Opportunities and Challenges in Sustainability
https://www.acadlore.com/journals/OCS

Blending Indian Black Cotton Soil with Municipal Solid Waste Incineration Ash and Other Additives for Strength Improvement: A Review

Karanbir Singh Randhawa*

Department of Civil Engineering, Punjabi University Patiala, 147002 Punjab, India

* Correspondence: Karanbir Singh Randhawa (karanbirsingh_randhawa@yahoo.com)

Received: 10-10-2024 **Revised:** 12-15-2024 **Accepted:** 12-20-2024

Citation: Randhawa, K. S. (2024). Blending Indian black cotton soil with municipal solid waste incineration ash and other additives for strength improvement: A review. *Oppor Chall. Sustain.*, *3*(4), 223-246. https://doi.org/10.56578/ocs030403.

Abstract: Municipal solid waste (MSW) management has become an urgent global issue, with incineration emerging as a viable waste-to-energy (WtE) technology. The process of incineration, which involves the combustion of organic compounds in waste, generates municipal solid waste incineration (MSWI) ash, a byproduct with potential applications in soil stabilization. This review explores the use of MSWI ash to enhance the engineering properties of Indian black cotton soil (BCS), a soil type known for its expansive nature and associated challenges in construction. Soil stabilization is a critical process aimed at improving the strength and durability of weak soils for use in civil engineering applications. The review discusses the mineralogical and morphological characteristics of MSWI ash, highlighting its potential to improve the mechanical properties of BCS. The addition of calcium-based additives, including lime and calcium hydroxide, facilitates the stabilization process by interacting with the expansive clay minerals present in the soil. This green technology not only improves the strength characteristics of BCS but also contributes to sustainable construction practices by reducing the demand for conventional building materials, lowering greenhouse gas emissions, and cutting costs. Experimental findings indicate that the optimal improvement in the unconfined compressive strength (UCS) and California bearing ratio (CBR) of BCS is achieved with the incorporation of 25% MSWI ash. Specifically, the UCS increases from 28.8 kPa to 53.4 kPa, and the CBR value rises from 3.38% to 9.38% with the addition of 25% ash. Such enhancements make MSWI ash a promising material for use in the construction of embankments, roads, and sub grade highways, where the improvement of expansive soil characteristics is critical for infrastructure stability.

Keywords: Indian black cotton soil; Municipal solid waste incineration ash; Expansive soils; Soil stabilization; Unconfined compressive strength; California bearing ratio

1. Introduction

Physical or chemical treatments that increase or preserve a soil's stability or enhance its engineering properties are called soil stabilization. Soil stabilization is the transformation of the physical properties of soil for long-term sustainable strength benefits. Soil's shear strength, as well as its total bearing strength, is increased to achieve stabilization. After stabilization, the damaging effects of freeze/thaw cycles and shrink-swell behavior of expansive soil are minimized, and a stable monolith is formed, which reduces permeability. The shrink-swell phenomenon refers to soil volume change based on water content (Paranthaman et al., 2024). Few soils expand by 10% or more. The sudden volume change can cause severe damage to a home, roadway, or some structure. The soil stabilization avoids the need for costly remove-and-replace procedures. Several soil-stabilizing agents that boost expansive soils in situ have been studied widely. For this reason, modern scientific soil stabilization techniques have now become available. Stabilized soil is a composite substance of constituent materials possessing properties of substances mixed and optimized. Geotechnical property is improved by adding cementing agents like lime, industrial by-products, cement-like slag, and fly ash (FA). In civil engineering, several primary and effective soil improvement techniques have been developed (Firoozi et al., 2017). To monitor engineering soil characteristics, such as moisture content, soils used for highways, buildings, or parking are often treated chemically.

Lime, lime-based materials, and Portland cement are other chemicals that stabilize soil. Hataf et al. (2018) demonstrated that a shrimp shell waste-derived biocompatible chitosan solution would help clay soils stay stable. In the clay's mechanical characteristics, the potential was evaluated at various times and conditions for curing, and for this, the chitosan solution was tested at various concentrations. The findings indicate that chitosan incorporation can create long-lasting connections between soil particles to enhance soil's inter-particle interaction and improve mechanical properties (Liu et al., 2024). The soil is permanently stabilized by providing enough material, so pre-project testing is essential. The subsequent soil layers would be thinner, resulting in a stabilized soil layer and significant cost savings, which is essential for integrating the structural design of the pavement. The microscopic process clarified the manifestations of the coupling effect (Wang et al., 2019).

1.1 Review of Soil Stabilization Methods

Geotechnical and transportation engineering divisions both need to deal with soil stabilizations. The term "soil stabilization" refers to various techniques for modifying the texture and plasticity of soil for a specific purpose to improve its strength, uniformity, or other qualities. There are several strategies for the stabilization process, and the stabilization of soils with materials like lime, ash, rubber, and glass fiber is the most effective soil stabilization method. Wang et al. (2018b) published preliminary research into microbial-induced calcite precipitation (MICP) treatment with a new polymer modification for soil to avoid water-induced erosion. The MICP cementation solution was made with a polyvinyl alcohol (PVA) solution instead of just water. A PVA-modified cementation solution provides an environment that is conducive to MICP. The cementation media concentrations and a comparative test were performed in the new process. Flume erosion measurements were used to show the effectiveness of the soil treatment, and an erosion feature apparatus (EFA) was used specifically to assess the credibility of the sand that has been treated. Several sub-grade performance stabilization situations were studied and compared in a laboratory. The C steel channel was utilized for a test kit with a footprint of 6 feet and a height of 4 feet designed for this purpose. In-situ compacted soil, geo-textile (GT) with geo-grid (GG) with aggregate base course (ABC), GT with cement-stabilized soil, and flowable fill were all investigated using the test kit. The efficiency of the sub grade layer for all stabilization techniques was improved, as revealed in the test results of the studies by Behnood & Olek (2020) and Song et al. (2020), which were the first to provide the ideal method for the most significant amount of calcium carbonate ($CaCO_3$) precipitation using high-and low-purity chemicals for the enzyme-induced carbonate precipitation (EICP) technique. Figure 1 depicts the various methods for the soil stabilization process. It is described as chemical stabilization, lime stabilization, cement stabilization, mechanical stabilization, and others, such as electrical, bitumen, geo-synthetics, grouting, and thermal stabilization methods.

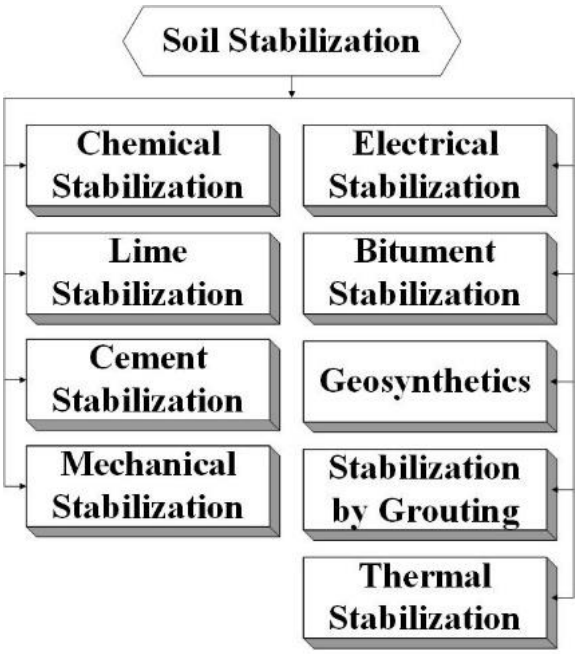

Figure 1. Different soil stabilization techniques

1.2 Benefits of Soil Stabilization Process in Engineering Properties of Soil

Minimizing site preparation time and soil stabilization may also reduce the time it takes to complete a project.

Wet ground can also be dried and reinforced through new techniques. The additive that reacts chemically with the minerals in the soil to improve its overall strength is the most extensively used lateritic soil-stabilizing approach (Horn et al., 2025). Successful soil stabilization allows for site-specific soils to be used, which can result in substantial cost reductions for a specific project (Li & Poon, 2017; Yin et al., 2024). With a growing emphasis on using more ecologically friendly and sustainable materials in both built and natural settings, eco-friendly alternative additives are becoming increasingly common to conventional chemical stabilizers and gaining popularity. Rashid et al. (2017) investigated the efficacy of xanthan gum in the stabilizing process. Field emission scanning electron microscopy (FESEM) testing, Emmett, Brunauer, regular direct shear testing, and UCS measurements were utilized. A low-quality soil transformed from liquid to solid impermeable medium for this stabilizing soil with binders is now a very cost-effective way. Housing, industrial units, reinforced earth systems, bulk fill applications, railways, pavements, and embankments can now be built in places where they have been historically unprofitable. This strategy has been known to work for a long time. For all construction projects, soil stabilization is transformed into the most cost-effective site preparation approach by combining this with the increasing costs of traditional civil engineering applications. Compared to the traditional granular sub-foundation soils, treated binders can be created to be durable. The strength is significantly increased due to this material used in pavement or base. Saneiyan et al. (2018) explored spectral-induced polarization (SIP) and shear-wave velocity to monitor calcite-driven soil strengthening processes. To complete the task, viable soil stabilization operations, long-term monitoring tools, and soil-strengthening characterization are essential, and the findings support the geophysical data. Both methods are vulnerable to SIP and calcite precipitation, providing additional details about precipitated carbonate's long-term stability. Direct techniques, such as Scanning Electron Microscopy (SEM) and direct sampling, have confirmed carbonate precipitation. Carbonate precipitation causes soil changes via microbes. In this process, a geophysical method as a monitoring tool is used for this soil strengthening. The thickness of the following layers, or the foundation's thickness, is reduced by using this soil strengthening technique.

