Effects of Industrial Wastes on the Engineering Properties of Heavy Metal Contaminated Expansive Soil

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Abstract- The engineering properties of expansive soil are problematic because of the high shrink-swell (volume change) attributes caused by the presence of clay minerals. These properties further deteriorate when expansive soils are contaminated with heavy metals. However, heavy metal-contaminated soil can be improved by using stabilization/solidification techniques in order to make it suitable for engineering works. In recent times, lime and cement have been replaced by low-cost and environmentally friendly industrial wastes. In this study, laboratory experiments was performed to determine the effect of lead (Pb) concentration on the engineering properties of expansive soil as well as the effect of different percentages (0%, 3%, 6%, 9%, and 12%) of fly ash and sugarcane bagasse ash on the contaminated soil. The results show that the atterberg limits and UCS decrease with increasing Pb concentrations. The natural expansive soil with a liquid limit of 76.2% was decreased to 66.2%, 60%, and 57.3% upon the addition of 500 mg, 1000 mg, and 1500 mg of Pb solution, respectively. Additionally, the initial plastic limit of 53.3% was decreased to 40%, 34.5%, and 29.7% when contaminated with 500 mg, 1000 mg, and 1500 mg of Pb solution, respectively. Moreover, the addition of fly ash and sugarcane bagasse ash also decreases the atterberg limits but increases the unconfined compressive strength with curing until the optimum levels were reached. The highest UCS value (1745 kg/cm^2) was obtained at day 28 for 500 mg Pb + 6% fly ash, while the lowest UCS value (218 kg/cm^2) was obtained at 1500 mg Pb + 12% sugarcane bagasse ash after 3 days of curing. The overall UCS results show clearly that fly ash has superior strength to that of sugarcane bagasse ash.

Indexed Terms- Atterberg limit, Expansive soil, Heavy metals, Industrial wastes, Unconfined compressive strength,

I. INTRODUCTION

Expansive soils are complicated in nature, and this complexity is primarily influenced by the interactions between the pore fluids and clay minerals, which give rise to their volume change habits[17]. In other words, pore fluid composition and soil mineralogy are essential for preserving expansive soils' ability to shift volume[8]. Montmorillonite, illite, smectite, and kaolinite are the most frequent minerals in expansive soils, and are in charge of the alternative expansion and shrinkage that severely affects their qualities and renders them unsuitable for engineering works. Moreover, when expansive soils are contaminated with heavy metals, their properties (mechanical and chemical) further deteriorate. This is primarily due to the low solubility and long-lasting capacity of these metals.

Due to increased urbanization and industrialization, heavy metal pollution in soil can be found worldwide and poses major risks to human and animal health. Even though there have always been heavy metals in soils, their levels have skyrocketed since the industrial revolution. Heavy metal polluted soil can be found in countries such as Australia, the United States of America (USA), Sweden, China, and Sweden[12]. [19]estimated that 500 million ha of land worldwide contains roughly 5 million locations with heavy metal-contaminated soils. [13] also reported that there are more than 10 million areas where heavy metal contaminated soils exist worldwide, with concentration mainly in industrialized areas like the aforementioned. For example, the USA alone has about 600,000 ha of land polluted with heavy metals, more than 250,000 heavy metal-polluted sites in Europe, 60.13% of the 5759 polluted areas in France are covered with heavy metals[1], and 25% of the farmland in China contains heavy metals[23], etc. soil. Contaminated soils are also found in developing countries like India, Pakistan, and Bangladesh. The toxicity of these heavy metals is well established as they can cause a variety of health and environmental issues, including soil contamination, decreased plant growth and crop production, harm to aquatic life, health hazards for humans, and deterioration of soil geotechnical qualities.

