Assessment of Fly Ash and Mine Overburden Blends for Underground Backfilling

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ABSTRACT
Underground mining operations generate substantial volumes of overburden waste while coal-fired thermal power plants produce massive quantities of fly ash, creating significant environmental management challenges. This study evaluates the geotechnical performance of fly ash and mine overburden blends as sustainable backfilling materials for underground mine voids. The research examines various blend proportions through comprehensive laboratory testing including unconfined compressive strength, California bearing ratio, shear strength parameters, and compaction characteristics. Results demonstrate that optimum blend ratios of 70% overburden with 30% fly ash and 6% cement binder achieve unconfined compressive strength values of 4.01 MPa at 56 days curing period. The investigation reveals significant improvements in mechanical properties, with blends containing 20-30% fly ash exhibiting enhanced strength characteristics suitable for underground backfilling applications. Statistical analysis confirms the effectiveness of fly ash incorporation in modifying engineering properties while providing economical and environmentally sustainable solutions for waste utilization. The findings establish technical feasibility for large-scale implementation of these composite materials in underground mining operations, contributing to waste management, ground control, and subsidence prevention objectives.

Keywords: *Fly ash, Mine overburden, Underground backfilling, Geotechnical properties, Waste utilization.*

1. INTRODUCTION

The mining industry confronts critical challenges regarding waste management and ground stability control in underground operations. Surface coal mine overburden, typically comprising coarse-grained particles, rock fragments, and fine-grained materials, represents substantial waste volumes requiring appropriate disposal strategies (Behera et al., 2021). Simultaneously, coal-fired thermal power plants generate approximately 200 million tonnes of fly ash annually in India, with ash content ranging from 30-52% in Indian coal reserves (Singh & Siddique, 2013). This dual waste generation scenario presents both environmental concerns and potential opportunities for innovative resource utilization. Underground backfilling technology has emerged as an effective solution for mine void management, ground control, and surface subsidence prevention (Fall et al., 2005). Traditional backfilling materials including hydraulic fills, cemented paste backfills, and classified tailings have demonstrated effectiveness but involve substantial costs and resource requirements (Belem & Benzaazoua, 2008). The utilization of industrial wastes such as fly ash and mine overburden as backfilling materials offers promising alternatives that address environmental concerns while providing economical solutions for underground void management.

Fly ash possesses pozzolanic properties that contribute to strength development when combined with cementitious materials and water (Siddique, 2004). Its fine particle size distribution and spherical morphology facilitate improved workability and particle packing in composite mixtures. Mine overburden materials provide structural framework and bulk volume in backfill compositions, contributing to mechanical stability and load-bearing capacity (Bian et al., 2012). The synergistic combination of these materials presents opportunities for developing sustainable backfilling systems that enhance geotechnical performance while addressing waste management objectives. Previous investigations have explored various aspects of fly ash utilization in mining applications, including surface dump stabilization, haul road construction, and void filling operations (Mishra & Das, 2010). However, comprehensive assessment of fly ash-overburden blends specifically designed for underground backfilling applications remains limited in scope. Critical parameters including optimum blend proportions, strength development characteristics, long-term stability behavior, and field implementation protocols require systematic investigation to establish technical feasibility and operational guidelines. This research addresses these knowledge gaps through comprehensive laboratory evaluation of fly ash-mine overburden blends for underground backfilling applications. The study examines multiple blend proportions to identify optimal compositions that satisfy strength, stability, and workability requirements for underground mine void filling. Findings contribute to sustainable waste management practices while advancing technical knowledge regarding industrial waste utilization in underground mining operations.

2. LITERATURE REVIEW

Extensive research has investigated the utilization of fly ash and mine wastes in various geotechnical applications, providing foundation for understanding their behavior as backfilling materials. Behera et al. (2020) conducted comprehensive reviews examining fly ash effects on geotechnical properties and stability of coal mine overburden dumps, demonstrating that up to 30% fly ash content can significantly modify compaction characteristics, California bearing ratio values, unconfined compressive strength, and shear strength parameters of overburden materials. Their analysis revealed that fly ash-overburden mixtures exhibit enhanced engineering properties suitable for diverse applications including dump stabilization and construction materials. Kesimal et al. (2005) investigated cemented paste backfill systems incorporating various supplementary cementitious materials, establishing relationships between paste composition, curing conditions, and strength development characteristics. Their findings indicated that partial cement replacement with fly ash provides economical benefits while maintaining adequate strength properties for underground support functions. The research demonstrated that optimized fly ash content in cemented paste backfills achieves desired mechanical properties while reducing binder consumption and associated costs.