1.3 Significance and Effects of Soil Modification

Stabilized soils offer a solid working basis, laying the groundwork for the project. The formation of persistent pozzolanic reactions transforms poor soils after stabilization techniques. This results in improved freeze-thaw resistance and decreased shrink-swell potential. In addition, the effects of litter breakdown and soil C storage on soil fauna might be favorable or detrimental (Frouz, 2018). Adding chemical stabilizers to earth brick stabilization are a typical method for enhancing performance and maintaining the brick’s construction application. The soil’s engineering properties are improved by their hygro-thermal characteristics and are not affected by cementitious materials agents' incorporation. Saidi et al. (2018) investigated the effects of stabilizers on compressed earth bricks' moisture isotherms and thermal conductivity. Soil also underwent some changes that resulted in its stabilization. Maximum dry density was easily achieved by making easier compaction. The PI is a crucial geotechnical statistic that considers the essential content of the soil. Soils are becoming increasingly brittle and workable when their plasticity is decreased.

This review examines the strength behavior of BCS after adding MSWI ash based on various experiments. The engineering features of expanding soil are improved when the BCS is blended with MSWI ash. A review of various studies for stabilizing weak soils and the incineration process of MSW was conducted. Engineering properties for the stabilization of soils and MSWI ash were identified. Without triggering any environmental problems, MSWI ash technology lowered the substantial volumes of MSW by around 90%. The impact of varying ash proportions on soil characteristics and engineering behavior depicts its use as a soil-stabilizing substance for surface modification. The findings of the experiments demonstrate a potential improvement in soil quality after adding MSWI ash to the soil.

2. Objectives and Research Methodology

BCSs are medium- to high-degree compressible clays and are an essential type of soil in India. These soils are known for their abnormal swelling and shrinkage capabilities. These soils are found mainly in India's central and western regions, covering roughly 20% of the country's land surface area. The essential purpose of this research is:

- To review and discuss the past studies related to the characterization of weak soils like BCS before and after the addition of MSWI ash to soil as well as discuss the stabilization procedure of BCS.
- To evaluate the potential of waste material MSWI ash for soil stabilization based on past studies and experiments conducted to characterize MSWI ash.
- Review the role of MSWI ash in constructing road base layers, parking lots, sub-base layers, and road sub-grades.

The vital issues reviewed in the study are resolving disposal issues, lowering raw material production costs, conserving natural resources, and using MSWI bottom ash (BA) as a construction material.

3. Need for Soil Stabilization and Incineration Process

Soil modification is a process of modifying soil to improve physical and chemical properties. The load-bearing ability of a subgrade is improved to support foundations and pavements by increasing the soil's shear strength and/or managing the shrink-swell qualities. Incineration is a necessary component of the hazardous and clinical waste disposal process (Wu et al., 2024). Medical waste must often be incinerated at high temperatures to remove pathogens and harmful contamination. Plants that treat waste water create a residue/sludge that needs to be disposed of in an environmentally friendly way. Jagaba et al. (2019) discussed incinerated sewage sludge ash (ISSA) as an agent for stabilizing the soil. X-ray diffraction (XRD), X-ray fluorescence (XRF), and the Toxicity Characteristic Leaching Procedure (TCLP) were performed to determine the oxide compositions.

The MSWI FA waste management was simplified as a consequence, which usually includes its transportation, and a stabilization procedure was performed before landfilling. It is fair to infer that the system in the study by Assi et al. (2020) can be directly applicable to incinerator plants. The proposed new urban mining solution for Europe was assessed with this economic benefit associated with reduced carbon dioxide emissions. For two reasons, stabilization of earthen building materials is usually done. One is improving the cohesiveness and soil strength that would otherwise be unfit for building. In most cases, technology offers an alternative structural solution to a functional problem, as studied by Liu et al. (2019b). Durability is another method that improves the material's resistance to corrosion caused by water.

3.1 Improvement of Soil Strength Through Soil Stabilization

Stabilization of soil is a technique for bonding soil particles together to decrease compressibility and increase soil strength (Abdullah & Shahin, 2023; Li et al., 2023). To achieve the necessary stabilizing action, soil is mixed with additives or grout. The organic soil must be improved before any engineering work can begin, as it has low shear strength, permeability, and compressibility. Ukritchon et al. (2017) explored and investigated the linear intensity gradient ratio's influence on the predicted failure mechanism of undrained face stability. Chang & Cho (2019) conducted several tests to study the interactions between soil and gellan gum on the strength-treated soil mixes (ranging from sand to clay). According to experiments, gellan gum treatment effectively improved the sand-clay combinations' strengths over plain sand or clay. It is responsible for acceptable particle aggregation, fine-to-coarse particle interconnectivity, and strengthening behavior. Gellan gum treatment increased both inter-particle stability and clay-containing soils' friction angle. To make predictions, the intensity rises at the stabilization period, and a hyperbolic function can be used (Rosone et al., 2018). The treatment causes a redistribution of development in the suction of the matrices, as well as increased porosity between macro and micro-pores, which is linked to a minimal reduction in the amount of water in the aggregate shrinkage, according to micro-structural research. The formation of pozzolanic chemicals in hardened clay aggregates causes bonding and a rise in the interlocking degree of the aggregates, resulting in increased shear strength. Since it is caused by pozzolanic materials forming on the surface aggregates of clay, it causes a link between clay aggregates and a connection between aggregates and an improvement in their binding; this behavior is regulated by lime concentration and curing time.

3.2 Different Types of Soils and Their Stabilization Processes

Chemical, electrical, biological, and physical stabilization methods stabilize the soil. Ghadir & Ranjbar (2018) utilized the ordinary Portland cement (OPC) and volcanic ash (VA)-based geo-polymer for the mechanical efficiency of clayey soil stabilization. Alkali activator molarity, alkali activator/clay, the VA/clay ratio, and time and curing conditions were all studied. It was discovered that treatment with geo-polymer is efficient in dry conditions (DC), whereas Portland cement performs admirably in wet environments. Table 1 shows the different soils and their stabilizing agents.

Table 1. Characteristics of soils and their stabilizing agents

S. No	Soil Types	Stabilizing Agent	Outcome
1	Clayey soil	OPC and VA-based geo-polymer	Molarity of the alkali activator and alkali activator-clay mixture improved the strength of compression of the geo-polymer (Ghadir & Ranjbar, 2018).
2	Clay soil	Chitosan solution is used in various concentrations.	The chitosan incorporation improves mechanical properties by enhancing soil particle inter-particle interaction (Hataf et al., 2018).
3	Laterite soil	Calcium-based silica from biomass as an additive	In this analysis, SH-85 is a suitable substitute for conventional stabilizers in building projects involving tropical residual soils (Latifi et al., 2017a).

Hataf et al. (2018) investigated the possibility of stabilizing clay soils with a shrimp shell waste-derived biocompatible chitosan solution. The chitosan remedy was tested at various concentrations on clay soil's mechanical properties and at various curing times and conditions. Time and soil moisture content highly influenced the inter-particle interaction; in the early days, when the soil was warm but lost its effectiveness as time passed, the chitosan solution provided additional particle interaction. At DC, the bond strength was ineffective.

3.3 Engineering Properties of Expansive Soils

Expansive soils possess a lot of swelling, and montmorillonite is a clay mineral responsible for this. When soil comes into touch with expansive clay minerals, the soil might inflate excessively and shrink when the soil dries out. Expansive soil is a clay type with a high plasticity (Gou et al., 2023). Its engineering prowess exemplifies that its form contracts under dehydration and softening as a consequence of the influence of water. Silt, sand, and clay are the three primary forms of soil found naturally (Chen et al., 2023). General clay soils are graded as "expansive." To expand (increase in volume) as water is absorbed and shrink (decrease in volume) as water is removed is that a given type of clay can appear (Al-Mohammedi & Seyedi, 2023).

In situ and compacted samples were used to examine the engineering qualities of soil. The soil-water characteristic curve described two air entry values: A low number that denotes macro-porous material and a high value corresponding to microporous drainage. At a low decrease during residual shrinkage and a steep decline during normal shrinkage, the curve of shrinking was discovered to be S-shaped, with low structural shrinkage. Phanikumar & Nagaraju (2018) presented a comparison of the effects of rice husk ash (RHA) and FA on expanding clay's index and engineering properties. At various amounts of RHA and FA, plasticity index (PI), plastic limit (PL), free swell index (FSI), unconfined compressive power, liquid limit (LL), and permeability coefficient (*k*) were determined. Proctor compaction testing was utilized to measure the swelling pressure, permeability coefficient, and UCS of the FA-clay and RHA-clay blends at their optimum moisture content (OMC) and maximum dry density (MDD). As FA and RHA levels rose, LL, PI, and FSI decreased significantly.

Table 2. Index and engineering properties of soil and additives (Chu et al., 2020)

Property	Soil	FA	RHA	Standard Designation
Clay size (%)	58	0	0	ASTM 98 D422-63
Gravel size (%)	0	0	0	ASTM 98 D422-63
OMC (%)	25	21	38	ASTM D698
FSI (%)	125	Non-swelling	Non-swelling	ASTM D5890-02
Silt size (%)	30	72	16	ASTM 98 D422-63
MDD (kN/m^3)	15.5	12.8	7	ASTM D698
CBR (%)	1	3	8	ASTM D1883
Specific gravity (*G*)	2.67	2.1	1.83	ASTM D854-02
USCS classification	CH	Non-plastic	Non-plastic	ASTM D2487-00
Sand size (%)	12	28	84	ASTM 98 D422-63
PL (%)	29	NP	NP	ASTM D4318-00
LL (%)	84	NP	NP	ASTM D4318-00
PI (%)	55	-	-	ASTM D4318-00

Table 2 demonstrates the engineering features of soil and a few additives. Swelling qualities of weak expansive soils are modified by introducing modifying agents. After alteration, performance degrades when subjected to a long time. As a result, this research looks into the effect of drying-wetting cycles on the compressibility and swelling of transformed weak soils containing calcium carbide slag and iron tailing sand. Initially, the swelling potential rises with the number of cycles and then decreases, peaking at the 7^{th} cycle and stabilizing after the 10^{th} cycle. The drying-wetting cycles degrade the soil composition, as depicted in the results. Mercury intrusion porosimetry (MIP) and SEM are used for micro-structural analysis. A degradation process is revealed in the micro-structural research findings of the study by Chu et al. (2020). The critical goal of the study by Mujtaba et al. (2018) is to mix ground granulated blast furnace slag (GGBFS) with soils to boost engineering properties. For this reason, two large soil samples were taken from the Pakistani cities of DG Khan and Sialkot. The classification tests reveal the DG Khan sample, soil classification scheme, and unified fat clay and lean clay. The GGBFS was applied to these soil samples in various amounts ranging from 0% to 55% to investigate its function in stabilizing these soils. According to laboratory tests conducted on composite soil samples, adding 50% GGBFS to both samples increased dry unit weight by 10%. The soil samples increased their engineering properties significantly. It is a cost-effective and environmentally friendly way to organize waste in the steel industry.

