Investigation of Synthetic Lightweight Aggregate as Hydraulic Backfilling Material

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Abstract

During the process of extracting minerals through underground mining methods, voids are created. These voids need to be filled to prevent the sinking of the ground and reduce problems that may occur after the mining activity. Traditionally, sand has been the primary material used for backfilling. However, due to the growing demand in the construction sector and the slow rate of replenishment, there has been a search for alternative backfill materials. Several researchers have suggested using fly ash as a replacement for sand. However, due to its slow settling rate and the creation of hydrostatic pressure, use of fly ash necessitates appropriate techniques be employed. This study involved combining fly ash (FA) and high-density polyethylene (HDPE) plastic in a ratio of 80:20 to create a synthetic lightweight aggregate. The investigation sought to evaluate its appropriateness as a hydraulic backfill material. The results exhibit an exceptionally high slake durability index, a low specific gravity that enables easy transportation of the material at low pressure, an enhanced grain size distribution, a sand-like morphology, and a permeability 25 times higher than that of pure fly ash. These findings indicate that the combined aggregates show potential as a hydraulic backfill material.

Introduction

The process of mining entails the extraction of essential minerals requisite for human requirements from the Earth, employing methods that ensure safety and economic viability. In the underground mining activities, the inevitable consequence of voids creation necessitates backfilling to prevent subsidence and address other post-mining issues. Backfilling is a technique employed to fill the voids left over from the extraction of minerals in underground mining. This approach is widely recognized as an environmentally acceptable means of waste disposal. The process of backfilling is of paramount importance in the comprehensive functioning of mining operations, as it provides appropriate support, minimizes the dilution of waste material, facilitates safe working conditions, and mitigates the potential risk of surface subsidence (Karfakis, et al., 1996). The materials utilized in this technique are commonly referred to as backfilling material, and are categorized into two primary groups: cemented and uncemented (Rankine et al., 2007). The selection of these materials is influenced by various factors, including their accessibility, cost, stowing system, grain size distribution, permeability, strength, stability, consolidation, compressibility, deformation, and load-bearing properties (Bhattacharya and Banerjee 1997; Karfakis, et al.,1996; Bhattacharya, 2003; Mishra, 2007). For several decades, the prominent method of backfilling involved utilizing sand as an uncemented backfill (Mishra and Rao, 2006), however the imperative to explore alternative materials has emerged due to the scarcity of sand resulting from huge demand in the construction industry and decreased replenishment rate emerging from the building of dams.

The material FA, a byproduct of coal combustion in thermal power plants, has proven to be a highly suitable alternative material for backfilling purposes, particularly in place of sand, otherwise a pollutant if stored in ash ponds. Its utilization in the mining industry has demonstrated positive benefits, particularly in terms of stowing applications. Additionally, the power sector stands to gain advantages from the use of FA as a means of waste disposal (Mishra, 2007). The presence of a significant proportion of SiO_2 contributes to enhanced strength, consolidation, and stability, while the presence of calcium oxide imparts cementing properties to the material (Singh, et al., 2016; Naik and Mishra, 2018). The spherical morphology of FA particles contributes to a frictionless flow, thereby minimizing the abrasion and erosion of pathways used for stowing (Mishra and Das, 2014). However, the presence of high percentage of fine particles, delayed settling, and escape of fines due to the light weight and fine particle nature of FA hinder the quick consolidation of particles; fast settling is necessary for efficient stowing to avoid development of hydrostatic pressure, for layer like deposition, and better consolidation overall (Mishra and Das, 2013). However, it may be possible to effectively stow FA by employing appropriate techniques.

Plastic stands out as one of the most environmentally detrimental substances on the planet. The predominant factors contributing to the excessive utilization of plastic include its affordability, lightweight nature, robustness, resistance to corrosion, and its exceptional thermal and electrical insulation properties. As a result, there has been a dramatic increase in the production of plastics over the past 80 yrs. However, only half of this quantity is being appropriately recycled or properly disposed. The aim of this research is to produce synthetic lightweight aggregates by combining two environmentally hazardous materials, FA and plastic, in a ratio of 80 FA:20 HDPE. The resulting aggregates are then compared with FA and sand for use as a feasible backfilling material in terms of environmental acceptability, where backfilling is achieved using the hydraulic stowing method.

