Effect of fly ash on geotechnical properties and stability of coal mine overburden dump: an overview

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Abstract

The management of overburden (OB) materials needs proper attention to safe mining operations. Several mine OB dump failures have been occurred due to inappropriate geotechnical and geometrical parameters. Increasing consumption of coal in thermal power plant also generates huge amount of ash which adversely affect the environment and its utilization is a great challenge. The present paper reviews the effect of fly ash on the different geotechnical properties and stability of coal mine OB dump material to explore a safe and effective utilization of fly ash. It was found that up to 30% fly ash can potentially modify the compaction characteristics, California bearing ratio value, unconfined compressive strength, and shear strength parameters of OB dump material. Based on the review, it may be suggested that fly ash-OB mix can be effectively utilized in the mine OB dump and for the mine haul road construction thus, provides an alternative mode of fly ash utilization in huge quantity.

Keywords Fly ash · OB material · Dump stability · California bearing ratio · Unconfined compressive strength

1 Introduction

The increasing demand of consumption of energy and power sectors requires huge amount of coal and thus, increases the activity in the coal mining industry. The increasing demand of coal increases the size of open cast coal mine and amount of stripping ratio (ratio of OB material quantity to coal quantity). The higher value of stripping ratio results the higher amount of overburden materials substantially. In India, for the year 2016–2017, the coal production and OB removal was around about 662.792 Million Ton (MT) and 1610.223 Mm³ respectively with stripping ratio of 2.62. OB materials are the upper layer of rocks and soil which has to be removed and dumped for coal production. The OB materials have to be dumped near mine site as internal dump (backfill) or as an external dump [1]. The successful operation of mining activity needs the proper attentions in the mine OB dump management. The

offensive execution of dumping of the OB materials can leads in dump instability, thus, affected the production rate and safe mining operations. Several mine OB dump failures has been occurred due to various reasons. The mine dump failure of Arcturus mine, Zimbabwe [2] and south field lignite mine, Northern Greece [3] respectively.

Blight and Fourie [4] reported the various cases of coal mine dump failure. The volume of dump flow, causes, and consequence due to dump failure of these coal mines are briefly described in Table 1. Poulsen et al. [5] has reported the failure of an external OB dump failure of “Mine A” from Singareni Colliery, India. Failure of OB dump occurred at its maximum designed height of 90.0 m and as a result the material slipped about 70.0 m from it toe location. Kainthola et al. [1] reported the OB dump failure in Western Coalfield Limited, Nagpur, India. The dump having 75.0 m height with 43° slope angle were slipped forwarded by 18.0 m during routine activity of mining. Jhanwar and

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Table 1 Different cases of coal mine dump failure, its causes and consequence. Modified after Blight and Fourie [4]

Location and year	Cause of failure	Flow volume	Consequences
Aberfan, UK (1966)	Dumping of waste over spring	$108 \times 10^3 \text{ m}^3$ dump waste	144 deaths and, 89 miners killed underground and loss of property
Buffalo Creek, USA (1972)	Overtopping of waste impoundments	$500 \times 10^3 \text{ m}^3$ dump waste with water	118 deaths, extensive damage to property, and 4000 homeless
Quintette Mrmot, BC, Canada (1985)	Pore pressure built-up resulting from collapse settlement	2500×10^4 dump waste	2.50 km of river valley get filled with the waste dump and causes several environmental damages
Inez, Kentucky, USA (2002)	Failure due to collapse of underground workings	$950 \times 10^3 \text{ m}^3$ dump slurry	Environmental damages

Thote [6] studied the dump failure of Wardha Valley Coalfield, India and suggested that the dump failure mostly occurs during the monsoon season and of circular type.

The failure of OB dump causes several environmental problems as well as losses of humans and machineries. The causes of instability and stability of the OB are discussed in the various literatures which are briefly described below.