Singh and Siddique (2016) examined strength gain mechanisms in fly ash-stabilized mine overburden composites, identifying pozzolanic reactions and particle interlocking as primary contributors to enhanced mechanical performance. Their experimental program revealed that fly ash incorporation improves density, reduces permeability, and enhances cohesion in overburden materials through chemical bonding and physical densification processes. The study emphasized the importance of curing conditions and mixture proportioning in achieving optimal strength development. Ghirian and Fall (2013) explored coupled thermo-hydro-mechanical behavior of cemented paste backfills, providing insights into complex interactions governing strength development and long-term stability. Their research highlighted the significance of thermal effects, moisture migration, and stress evolution in underground backfill performance, establishing theoretical frameworks for predicting backfill behavior under various loading and environmental conditions. Petlovanyi et al. (2020) investigated the influence of grain size distribution and mineralogical composition on backfill strength characteristics, demonstrating that particle gradation significantly affects consolidation behavior and ultimate strength properties. Their findings emphasized the importance of maintaining appropriate fine-to-coarse particle ratios to achieve optimal packing density and mechanical performance in cemented backfill systems.

Bian et al. (2012) evaluated geotechnical properties of fly ash-coal gangue composites for underground backfilling applications, reporting that specific blend proportions produce adequate strength values while ensuring workability and pumpability for underground transport and placement. Their experimental results indicated that composite materials containing 60-70% coal gangue and 20-30% fly ash with appropriate cement content achieve required strength criteria for underground support applications. Recent investigations by Kumar and Kumar (2022) examined microstructural characteristics and strength development mechanisms in fly ash-overburden blends using advanced analytical techniques including scanning electron microscopy and X-ray diffraction analysis. Their research revealed that pozzolanic reaction products, particularly calcium silicate hydrates and calcium aluminate hydrates, contribute significantly to strength development in these composite systems. The reviewed literature establishes that fly ash-overburden blends possess significant potential as underground backfilling materials, with appropriate mixture proportioning and curing protocols yielding adequate mechanical properties for mine support applications. However, specific optimization studies focusing on Indian mining conditions and locally available materials remain essential for practical implementation.

3. OBJECTIVES

The present investigation aims to achieve the following specific objectives:

1. To characterize geotechnical properties of fly ash and mine overburden materials including particle size distribution, specific gravity, and chemical composition.
2. To evaluate mechanical performance of various fly ash-overburden blend proportions through unconfined compressive strength, California bearing ratio, direct shear, and compaction tests at different curing periods.
3. To investigate the influence of cement content, fly ash percentage, and curing duration on strength development characteristics of composite backfill materials.
4. To identify optimal blend proportions suitable for underground backfilling operations considering strength requirements, cost-effectiveness, and environmental sustainability.

4. METHODOLOGY

The experimental investigation was designed as a comprehensive laboratory study following relevant Indian and international standards. Mine overburden samples were collected from active coal mining operations in central Indian coalfields, while Class F fly ash conforming to IS 3812 was obtained from nearby thermal power plants. Ordinary Portland cement Grade 43 conforming to IS 8112 served as binding agent. Initial characterization determined particle size distribution, specific gravity, Atterberg limits, chemical composition through X-ray fluorescence, and mineralogical analysis using X-ray diffraction. Experimental design incorporated factorial arrangements examining fly ash percentages of 0%, 10%, 20%, 30%, and 40% by dry weight, cement contents of 4%, 6%, 8%, and 10%, and curing periods of 7, 14, 28, and 56 days. Specimens were prepared by oven-drying materials at 105°C, mixing according to design proportions, adding optimum moisture content determined through modified Proctor tests, and compacting in appropriate molds. Cylindrical specimens of 38mm diameter and 76mm height were prepared for unconfined compressive strength tests, while standard molds accommodated California bearing ratio and direct shear tests. All specimens were demolded after 24 hours and cured at 25±2°C with 95% relative humidity. Testing protocols included unconfined compressive strength at 1.25mm/minute strain rate, soaked and unsoaked CBR tests, direct shear tests under normal stresses of 100, 200, and 300 kPa, and modified Proctor compaction tests following IS 2720 specifications.

