

Assessing the suitability of plastic mixed fly ash aggregates for hydraulic backfilling



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ABSTRACT

A significant percentage of power production in the country is still dependent on thermal power plants that use coal as their fuel, which has led to massive production of fly ash (FA) as an industrial by-product. Disposing fly ash and especially the storage of ash in an ash pond has become a major environmental and operational challenge facing thermal power stations. Simultaneously, the growing need in sand and aggregates in construction, roads, and geotechnical practices has caused faster exploitation of natural resources. In that regard, the current research examines how alternative aggregates can be developed by applying different percentages of fly ash and plastic waste. The environmentally hazardous plastic materials were obtained as municipal solid waste streams and added to encourage resource recovery and waste valorization. The two-fold environmental advantages of using fly ash and plastic waste as constituents of aggregates relate to the lightness of their disposal and the reduction of reliance on natural aggregates. The fly ash plastic aggregates were formed by the rotary extruder into seven mix proportions. The slake durability and point load strength index tests were used to compare the engineered aggregates in terms of durability and mechanical performance, respectively. Moreover, the essential physical and geotechnical characteristics were calculated and identified and compared to the values of fly ash alone to evaluate the impact of plastic inclusion. The study shows that the addition of plastic increases the durability of the aggregates and has a positive effect on their physical and geotechnical properties, which implies that the derived synthetic lightweight aggregates could be useful in hydraulic backfilling works in underground mines.

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1 Introduction

The mining industry plays a critical role in meeting global demands for energy and raw materials. However, it faces sustained challenges that include ground containment, waste management, and environmental sustainability. The stability of underground mine workings is one of these challenges, and its successful implementation depends heavily on the use of efficient backfilling measures [1, 2]. By enhancing the load-bearing behaviour of rib pillars, backfilling reduces surface subsidence, governs ground displacement, and improves overall mine safety [3–5]. Traditionally, river sand (RS) has been the most common backfilling material because of its availability, operational convenience, and favourable mechanical properties. Nevertheless, the overexploitation of RS and low replenishment rate due to construction of dams upstream, caused river bed erosion, ecological crisis, regulatory limitations, and cost increases [6]. Therefore, there has been an increased pressure in the mining industry to be able to find alternatives to RS which despite their changes can offer similar or better functioning without negative environmental effects.

In this regard, a promising substitute material for mine backfilling is fly ash (FA), an industrial by-product of coal-based thermal power plants. The use of fly ash as backfilling material offers several advantages, including reduced problems associated with ash disposal, preservation of natural resources, and a smaller environmental footprint [3, 5, 7]. Although backfilling with FA has numerous benefits, the data shows that the FA usage for mine backfilling has been below 7% over the years [8], since the practical use of fly ash as a hydraulic backfilling material is low, as it is ultra-fine in nature with low cohesion, high segregation tendency, and is easy to wash away. Such characteristics typically result in poor load transfer, inadequate confinement, and low reinforcement efficiency when fly ash is used in its pure state.

Recent studies have aimed to overcome these limitations by changing FA slurry properties with surfactants, flocculants, and chemical additives [9]. While these methods show short-term improvements in flow and settling, their effectiveness under load remains

inconsistent. Chemical modifications tend to be unstable over time, decay in performance, and are less capable of providing long-term structural support [10]. Recent advancements in sustainable material engineering suggest that mechanically stabilized and composite backfill materials can demonstrate improved performance concerning particle integrity, interlocking, and load-transfer mechanisms [11]. The use of plastic waste (PW) as binding agents in geotechnical applications has attracted significant interest due to their strength, versatility, and ability to enhance the behavior of composites. Integrating FA particles with PW not only mitigates the shortcomings of unconfined FA but also presents an effective strategy for the valorization of PW, which is consistent with the principles of a circular economy.