Numerous studies have demonstrated that the engineering properties of expansive soils are negatively affected when they become contaminated with heavy metals[33], [6],[21]. According to[28], expansive soils lose shear strength as heavy metal concentrations rise. [7] investigated the geotechnical characteristics of clay soil contaminated with zinc and found that as zinc concentration increased, the soil's compression coefficient, compressibility, and relative density all increased while the liquid limit, plastic limit, compression modulus, and relative density all decreased. Three bentonite admixtures (sand-bentonite spruce, sand-bentonite, and sand-bentonite-forest soil) contaminated with heavy metals (Pb, Cu, and Cd) were investigated by[20]. The results revealed that the forest soil had the best ability for retentiveness, while Cadmium had higher mobility than copper and lead. The engineering characteristics of zinc-contaminated high-plasticity clay stabilised with cement were studied by[9]. The findings demonstrate that zinc contamination had a considerable impact on the soil's UCS. [11] studied the index properties of two bentonites contaminated with heavy metals (Zn^{2+}, Pb^{2+} and Cu^{2+}). The results revealed that the hydraulic conductivity increased while the liquid limit, free swell, swelling pressure, and swelling potential decreased with increasing heavy metal concentration. Clay soil also swells tremendously when it is contaminated with heavy metals[34].

However, a number of remediation techniques have been used to address the damaging effects of heavy metals on soils. These innovations restore their flexibility and volume change properties while also making them easier to deal with. They also address the environmental issues that heavy metals and other toxins cause. These techniques alter the microstructure of soil with further processes of hydration, and compaction of particles, as well as the decomposition of organic components. Some effective remediation methods include microbial decomposition, Vitrification, composting, phytoremediation, soil capping, stabilization/solidification, etc.

A. Microbial Decomposition

By utilising them as food, bacteria and fungi break down organic contaminants in soil through a process known as microbial decomposition. Microbial decomposition is widely use worldwide because it is cheap, simple, and highly efficient and can also be used for the remediation of heavy metals. During this process, the physical and chemical properties of the metals are being altered and reduced the environmental toxicity of soil[3], [27]. For example, [32] investigated the used of bacteria species (Flavisoli bacteria and Anthrobacter) to remediated heavy metals (As^{3+} and Cr^{6+}) from paddy field polluted soil. The results showed that Cr^{6+} remediation was significantly enhanced.

B. Vitrification

Vitrification is a very safe but complicated technology that uses heat (temperatures at or above 20000 ^{0}C) to treat contaminated soils[10]. During this process, heat is applied to the contaminated soil in order to reduce the mobility of heavy metals, resulting in the formation of vitreous materials (ex: stable glasses). Vitrification can also be used for the treatment of soil containing organic contaminants[22], even though it does not work properly in soils with high moisture and organic gas content. [25] conducted vitrification using solar technology to remediate wastes from silver-lead mines. On the one hand, Zn, Mn, Ni, Fe, and Cu were immobilised at 1350^{0}C, while Mn, Zn, Ni, and Cu were immobilised at 1050^{0}C. [23] used the Cold Top ex-situ vitrification method to remediate and immobilize chromium-contaminated soil derived from chromite-ore processing sites. Results from the toxicity characteristic leaching procedure (TCLP) show that vitrification is an effective method for treating contaminated soil.

C. Composting

Composting remediation is the process of adding decomposed organic matter to contaminated soil in order to reduce the bioavailability of heavy metals and decay organic matter[4]. In this process, decomposed organic matters combined with the heavy metals and reduce their availability. [26] reported that stabilized organic matter is effective in reducing the availability and mobility of heavy metals is soil thereby reducing their absorption by plants. [15] immobilized heavy metals in Sus scrofa (a composted hog) using organic material. The results indicated a reduction in the concentration of zinc, copper and manganese in the leachates.

D. Phytoremediation

Phytoremediation, often known as uptake by vegetation, is an in-situ remediation method used specifically to remove metals from soil. Here, the metals in the soil are either absorbed by the roots of plants or are adsorbed on their surfaces. According to[35], phytoremediation is crucial for preventing soil erosion and minimising pollutant leaching into groundwater. [5] studied plants growing on soil (from an abandoned mine in northern Spain) contaminated with zinc, lead, and cadmium. After a careful study of some plant species, it was seen that a large quantity of lead nitrate was accumulated in *Daphne tangutica* and *Daphne jasmine,* and *Noccaea caerulescens* had the highest accumulation of zinc.