Materials

Fly Ash

For the current investigation, FA is sourced from the Chandrapura Thermal Power Station (CTPS) of the Damodar Valley Corporation (DVC). The DVC-CTPS, a 500 MW power plant situated in Chandrapura town, Bokaro district, Jharkhand state, India, acquires coal from the Central Coalfields Limited (CCL) a subsidiary of Coal India Limited (CIL). Table1 shows the physical properties of FA, determined as per the American Standards of Testing Materials (ASTM), and Figure 1 shows the particle size distribution of FA. FA falls under the Class F category as per ASTM C618.

Table 1. Physical properties of FA.

S.no	Test	Results
1.	Specific gravity	2.00
2.	Grain size analysis	$D_{10} = 0.032$ $D_{30} = 0.044$ $D_{60} = 0.075$ Fine grained soil
3.	Optimum moisture content	35.3%
4.	Maximum dry density	1.15 g/cc
5.	Coefficient of permeability	$1.387*10^{-6}$ m/sec

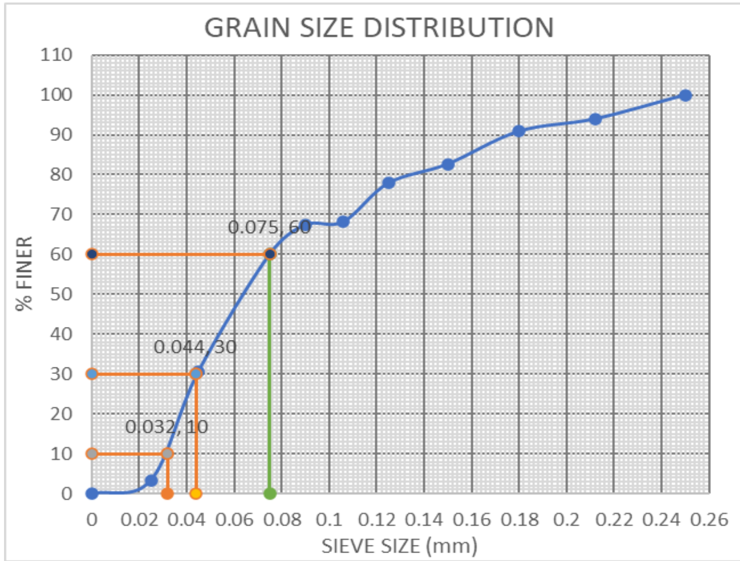

Figure 1. Grain size distribution of FA.

Plastic

Plastic is used in the study as a binding material to make SLAs. HDPE obtained for the fabrication of SLAs is sourced from the local municipal solid waste collector. The acquired plastic is subjected to a drying process and subsequently shredded into small chips. Table 2 gives the basic information of HDPE plastic (Kavendra, et al., 2015; Mohan, et al., 2021). Figure 2 shows the plastic and FA.

Table 2. Basic information of HDPE plastic.

S.no	Property	Value
1.	Density	0.95 g/cc
2.	Softening point	78 ºC
3.	Melting point	130-136 ºC
4.	Crystalline point	110 ºC

Figure 2. FA and HDPE plastic.

River sand

The river sand employed for comparative analysis in this study was gathered from the Godavari River in the state of Telangana, India, and is conventionally utilized for backfilling in Singareni coal mines. The assessment of its physical properties was conducted in accordance with the ASTM, and results are provided in Table 3. Figure 3 shows the particle size distribution curve of sand.

Table 3. Physical properties of River Sand.

S.no	Test	Results
1.	Specific gravity	2.66
2.	Grain size analysis	D_{10} = 0.26 D_{30} = 0.41 D_{60} = 0.9 C_U = 3.46 C_C = 0.72 Poorly graded sand
3.	Optimum moisture content	5.16%
4.	Maximum dry density	1.66 g/cc
5.	Coefficient of permeability	$1.29*10^{-4}$ m/sec

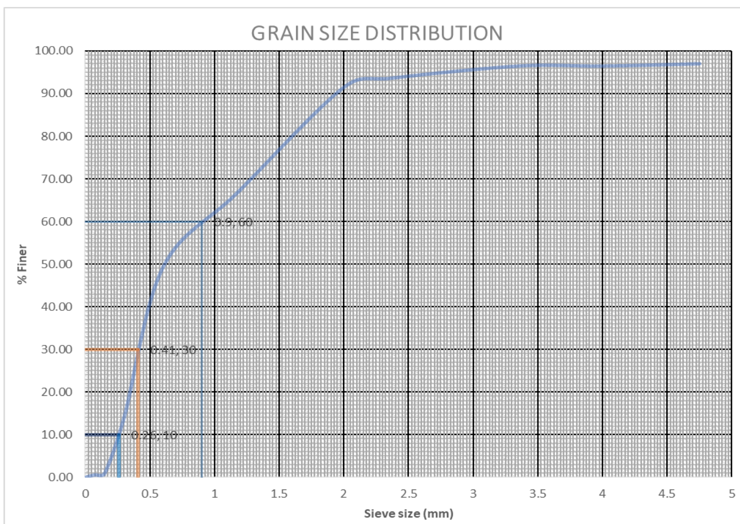

Figure 3 Grain size distribution curve of sand.