Considering this context, the primary goal of this study is to develop rotary-extruded synthetic lightweight aggregates (SLAs) that incorporate FA and plastic waste PW as a dual-waste approach for developing synthetic aggregates for hydraulic mine backfilling. This study diverges from traditional FA slurries, which are susceptible to segregation, poor drainage, and from sintered artificial aggregates, which are energy-intensive. Instead, it introduces an extruder-based valorization method. This technique efficiently encapsulates ultrafine FA within a polymer matrix while optimizing particle grading and permeability to align with the performance needs. This study systematically produced SLAs by employing rotary extrusion across six distinct ratios of FA to PW, utilizing four types of polymers, polyethylene terephthalate (PET), high-density polyethylene (HDPE), low-density polyethylene (LDPE), and polypropylene (PP). This study assessed the durability of these aggregates using the slake durability index (SDI), point load strength tests, and microscopic analysis, while also examining the geotechnical properties essential for backfill applications.

2 Materials and methodology

2.1 Materials

FA for developing SLA was procured from the Singareni Thermal Power Plant (STPP) located in the Mancherla district, Telangana, India (18°49'N, 79°34'E).

Table 1 details the physical, geotechnical, and chemical properties, while Figure 1 illustrates the particle size distribution, and Figure 2 presents scanning electron microscope (SEM) micrographs of FA. Plastics used as binders were sourced from municipal solid waste streams, subsequently purified, shredded, and classified according to the ASTM D-7611 resin identification code (RIC). The study examined four polymer types: PET (RIC-1), HDPE (RIC-2), LDPE (RIC-4), and PP (RIC-5).

Table 1 Physical, geotechnical properties and chemical composition of FA

Property	Value	Indian standard procedure
Specific gravity	2.06	IS 2720-3-2 (1980)
C_u , C_c , and soil type	2.34, 0.81, and poorly graded	IS 2720-4 (1994)
Permeability (cm/s)	0.33×10^{-3}	IS 2720-17 (1986)
Chemical composition	56.89%-SiO ₂ , 23.27%-Al ₂ O ₃ , 7.21%-Fe ₂ O ₃ , 4.67%-CaO, 2.24%-TiO ₂ , 2.60%-K ₂ O, 1.12%-MgO, 1.65%-LOI (Class-F)	

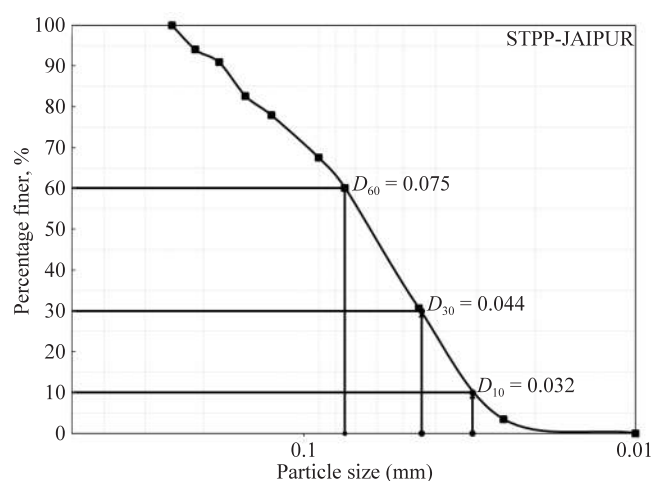


Figure 1 Grain size distribution curve of FA

2.2 Methodology

The methodology employed in this study initially involves the characterization of FA to ascertain its physical, geotechnical, and morphological properties. Subsequently, SLAs were synthesized using varying proportions of FA and PW. The synthesized SLAs were