E. Surface capping

Surface capping is a non-intrusive, cost-effective technique that is used only for the remediation of highly contaminated soils and can be applied to small areas. The polluted soil is shielded during this procedure by a waterproof covering. This covering acts as a barrier to prevent the soil from contaminating groundwater and surface water. This method reduces heavy metals' mobility, solubility, and environmental exposure but does not eliminate or alter their reactivity. The attributes of the site and remediation goals have an impact on the kind of capping materials (asphalt, clay, etc.) and system utilisation. Kaolin and bentonite have been studied by [2] as capping materials to stop the leaching of Cr and Cu from polluted sediments. These two capping materials were effective in stopping the leaching of the metals, according to the results of the laboratory tests. However, this method cannot be used in swampy locations (marsh land and small bodies of water), as the layers may be washed away.

F. Stabilisation/solidification

Low-cost remediation techniques like stabilisation/solidification involves combining a soil with chemicals to improve their properties. It is a robust and time-efficient process that immobilizes heavy metals and other contaminants and converts them into less soluble materials that densify into a single matrix[36]. The atterberg limits, unconfined compressive strength, volume change tendencies, and other properties of soils are improved by stabilisation and solidification, and the mobility of heavy metals and pollutants discharged into the environment is reduced[30]. Mechanical stabilization and chemical stabilization are the two main categories under which stabilisation and solidification fall.

Mechanical stabilization is the process by which mechanical energy is used to alter the physical properties of soil through a series of compactions and induced vibrations. It occurs when cohesionless particles are rearranged and solidified to achieve the desired effect of compaction.

Chemical stabilization entails the inclusion of cementitious chemicals. These chemicals improve the strength, permeability, and compressibility of soil while also preventing contaminants from moving around. They solidify and convert hazardous wastes into less hazardous wastes. To stabilise and solidify subgrade and polluted soils, however, raw materials must be extracted, and additives like lime and cement must be produced. This greatly contributes to environmental contamination[31], [37]. Additionally, the cost of these chemicals is rising as a result of restrictions placed by environmental regulators in several nations.

In light of all of these difficulties, using industrial wastes (fly ash, bagasse, rock dust, and blast furnace slag) is one viable solution. [38] stabilized lead contaminated soil using ladle furnace slag (LFS) and carbon dioxide (CO_2). The result showed that the concentration of lead leached after stabilization was reduced significantly. [24] effectively stabilized chromium, cadmium, and lead in contaminated soil using silicon-iron stabilizer. Different percentages of fly ash were used by[18] to stabilized chromium contaminated soil. The TCLP results showed decrease in the concentration of chromium with increase in the percentage of fly ash.

How effective industrial wastes (sugarcane bagasse ash and fly ash) are in stabilizing expansive soil that has been experimentally poisoned with lead is thoroughly investigated in this study.

II. MATERIALS AND METHODS

A. Materials Characterization

Experimental analysis was carried out using four materials, including expansive soil, lead nitrate, sugarcane bagasse ash, and fly ash. Expansive soil is a weak soil that is not suitable for construction purposes. It becomes even more unsuitable when it is contaminated with heavy metals like lead, arsenic, zinc, cadmium, etc. Under laboratory conditions, the expansive soil was contaminated with lead nitrate solution, which further weakens its performance and competence. In actuality, contaminated expansive soil is weak and a treat to the environment as it contaminates the soil, groundwater, and the environment as a whole. Therefore, stabilization/solidification method is used to improve the quality of the contaminated soil.

In this study, sugarcane bagasse ash and fly ash are used to stabilize the contaminated expansive soil. These materials were applied to the soil separately and in different percentages. Finally, their effectiveness was determined after stabilization by testing the UCS and atterberg limits of the soil.

B. Expansive Soil

The expansive soil used in this study was obtained in Surat, India. The soil was collected by open excavation at a depth that varies from 0.3m to 1m. It was oven-dried at a temperature of about 105^0C for 24 hours. After drying, the soil was crushed using a hammer; lumps were removed and sieved using a 4.75-mm sieve.