Synthetic lightweight aggregates

In this study, SLAs are synthesized through the combination of 80% FA and 20% HDPE plastic. The procedure involves the measurement of an appropriate weight of plastic, which is subsequently transferred to a specially prepared mild steel mould for the purpose. The mould is then placed in a muffle furnace preheated to 369°C for 30 mins to facilitate the plastic melting process. Following this, FA is introduced into the molten plastic and thoroughly homogenized using a stirring rod before subjecting the mixture to an additional 10 mins of furnace exposure. Subsequently the heated amalgamation is transferred to a disc pelletizer set at a 45° angle rotating at 15 rpm, facilitating the preparation of the aggregates. Figure 4 shows the step-by-step process of the SLA preparation.

Figure 4. Step-by-step process of SLAs synthesis, starting at the top left image.

Methods

This study involves the formulation of SLAs by amalgamation of FA and HDPE plastic, followed by laboratory analysis of the SLAs in accordance with the ASTM. Subsequently, a comparative assessment of the results is conducted with respect to both FA and river sand. The backfill properties examined in this study includes specific gravity, grain size analysis, and permeability. Additionally, a comparative morphological analysis of the backfill materials is undertaken, and a slake durability test is conducted on the SLAs.

Results and Discussion

Slake Durability Index

The Slake Durability Test serves to quantify the resistance of fragile rocks to weakening and disintegration resulting from cycles of drying and wetting, and is an index test specifically tailored for the differentiation of rocks based on their response to wetting and drying. Conducted in accordance with ASTM D4644, the test involves placing a 400 g sample of 40–50 mm diameter into a No.10 square mesh cylindrical drum measuring 140 mm in diameter and 100 mm in length, and rotating at a speed of 20 rpm for 10 mins. The test results for SLAs, denoted as I_{d1} and I_{d2}, yield values of 97.09 each, and fall under the extremely high durability class as per Franklin and Chandra (1972), surpassing the standards articulated in Karfakis et al. (1996), wherein the prescribed criteria for a standard backfill are $I_{d1} > 95$ and $I_{d2} > 85$. Figure 5 shows the standard slake durability test apparatus.

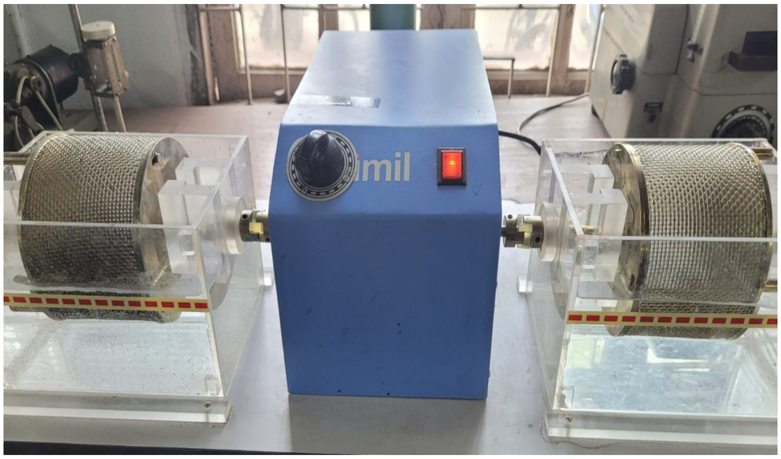

Figure 5. Slake durability test apparatus.

Specific Gravity
The dimensionless quantity of specific gravity plays an important role in influencing the storage and transportation of backfill materials. Specific gravity was determined in accordance with ASTM D550. Figure 6 illustrates the comparative specific gravity values of the SLAs, FA, and sand.