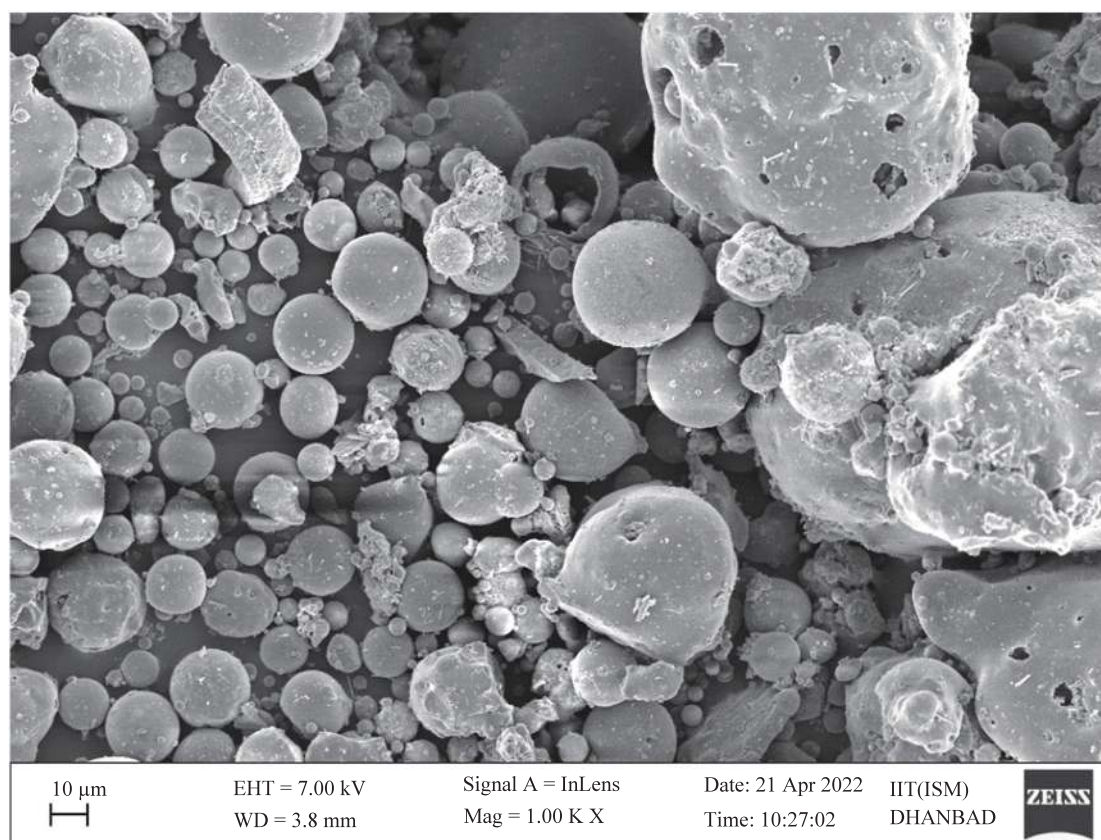


Figure 2 SEM micrograph of fly ash

then assessed for their durability and stability characteristics. Following these evaluations, the SLAs were crushed and subjected to further physical, geotechnical, and morphological testing to facilitate a comparative analysis between the properties of the SLAs and those of FA alone.

2.2.1 Preparation of synthetic lightweight aggregates

FA and PW were combined in specific predetermined ratios to synthesize SLAs. Six distinct SLA formulations were developed, namely 80FA20MIX, 85FA15MIX, 85FA15HD, 80FA20PP, 85FA15PP, and 80FA20LD. Each formulation involved the precise weighing of the constituent materials according to the designated proportions, followed by mechanical mixing to ensure a uniform blend. The resultant mixture was then processed through a rotary extruder to produce a cohesive paste, which was subsequently allowed to dry under ambient laboratory conditions. The SLAs thus formed were collected and subjected to rigorous testing to evaluate their durability and structural integrity upon solidification. The aggregates were then crushed to facilitate further physical and geotechnical analysis. **Figure 3** provides a schematic representation of the SLA preparation process.