C. Additives/Stabilizers

Fly ash and sugarcane bagasse ash are the additives/stabilizers used in this study because they are recognized to have pozzolonic characteristics. They both were purchased from India’s Natural and Green located in Jamnagar, Gujarat.

D. Lead

Lead, denoted by the symbol “Pb” and having atomic number 82, is a greyish or silvery-white soft metal belonging to group 14 (IVa) on the periodic table. Lead is toxic to humans and the environment. Solid lead nitrate prepared into lead nitrate solutions from the environmental engineering laboratory at Pandit Deendayal Energy University, Gujarat, India, was used for this study.

E. Preparation of Samples

Sample preparation was carried out by mixing the expansive soil with different quantities of lead nitrate solution in order to contaminate it. 500mg, 1000 mg, and 1500mg of lead nitrate solution were separately prepared from solid lead nitrate. Fly ash and sugarcane bagasse ash for stabilization were oven-dried at 105^0C for 24 hours, sieved using a 425µm sieve, and stored in airtight bags.

F. Testing Methods

This study is based on laboratory experiments to determine the engineering properties of artificially contaminated expansive soil stabilized with different proportions of fly ash and sugarcane bagasse ash. The soil was oven-dried and sieved using a 4.75-mm sieve. Artificial contamination was done by adding 500mg, 1000mg, and 1500mg of lead nitrate solution to the soil.

Both fly ash and sugarcane bagasse ash were separately mixed with the Pb-contaminated expansive soil in varying percentages, that is, 3%, 6%, 9%, and 12%, in order to obtain the optimum quantity required for stabilization. Engineering properties, including liquid limit, plastic limit, plastic index, and unconfined compressive strength, were determined in accordance with the Bureau of Indian Standards (BIS). Specimens were prepared using expensive soil-lead nitrate solution-fly ash and expansive soil-lead nitrate solution-sugarcane bagasse ash and cured for 3, 7, and 28 days. This was done to ascertain their unconfined compressive strengths and compare them to those of the natural soil, as well as to determine the most effective additives (fly ash and sugarcane bagasse ash) for stabilizing the contaminated soil.

III. RESULTS & DISCUSSION

A. Index Properties of the Expansive Soil

The expansive soil was oven-dried and kept at room temperature. Its geotechnical properties, including liquid limit, plastic limit, specific gravity, electrical conductivity, maximum dry density, optimum moisture content, unconfined compressive strength, and PH, were determined without adding any stabilizing agent in accordance with the Bureau of India Standard (BIS). The index properties of the expansive soil are presented in table 3.1. The specific gravity, free swell index, maximum dry density, optimum moisture content, and electrical conductivity are 2.62, 90%, 1.49 g/cm^3, 24%, and 0.876 ds/m, respectively. Moreover, the soil was classified as highly plastic according to BIS because it had a liquid limit of 76.2% and a plastic index of 22.9%.

TABLE 1. GEOTECHNICAL PROPERTIES OF THE NATURAL EXPANSIVE SOIL

Geotechnical Property	Value
Specific Gravity	2.62
Free Swell Index (%)	90
Liquid Limit (%)	76.2
Plastic Limit (%)	53.3
Plastic Index (%)	22.9
Shrinkage Limit (%)	14.2
PH	8.5
Electrical Conductivity (ds/m)	0.876
Maximum Dry Density (g/cm^3)	1.49
Unconfined Compressive Strength (kg/m^2)	110.3
Water Content (%)	24