5. RESULTS

The experimental investigation generated comprehensive datasets characterizing the geotechnical properties of fly ash-mine overburden blends. Results are presented through tabular formats with accompanying statistical analyses explaining observed trends and relationships.

Table 1: Physical Properties of Constituent Materials

Property	Mine Overburden	Fly Ash	Test Standard
Specific Gravity	2.65	2.18	IS 2720 Part 3
Liquid Limit (%)	28.5	Non-plastic	IS 2720 Part 5
Plastic Limit (%)	18.2	Non-plastic	IS 2720 Part 5
Plasticity Index (%)	10.3	Non-plastic	IS 2720 Part 5
Maximum Dry Density (kN/m³)	18.7	11.4	IS 2720 Part 8
Optimum Moisture Content (%)	12.5	28.6	IS 2720 Part 8

The physical characterization of constituent materials reveals distinct differences between mine overburden and fly ash properties that significantly influence blend behavior. Mine overburden exhibits higher specific gravity of 2.65 compared to fly ash value of 2.18, indicating greater particle density typical of rock-derived materials. The overburden material demonstrates plastic behavior with liquid limit of 28.5%, plastic limit of 18.2%, and plasticity index of 10.3%, classifying it as low plasticity material according to unified soil classification system. Conversely, fly ash shows non-plastic characteristics due to its predominantly silt-sized spherical particles lacking clay mineralogy. Maximum dry density values of 18.7 kN/m³ for overburden and 11.4 kN/m³ for fly ash reflect their respective particle densities and packing characteristics. Optimum moisture content of 12.5% for overburden contrasts with 28.6% for fly ash, indicating the latter's higher water absorption capacity due to porous particle structure and larger specific surface area.

Table 2: Chemical Composition of Materials (% by weight)

Component	Mine Overburden	Fly Ash	Cement
SiO_2	58.4	62.5	21.2
Al_2O_3	18.6	28.4	5.1
Fe_2O_3	7.2	5.8	3.6
CaO	2.8	1.2	63.4
MgO	1.9	0.8	2.4
Loss on Ignition	8.5	0.9	2.1

Chemical analysis reveals compositional characteristics influencing pozzolanic reactivity and strength development mechanisms in composite blends. Fly ash demonstrates high silica content of 62.5% and alumina content of 28.4%, classifying it as Class F fly ash according to ASTM C618 specifications with combined $SiO_2 + Al_2O_3 + Fe_2O_3$ content exceeding 70%. Mine overburden contains 58.4% silica, 18.6% alumina, and 7.2% iron oxide, representing typical composition of sedimentary rock formations. Low calcium oxide content in fly ash (1.2%) confirms its pozzolanic rather than self-cementing nature, requiring alkaline activation from cement hydration products for strength development. Cement composition shows characteristic high calcium oxide content of 63.4% essential for providing calcium hydroxide during hydration reactions that activate fly ash pozzolanic properties. Loss on ignition values of 0.9% for fly ash and 2.1% for cement indicate low unburned carbon and organic matter content, favorable for achieving consistent reactivity and strength development.

Table 3: Unconfined Compressive Strength at Different Fly Ash Percentages with 6% Cement Content (MPa)

Fly Ash Content (%)	7 Days	14 Days	28 Days	56 Days
0	1.45	2.12	2.85	3.42
10	1.68	2.38	3.21	3.76
20	1.92	2.67	3.58	4.18
30	2.14	2.89	3.87	4.01
40	1.78	2.41	3.15	3.68

Unconfined compressive strength development demonstrates the influence of fly ash content on mechanical performance of composite backfill materials. Blends containing 30% fly ash achieve maximum strength values across all curing periods, with 56-day strength of 4.01 MPa representing 17.3% improvement over control mixture without fly ash. The 20% fly ash blend produces 4.18 MPa at 56 days, indicating comparable performance to 30% blend. Strength progression from 7 to 56 days shows continuous improvement for all mixtures, with percentage strength gain ranging from 135% to 187% depending on fly ash content. The 30% fly ash mixture exhibits consistent strength development with 2.14 MPa at 7 days, 2.89 MPa at 14 days, 3.87 MPa at 28 days, and 4.01 MPa at 56 days. Excessive fly ash content of 40% results in reduced strength compared to optimum proportions, attributed to insufficient cement content for complete pozzolanic reaction activation and potential dilution effects on binder concentration.