Because of the expansive soil's heavy mineral composition, which is hydrophilic, its structure contracts under dehydration and expands under the effects of inflation and softening. Biochar is made through slow pyrolysis (GuhaRay et al., 2019). Biochar is uniformly blended with three separate percentages of expansive BCS at the same compaction state (5, 10)%. Geo-technically, the CBR, permeability, free swell, consistency limits, shear strength and physicochemical (specific gravity, pH, cation exchange potential), and micro-structural (energy-dispersive X-ray spectroscopy, scanning electron microscope, Fourier-transform infrared spectroscopy, XRD) tests were undertaken on soil with and without the addition of biochar.

3.3.1 Characterization of expansive soil

The expansive soil index properties from the outskirts of Bhubaneswar (20°11′06.7″N 85°47′23.7″E) were studied. Silt and clay comprised 40% and 52% of the grain size distribution. With a measure of plasticity of 22%, the soil was highly plastic. With a very high degree of swelling, Gayatri & Verma (2020) found that MDD and OMC of soil were 16.4kN/m^3 and 19.6%, respectively. Using dross (alumina refining waste) reduces swelling potential and shrinkage ratio, as this soil is troublesome in its current state. The characteristics of expansive soils are depicted in Figure 2.

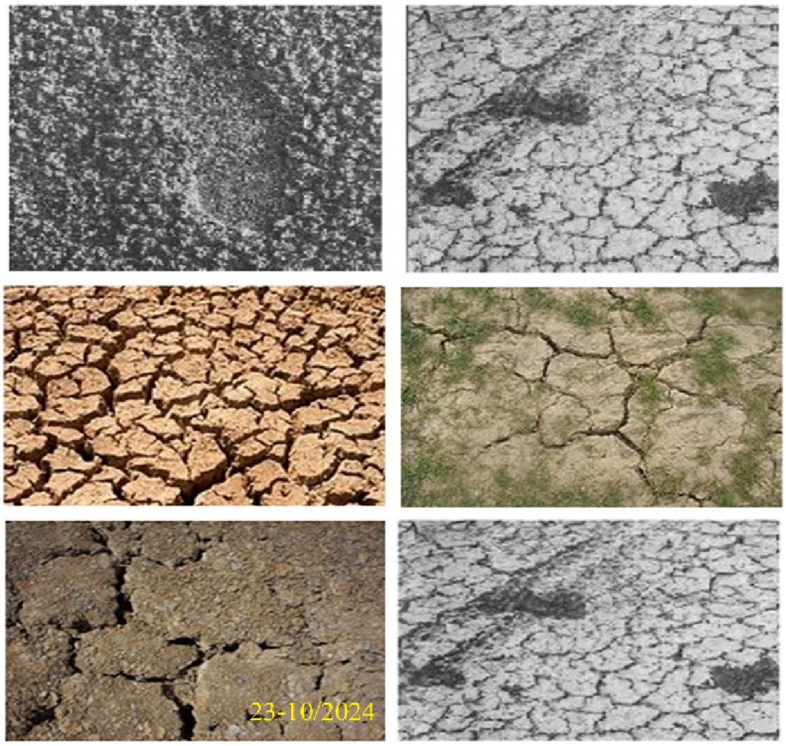

Figure 2. Different characteristics of expansive soils

Figure 2 illustrates the characteristics of expansive soils, denoted as soil with a "popcorn" texture, soil with cracks, cracked soil, parched soil, highly expansive soil, and roads of expansive soil. Deposits of BCS that cover vast areas of India have low strength and resistance to deformation under load and are examples of inferior subgrade characteristics. Soil stabilization is a viable option for improving subgrade performance over time. Lime and cement are the two most popular conventional chemical stabilization agents. It is essential to update conventional stabilization strategies using readily available waste products because of environmental and economic considerations. Chavali & Reshmarani (2020) concentrated on efficiently using lingo-sulfonate, an industrial by-product, to satisfy the ever-increasing demand for subgrade stabilization materials. A lingo-sulfonate is a lignin-based organic polymer produced by a waste by-product in the paper and wood industry. The annual production of lingo-sulfonates worldwide is estimated at around 1.8 million tons. Fertilizers, binders, flocculants, concrete additives, anti-oxidants, mining dust suppressants, dispersants, and metal absorbents are the various applications of lingo-sulfonates.

3.3.2 Classification and different types of expansive soils

Soils comprise several materials, most of which do not grow when exposed to moisture. Clay minerals in various forms are expansive. These minerals are beidellite, montmorillonite, chlorite, smectite, vermiculite, attapulgite, bentonite, and nontronite. In addition to their arterial transport roads, facilities, and houses, many of the world's largest towns and cities are built on rocks and clay-rich soils (Withanage et al., 2024). Local site changes, like leaks in the water supply pipelines or drains, may be a significant threat to engineering constructions due to their tendency, as seasonal fluctuations in moisture content cause it to shrink or swell. This vast soil contains a considerable amount of clay. It has a distinct shrinkage nature when dry. Fine-grained or decomposed rocks showing a considerable volume variation when exposed to moisture content variations are known as expansive soils (Huang et al., 2024). Swell shrinks are likely to occur near the ground level as they are directly affected by seasonal and environmental changes. Unsaturated soils with montmorillonite clay minerals are most common in expansive soils. The amount of monovalent cations mixing with clay minerals causes heavy loss to residential structures and other civil engineering structures constructed on top of vast soils. Dang et al. (2017) analyzed and added several experimental tests; the effects of bagasse fiber and hydrated lime on stabilized soils' engineering parameters and swelling behavior were investigated. Bagasse fiber is an industrial waste by-product left over after crushing sugarcane for juice extraction, and it was used as a reinforcing agent in this study to stabilize expansive soil.

All around the world, expansive soils can be found and are considered potential disasters for engineering systems. Direct laboratory experiments are critical to ensuring that the appropriate design technique is used for early detection of these soils. Türköz (2019) established computer-controlled equipment for directly measuring swell parameters, which is far more ergonomic than traditional consolidation devices. The swell parameters on compacted samples and their measurements were taken. The ideal moisture content and dry density values for the preparation of all samples were revealed due to the standard proctor compaction experiment. Zhang et al. (2020) investigated the hydro-mechanical activity of unsaturated and expansive soils over a broad suction range by using the axis-translation technique and force suctions on an expanding soil using the vapor equilibrium technique with a saturated salt solution. Above 250 kPa, the void ratio decreased as the suction was increased. As a result, research into unsaturated soil's hydro-mechanical behavior over a broad suction range is needed.

3.4 Introduction to Indian BCS

One of the main groups of inorganic clays is BCS, which can be found worldwide. With seasonal variations in water content, it undergoes significant volume changes (Obaid et al., 2024). Due to montmorillonite's clay mineral in the soil, it heaves up when wet and shrinks, creating cracks when dry. Drying and wetting of the soil can cause stress, structural harm, and changes in volume (Kulkarni & Ranadive, 2024). Soil stabilization has proven to be a successful strategy for treating poor soil and achieving the desired engineering properties. For improving soil geotechnical properties, the methods that have been used for many years include stabilization through cement, lime, and bitumen (Jethwa et al., 2023). The geotechnical properties affected by adding nano-copper to BCS include swelling strain, UCS, compaction characteristics, CBR value, and LL, according to Pusadkar et al. (2017). Three different percentages of nano-copper were combined with soil. BCSs are made up of inorganic clays with a low to heavy compressibility range, and they are a significant soil community in India. They are known for their extraordinary capacity for shrinking and swelling. BCSs are found mainly in India's central and western regions, covering roughly 20% of the country's total land area. As a result, BCS has a poor bearing capacity and exhibits swells and shrinks excessively (Miao et al., 2017). Its unique traits make it a weak base material for road building. BCSs have CBR values within the 2 to 4% range when tested in the laboratory.

The strength of the sub-base and sub-grade of soil and the traffic volume determine the life and maintenance of roads. Because of its significant swelling and shrinking properties under changing moisture contents, BCS causes hindrances in the construction and maintenance of roads. The process of stabilizing BCS's behavior with GGBFS and GGBFS-lime mix is illustrated in the experimental results of the study by Pai & Patel (2019). The strength of the stabilized soil was measured using tests such as UCS and CBR. GGBFS dosages of 3, 6, 9, and 12% by dry soil's weight were tested in the soil-GGBFS mix, and the 2-part GGBFS and 1-part lime. Expansive soils can be found all around the globe, including in India, Australia, Ethiopia, Sudan, and the United States, as a type of BCS. The construction industry loses millions of dollars annually due to the distress caused by BCS's swelling and shrinkage action. Experimental investigations to stabilize BCS using FA and RHA-based geo-polymers were carried out by Murmu & Patel (2020). The alkaline activator solution comprises sodium hydroxide (SH) and sodium silicate (SS) in a ratio of 1:5.

3.4.1 Engineering characteristics of Indian BCS

BCS is a clayey soil. The presence of titanium oxide in small amounts makes BCS black. The BCS's blackish-grey clay is primarily montmorillonite in structure (Kami & Mishra, 2024). Srikanth Reddy et al. (2018) investigated whether BCS with lime stabilization and brick powder (BP) mixture could be utilized as a flexible pavement sub-base material. When BCS was checked for suitability as a sub-base material, it was inappropriate because it had a low CBR value. Even lime stabilization of the BCS under investigation did not achieve the necessary CBR value set by MORTH for the pavement sub-base content. As a result, to obtain the best mixture for a better value of CBR, BP was mixed into the lime-stabilized BCS. The CBR value of a blend of 20% BP and 80% lime-stabilized BCS under investigation increased by about 135% as compared to BCS with lime stabilization only.