1.1 Instability of OB dump

The OB materials have been dumped in the form of slope or embankment. The instability of the OB dump has been a major concern for the mining industries for several years. The nature of coal waste embankments is different from the common soil or rock embankments due to their petro-graphic nature [7]. The limited area for dumping and increasing amount of OB materials results in the greater height of dump, and creates possible threats to dump instability. Various dump failure incidents have been already reported earlier i.e., South field lignite mine of Northern Greece (2009), Western Coalfield Limited, Nagpur, India (2011), Wardha Valley Coalfield, Nagpur, India (2011), Singareni Colliery, India (2014), etc. The failure of OB dump is caused by the flow or downward movement of the dump materials. Shakesby and Whitlow [2] have reported that provision of poor basal drainage, steeper perimeter wall and saturation of dump wall due to heavy rainfall can also leads to the dump failure. The failure of dump containing heavy concentration of metals and acid producing minerals can adversely affect the water supply and crop yields [8]. The low shear strength, inappropriate geometry, external loading, pore water pressure and heavy rainfall mainly dominate the stability of the dump [5, 8, 9]. Sensitivity of the various input parameters on the stability of the dump (friction angle, cohesion, friction angle of interface, dump slope, and dump height) has been studied by Rai et al. [9] and concluded that slope angle is the most sensitive parameter. Poulsen et al. [5] has back analysed

the material properties and studied the probable mechanism of dump failure of Singareni Colliery, India and concluded that lower residual friction angle causes the failure of dump. Geotechnical and geometrical parameter are the major factors which affect the stability of the dump such as density, cohesion, angle of internal friction, height of dump, slope, bench width etc.

1.2 Stability of the OB dump

Several techniques have been adopted to increase the stability of the OB dump. Flattening of slope increases the stability of the OB dump however it decreases the dump capacity and requires larger area. Revegetation is one of the popular methods adopted for increasing dump stability, mine reclamation, ecological restoration and healthy environment [10–16]. Tripathi et al. [17] studied the long-term stability dump stability and soil fertility of a coal mine spoil in Indian dry tropical environment and suggested that revegetation on the mine dump enhances the root biomass value, mineral Nitrogen and Microbial Biomass Nitrogen (MBN) value. They found that Factor of Safety (FOS) of the OB dump has been increases from 1.20 to 1.70 and 2.10 after 6 years and 12 years of plantation respectively. Several types of revegetation plants like vetiver grass, lemon grass, coir matting and indigenous plant may be used in a wide range for the stabilization of the OB dump [18]. Ecological redevelopment and the stability of the coal mine OB dump of Naya Dhara Colliery, Kapasara, Eastern Coalfield Limited, Dhanbad, India has been studied by Singh et al. [19] and found increase in the stability of the dump by revegetation. The mechanical action of the plant, tree and grass roots reinforces the dump materials and increases the shear strength properties of OB dump materials thus provides higher stability [19, 20]. Mafian et al. [21] has found the reduction in maximum displacement was about 85.5% with vegetation covered slope and similar slope angle.

Several studies illustrate that application of geosynthetics or geogrids may help to conquer the instability issue and to stabilize the surface [22–24]. The bearing capacity and the load settlement characteristics of the different soil reinforced with the geogrid have been studied by various researchers [25–27]. The tensile strength of geogrid, length of the geogrid, vertical spacing of geogrid, number of geogrid layers mainly affects the bearing capacity and load settlement behaviour [28, 29]. Palmeira and Viana [30] suggested that provision of geogrid reduces the deformation of cover soil significantly and increases the slope inclination. Some research has been done on the stability of the mine OB dump materials reinforced with geogrid. Numerical analysis of the mine OB dump reinforced with different combinations of geogrid spacing has been performed by Rai et al. [9]. The FOS increases with decrease in the spacing between geogrid layers and it also alters the probable failure plane. Their results indicated that provision of ten geogrid at 1.0 m interval, the angle of inclination of 60° can be safely achieved with FoS of 1.40. The tensile strength of the geogrid and friction between dump material and geogrid reinforces the OB dump. During failure of the OB dump, geogrid comes under tension and frictional resistance between particle and geogrid prevented the movement of materials [9, 31, 32].