B. Atterberg Limits

The oven-dried soil was sieved using a 425μm sieve for determination of atterberg limits. Similar to the work done by[39], atterberg limits were determined in accordance with IS code (IS: 2720 (Part 5). Firstly, the soil was contaminated with different quantities (500mg, 1000 mg, and 1500mg) of lead nitrate solution. The increase in lead nitrate concentration led to a decrease in the atterberg limits, as shown in *figures 1 and 2.* This decrease is caused by the reduction in thickness of the soil's diffuse double layer, which led to repulsion between the particles. The liquid limit of the natural soil was 76.2% but after contamination with 500mg, 1000mg, and 1500mg of lead nitrate solution, it was decreased to 66.2%, 60%, and 57.3%, respectively. Moreover, the natural soil plastic limit was 53.3% but was decreased to 40%, 34.5%, and 29.7% for 500mg, 1000 mg, and 1500mg, of lead nitrate respectively. Secondly, the soil was contaminated and stabilized with different percentages (3%, 6%, 9%, and 12%) of fly ash and sugarcane bagasse ash. The results obtained are shown in table 2. Here also, the atterberg limits decreased with an increase in the additives concentration. However, the atterberg limits decreased significantly with the addition of fly ash compared to sugarcane bagasse ash (*figures 3 to 8*).

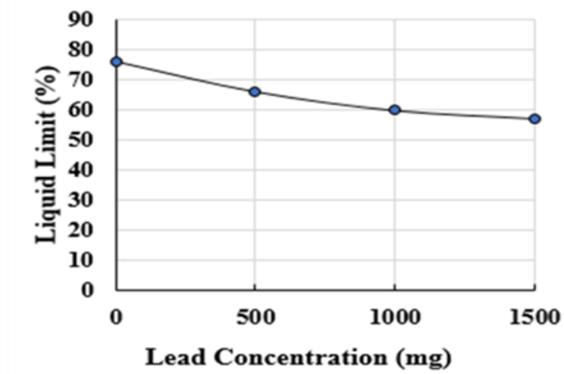

Fig.1 Relationship between the Heavy Metal Ion and Liquid Limit of the Expansive Soil.

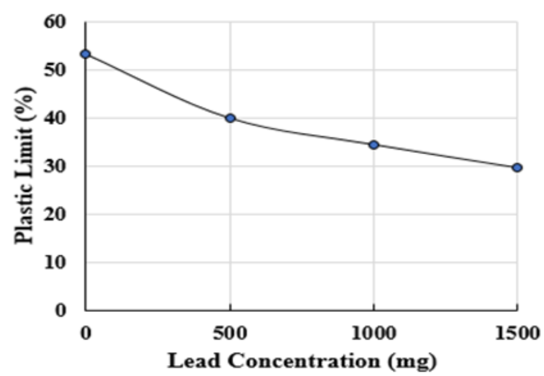

Fig. 2 Relationship between the Heavy Metal Ion and Plastic Limit of the Expansive Soil

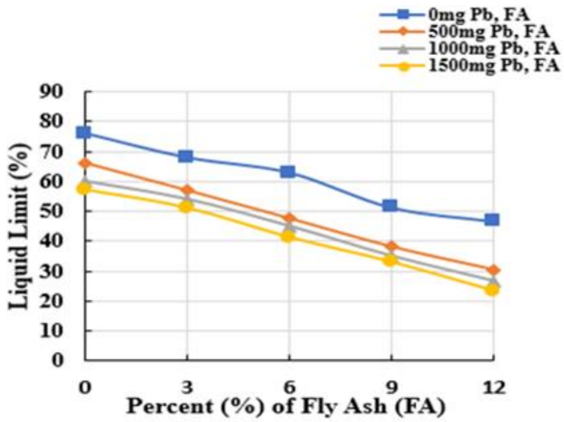

Fig.3 Effect of Fly Ash on the Liquid limit of the Heavy Metal Contaminated Expansive Soil

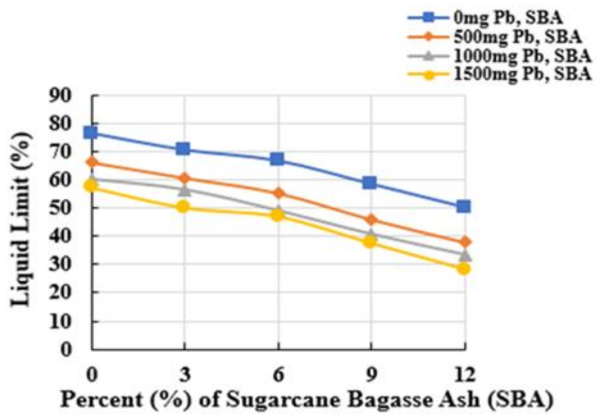

Fig. 4 Effect of Sugarcane Bagasse Ash on the Liquid limit of the Heavy Metal Contaminated Expansive Soil