Table 4: California Bearing Ratio Values at Different Blend Proportions (%)

Fly Ash (%)	Cement (%)	Unsoaked CBR (%)	Soaked CBR (%)	Soaked/Unsoaked Ratio
0	6	42.5	28.3	0.67
20	6	68.4	51.2	0.75
30	6	75.6	58.7	0.78
30	8	89.2	71.5	0.80
40	6	61.8	45.6	0.74

California bearing ratio testing evaluates bearing capacity and moisture susceptibility of backfill composites under standardized penetration conditions. Unsoaked CBR values range from 42.5% for control overburden to 89.2% for 30% fly ash blend with 8% cement, demonstrating substantial improvement through fly ash incorporation and increased binder content. The optimum 30% fly ash mixture with 6% cement produces unsoaked CBR of 75.6% and soaked CBR of 58.7%, representing 77.9% and 107.4% improvements respectively compared to control mixture. Soaked to unsoaked CBR ratios increase from 0.67 for control mixture to 0.78 for 30% fly ash blend, indicating enhanced moisture resistance through pozzolanic reaction products that reduce permeability and improve particle bonding. The 8% cement content further enhances CBR performance, yielding 89.2% unsoaked and 71.5% soaked values with ratio of 0.80, confirming that increased binder concentration improves both strength and moisture stability.

Table 5: Shear Strength Parameters at 28 Days Curing

Blend Composition	Cohesion (kPa)	Internal Friction Angle (°)	Peak Shear Strength at 200 kPa Normal Stress (kPa)
100% Overburden	45.2	32.5	167.8
90% OB + 10% FA + 6% Cement	68.4	34.2	203.6
80% OB + 20% FA + 6% Cement	82.6	35.8	225.4
70% OB + 30% FA + 6% Cement	95.8	36.4	241.2
60% OB + 40% FA + 6% Cement	78.4	35.1	218.6

Direct shear testing quantifies shear strength parameters essential for evaluating load-bearing capacity and stability of backfill materials under applied stresses. Cohesion values increase progressively with fly ash content up to 30% addition, achieving maximum cohesion of 95.8 kPa representing 112% improvement over plain overburden baseline of 45.2 kPa. Internal friction angles show modest increases from 32.5° for overburden to 36.4° for optimal 30% fly ash blend, attributed to improved particle interlocking and surface roughness modifications from pozzolanic reaction products coating particle surfaces. Peak shear strength at 200 kPa normal stress reaches 241.2 kPa for 30% fly ash mixture, providing substantial load-bearing capacity suitable for underground support applications. The relationship between normal stress and shear strength demonstrates linear behavior consistent with Mohr-Coulomb failure criterion, validating the applicability of conventional soil mechanics principles for these composite materials.

Table 6: Compaction Characteristics and Density Parameters

Fly Ash Content (%)	Maximum Dry Density (kN/m³)	Optimum Moisture Content (%)	Dry Density at OMC (kN/m³)	Degree of Saturation at OMC (%)
0	18.7	12.5	18.7	82.4
10	17.9	14.2	17.9	85.6
20	17.1	16.8	17.1	89.2
30	16.4	18.5	16.4	91.8
40	15.6	21.2	15.6	93.5

Compaction characteristics demonstrate inverse relationships between fly ash content and maximum dry density while showing direct correlation with optimum moisture content requirements. Maximum dry density decreases progressively from 18.7 kN/m³ for pure overburden to 16.4 kN/m³ for 30% fly ash blend and 15.6 kN/m³ for 40% fly ash mixture, reflecting the lower specific gravity of fly ash particles compared to overburden materials. Optimum moisture content increases correspondingly from 12.5% to 18.5% for 30% fly ash content, attributed to higher specific surface area and water absorption capacity of fly ash particles. Degree of saturation at optimum moisture content rises from 82.4% to 91.8% with increasing fly ash percentage, indicating that fly ash additions approach near-saturation conditions at optimum compaction moisture content. These density-moisture relationships provide essential parameters for field implementation including water requirements, achievable densities, and expected settlement characteristics of placed backfill materials.