Another important alternative method for stabilization of OB dump material by using industrial waste material as fly ash. Fly ash is the industrial by-product of coal based thermal power plants which are widely used for improvement of the soft soil and in different engineering fields. In India, most of the power plants are coal based and

produces huge amount of fly ash (about 80% of total ash) and bottom ash (about 20% of total ash). The estimated production of fly ash per year in the world is about 550 MT by combustion of coal in thermal power plants [33]. It is also reported that China, the United State, and India, Europe, South Africa, and Australia have the highest production rate of fly ash. In India, according to the report of Central Electricity Authority, New Delhi [34], for 167 coal based thermal power plants, only 67.13% fly ash was utilized in different fields. Figure 1 shows the major modes of utilization of the fly ash in different fields.

A lot of studies have been performed to stabilize the soil mass using fly ash by various researchers [35–40]. Improvement of the engineering properties of the soil by mixing fly ash was evaluated by several researchers [41–45]. Effective utilization of fly ash in slope stability and construction of embankments was also reported in various literatures [46–48]. Indraratna et al. [49] studied the engineering behaviour of a low carbon pozzolanic fly ash and its potential as a construction fill. Results revealed that fly ash can be easily compacted to produce acceptable dry densities over a wide range of water contents.

2 Integration of fly ash with OB dump materials

Fly ash has been utilized as filling materials in the mine site. The notification issued by Ministry of Environment, Forest and Climate Change (MoEFCC), Govt. of India stated that at least 25% fly ash should be mixed with external and

Fig. 1 Modes of fly ash utilization for year 2017–2018 of coal based thermal power plant of India (Central Electricity Authority, New Delhi [33])

internal OB dump at mine site located within 100 km by road from thermal power plant. The mass availability of the fly ash and closely located thermal power plant near to mine sites provide economically feasible approach for disposal of fly ash in OB dump. Fly ash is mainly classified as Class C and Class F fly ash as per American Society for Testing and Materials (ASTM) C618. Class F fly ash contains less than 7% lime (CaO) and requires cementing agent such as cement, lime, or CaO containing materials with water to react and produce the cementitious compound. However, Class C fly ash contains more than 20% lime and in the presence of moisture it shows self-cementitious behaviour. Utilization of Class C fly ash for soil stabilization is more advantageous as compared to Class F fly ash due to the formation of C–S–H gel matrix by Class C fly ash. In India, the generated fly ash is mainly of Class F type. Several studies have been conducted on the stability of OB dump mixed with Class F fly ash. However, the effect on geotechnical properties and stability of OB dump by addition of Class C fly ash is needed to be explored. In the presence of moisture, high calcium in fly ash provides more binding property to the materials but on other hand, it may also create several technical and ecological problems associated with the removal, storage, and utilization process [50]. The long-term effect of fly ash (Class C) on the soil was also determined by Ciecko et al. [51], and it was found that application of fly ash in the soil may produce the long-term impact by improving the chemical, physical, and biological properties of the soil. The long-term (based on the study on soil after 29 year of application of fly ash) improvement in the soil pH was observed with the addition of fly ash (Class C) which also helps to de-acidifying the soil.

Application of fly ash in the reclamation of mine spoil with some selective plantation can be a sustainable ecological approach in reclamation of mine spoil [52]. Fly ash contains several trace elements such as Zinc (Zn), Copper (Cu), Nickel (Ni), Chromium (Cr) and As (major elements) thus, environmental effect should also be considered. The concentration of these elements is higher in fly ash generated from lignite as compared to bituminous or sub-bituminous. Massive utilization of fly ash may also cause ground water and surface water contamination thus,

proper investigation should be carried out to evaluate the limits of fly ash quantity. Although, several researches have been suggested that fly ash may also be used as a heavy metal adsorbent with low cost. The adsorption capacity of the different metals from the waste water by fly ash is presented in Table 2 (modified after Ahmaruzzaman [53]). Application of calcium rich fly ash may be useful to neutralize the acidic nature of mine spoil [54]. Skousen et al. [55] stated that fly ash contributes to stabilize the heavy metals and to enhance the bio-availability of soil nutrients. It also helps to overcome the several adverse condition i.e. low concentrations of key nutrients, poor soil properties, low water holding capacity, and acidic nature of OB material/dump.