2.2.2 Experimental procedure

The slake durability test (SDT) and point load strength index (PLI) are employed to evaluate the integrity of the SLA. The SDI of SLAs is determined in accordance with the ASTM D4644 (1987) [12] standards, while the PLI is assessed following ASTM D5731 (1995) [13]. A comprehensive series of physical property tests was conducted on FA and SLAs in compliance with relevant Indian Standards (IS). The specific gravity of the materials was determined according to IS:2720 (Part 3/Section 2):1980 [14]. Grain size distribution analysis was performed in accordance with IS:2720 (Part 4):1994 [15]. The coefficient of permeability was evaluated as per IS:2720 (Part 17):1986 [16], utilizing the falling head method for FA and the constant head method for SLAs. Field emission scanning electron microscopy (FESEM), equipped with energy dispersive X-Ray (EDX), was used for the microscopic imaging and elemental analysis the SLAs, and surface and cross-sectional analyses of aggregates were conducted.

3 Results

This section presents the results of the experimental investigations conducted on SLAs in two stages. In the



Figure 3 Aggregate production scheme illustrating the mixing of fly ash and waste plastic, thermal processing in a rotary extruder, and subsequent cooling to form synthetic lightweight aggregates

first stage, slake durability and point load index tests were performed on the aggregates in their as-produced condition, following cooling after extrusion. In the second stage, the aggregates were crushed using a jaw crusher and subsequently evaluated for their physical and geotechnical properties, microscopic and elemental configuration.

3.1 Durability and PLI of SLAs

Table 2 presents the SDI and PLI values for the SLAs, along with their classifications according to established criteria. SDI values ranged from 94.8% to 98.57% after the first cycle and 91.17% to 96.73% after the second cycle. Aggregates ranked by durability as 80FA20PP > 80FA20MIX > 85FA15MIX > 80FA20LD > 85FA15HD > 85FA15PP, with all 80FA20 PW mixes (except 80FA20LD) classified as extremely high durability and lower PW content (85FA15) mixes as very high durability [17]. PLI values spanned 0.81–2.19 MPa, with 85FA15HD exhibiting the highest strength ($I_s(50) = 2.19$ MPa; strong category), 80FA20LD the lowest (0.81 MPa; low strength), and remaining mixes in the average strength range [18] PLI-based ranking followed 85FA15HD > 80FA20MIX > 80FA20PP > 85FA15PP >

85FA15MIX > 80FA20LD.

3.2 Physical and geotechnical properties of SLAs

Table 3 illustrates the SG values of the SLAs. The SG of SLAs ranges between 1.65 and 1.77, which is lighter than that of FA. It shows that the addition of PW into the matrix reduces the SG of aggregates, makes SLAs lighter, and categorizes them as lightweight aggregates. The GSA results show that plastic addition has increased the range of grain sizes ($C_U = 2.34$ for FA to 8.6 to 46.3 for SLAs). Figure 4 presents the combined grain size distribution curves of SLAs, showing that none of the proportion has more than 10% of silt size particles, and all expect 85FA15PP fall into the well-graded soil classification ($C_U > 6$, $C_C = 1$ to 3). The k values also show that the SLAs permeability has increased multiple fold compared to that of FA.

3.3 Microscopic and elemental configuration

Figure 5 presents FESEM images and corresponding EDS spectra of SLA. The micrographs reveal that FA microspheres and angular particles are densely

Table 2 Slake durability and PLI of SLAs

Property proportion	SDI (%)		Franklin and Chandra [17]	PLI (MPa)	Bieniawski [18]
	$I_d(1)$	$I_d(2)$			
85FA15HD	95.68	93.52	Very high	2.19	Strong
80FA20MIX	95.53	95.34	Extremely high	1.39	Average
85FA15MIX	94.8	94.2	Very high	1.11	Average
80FA20PP	98.57	96.73	Extremely high	1.37	Average
85FA15PP	95.41	91.17	Very high	1.17	Average
80FA20LD	95.99	93.88	Very high	0.81	–