- Engineering properties of BCS: Shear strength, compaction, plasticity, compressibility, and permeability are soil's engineering assets.
- Permeability: A characteristic of porous material that allows water to move by its interconnecting voids is called permeability.
- Plasticity: It is a soil property that can quickly deform without elastic rebound or volume change.
- Compaction: Compaction is a mechanical process that artificially rearranges and packs soil particles into a closed state of contact to reduce the porosities of soil and thereby increase its dry density.
- Compressibility: Compressibility is a property of soil mass that refers to its susceptibility to volume loss under strain.
- Shear strength: Persistent shear displacement causes deformation under the action due to the shear stress of this resistance of soil particles or masses.
- Index properties of BCS: Index properties are soil properties that aren't of prime importance to geotechnical engineering but represent engineering properties.
- Particle size analysis: This is a technique for separating soils into various fractions based on the particles found in the soil. It is graphically depicted on a particle size distribution curve.
- Specific gravity: It is defined at the same temperature, i.e., the weight of an identical volume of distilled water divided by the weight of a specific amount of soil solid at the same temperature, with all weights taken in air.

For coarse-grained soil, the flask or pycnometer method is appropriate; however, the density bottle method is the most reliable and applicable to all soil forms (Singh et al., 2022; Verma et al., 2023). An oedometer apparatus and various loading patterns used in Indian BCS for the time-dependent actions over a long period were examined by Singh et al. (2020). To predict the operation of creep and swelling of BCS over time, a non-linear mechanism was utilized to depict the experimental result. The pressure rate's behavior with time and the most effective stress were investigated using non-linear function. After primary consolidation, the strain rate decreased non-linearly to achieve an equilibrium state unaffected by the load. The BCS had a lot of potential to swell at various stages of loading-reloading periods, as shown in the results. The BCS's property tensile power was affected by polypropylene (PP) fiber combined with silica fume. Murthi et al. (2021) blended BCS with 5%, 10%, 15%, and 20% silica fume and performed experiments with 0.5%, 1.0%, 1.5%, and 2.0% PP fiber.

4. Incineration of Waste Particles and Soil Stabilization Process

Incineration is a waste disposal method that entails burning organic compounds in waste. "Thermal treatment" relates to incinerators and other high-temperature waste treatment systems (Wang et al., 2023). The incineration of waste materials produces flue gas, heat, and ash. Incineration is the disposal process of waste materials by burning detected organic compounds in the waste materials (Sun et al., 2023). It transforms waste into heat, flue gas, and ash. Waste products come in different types that can be effectively used after proper treatment and analysis. Heat accounts for considerable waste that can be used to produce electricity (Zhou et al., 2022). Flue gases include traces of carbon dioxide, nitrogen, and sulfur dioxide; these oxides are more efficiently utilized when appropriately used. Nitrogen may be used to improve crop yields as fertilizer; carbon dioxide can be utilized for fire fighting; and sulfur can be used for dental care (Tabassum et al., 2022). The ash produced in solid lumps can be used for construction purposes (Nidoni, 2017).

Chen et al. (2019b) conducted experiments after the incineration of MSW in a furnace, a mechanical grate, and a circulating fluidized bed. The findings revealed that the generated types of FA had a high CaO content, indicating that they could provide enough Ca for MICP care. The viability of using FA from MSWI as the effectiveness of an addition for strengthening pre-treated cement-stabilized soil was investigated by Liang et al. (2020). MSWI FA samples after pre-treatment with 5% and 10% ratios were incorporated into soil stabilized with 10%, 15%, and 20% of OPC content. Huang et al. (2019) reported that pre-treated fly ash (PFA) and OPC material increased internal friction, UCS of cement-stabilized soil, and cohesion. The same result was seen on UCS after 10% PFA was added as a substitute for 5% OPC. Heavy metal leaching concentrations in cement-stabilized soil in subsequent X-ray powder diffraction were significantly lower than the limit value.

4.1 MSWI Ash as a Soil Stabilizer

The incineration of MSW has become increasingly important in managing high waste generation triggered by population growth and advances in established and developing economies' socio-economic well-being. The rise in the generation of MSW has placed pressure on urban governments to find alternative treatment options when dealing with limited land space. This increase in the generation of MSW has also created new opportunities, like supplying raw materials to the WtE industry. Because of its tremendous meta-heavy material, FA, a result of MSWI, stands for urban solid waste incineration and is categorized as hazardous waste. FA may be recycled in the building industry or disposed of in landfills, putting oneself in danger to the atmosphere and human health. To determine the best pH storage conditions for the FA, Yakubu et al. (2018) set out to create a theoretical foundation. To solidify/stabilize heavy metal (Cr, Zn, Pb, Cu, Cd, As, and Mn) contents when leached at various pH levels, a sample of MSWI FA was taken from the trash incineration power facility in Xinghuo and investigated by Funari et al. (2019). Heavy metal concentration in the sewage was presumed to represent the degree of its solidification/stabilization (S/S). The study's findings showed that raw FA had heavy metal at a greater level than the permissible limits. Compared to highly alkaline environments, extremely acidic conditions favored heavy metal leaching. Using the MICP technique, Xu et al. (2019a) proposed a process to solidify/stabilize MSWI FA. This way, the abundant calcium in FA was employed in MSWI to induce calcite precipitation, which differs from the previous studies that used an extra calcium source. FA sample contained 44.5% of CaO, and the concentrations of leaching Zn, Cr, and Pb exceeded the limits of China's hazardous waste detection level.

Approximately 64% of MSWI BA is landfilled in Japan (Caprai et al., 2018). The landfill body is exposed to natural disasters since Japan's landfills are not capped. Because rain water seeps into landfill materials and interacts with them, a rise in the downpour of heavy rain is projected to influence chemical stabilization in BA landfills. For the leaching activity of ions and total organic carbon (TOC) in BA having 10 mm particle size, Linh et al. (2020) investigated the effect of daily rainfall; a percolation column test was used (15 mm/hr) at extreme rainfall (25, 50, and 100 mm/hr). Following severe rain and rising temperatures after regular rainfall, the leachate component was reduced, as shown in the results. Furthermore, after heavy rain, the pH fluctuated between 11 and 12, but after regular rain, it fell down to 7-9. The carbonation of the leachate and BA layers is a significant factor in reducing the pH. Variations in ion concentrations and TOC may be explained by the contact time of water molecules and BA particles, dissolution, and dilution, according to the study by Huber et al. (2018). It was found that heavy downpours of rain intensities did not alter ion release rates and TOC.

4.2 Utilization of MSWI Ash for Stabilizing BCS

Researchers have attempted to stabilize limed BCS to improve its shrinkage and swelling characteristics. In recent years, lime's cost has risen; FA and rice husk are cost-effective waste materials, necessitating substitutes. To stabilize it, Vavva et al. (2017) investigated FA on a laboratory scale. In terms of both chemical and physical characteristics, it is graded by Council Decision 2003/33/EC, using the EN 12457/2, European standard leaching inspection; water washing and phosphoric acid stabilization were also investigated. First, the FA was fully characterized. Elemental composition, mineralogy, morphology, thermal gravimetric analysis, moisture content, particle size distribution, pH, specific surface area, density, and leachate analysis are all part of the residue characterization process. Combined phosphoric acid and water cleaning was investigated as a means of chemical stabilization of FA. By incorporating supplementary cementitious materials (SCMs) and green stabilizers, Chen et al. (2019a) created a new, cleaner approach for the stabilization of incineration fly ash (IFA). Toxic elements are contained in IFA, which slows down the process of cement hydration, according to thermogravimetric (TG) and quantitative XRD measurements by Xu et al. (2019b). A single cement application was ineffective for immobilizing toxic elements, especially Pb. Additional cement hydrates were formed that decreased Pb leachability by 36.3%. The wood also improved the immobilization of toxic elements in waste-derived biochar, and green stabilizers were added to potassium di-hydrogen phosphate (KDP). A significant economic and environmental burden is the MSWI FA disposal in landfills. Phosphate-modified calcium aluminate cement (CAC) in this study was utilized for stabilizing/solidifying (S/S) municipal incinerated fly ash (MIFA); for this, a new and high-efficiency system was proposed by Chen et al. (2021).

4.2.1 Physical and engineering properties of MSWI ash

BA from MSWI is an alternative to conventional aggregates; it is utilized in road construction. Le et al. (2018) continued the analysis of the mechanical efficiency of BA. Initially, a physicochemical test was conducted on a wetting path, followed by oedometer tests. The position of the BA concerning the main mineralogical components and, in addition, the connection with its hydro-mechanical properties were highlighted in this combined evaluation. According to the tests, SiO_2, which influences the BA characteristics, is the main constituent of this ash. The chemical reactions demonstrate the importance of BA in road works. BA's other factors and the SiO_2 physical stability generate a compacted material that is less sensitive to water.

Figure 3 shows the SEM diagram of the irregular shape of ash particles (Singh & Kumar, 2020). To simulate the impact of cement and fiber, several experiments were conducted for inclusion on the subject of an action for MSWI BA. During the research, the CBR review was utilized as an essential parameter. The impact of different parameters on the behavior was investigated for various properties of the composite of peak strength, such as shear, compressive, and tensile strength. An increase in these parameters was found as the amount of fiber rose. The study performed by the other researchers compared the different soils, such as sandy soil, silty soil, and clayey soil, using the CBR as a baseline and based on some parametric tests.