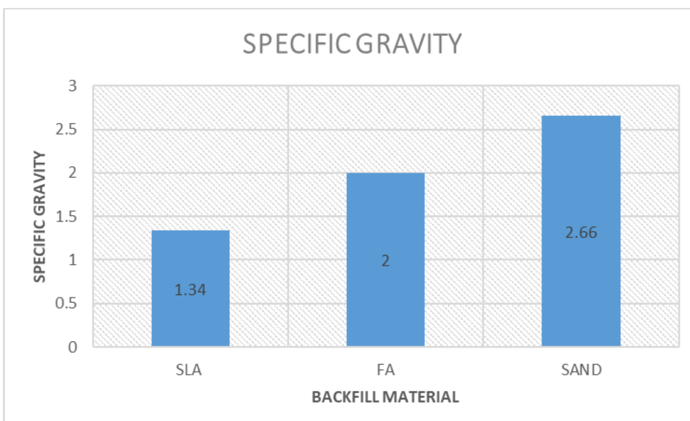

Figure 6. Specific gravity values of SLA, FA and sand.

The specific gravity of the SLA composed of 80% FA and 20% HDPE plastic is determined to be 1.34, classifying it as an artificial synthetic lightweight aggregate. Comparative analysis reveals that the SLA exhibits a lighter specific gravity in comparison to both FA and sand. Notably, research by Ghosh et al. (2008) and Mishra and Das (2014) assert that the utilization of lighter particles contributes to a reduction in transportation costs for backfill, achieved through a mitigation of head loss in hydraulic backfilling techniques.

Grain Size Analysis
Grain size, or particle size analysis, involves the quantitative categorization of soil particles based on mass, contributing to the classification of soils. The testing procedure, in adherence to the standard protocol ASTM D2487, facilitates this analysis. Gupta and Paul (2017), asserted that grain size analysis provides an estimation of pore size and connectivity, influencing the water passage. Figure 7 illustrates the grain size distribution curve specific to SLAs.

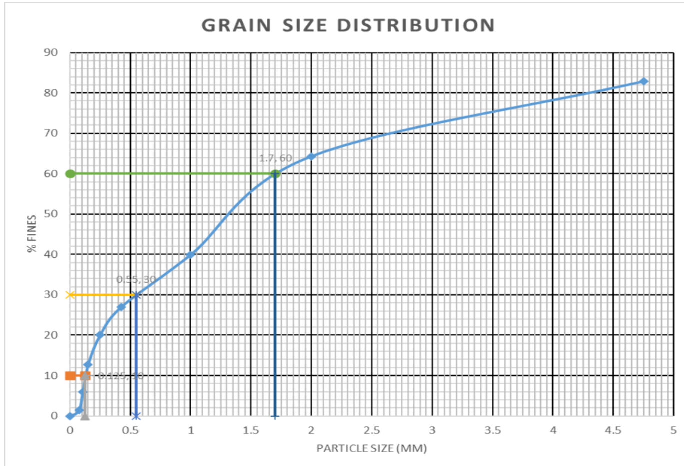

Figure 7. Grain size distribution curve of SLAs.

The grain size analysis of SLAs discloses specific parameters, including D10 at 0.125, D30 at 0.55, D60 at 1.7, C_U = 13.6, and C_C = 1.42. Remarkably, SLAs demonstrate a fineness < 75 µm in < 5% of the composition, thereby aligning with established standards that categorize them as well-graded sand and an optimal material for hydraulic backfill applications. Thomas et al. (1979) recommended that grains within the range of 40–150 µm should constitute a minimum of 15% of the particle composition. Karfakis et al. (1996) stipulate that backfill materials should not exceed 10% of particles finer than 75 µm. Comparative grain size distribution curves of SLAs with FA and sand are depicted in Figure 8.

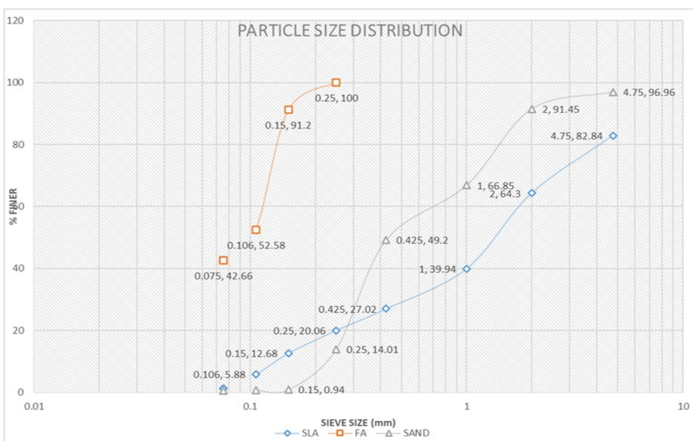

Figure 8. Comparative grain size distribution curves of SLA, FA, and sand

The comparative analysis curve discloses that SLAs exhibit a broader distribution of particles in contrast to FA, closely resembling the distribution curve of sand. A wider curve signifies a diverse range of sizes, well-graded soil which on compaction possess high shear strength Arora (2004). Consequently, the findings suggest that SLA behaves similarly to sand when utilized as a backfill material.