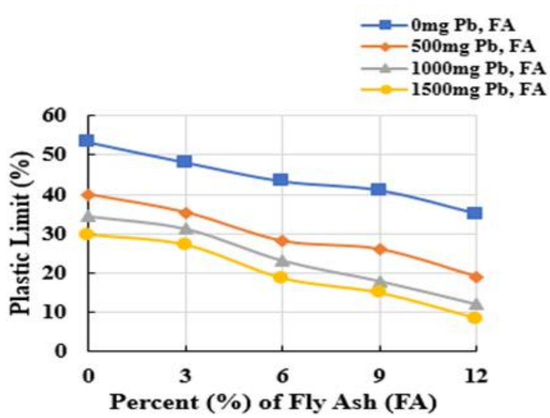

Fig. 5 Effect of Fly Ash on the Plastic Limit of the Heavy Metal Contaminated Expansive Soil

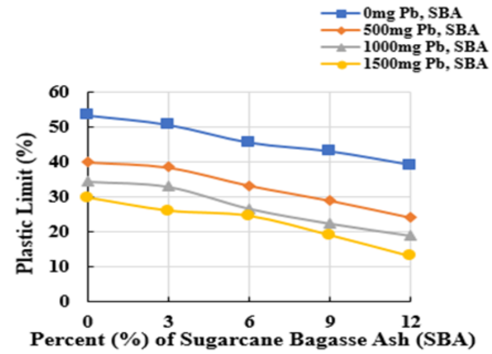

Fig. 6 Effect of Sugarcane Bagasse Ash on the Plastic Limit of the Heavy Metal Contaminated Expansive Soil.

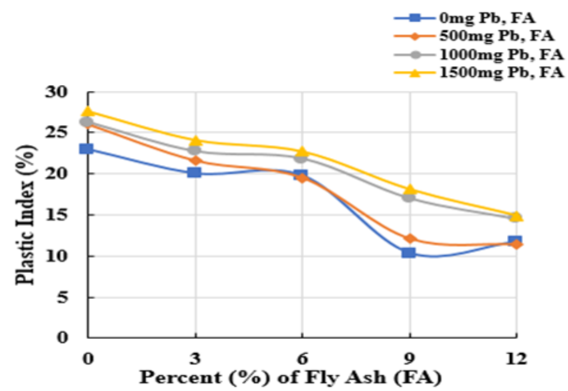

Fig. 7 Effect of Fly Ash on the Plastic Index of the Heavy Metal Contaminated Expansive Soil.

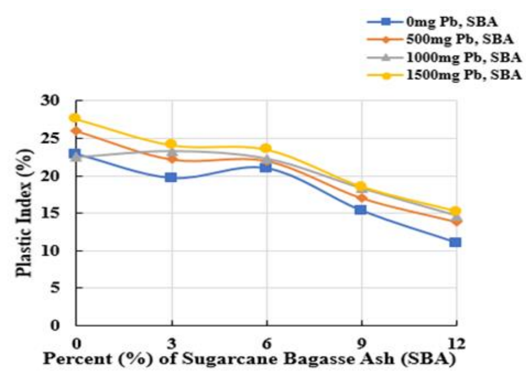

Fig. 8 Effect of Sugarcane Bagasse Ash on the Plastic Index of the Heavy Metal Contaminated Expansive Soil.

C. Unconfined Compressive Strength (UCS)

1) Effect of Lead Concentration

Figure 9 shows that the increase in lead concentration had an adverse impact on the unconfined compressive strength of the expansive soil. Clearly, one can see that unconfined compressive strength decreases with an increase in lead concentration. The unconfined compressive strengths for 500 mg/kg, 1000 mg/kg, and 1500 mg/kg of lead nitrate solution concentration were 100 kg/cm^2, 72 kg/cm^2, and 60 kg/cm^2, respectively. Moreover, samples of the Pb-contaminated soil were cured for 3, 7, and 28 days to determine the impact of curing on their strengths. The results showed that the unconfined compressive strength increased with increasing curing time, with the highest strength obtained after 28 days.