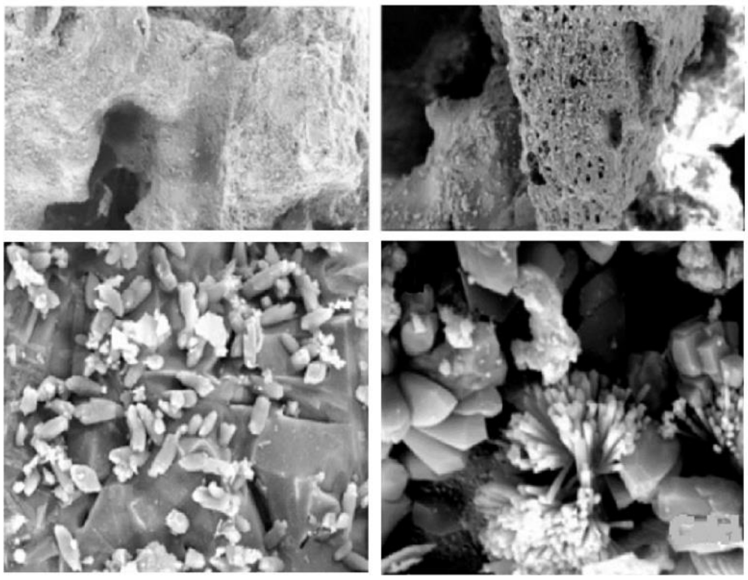

Figure 3. SEM images showing irregular shape of ash particles (Singh & Kumar, 2020)

4.2.2 Characterization of MSWI ash

Chemical composition, elemental distribution, leaching activity, mineralogy, and granulometry as a function of grain size of MSWI residues generated in two types of facilities were all thoroughly investigated by Hu et al. (2018). Fresh MSW characteristics are crucial when planning, constructing, running, or updating systems for solid waste disposal. The most critical features of MSW to consider in device planning are physical structure, compacted unit weight, moisture content, and permeability. Singh & Kumar (2017b) studied the geotechnical activity of cement and fiber-stabilized municipal waste incineration ash. Laboratory testing was conducted to see how adding cement and fiber to MSWI ash affects compaction and strength behavior. While cement contents were 2, 4, 6, and 8%, PP fiber in varying amounts of 0.5, 0.75, and 1% of a whole mix of specimens' dry weight and PP fibers with 6, 12, and 18 mm lengths were used.

After 7, 14, and 28 days of curing, the mix specimens were examined for tensile, split, and UCS. To assess the morphological features of the surface and hydraulic compounds produced during the phase, SEM and XRD tests were also performed by Yang et al. (2018). Hazardous wastes have higher storage, transport care, and disposal costs than non-hazardous wastes. MSWI facility operators go to great lengths to ensure their ash passes the TCLP (Liu et al., 2019c). Sludge fly ash (SFA) was utilized for pyrolysis on a small scale in the lab and the TG study of MSW characterization (Gao et al., 2020). By lowering the reaction's activation energy, the TG analysis revealed that SFA was discovered to be an essential ingredient in the pyrolysis process.

4.2.3 Chemical composition of MSWI ash

The chemical structure of MSWI ash was determined using the sample's XRF. Compared to other heavy metals, Zn and Pb usually occur in the highest quantities; however, extreme metal bands like Hg, Cr, Ni, Cu, Pb, Zn, and Cd are most frequently contained in MSWI FA. Fluorescence spectrometry of X-rays was used to investigate whether both the BA fractions have the same chemical makeup (Du et al., 2018). At 550^{0}C, a coulometric carbon/sulfur analyzer, Behr CS30HT, was used to assess the total organic content (TOC). Alam et al. (2019) used a Bruker D4 fitted with a Lynx Eye detector to perform XRD measurements on BA fractions, both untreated and size-separated. The PANalyticalX'Pert Pro with an X'Celerator detector was used to test all other samples.

Table 3 shows the chemical composition of MSWI ash as studied by different researchers. MSW is primarily incinerated for energy recovery and volume reduction (Marieta et al., 2021). Leftovers from toxic air pollution control (APC) must be treated and disposed of in suitable landfills, regardless of the incineration of MSW (Tome et al., 2021). Material recycling is another choice for landfilling that results in the reuse of valuable materials and reduced hazardous waste volumes. APC residues derived from MSW have a chemical composition that makes them desirable for the recovery of metal and salt, but the waste's variability makes developing material recovery processes difficult. Between 2006 and 2020, 895 XRF studies of FA samples and dry scrubber residue were obtained in Norway and Sweden and examined by Nedkvitne et al. (2021) to see if there is any difference in the chemical composition of incineration plants inside and between them. APC residue's average ability of elemental relative standard deviation to concentrate within plants was calculated to be 30%.

Table 3. Chemical composition of MSWI ash

Composition of Chemical Mixtures in MSWI Ash (%)							
SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	References
65.24	17.27	5.14	3.32	3.46	3.47	0.83	(Yang et al., 2020)
55.37	9.20	4.93	19.39	0.41	0.43	0.24	(Singh & Kumar, 2017b)
64.50	20.72	7.67	-	2.11	-	3.18	(Latifi et al., 2017b)
16.88	4.24	19.37	33.53	11.52	0.58	0.59	(Zhao et al., 2020)
2.70	0.850	0.578	32.1	1.41	6.52	13.9	(Dontriros et al., 2020)
2.1	0.4	0.8	45.3	1.2	8.2	9.9	(Wang & Fan, 2020)
3.43	0.8	0.78	41.1	1.14	6.63	13.0	(Zhan et al., 2021)
4.17	0.97	1.05	44.4	1.08	5.13	10	(Liu et al., 2021)
3.23	1.58	-	44.02	1.33	-	-	(Geng et al., 2020)
12.2	4.26	12	32.4	2.28	0.88	0.47	(Nikravan et al., 2020)
53.82	14.18	6.18	14.44	3.26	2.52	2.24	(Huang et al., 2020)
6.73	2.43	2.18	37.11	-	7.05	6.94	(Ma et al., 2019)
10.16	7.19	6.53	29.63	1.67	1.08	0.93	(Caprai et al., 2019)
15.8	0.9	4.2	38.1	3.5	7.3	0.2	(Wongsa et al., 2017)
19.122	12.037	9.313	43.115	2.116	0.848	2.359	(Gao et al., 2017)
5.39	2.51	1.14	51.95	2.29	4.19	5.26	(Wang et al., 2018a)
12.13	1.91	3.86	51.84	0.91	-	-	(Mao et al., 2020)

4.3 Analysis of Different Municipal Wastes and Their Types

MSW's engineering properties are primarily determined by the level of deterioration and the waste's initial composition. MSWs usually contain a high proportion of kitchen waste in developing countries, called HKWC MSW (Zhan et al., 2018). Waste is characterized as discarded and unfit-for-use material. Garbage is termed waste that comes into people's daily lives. Waste from schools, offices, and other public buildings (municipal waste) and industries and factories (industrial waste) is a form of solid waste that includes waste from people's homes (domestic waste) (Liu et al., 2019a). The four categories of waste sources are agricultural, domestic, commercial, and industrial.

- Industrial waste: This waste is generated in factories and industries. Most factories spill their waste into rivers and seas, causing significant pollution.
- Commercial waste: Schools, universities, stores, and offices generate commercial waste.
- Domestic waste: Domestic waste is the various home waste obtained during cooking, washing, and other household chores.
- Agricultural waste: Agricultural waste refers to various wastes produced in the agricultural sector.

The oxygen source in incineration applications is air, and fuel is mostly waste, though fossil fuels can be co-fired. Most stable end products are produced by burning, whether the fuel is wood, natural gas, coal, oil, municipal and medical waste, or radioactive waste. One of the earliest types of construction materials is burnt clay tile. The high carbon footprint reduces the usage of recycled materials. Li et al. (2018) found that FA was utilized to make the bricks (a coal by-product) and traditional earthen materials and the coal power plant provided the FA. Waste eradication is the world's most pressing environmental issue. Landfill sites are scarce to a large extent in the world. As a result, dumping waste pollutes the atmosphere and puts a strain on the planet. Pak Bricks Company provided the clay in Multan (Pakistan) for the analysis by Abbas et al. (2017).

A local coal-fired power station provided the FA for this project. During the research, no refining was done on the clay and FA, which are raw materials. Sieve analysis, chemical analysis, and XRD were used to determine the chemical and mineralogical characterization of FA and clay ash. Kaur et al. (2019) discussed the strength properties of concrete and presented the impact of ash from biomedical waste incineration as an acceptable aggregate substitute. Gao et al. (2021) presented the concrete's performance in terms of strength and durability. The experiment's outcome shows that using partial sand (5%) of Incinerated Biomedical Waste Ash (IBWA) substitute improved the strength of concrete. Up to the age of 56 days, compressive and break tensile strength tests and water absorption, rapid chloride penetrability test (RCPT), and sorptivity, including leachate analysis test, were conducted. The findings revealed that it was not hazardous for the TCLP test.

Tang et al. (2020) developed cold-bonded lightweight aggregates (CBLAs) of 100% wt. solid wastes, such as concrete slurry waste (CSW) and ISSA, to recycle MSW as a secondary resource. This included deciding the viability of implementing ISSA in CBLAs and its impact on thermal stability. Rissler et al. (2020) investigated the impact of using calcium sulphate whiskers (CSW) as another option for OPC as a binder, calculated the advantages of CO_2 curing over steam curing and assessed the effects of adding waste wood fine (WWF) to CBLAs on their characteristics. Higher water absorption values and lower bulk densities result from the addition of wood fine (WF) to CBLA’s increased porosity.

4.4 Usage of Important Waste Materials for Improving Expansive Soil Properties

The public faces weak soil, leading to substantial economic losses and significant structural and infrastructural damage. Soil enhancement is one of the most essential strategies for increasing ground strength and reducing the swells of expansive soils. This has been implemented in various vital ways, i.e., chemical and mechanical enhancement. Various mechanical approaches have been put forward, including surcharge imposition, limestone, waste stabilization, pre-wetting, compaction control, and water content management, to improve expanding soil qualities. Khazaei & Moayedi (2019). highlighted the potential of employing petrochemical waste as a stabilizer. The petrochemical process of water softening supplied the wastes. Building on expansive soils has produced issues for civil engineering projects worldwide, such as reservoirs, foundations, roads, and trains. Improving expansive soils, especially for road development, is so vital.