Permeability

Permeability is the ease of water flow through the soil pores (Arora, 2004), and holds significance in the selection of hydraulic backfill material. Constant head permeability test is used in measuring the permeability of sand and SLAs, while falling head test is used for FA. Gupta and Paul (2017) highlight the importance of maintaining fill moisture content of ~ 20% for effective ground control. Mishra and Das (2013) state that water drainage efficiency is contingent upon permeability, emphasizing that rapid drainage prevents the development of hydrostatic pressure, promoting the better settlement and effective consolidation. Karfakis et al. (1998) assert that pore water pressure is influenced by permeability, and backfill material with low permeability experience deformation during consolidation, and recommend a minimum permeability of 2.78×10^{-5} m/sec or 100 mm/hr for optimal backfill performance. Figure 9 compares the permeability of SLAs with those of FA and sand.

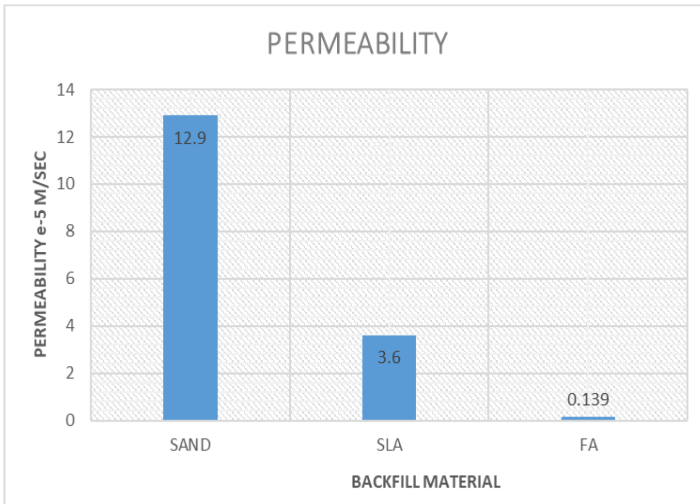

Figure 9. Permeability comparison of SLAs, FA, and sand in 10^{-5} m/sec.

The permeability of SLAs was found to be 3.6×10^{-5} m/sec, which is 25 times higher than that of FA. Despite being significantly lower than the permeability of sand, the permeability of SLAs surpasses the recommended threshold established by Karfakis et al.

Morphology

The scanning electron micrographs (SEMs) of FA, SLAs, and sand, magnified at 1, 5, and 10k using a Zeiss FE-SEM Supra 55, are seen in Figure 10. The images of FA illustrate that FA particles are spherical, hollow, and composed of smaller particles within the larger hollow particles. Satish et al. (2016) asserts that the hollow particles found in FA are highly suitable for the formation of aggregates, since they have the propensity to absorb binders. The SLA images reveal that the aggregate is a solid and irregular combination of FA particles that are closely bound to each other. This indicates an increased size compared to natural FA particles, with a reduced number of hollow particles. The aggregate exhibits a resemblance to naturally solid sand particles.