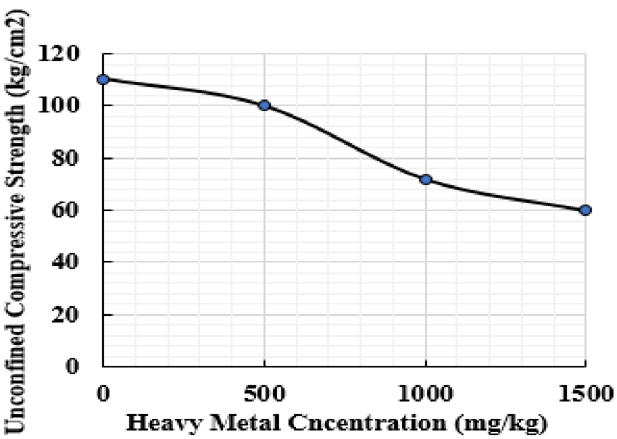

Fig. 9 Relationship between the Heavy Metal ion and the UCS of the Expansive Soil.

2) Effects of Curing, Type and Content of Additive

Unconfined compressive strength tests were performed according to IS 2720 (Part 10) on natural, contaminated, stabilized-contaminated, and unstabilized-contaminated soil samples (Figure 10 and Table 2) to ascertain the effects of the additives (fly ash and sugarcane bagasse ash) and curing on their strength. Each UCS value was determined as an average after three tests were conducted. The primary reason for conducting the unconfined compressive test was to determine the optimum level of fly ash and sugarcane bagasse required to stabilize the Pb-contaminated soil. Various contents of fly ash and sugarcane bagasse ash (0%, 3%, 6%, 9%, and 12%) samples were used for the determination of unconfined compressive strength at 3, 7, and 28 curing days. It was observed that the UCS values increased with increasing additive and curing time until the optimum levels of 6% for fly ash and 9% for sugarcane bagasse ash were reached (table 2). This increase in UCS can be attributed to pozzolanic reactions that occur as the soil is solidifying or stabilizing and to the hydration reactions of minerals (silicates, calcium, etc.).

The unconfined compressive strength of the natural soil was low (110.3 kg/m^2) but increased to 684 kg/m^2 after 28 days of curing, which is more than the unstabilized contaminated soil samples (figure 10). This is attributed to the presence of lead in the contaminated soil. The highest UCS value (1745 kg/cm^2) was obtained for a sample containing 500mg Pb and 6% fly ash at 28 days of curing, while the lowest was 218 kg/cm2 for a sample containing 1500mg Pb and 12% SBA at 3 days of curing. From the results (table 2), it is clearly seen that fly ash has superior strength to that of sugarcane bagasse ash.

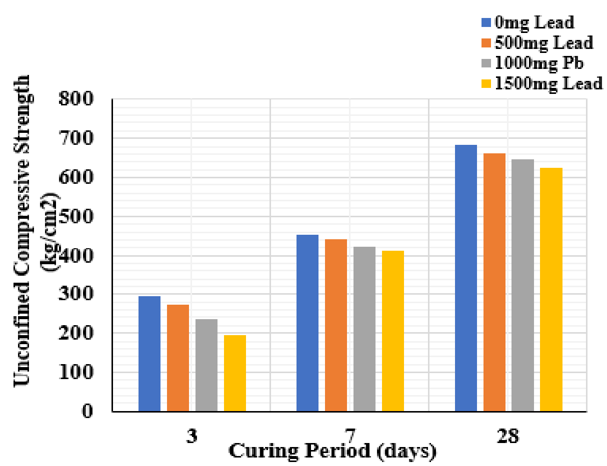

Figure 10 Effect of Curing on the Heavy Metal Contaminated Expansive Soil.