For this investigation, Blayi et al. (2020) studied enhancing the strength of different soil types by adding additional material and waste glass powder (WGP). The WGP was pulverized and blended in different percentages: 2.5, 5, 10, 15, and 25% with a soil sample by dry soil weight. Waste tire textile fibers (WTTFs) are toxic waste substances, usually burnt per international law, as a by-product of the treatment procedure for end-of-life tires (ELTs). The rising demand for tires and automobiles puts high environmental burdens on disposing of WTTFs primarily for two reasons: i) they consume huge precious areas in sites, and ii) trying to burn them leads to harmful gas emissions. To examine the viability of the re-use of WTTFs, Narani et al. (2020) examined an immense amount of soil using a large selection of laboratory experiments, i.e., volumetric shrinking, desiccation cracking testing, swelling-consolidation, standard compacting, and split tensile strength (STS). Based on the results, all expansive soil's geotechnical qualities can be enhanced by WTTFs.

5. Critical Variables of the Soil Stabilization Process

Significant stabilizing aspects, like dosage, materials processing, curing conditions, etc., have been examined, and a significant comparison between cement and quicklime use recommendations has been developed. There have also been recognized demands for further research and specific recommendations. The stabilizer requirement to obtain a desired level of stability is thus virtually defined in its fundamental properties, making it a main parameter (Verbinnen et al., 2017). Based on the pH of the soil, lime, and water mixes, a method was devised to calculate the lime amount that can sufficiently supply the required quantities of calcium. A constant soil weight (with a dry oven) and water amount (150 ml) were utilized in this test, with varying lime quantities ranging from 2% to 6% in increments of 1%. In an hour, the pH of such combinations of the soil-lime was measured and was deemed appropriate for the stability of the soil under study to be the minimum lime that offers a 12.4 pH measure (an additional lime dose is also allowed in this test when it isn't possible to accomplish the required pH). The test is typically used since it is straight-forward, comfortable, fast, and cheap.

5.1 Influence of Stabilizers on Geotechnical Characteristics of Soil

Soil modification is one of the geotechnical engineering approaches for soil improvement. Lime and cement stabilization in recent years are also two of the most popular approaches of geotechnical engineers, as demonstrated by Amini & Ghasemi (2019). Using lime and cement to stabilize soils is one of the approaches to improve and enhance the strength characteristics of soils in a naturally and practically trustworthy way. Cement-stabilized soil consists of fine-grained and coarse compounds fused to generate a rigid and hard mass by the stabilizing agent. Concrete and asphalt floors often have a stable bed in cement. In base and sub-base applications, these materials can boost the soil's capacity for bearing. Yadav & Tiwari (2017) emphasized that some geotechnical properties of cemented clay are affected by the incorporation of discarded rubber tire fibers. The study examined the cement with three percentages (0%, 3%, and 6%) and the rubber fibers with five percentages (0%, 2.5%, 5.0%, 7.5%, and 10%). Compaction, wet/dry cycles durability, unconfined compressive power, swelling pressure, CBR, STS, and SEM were conducted for the mixture of clay-cement-rubber and fiber to assess the suitability of rubber fibers with cement-stabilized clay.

The test findings showed that the integration of rubber fibers decreases the compressive strength of unrestricted cement-stabilized clay but successfully increases its rate, and the fragile failure solidified clay's behavior into a ductile. The outcomes of the bearing test in California have shown that resistance to cement-reinforced clay penetration diminishes with a rise in rubber fiber content. Momeni et al. (2020) tried to analyze the impacts of acidic and alkaline waters, with pH values changing between 3 and 8, on the geotechnical characteristics of a specific type of low-plastic clay in the north eastern parts of Isfahan. Maldonado-Alameda et al. (2021) arranged the remodeled specimens in moulds with various pH values and years of deposition under the influence of acidic and alkaline rains. The soil mechanical alterations relative to soil with neutral acidity were assessed through UCS, CBR testing, soil permeability coefficient, and Atterberg limits testing of specimens with different pH values. The SEM and pH-drainage testing of samples was done for internal structural mechanisms of soil during the artificial harvesting of the samples.

5.2 Effect of Types of Soils on the Stabilization Process

Oliveira et al. (2017) studied the effect of soil type on the $CaCO_3$ precipitation method. To assess the effects on strength and rigidity, based on the outcomes from UCS, scanning tests, and SEM examinations, this methodology was evaluated for five types of soils (poor-grade sand, two silty sands, a soil, and an organic soil). The UCS test results indicated that $CaCO_3$ precipitation by enzymes in sandy and silty soils boosted the soil, while a damaging effect was achieved in organic soil. The SEM examination revealed the presence of traces of calcium in all of the soils, indicating that $CaCO_3$ precipitation occurs with a varying effect on soil strength for each type of soil. The main reasons for the bio-stabilization process' inefficiency are the combined organic soil's low pH value and dirt particles with an organic covering indicated in the result.

Clayey soils become rigid once dry, but they lose their stiffness after becoming moist. Soft clays are well-known for their small compacting strength and rapid settlement. Buildings and foundations suffer significant damage and loss of strength due to moisture. The actions of the soil make it tougher for the builder to construct infrastructure on such clays. The damage caused by vast soils is estimated to be $1 billion in the United States, £150 million in the United Kingdom, and several billion pounds worldwide every year, as reported by Firoozi et al. (2017). The losses due to expansive soils are due to the failure to recognize the presence and extent of these soils' growth during the beginning stages of project planning instead of the lack of appropriate engineering solutions. The other significant impacts of soil-cement stabilization include decreased shrinking and swelling potential, increased strength, elastic module, moisture, freezing, and thawing resistance. Soils treated with cement display better behavior than soils that have not been treated. Cement can be placed except for soils in organic matter that are more significant than 2% or have a pH lower than 5.3 to stabilize the soil. Cement in granular soils has proved cost-effective because a minor quantity of cement is needed for stabilization (Tang et al., 2017).

6. Experimental Analysis of Expansive Soil Stabilization Using MSWI Ash

The mass of MSW is reduced by 70%, and volume is reduced by 90% during incineration. The BA makes up 75-80% of the total residue after incineration of MSW, and FA and BA are the two types of ashes produced. BA is usually hazardous-free and may be utilized in several applications in civil engineering, such as road building, cement and glass production, and embankments, among others, whereas FA is hazardous. Oxides of calcium, silicon, iron, and aluminium comprise 70-80% of MSWI ash. These pozzolanic oxides may be used in civil engineering projects and cement production. The variations in chemical properties of MSWI ash, as examined by different authors, contribute to the quality and nature of MSW and burning procedures. The technical features of expansive soils, as assessed by experts in the literature, are almost similar. In several experiments, MSWI ash content utilized as a stabilizing agent ranged from 0% to 50%. MSWI ash was determined to have an optimal effective content between 10% and 30%. The expansive soil's UCS improves from 28.8kPa to 53.4kPa with 25% ash content in the mixture of expansive soil, and the CBR value improves from 3.38% to 9.38%.

The most effective techno-economic route for managing MSW has been revealed to be the incineration of MSW and its usage in several civil engineering works. Without causing any environmental issues, it helps to dispose of vast quantities of MSW and its reuse using ash for soil stabilization. The MSWI ash quantity used to substitute cement can be increased up to 75% without affecting the mix's strength. In various civil engineering projects, MSWI ash must be used extensively. The number of MSWI ash plants is limited in India. There are no such plants in some major cities and even some states. Along with other WtE plants, there are 92 MSWI ash plants. The large-scale implementation of this technique canexpedite the efficient disposal of massive amounts of MSW produced each year while posing no environmental risk. During the operation, electricity can be generated as well. Most research on soil stabilization has used thermal power plants' ashes, but few studies have used MSWI ash. Therefore, MSWI ash usage mixed with other additives was also investigated for soil modification and reinforcement.

6.1 Test Method Standards of Indian BCS and MSWI Ash

One of the most challenging materials to work with is BCS. Although several empirical relations exist, they cannot be generalized to all terrains and places where the characteristics of BCS are evaluated.

6.1.1 Testing of BCS

UCS experiments were performed on lime-treated and untreated BCS in compliance with IS 2720-Part 10 for 0, 7, 14, and 28 days of curing time, and lime content of 0%, 5%, 7%, and 9% was mixed with soil. The effect of increased curing time and lime on UCS was studied. The soil's strength increases dramatically by adding lime to BCS. The compactive effort applied to the soil differs between the two forms of compaction. The energy compaction for British Standard Heavy (BSH) was weighed with a 4.5 kg hammer, which fell freely of five compacted layers by 45 cm, each receiving 27 blows. Three compacted soil layers were used to test the British Standard Light (BSL) compaction effort, each enduring 27 equally spaced blows from a 2.5 kg hammer dropped freely across 30 cm. A 1000 cm^3 mould was used for both compactions, with a mix of additives, soil samples, and water laid out, stacked, and compressed within the mould.

The BS 1377 technique was employed to measure the CBR, an index of soil strength and bearing force. CBR was measured for both unsoaked and soaked soils after compaction. The soaked samples were immersed in water for 96 hours. After that, the compressed mixture was fed into the CBR machine with a 1.25 mm/min penetration rate. The load values for penetrations ranging from 0.0 mm to 12.5 mm were reported wherever applicable. Differential free swell (DFS), called the FSI, is one of the three parameters used to classify expansive soils. Pore fluids of kerosene or carbon tetrachloride (CCl_4) and water compare the volume changes in an expansive soil. A non-polar liquid (kerosene) was contained in the 100 cm^3 graduated glass cylinder and left undisturbed for 24 hours, and two 10 gm sieved sample specimens were taken and poured into two cylinders containing water and kerosene oil. Volumes of soil were measured after 24 hours, and the DFS was determined using Eq. (1) (Ikeagwuani et al., 2019). The DFS values can be linked using the relation to determine the degree of expansiveness. The correlation utilized to define the DFS values is proportional to the degree of expansiveness, which is described as follows:

$$DFS = \frac{Soil\ Volume\ in\ Water\ -\ Soil\ Volume\ in\ Kerosene}{Soil\ Volume\ in\ Kerosene} \times 100 \quad (1)$$

BSL compaction had an optimal moisture content of 38% with a maximum of 1.31 gm/cm^3 dry density. BSH had 30% optimum moisture content, with a dry density maximized as 1.49 gm/cm^3. The compaction effort curve of the BSH was steeper than the BSL. The amount of water necessary for the compaction of BSH was similarly lower than the overall dry density required for the compaction of BSL. Because of this, the higher the compaction effort, the sooner the air is ejected from the vacuum of the soil, and the more compression is obtained, which is consistent with previous trends. This also needs less water for soil lubrication.