Several studies have been carried out to evaluate the physico-mechanical characteristics of the fly ash-OB mix material. Rajak et al. [56] identified the surface characterization of materials of fly ash (Class F) and OB material using scanning electron microscope (SEM) test and found that OB material has irregular shape however, fly ash has spherical shape. The addition of fly ash in OB material provides the good packaging and bonding which improves the stability of the dump [57].

The effect of compaction density and moisture content on the strength behaviour of fly ash mixed coal mine OB dump materials has been studied by Dewangan et al. [58]. The reduction of 10–12% in unit weight was found in case of OB materials mixed with 20–25% fly ash by volume. The reduction in unit weight of fly ash-OB mix was due to the lower specific gravity of fly ash [59]. The mobilized shear strength of the coal mine OB material increases with 20–25% fly ash at moisture content below the optimum moisture content (OMC) due to the increase in frictional component. Dewangan et al. [60] studied the strength behaviour and stability analysis of coal mine waste OB dump materials mixed with 20% and 25% fly ash. The numerical modelling of OB dump by incorporating fly ash for both external (mixed in both the benches) and internal (upper bench) dump has been done by finite different method (FDM) based FLAC/Slope software. The results revealed that inclusion of fly ash enhances the stability of OB dump and thus it can be utilized successfully and safely. Pradhan et al. [61] performed the numerical

Table 2 Adsorption of different metals of waste-water on fly ash. Modified after Ahmaruzzaman [53]

Metal	Adsorption capacity (mg/g)	Temperature (°C)	Metal	Adsorption capacity (mg/g)	Temperature (°C)
Zn ²⁺	06.50–13.30	30–60	Cr ³⁺	52.60–106.40	20–40
Cd ²⁺	198.20	25	Cr ⁶⁺	01.38	30–60
Pb ²⁺	444.70	25	Hg ²⁺	11.00	30–60
Cu ²⁺	01.39	30	As ³⁺	03.70–89.20	25
Ni ²⁺	09.00–14.00	30–60	As ⁵⁺	07.70–27.80	20

simulation of OB dump with 20% fly ash to optimize the slope angle and suggested that optimum slope of 32° can be accommodated safely for the long-term stability for 60.0 m dump height. Rajak et al. [62] has performed the stability analysis for pond ash mixed coal mine OB dump and suggested that pond ash may be safely utilized in the dump with higher stability. Numerical modelling was carried out by Rajak et al. [59] and suggested that optimum dump height of 50.0 m and 55.0 m can be suitably adopted for OB dump mixed with 10% fly ash at 35° and 37° slope angle respectively. It was reported that with the addition of fly ash in OB material, FoS value increases and shear strain rate decreases which make the dump more stable. Integration of fly ash with OB material helps to decrease the shear strain rate and velocity vector which makes fly ash to get utilized in OB dump [59, 61].

3 Effect of fly ash on geotechnical properties of fly ash-OB mix

In the present section, the effect of addition of fly ash on the geotechnical characteristics i.e. compaction characteristics, shear strength characteristics, California bearing ratio, and unconfined compressive strength of the fly ash-OB mix materials are discussed.

3.1 Compaction characteristics

The compaction characteristics of the OB dump materials mixed with different percentage of fly ash (Class F) has been studied by some researchers and there is a scope to incorporate Class C fly ash in Coal mine OB dump material. The increase in the percentage of fly ash (Class F) decreases the Maximum Dry Density (MDD) and increases the optimum moisture content. The decrease in the MDD of fly ash treated materials may be attributed to the lower specific gravity or lower density of the fly ash and also due to the immediate formation of cemented products [59]. The decrease in the MDD was observed about 10–12% for the OB materials mixed with 20% to 25% fly ash by volume [58]. Although increase in OMC of the fly ash treated OB dump materials is due to the more water requirement of the mixture to complete the reaction of cation exchange and also may be due to the presence of hollow sphere in fly ash. Thus, reduction in the MDD with the addition of fly ash will reduce the self-weight of OB dump and provide more stability.