Table 3 Physical and geotechnical properties of SLAs

Property proportion	SG	Grain size analysis			$k(\text{cm/s})$
		C_U	C_C	Classification	
85FA15HD	1.70	36.6	2.2	Well graded	2.93×10^{-3}
80FA20MIX	1.65	30.5	1.8	Well graded	3.55×10^{-3}
85FA15MIX	1.76	35.7	2.5	Well graded	3.28×10^{-3}
80FA20PP	1.67	8.6	2.9	Well graded	4.13×10^{-3}
85FA15PP	1.73	46.3	3.7	Poor/gap graded	2.90×10^{-3}
80FA20LD	1.77	18.8	2.1	Well graded	3.20×10^{-3}

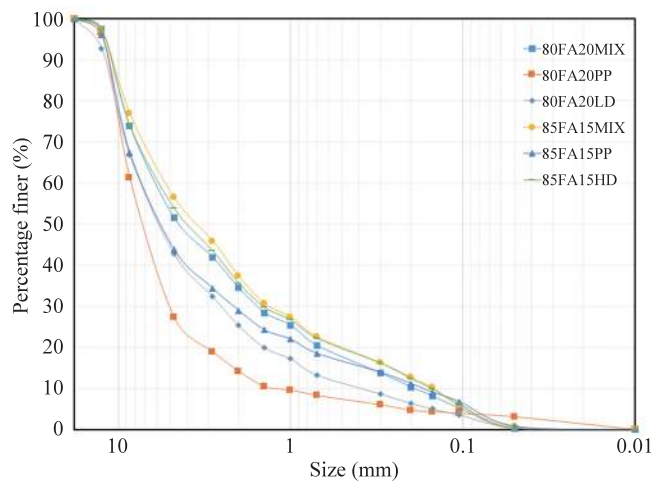


Figure 4 Combined grain size distribution curves of SLAs

embedded within a continuous polymer matrix, forming composite clusters with rough, interlocking surfaces (Figures 5(a), (b)). EDS analysis confirms the hybrid composition, with dominant peaks for Si, Al, O, and minor Fe, K, Ca signals alongside elevated C.

4 Discussion

From the SDI and PLI results, it is evident that both PW

dosage (20% > 15%) and polymer type exert significant control over SLA performance, with PP and mixed PW formulations optimizing durability while HDPE maximizes strength. This performance can relate to the higher melt viscosity, stiffness, and thermal stability of HDPE, which enabled effective encapsulation of FA and restricted moisture ingress [19]. The low SG nature of SLAs aids the hydraulic filling in low head for the pumping of the materials through pipes, the coarse particle nature of SLAs helps in faster settlement of material [20] Click or tap here to enter text., well graded nature presents low void ratio and better consolidation [21]. Permeability plays a major role in drainage of water [22], high permeability implies that it helps in the dissipation of pore water pressure and in avoiding liquefaction [3]. Notably, PW manifests as a bridging film coating multiple FA particles, reducing isolated fines, and promoting agglomerate formation. The microstructural evolution from loose FA powder to plastic-bound pellets, correlates directly with the measured property enhancements of increased grain size range, higher durability indices, and elevated permeability.