6.1.2 Testing of MSWI ash

The following tests were conducted on MSWI ash (Reddy et al., 2018).

• Specific gravity test: To assess the use of the geotechnical aspect of MSWI ash, specific gravity is an essential physical property. Following IS 2720 (Part-3)-1980, the test was performed. MSWI ash had a specific gravity of 2.2, consistent with previous studies, as the specific gravity of MSWI BA changed from 1.1 to 2.7.

• XRD test: The XRD analysis is a material science technology used to determine a material's crystallographic form. XRD is a method of estimating the intensities and scattering angles of X-rays that exit a sample after they have been irradiated with incoming X-rays.

The test was performed to find the mineralogy of a material. It determines the mineral content in MSWI ash. Figure 4 depicts the predominant presence of SiO_2 and Al_2O_3 in MSWI ash, as denoted by *Q* and *C*. This is indicated by the diffraction image's most substantial peaks of such minerals. Due to the stabilization of BCS, a comparative summary of the mineralogical changes occurred. A pozzolanic reaction, aiming at a three- to seven-day setting interval, is caused by 16% saw dust ash (SDA) and 4% lime in the BCS. There were also aluminum, standard CSH, and magnesium-integrated CSH stages. Since the hydrate of zinc phosphate is a popular cementer, phlogopite [KMg_3 (Si_3al) O_{10} $(OH)_2$] is a micro-mineral. Another result is that the montmorillonite mineral collapses on the seventh day of curing.

a) SEM test: SEM is a research method that involves scanning a sample with an electron beam and analyzing the magnified signal. When lime was added to the mix at a rate of 2%, flocculation began, and at 4% and 6% of lime addition, agglomeration and flocculation became entirely apparent. BCS, BCS + 16% SDA + 2% lime, BCS + 16% SDA + 4% lime, and BCS + 16% SDA + 6% lime had pore areas of 2180.18 lm^2, 557.51 lm^2, 210.65 lm^2, and 431.41 lm^2, respectively, according to a study using the SEM machine. Due to flocculation and agglomeration, the pore spaces in the stabilized soil are much narrower than the average BCS. Compaction, Atterberg's limits, natural gravity, and CBR effects are all examples of this. The highest value was obtained by combining BCS + 16% SDA + 4% lime. Since pozzolanic reactions had not begun at this stage, the 6% lime addition yielded lower strength gains than the 4% lime addition.

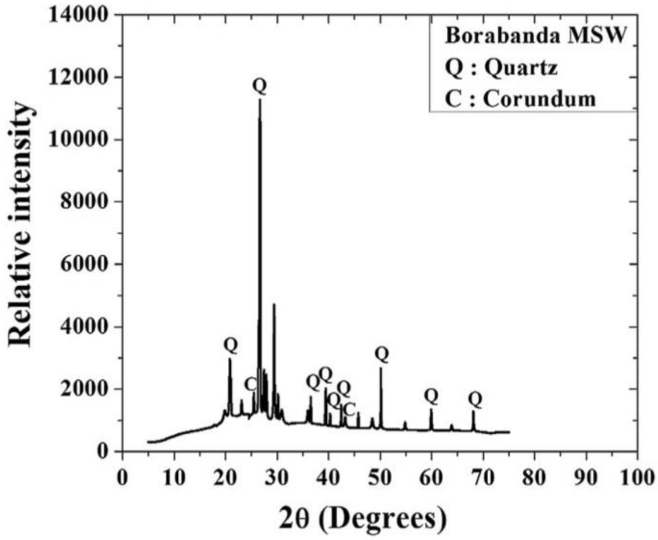

Figure 4. XRD pattern for MSWI ash (Reddy et al., 2018)

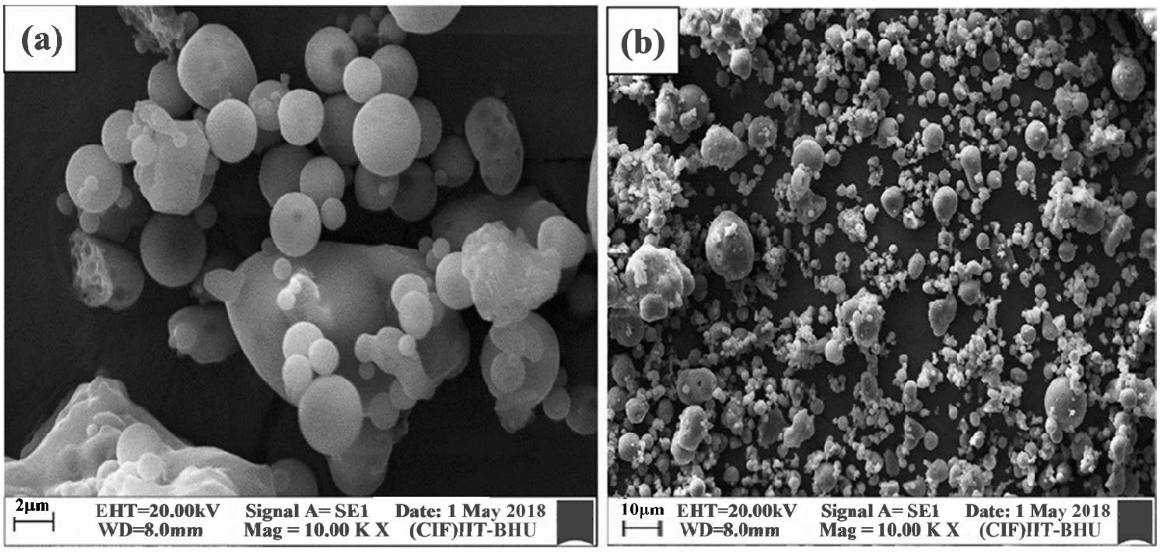

Figure 5. SEM analysis of MSW particle, a) 10.00Kx, b) 1.00Kx (Reddy et al., 2018)

This examination was employed to determine the morphology of MSWI ash. The SEM examination for this study took place in Varanasi. After passing it through a 75-micrometer sieve, a specimen of one gm of municipal waste was used. The test was completed, and the specimen was then positioned in the SEM machine's vacuum chamber. A beam of primary electrons was used to scan the sample's surface, and images were collected using a beam of secondary electrons, which were emitted from the MSW sample and portrayed the MSW sample's morphology. MSWI ash particles were revealed to be circular in form and smooth in texture, as depicted in Figure 5. The research used an SEM with a 20 kV EHT voltage system at different magnification levels.

b) Energy Dispersive X-ray (EDX) Test: The EDX, also known as EDS or EDAX, employs X-rays to determine the elemental composition of materials. EDX and SEM are different methods. SEM produces precise, high-resolution images of the sample by focusing an electron beam around the surface and detecting backscattered or secondary electron signals.

The EDX method generates spectra depicting peaks corresponding to the elements that make up the actual composition of the sample under investigation. MSWI ash's chemical composition was determined in this study. Oxygen (O), silicon (Si), iron (Fe), potassium (K), carbon (C), aluminium (Al), and calcium (Ca) were revealed in the ash as per Figure 6.

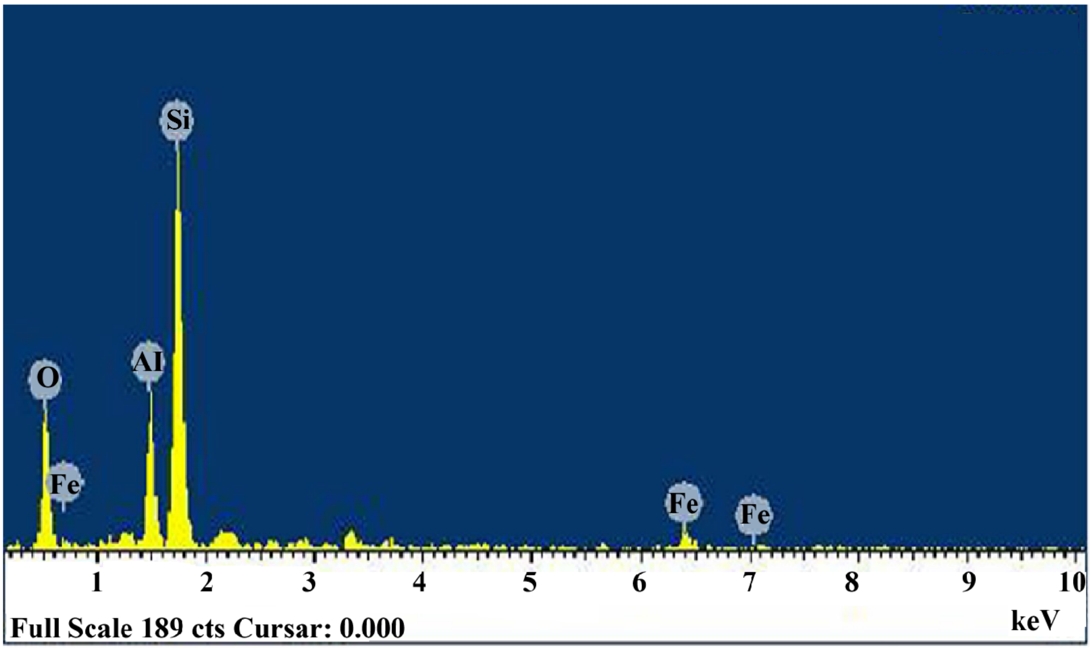

Figure 6. EDX diagram of MSW (Reddy et al., 2018)

c) CBR test: A penetration measure that defines the frequency of the pavements and road subgrade is the CBR. A conventional piston with a diameter of 50 mm (1.969 inches) penetrates at a rate of 1.25 mm/minute in the soil in this penetration test. For the BSH and BSL standard compaction efforts, the CBR values after being soaked were 4.0% and 5.98%, respectively. The CBR values for the BSH and BSL standard compaction efforts were 9.2% and 11.4%, respectively, using a load that corresponded to a penetration depth of 2.5 mm.

d) UCS test: This test depicts the laboratory test determining a rock specimen's UCS. The highest axial compressive force that a sample can withstand under no confining stress is known as UCS. A version of the unconfined compression test is the uni-axial compression test when stress is applied to the longitudinal axis. UCS is a commonly used parameter in geotechnical design but does not accurately represent in-situ pressure. Discontinuities, faults, and weathering, among other factors, significantly affect the rock mass resources on a large scale.