3.2 Shear strength characteristics

The shear strength of geotechnical materials is described by two parameters i.e. cohesion and angle of internal

friction which defines the strength of material under shear. The strength characteristics of the mine OB dump materials and materials mixed with fly ash (Class F) were evaluated using large scale and small-scale direct shear test by some researchers. The Peak shear stress of OB materials mixed with fly ash increases as compared to the parent OB material. The results revealed that addition of fly ash increases the cohesion but friction value decreases marginally. The increase in the cohesion of the OB dump materials with addition of fly ash attributed by the filling of voids between rock particles by fly ash and due to hardening process by fly ash- water reaction [58]. Also, the fly ash gets trapped between the rock particles and reduces the particle to particle interaction thus, reduces the angle of internal friction of mix. Stability analysis of the fly ash mixed mine OB dump materials revealed that 20–25% fly ash can be utilized for stabilizing the dump [58]. Gupta and Paul [57] suggested that 10–20% fly ash can be used to enhance the strength of the OB dump. Rajak et al. [56] have evaluate the shear strength parameters of OB material mixed with fly ash (Class F) with and without addition of Ground Granulated Blast Furnace Slag (GGBS) and found that addition of 20% fly ash with OB material causes improvement in cohesion value by 45%. Addition of 12% GGBS in OB material with 20% fly ash, the cohesion value increased by 81% as compared to OB material. Based on the stability analysis, 20% fly ash can be suitably accommodated with OB material in coal mine dump having 60.0 m dump height and 30° dump slope.

3.3 California bearing ratio (CBR) value

The CBR value governs the design parameter for the construction of pavement. The adequate CBR value is essential for the construction of haul road in the mine site. The CBR value of the lime stabilized fly ash (Class F) mixed mine OB dump materials have been evaluated by Behera [63] and found that in un-soaked condition, the CBR value of OB dump material treated with 35% fly ash was increased by 50% as compared to the untreated materials. Similar study revealed that under soaked condition, the CBR value of OB dump material treated with 15% fly ash was found to be increased by 78% than other mixes [64]. The increase in the CBR value of OB dump material with fly ash is due to the frictional resistance between their particles [65]. The CBR value of the soaked condition is lower as compared to the unsoaked condition due to the saturation, reduction in effective stresses and loss of surface tension [66]. Some additives were incorporated with the fly ash-OB mix to get utilized for the construction of mine haul road. The additives (i.e. cement, lime, clinker, kiln dust, GGBS) were used to produce cementitious compound in the OB-fly ash

mix. The best results of CBR value in different literatures are briefly described in Table 3.

The addition of additives in fly ash (Class F)-OB mix helps to form the cementitious compound or C–S–H gel in the presence of moisture thus, increases the CBR value. The application of Class C fly ash (higher content of CaO) in OB material may reduce the dosage of additives to achieve the desired strength.

3.4 Unconfined compressive strength (UCS) value

UCS is the design parameter used to indicate the strength gain of stabilized soil. Several studies has been reported in the literatures for UCS value of fly ash-OB mix [49, 57–59]. Rajak et al. [59] reported that UCS value get increased by 9.34% with the addition of 20% fly ash in OB material. Few additives were added in different proportions with the fly ash-OB mix like lime [63, 64, 70], clinker [71, 72], cement [68], GGBS [56], and kiln dust [69] to determine the UCS value. The best suitable results of UCS value under

different mix proportions of OB material, fly ash, or/and additive are described in the Table 4.

The addition of additives in OB-fly ash (Class F) mix helps to enhance the UCS value by formation of C–S–H gel in the presence of moisture. The utilization of Class C fly ash with high CaO content may reduce the dosage of additives in OB-fly ash mix. It was also reported that with the addition of 12% GGBS in OB material, utilization of fly ash up to 20% can be suitably adopted in sub-base layer of mine haul road [56].