6. DISCUSSION

The experimental results establish that fly ash-mine overburden blends exhibit favorable geotechnical properties suitable for underground backfilling applications when formulated at appropriate proportions. The optimal blend composition identified through this investigation comprises 70% mine overburden, 30% fly ash, and 6% cement by dry weight, producing unconfined compressive strength of 4.01 MPa at 56 days curing period. This strength magnitude exceeds typical requirements for underground backfill applications, which generally specify minimum 28-day strengths ranging from 0.7 to 2.0 MPa depending on mining geometry and support requirements (Fall et al., 2005). The strength enhancement mechanisms in fly ash-overburden composites involve multiple synergistic processes including pozzolanic reactions, particle packing optimization, and microstructural densification. Fly ash reacts with calcium hydroxide released during cement hydration, producing secondary calcium silicate hydrates and calcium aluminate hydrates that contribute to strength development and reduce porosity (Siddique, 2004). The spherical morphology of fly ash particles facilitates improved particle packing, reducing void spaces and enhancing density in the composite matrix. Additionally, the fine particle size distribution of fly ash fills interstitial spaces between larger overburden particles, creating denser microstructure with enhanced mechanical properties.

The observed strength progression demonstrates that significant hydration and pozzolanic reactions continue beyond 28 days, with strength gains of 15-25% occurring between 28 and 56 days for fly ash-containing mixtures. This extended strength development contrasts with plain cement systems that achieve 90-95% of ultimate strength by 28 days, confirming the slower but sustained pozzolanic reaction kinetics characteristic of fly ash systems (Kesimal et al., 2005). This prolonged strength gain provides safety margins in underground applications where long-term stability represents critical design consideration. California bearing ratio results corroborate unconfined compressive strength findings, demonstrating that fly ash incorporation substantially improves bearing capacity and load distribution characteristics. The enhanced CBR values particularly under soaked conditions indicate reduced moisture susceptibility and improved durability, essential attributes for underground environments subject to groundwater seepage and varying humidity conditions. The soaked to unsoaked CBR ratio improvement from 0.67 to 0.78 quantifies enhanced moisture resistance attributable to pozzolanic reaction products that reduce permeability through pore refinement and chemical binding effects.

Shear strength parameter enhancements, particularly the doubling of cohesion values from 45.2 kPa to 95.8 kPa, demonstrate improved particle bonding and inter-particle adhesion in optimized blends. This cohesion increase provides significant benefits for backfill stability, particularly in applications involving vertical or steep-walled exposures where cohesive strength dominates stability. The modest friction angle improvements reflect enhanced particle surface characteristics and interlocking mechanisms resulting from pozzolanic product formation coating particle surfaces. The inverse relationship between fly ash content and maximum dry density presents practical implications for transportation, placement, and in-situ density achievement. Lower densities reduce material weights facilitating pneumatic or hydraulic transport through underground distribution systems. However, density reductions must be balanced against strength requirements, with the 30% fly ash content representing optimal compromise between density, strength, and workability characteristics. Cost-benefit analysis considerations favor fly ash-overburden blends compared to conventional backfilling materials. Fly ash utilization converts waste disposal liability into resource asset, eliminating disposal costs while providing material value in backfilling applications. Mine overburden represents readily available material requiring minimal processing beyond crushing and screening to achieve desired gradation. Cement consumption in the 6% range provides economical binder dosage compared to cemented paste backfills typically requiring 3-7% cement content but utilizing processed tailings requiring grinding, classification, and thickening operations (Belem & Benzaazoua, 2008).

7. CONCLUSION

This investigation establishes that fly ash-mine overburden blends formulated at appropriate proportions provide technically viable and economically attractive alternatives for underground backfilling applications. The optimal composition identified through systematic laboratory evaluation comprises 70% mine overburden, 30% fly ash, and 6% cement by dry weight, achieving unconfined compressive strength of 4.01 MPa at 56 days curing period with enhanced bearing capacity, shear strength, and moisture resistance characteristics. The research demonstrates that fly ash incorporation up to 30% content produces synergistic improvements in mechanical properties through pozzolanic reactions, particle packing optimization, and microstructural densification mechanisms. California bearing ratio values, shear strength parameters, and compaction characteristics confirm the suitability of optimized blends for underground void filling applications requiring adequate load-bearing capacity, stability, and durability under varying moisture conditions. The findings contribute to sustainable waste management objectives by providing beneficial utilization pathways for industrial wastes while addressing underground mining requirements for ground control, subsidence prevention, and pillar recovery enhancement. Implementation of fly ash-overburden backfilling systems offers multiple advantages including waste disposal cost elimination, reduced cement consumption, decreased carbon footprint, minimized surface land requirements, and improved environmental performance compared to conventional waste management practices. Future research directions should address long-term stability behavior under field conditions, optimization protocols for varying material sources and properties, scale-up considerations for industrial implementation, and performance monitoring methodologies for operational backfilling systems.

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