UCS RESULTS OF THE STABILIZED CONTAMINATED SOIL

Composition of Matrix	Unconfined Compressive Strength (kg/cm2)		
	3 days	7 days	28 days
Natural Soil	297	451	684
0mg lead + 3% FA	587	903	1387
0mg lead + 6% FA	729	1167	1763
0mg lead + 9% FA	523	813	1074
0mg lead + 12% FA	455	645	861
500mg lead + Natural Soil	273	431	653
500mg lead + 3% FA	565	884	1373
500mg lead + 6% FA	712	1148	1745
500mg lead + 9% FA	510	789	1050
500mg lead + 12% FA	423	633	849
1000mg lead + Natural Soil	239	418	620
1000mg lead + 3% FA	548	867	1358
1000mg lead + 6% FA	693	1119	1721
1000mg lead + 9% FA	481	755	1036
1000mg lead + 12% FA	414	606	817
1500mg lead + Natural Soil	194	398	625
1500mg lead + 3% FA	518	845	1331
1500mg lead + 6% FA	667	1081	1694
1500mg lead + 9% FA	456	739	1008
1500mg lead + 12% FA	382	575	771
0mg lead + 3% SBA	376	608	790
0mg lead + 6% SBA	544	767	986
0mg lead + 9% SBA	628	889	1123
0mg lead + 12% SBA	247	432	772
500mg lead + 3% SBA	361	595	774
500mg lead + 6% SBA	535	750	955
500mg lead + 9% SBA	616	872	1094
500mg lead + 12% SBA	260	383	750
1000mg lead + 3% SBA	347	583	766
1000mg lead + 6% SBA	511	734	923
1000mg lead + 9% SBA	592	850	1077
1000mg lead + 12% SBA	243	324	663
1500mg lead + 3% SBA	329	564	741
1500mg lead + 6% SBA	484	717	897
1500mg lead + 9% SBA	574	825	1040
1500mg lead + 12% SBA	218	575	771

CONCLUSION

The increased utilisation of industrial waste by many industrialised nations is beneficial because it lowers environmental pollution and waste management costs. Industrial wastes with pozzolanic properties, such as fly ash, steel slag, blast furnace slag, and sugarcane bagasse ash, are appropriate for construction projects. They can also be applied to the clean-up of contaminated soil. In this study, lead was consolidated and immobilized in expansive soil using industrial wastes (fly ash and sugarcane bagasse ash). The results demonstrate that fly ash and sugarcane bagasse ash can be used to enhance the engineering properties of heavy metal contaminated soil. Laboratory studies were also carried out to examine the atterberg limits and unconfined compressive strength of the expansive soil contaminated with various lead concentrations. The outcomes demonstrate that lead absorption had a significant impact on these properties. An increase in lead concentration causes an increase in the absorption of H^+ ions which lowers the atterberg limits and UCS. Finally, operating envelopes for FA and SBA solidification/stabilization that can be generally applicable to similar soil types damaged by the same kind of contamination is presented in this study. The following conclusion were realized from the study:

- Lead concentration changes the index properties of a soil by decreasing the thickness of the diffuse layer.
- The atterberg limits of the soil decrease with increasing lead concentration. This happens because lead concentration increases the particle size, subsequently reducing the clay content.
- Both additives (sugarcane bagasse ash and fly ash) decreased the atterberg limit of the expansive soil. However, the fly ash decreased the atterberg limit more significantly than the sugarcane bagasse ash.
- Up until their optimum levels, the UCS of the soil increases with additives (fly ash and sugarcane bagasse ash). The optimum levels of fly ash and sugarcane ash were 6% and 9%, respectively.
- With longer curing times, the expansive soil's UCS rises, reaching its highest level at day 28. In comparison to sugarcane bagasse ash stabilized contaminated expansive soil, fly ash stabilized contaminated expansive soil had a greater UCS. The highest UCS for fly ash stabilized soil was 1763kg/cm^2 while for sugarcane bagasse ash stabilized soil it was 1123kg/cm^2. This variation in strength is due to their composition.

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