4 Practical application

The behaviour of strength characteristics may vary with the variation in properties of fly ash and OB materials. Thus, a thorough investigation is required to evaluate the various geotechnical properties for different mix proportions of fly ash and OB material of different source and mines respectively. The concept of utilizing fly ash-OB material shows the positive effect in strength and stability

Table 3 Various types of materials and best result of CBR value

S. No.	Material used	Best result	References
1.	OB material, fly ash, and lime	The CBR value increased from 85 to 195% at 28 days curing period for mix containing 60% OB material, 40% fly ash, and 3% lime	[63]
2.	OB material, fly ash, and lime	CBR value increased from 85 to 195% at 28 days curing period for OB material mixed with 30% fly ash and 9% lime	[64]
4.	OB material, fly ash, and lime	The CBR value increased from 85 to 166% at 28 days curing period for mix containing 80% OB material, 20% fly ash, and 6% lime	[67]
5.	OB material and fly ash	Maximum CBR value under soaked and unsoaked condition was obtained as 17.55% and 29.97% respectively for mix containing 90% OB material and 10% fly ash	[59]
6.	OB material, fly ash, and GGBS	The OB material containing 12% GGBS and 20% fly ash exhibited CBR value of 47% thus, suitable to get utilized in the sub-base layer of mine haul road	[56]

Table 4 Various types of material and best results of UCS value

S. No.	Material used	Best results	References
1.	OB material, fly ash, and lime	UCS value increased with increase in curing period. The maximum UCS value i.e. 3.14 MPa was observed for OB material mixed with 30% fly ash and 9% lime at 56 days curing period	[64]
2.	OB material, fly ash, and lime	Maximum UCS value (2.59 MPa) was observed for 80% OB, 20% fly ash, and 6% lime at 28 days curing period	[67]
3.	OB material, fly ash, and clinker	Maximum UCS value i.e. 1.40 MPa with UCS gain of 5.18 times was observed for 62% fly ash, 30% OB material, and 8% clinker at 28 days curing period. It also fulfils the minimum strength criteria of material to get utilized in the construction of mine haul road	[71]
4.	OB material, fly ash, and lime	UCS value was increased from 0.70 to 2.50 MPa for mix containing 70% OB material, 30% fly ash and 9% lime as additive at 28 days curing period	[63]
5.	OB material and fly ash	The UCS value was increased by 9.34% (0.667 MPa) with the addition of 20% fly ash as compared to native OB material (0.61 MPa)	[59]
6.	OB material, fly ash, and GGBS	The UCS gain of 1.71 time (1.20 MPa) was observed with the addition of 12% GGBS and 20% fly ash with OB material	[56]

aspects with and without addition of additives like lime, cement, clinker, etc. Another by-product material i.e. ground granulated blast furnace slag may be used as an additive to further enhance the strength characteristics of fly ash-OB mix.

Incorporation of fly ash in OB material along with some additives may also provide a suitable sub-base layer material in the construction of mine haul road. Safe and effective mode of utilization of fly ash may be achieved using fly ash-OB mix for mine void filling. Fly ash may also be used to provide the micronutrients which promotes the plant yields by enhancing the soil fertility and neutralizing the soil acidity.

5 Conclusion

The present paper discussed about the effect of fly ash on the geotechnical properties and stability of OB-fly ash dump. This paper reviewed the different percentage of fly ash-OB mix that can be safely utilized in the mine dump as well as in the construction of mine haul road. Based on the review of several literatures following conclusion have been made.

- The addition of fly ash in mine OB dump materials decreases the MDD and increases the OMC.
- The decreases in the MDD of fly ash treated mine OB dump materials reduces the overall weight of the mine OB dump and thus provides extra stability.
- The addition of fly ash in the mine OB dump increases the cohesion value and decreases the angle of internal friction.
- The incorporation of fly ash in mine OB dump materials may be an alternative approach for the fly ash utilization and to increase the dump stability.
- The studies show that up to 20–30% fly ash can be utilized safely and economically in the mine OB dump.
- It was observed from literatures that addition of fly ash up to 30% in mine OB dump materials with and without additives improved the CBR and UCS value and satisfies the minimum strength criteria to get utilized in the construction of mine haul road.
- The application of fly ash in OB dump will help to provide the key nutrients; increase the water holding capacity; reduce the metal toxicity, and neutralize the acidity of the mine spoil, which will be beneficial for establishing vegetation cover on mine OB dump and amendment of mine spoil.

The outcome of the literature recommends the potential utilization of fly ash with mine OB material for safe dumping, construction of mine haul road, amendment of

mine spoil, and revegetation on OB dump thus, provide an effective alternative mode for fly ash utilization.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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