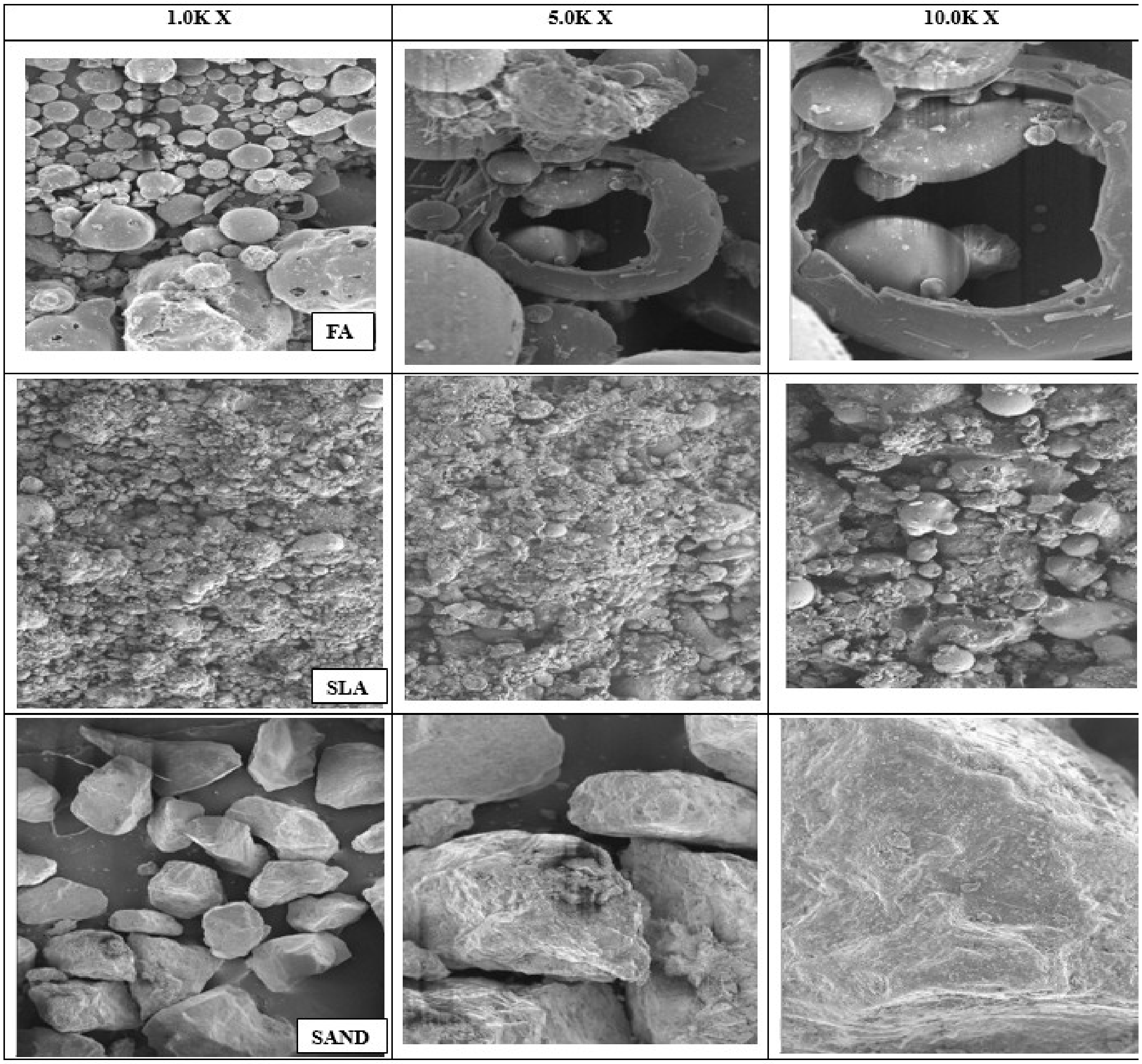

Figure 10. SEMs of FA, SLA, and sand at three levels of magnification.

Conclusions

The investigation into the utilization of SLA as a hydraulic backfilling material, achieved through the amalgamation of 80% FA and 20% HDPE plastic, yields the following conclusions:

1. The Slake Durability Index of SLAs registers as Id1= Id2= 97.09, classifying them within the extremely high durable category, surpassing prescribed values for backfill material.
2. The specific gravity of SLAs suggests their ease of transportation using the hydraulic backfilling method at low head, owing to their lightweight nature.
3. Grain size analysis reveals that SLAs possess < 10% of particles < 75 µm, exhibiting a curve akin to sand. This signifies the presence of a diverse particle range, contributing to improved shear strength.
4. Permeability of SLAs increases by 25 times compared to FA; although lower than sand, it still exceeds recommended values for hydraulic backfill material.
5. SEM images illustrate that SLAs exhibit a solid, irregular morphology with fewer hollow particles and increased size compared to FA, potentially aiding in particle settlement.

In conclusion, this study establishes that SLAs possess enhanced properties compared to FA, showcasing similarities to sand in grain size analysis and morphology. This positions SLAs as a promising alternative hydraulic backfill material to both sand and FA.

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Acronyms

FA	Fly Ash
PWP	Pore Water Pressure
SLAs	Synthetic Lightweight Aggregates