively, it has more spherical particles compared with the other fly ash samples, and this feature would create a lubricating effect, known as the ball-bearing phenomena, resulting in a frictionless flow in stowing pipelines.

Figure 4. SEM Photomicrographs of F1, F2, F3 and F4 fly ash samples at 5000x

Figure 5. SEM Photomicrographs of F5, F6, and F7 fly ash samples at 5000x and 1000x
3.2. Chemical and mineralogical properties

The chemical properties of the coal ashes greatly influence the environmental impacts that may arise out of their use/disposal as well as their engineering properties and also the chemical composition of fly ash is important indicators of suitability of a material for geotechnical applications. Hence, this calls for a detailed study of their chemical composition. The major constituents of these samples are silica (SiO₂), alumina (Al₂O₃), and iron oxide (Fe₂O₃). Minor quantities of calcium oxide (CaO), magnesium oxide (MgO), sodium oxide (Na₂O), potassium oxide (K₂O), titanium oxide (TiO₂), and other compounds are also observed to be present in lesser quantity (Table 4).

The abundance of SiO₂ (≈ 62% of the total composition) in all the fly ash samples would help in increasing the strength of the filling material and offer better load-bearing capacity in taking the load of the overlying strata after filling the mine voids. Because of a small amount of free lime (CaO) content (<1%), the fly ash samples possess negligible pozzolanic or cementing properties. Because the sum total of SiO₂, Al₂O₃, and Fe₂O₃ is > 70% and CaO content is < 6% in all the fly ash samples tested, they are classified as class F fly ash (ASTM C 618-94, 1995). F₁ fly ash sample contains little higher calcium oxide content compared to other fly ash samples which would help in strength gain.

The elemental composition of fly ash samples is shown in Table 5, as obtained from XRF, a bulk technique that can determine average chemical composition of bulk fly ash and identify differences in matrix composition between individual particles (Hansen and Fisher, 1980). The results show that all the fly ash samples are abundant in Si and Al, and possess minor concentrations of Fe, Ca, Mg, K, Ti, and P. In the ash samples, the elements present in decreasing order of abundance are O, Si, Al, Fe, Ti, K, Ca, P, and Mg.
<table>
<thead>
<tr>
<th></th>
<th>0.76</th>
<th>0.685</th>
<th>0.78</th>
<th>1.07</th>
<th>0.918</th>
<th>1.13</th>
<th>0.62</th>
<th>0.92</th>
</tr>
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<tbody>
<tr>
<td>K</td>
<td>0.314</td>
<td>0.309</td>
<td>0.274</td>
<td>0.228</td>
<td>0.347</td>
<td>0.464</td>
<td>0.203</td>
<td>0.327</td>
</tr>
<tr>
<td>Mg</td>
<td>0.086</td>
<td>0.070</td>
<td>0.056</td>
<td>0.064</td>
<td>0.075</td>
<td>0.082</td>
<td>0.058</td>
<td>0.067</td>
</tr>
<tr>
<td>Na</td>
<td>0.157</td>
<td>0.142</td>
<td>0.062</td>
<td>0.116</td>
<td>0.137</td>
<td>0.210</td>
<td>0.123</td>
<td>0.112</td>
</tr>
<tr>
<td>P</td>
<td>0.044</td>
<td>0.072</td>
<td>0.025</td>
<td>0.033</td>
<td>0.124</td>
<td>0.040</td>
<td>0.029</td>
<td>0.055</td>
</tr>
<tr>
<td>Si</td>
<td>21.56</td>
<td>19.97</td>
<td>20.31</td>
<td>19.98</td>
<td>18.48</td>
<td>20.96</td>
<td>20.73</td>
<td>20.89</td>
</tr>
<tr>
<td>Ti</td>
<td>1.145</td>
<td>1.286</td>
<td>1.099</td>
<td>1.087</td>
<td>0.989</td>
<td>1.01</td>
<td>1.195</td>
<td>1.239</td>
</tr>
<tr>
<td>Al</td>
<td>16.14</td>
<td>17.70</td>
<td>15.29</td>
<td>13.95</td>
<td>15.418</td>
<td>15.79</td>
<td>15.58</td>
<td>17.516</td>
</tr>
</tbody>
</table>

Low calcium/class F fly ash has a relatively simple mineralogy consisting of aluminosilicate glass and varying amounts of the crystalline phase assemblage: quartz, mullite, hematite, and ferrite spinel (McCarthy et al. 1981). The XRD patterns of the various fly ash samples are presented in Figures (6-9). The X-ray diffraction profiles of the fly ash samples indicate the presence of crystalline phases. The major mineral constituents of fly ashes are Quartz (SiO₂) and Mullite (Al₆Si₂O₁₃). The other mineralogical fraction of the fly ash indicated the presence of hematite (Fe₂O₃), magnetite (Fe₃O₄), and rutile (TiO₂) (White & Case, 1990, Singh and Kolay, 2002). The diffractograms show that they have similar diffraction patterns. Crystalline phase quartz may be considered as the primary mineral present in all the fly ash samples, indicated by sharp peaks in the diffraction patterns (Trivedi and Singh, 2004). The peak near 2θ=25.50° are identified as mullite. The peaks which occur near 2θ=16.5° are identified as refractory mullite (Sarkar et al., 2006). Along with the alumino-silicate mineral, the occurrence of strong peaks close to 2θ=26.49° indicates quartz. The presence of heavy minerals such as magnetite and hematite are identified by their respective peaks near 2θ=21.4° and 2θ=26.2°.

Figure 6. XRD Pattern of F₁ fly ash sample
4.0 Concluding remarks
The primary objective of this study was to select the best mine filling material out of the seven fly ashes studied. On the basis of the results reported in this study, I draw the following conclusions.

a. F₁ fly ash has good particle size distribution \( (C_u > 6) \) compared with the other fly ashes, thereby fulfilling the requirements as a good grading material.
b. It has got greater amount of fine particles which will favor for effective cover of surfactant on the surface of particles in the wet-modification process.

c. $F_1$ fly ash has a higher specific surface area compared with the other $F$ class fly ashes, facilitating possible surface modification by chemical additives for smooth flow in the pipelines.

d. $F_1$ fly ash has much superior particle morphology compared with the other $F$ class fly ashes. Comparatively, $F_1$ has more spherical particles, a feature that would create a lubricating effect due to the ball-bearing phenomena, resulting in a frictionless flow in stowing pipelines.

e. The $F_1$ sample has relatively high CaO content that would assist in strength enhancement without sacrificing its flow attributes.

f. The abundance of silica would increase strength and CaO would enhance cementing properties.

g. $F_1$ fly ash sample has also lower specific gravity value compared to other samples which would help in keeping the particles floated in pipelines during its transportaition.

Overall results have indicated that the $F_1$ fly ash have several superior desirable properties that would make it attractive to fill mine voids. Therefore, this fly ash material was selected for further study with respect to its flow and in-place strength characteristics.

References