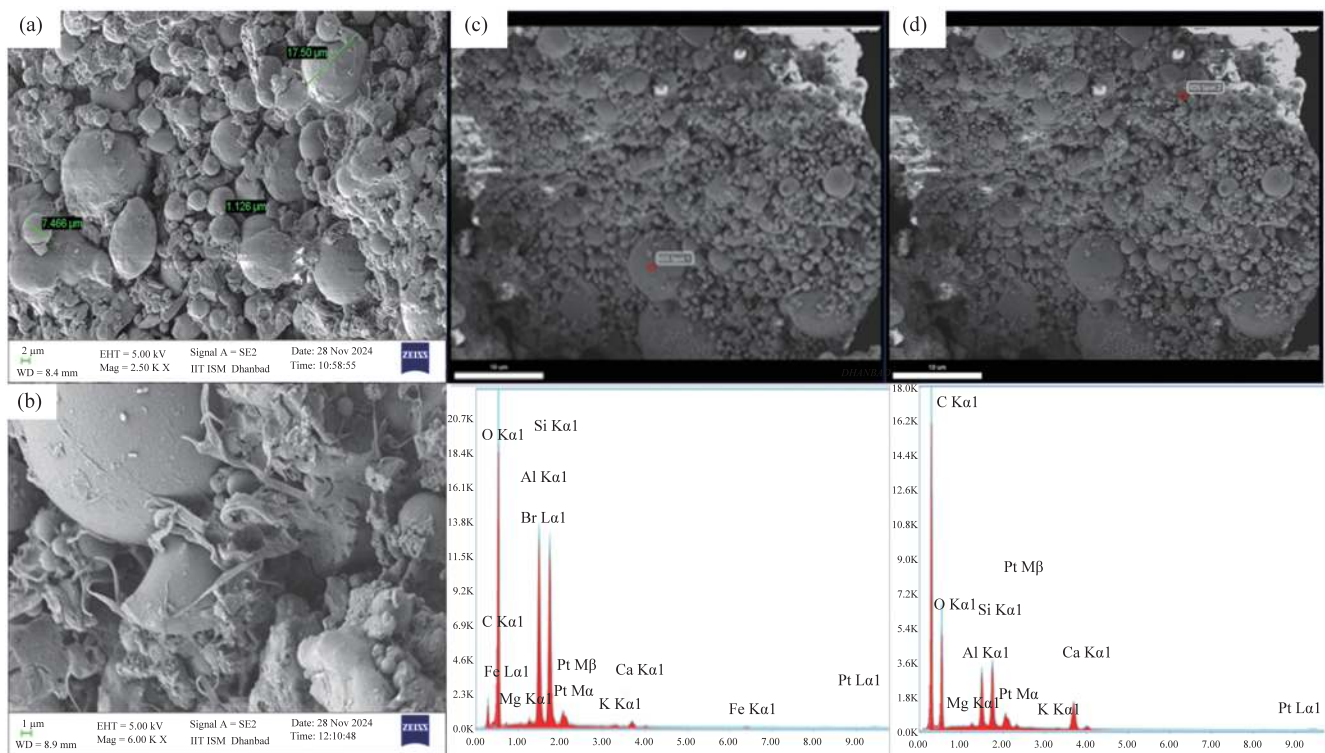


Figure 5 FESEM micrographs (a) surface, (b) cross-sectional and EDS spectra (c, d) of SLAs

5 Conclusions

The present study focused on the development of SLAs using FA and PW for potential application in hydraulic backfilling systems. Based on the experimental investigations, the following conclusions may be drawn:

(1) Durable aggregates can be successfully produced through the combined utilization of FA and PW. The durability and structural integrity of the SLAs are strongly influenced by both the presence and type of plastic, with aggregates incorporating high-density polyethylene exhibiting comparatively stronger bonding characteristics, followed by the 80FA20PW proportions.

(2) The specific gravity values indicate that the developed SLAs fall within the range of lightweight aggregates, which may facilitate ease of transportation and pumping through pipelines during hydraulic backfilling operations.

(3) The incorporation of plastic promotes the formation of coarser and well-graded aggregates, resulting in a reduction in void ratio and compressibility, thereby contributing to improved stability of the backfilled mass.

(4) The SLAs exhibit a notable improvement in hydraulic conductivity compared to fly ash alone, which is expected to enhance drainage performance and promote effective dissipation of excess pore water pressures.

(5) FESEM&EDS analysis reveals that PW binding induces a durable, coarsened, and permeable micro-structure in SLAs, providing a mechanistic basis for the observed improvements in SDI, PLI, grain size distribution, and hydraulic conductivity compared to untreated FA.

Overall, the findings suggest that the developed SLAs demonstrate performance characteristics suitable for consideration as an alternative hydraulic backfilling material in underground mining applications.

Declarations

The authors declare that they have no conflict of interests.

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