7. Research Problem Definition and Motivation

Agriculture, household operations, domestic and industrial activities, construction, demolition, and other industries generate enormous waste worldwide. These wastes are dangerous and pose significant environmental concerns due to the existence of radioactive substances. Some of these wastes are used in structural engineering applications, which include landfilling, soil stabilization, and embankment construction, among others, which help to mitigate these problems. Many studies have looked into the geotechnical activity of pond ash. FA is a waste by-product generated when pulverized coal is burnt in power plants. One of the critical challenges in rural and urban settings in recent years has been trash disposal in a safe manner, such as municipal waste, manufacturing, and harmful waste. Since some of the waste is not biodegradable, it causes contamination in the surrounding disposal area. MSWI is a common way to reduce the waste volume that must be inclined in a landfill. Some researchers have discovered that MSWI ash can be used for geotechnical purposes such as aggregate in road building, embankment construction, and landfill construction. The ash from MSWI is also combined with soils, lime, cement, or concrete to enhance the finished product's physical qualities. MSWI ash is used in geotechnical systems to address various geo-environmental problems and issues. The incorporation of cement only aids in absorbing heavy metals because of water's high alkalinity. Researchers have used physicochemical parameters as a driving media for amending the properties of end products.

8. Current Research Trends and Developments

Several research initiatives are ongoing in the Strategic Initiative Materials program, which strives to improve a toolbox for separating usable derivatives from waste and utilizing them in building construction. Urban solid waste incineration ashes utilized to create new cement and construction materials are dealt with by the ASHCEM project using a SUPER Metal Extractor. While the Sustainable Metal Extraction from Tailings (SMART) technique develops a tool for extracting metals from tailings, the SUPERMEX project investigates the long-term transformation of fresh and landfilled solid industrial waste. After studying heavy metal leaching, it was discovered that the carbonation had accelerated after four weeks and Cu leaching was under control. Due to the high humidity of the stack gas being described as the main impediment to its use, rapid carbonation with condensate forming was also carried out using the gas from the stack of incinerator. The Revasol method was designed to make MSWI ashes non-hazardous and fit for use by reducing soluble material and the leachable content of heavy metals, as well as destroying persistent organic pollutants (POPs).

9. State-of-the-Art Survey

The engineering characteristics of expansive soil and MSWI ash were used in this analysis. BCS is a dense clay soil with a light to dark grey color and consistency that ranges from clay to loam. Cotton thrives in this kind of environment. When lime is applied to BCS, a pozzolanic reaction occurs, resulting in stabilization. The hydrated lime interacts indefinitely with the clay particles. Table 4 summarizes the experimental outcome of the survey.

Table 4. State-of-the-art survey

S. No	Author	Objective	Findings
1	Baruah et al. (2020)	An experimental study of the effects of various percentages of MSWI ash on the UCS of clay.	A potential increase in soil strength confirmed that the ash can strengthen the MSWI field.
2	Kumar et al. (2017)	When the expansive soils are used for building, they must be stabilized. The expansive soil properties are discussed in this regard.	A sample of expansive soil containing 30% copper slag stabilized with FA at 2% intervals up to 10%, and findings were subjected to regression analysis.
3	Singh & Kumar (2017a)	MSWI ash and cement mix specimens were subjected to some tests, i.e., UCS, CBR, STS, and pH tests.	Embankments and road construction are the variety of structures where lightweight filler MSWI ash and cement are used.
4	Batari et al. (2017)	The outcome of laboratory studies on bagasse ash as a cement-stabilized blend of BCS is presented in the study.	5% ash with 8% cement as a sub-base in compact pavement construction is recommended in this report.
5	Sefene (2021)	To identify the best wood-ash proportion for stabilizing BCS and to assess the soil sample's different geotechnical properties.	The optimum wood-ash content for stabilizing BCS is 10% - 15% of the soil mass, with a preference for results between 13% - 15%.
6	Selvaraj et al. (2020)	By weight of the mix of dry soil, 8%, 12%, 16%, and 20% crystalline silica were mixed into the BCS. The quality of the mixture was tested experimentally to determine UCS, CBR, and the standard proctor compaction test.	The study suggests that using crystalline silica as an admixture to stabilize BCS has much potential. The use of crystalline silica can benefit the environment as well as construction costs.
7	Rawayau et al. (2019)	The potential for BCS stabilization by bauhinia thinning fruit ash (BTFA) was investigated using XRF testing while cooling and sieving via a regular 75µm sieve.	Based on these findings, BCS treated with BTFA is suitable for use as a sub-grade material in road building, with a content of 10% being ideal.
8	Goel & Kalamdhad (2017)	The use of degraded MSW as fuel in fire brick components with alluvial and lateritic soil in varying proportions varying between 5 to 20%.	20% addition of depleted MSW would result in an 8% net reduction in external fuel consumption.
9	Chhabra et al. (2019)	To investigate the interactions between different components and to calculate the combined kinetic parameters, urban solid waste pyrolysis, and the TG analysis were applied. Thus, kinetic parameters changed due to the interaction of the components.	Maximum synergistic relations had a detrimental influence on biomass and plastic mixture pyrolytic disintegration behaviors, respectively, for a 0.9 and 0.95 overlap scale.

10. Review Summary/Conclusions

- Incineration of MSW reduces its mass and volume by 70% and 90%, respectively, and BA constitutes 75-80% of total residual waste, and the remainder is FA.
- BA, being non-hazardous, is fit for use in different civil engineering activities, e.g., cement and glass manufacture, road building, embankments, etc., but FA is toxic.
- The significant constituents (70-80%) of MSWI ash are oxides of calcium, silicon, iron and aluminum. Being pozzolanic, these are suited for various civil engineering applications, including cement manufacturing.

• Various studies on the chemical composition of MSWI ash depict slightly varying results due to the different compositions of MSW and incineration techniques.

• The maximized proportion of MSWI ash for soil stabilization varies between 10% and 30%. Adding 25% MSWI ash by weight of weak soil enhances the UCS of soil from 28.8kPa to 53.4kPa. An increase from 3.38% to 9.38% was also observed in CBR value.

• The incineration of MSW helps to manage large volumes of this waste judiciously, and its residue can be reused for soil stabilization.

• Stabilization through lime and cement is a costly affair. MSWI ash replaces these costly materials up to 75% without losing strength.

• Using the MSWI technique on a large scale can greatly facilitate the disposal of the vast quantities of MSW generated annually worldwide.

Most studies on soil stabilization are based on thermal power plant ashes, whereas there are fewer studies on using MSWI ash. There is a scope for further studies to evaluate the use of MSWI ash after mixing it with other additives for the stabilization and reinforcement of soil.

Data Availability

The datasets generated during and/or analyzed during the current study are available in the present work.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

References

Abbas, S., Saleem, M. A., Kazmi, S. M., & Munir, M. J. (2017). Production of sustainable clay bricks using waste fly ash: Mechanical and durability properties. *J. Build. Eng.*, *14,* 7-14. https://doi.org/10.1016/j.jobe.2017.09.008.

Abdullah, H. H. & Shahin, M. A. (2023). Geomechanical properties of clay stabilised with fly ash-based geopolymer subjected to long-term sulfate attack. *Int. J. Geosynth. Ground Eng.*, *9*(6), 75. https://doi.org/10.1007/s40891-023-00493-4.

Alam, Q., Schollbach, K., van Hoek, C., van der Laan, S., de Wolf, T., & Brouwers, H. J. H. (2019). In-depth mineralogical quantification of MSWI bottom ash phases and their association with potentially toxic elements. *Waste Manag.*, *87*, 1-12. https://doi.org/10.1016/j.wasman.2019.01.031.

Al-Mohammedi, A. A. S. & Seyedi, M. (2023). Enhancing geotechnical properties of clayey soil with recycled plastic and glass waste. *Rev. Compos. Mater. Avanc.*, *33*(6), 363-369. https://doi.org/10.18280/RCMA.330603.

Amini, O. & Ghasemi, M. (2019). Laboratory study of the effects of using magnesium slag on the geotechnical properties of cement stabilized soil. *Constr. Build. Mater., 223,* 409-420. https://doi.org/10.1016/j.conbuildmat.2019.07.011.

Assi, A., Bilo, F., Zanoletti, A., Ponti, J., Valsesia, A., La Spina, R., Zacco, A., & Bontempi, E. (2020). Zero-waste approach in municipal solid waste incineration: Reuse of bottom ash to stabilize fly ash. *J. Clean. Prod.*, *245,* 118779. https://doi.org/10.1016/j.jclepro.2019.118779.

Baruah, D., Goel, S., Gupta, C., & Sahu, A. K. (2020). Ground improvement using municipal solid waste ash. *In Advances in Sustainable Construction Materials and Geotechnical Engineering: Select Proceedings of TRACE 2018,* 271-280. https://doi.org/10.1007/978-981-13-7480-7_25.

Batari, A., Chinade, A. U., Saeed, S. M., Ikara, I. A., Kabir, N., & Mamuda, A. (2017). Effect of bagasse ash on the properties of cement stabilized black cotton soil. *Int. J. Transp. Eng. Technol.*, *3*(4), 67-73. https://doi.org/10.11648/j.ijtet.20170304.14.

Behnood, A. & Olek, J. (2020). Full-scale laboratory evaluation of the effectiveness of subgrade soil stabilization practices for Portland cement concrete pavements patching applications. *Transp. Res. Rec.: J. Transp. Res. Board.*, *2674*(5), 465-474. https://doi.org/10.1177/0361198120916476.

Blayi, R. A., Sherwani, A. F. H., Ibrahim, H. H., Faraj, R. H., & Daraei, A. (2020). Strength improvement of expansive soil by utilizing waste glass powder. *Case Stud. Constr. Mater.*, *13*, e00427. https://doi.org/10.1016/j.cscm.2020.e00427.

Caprai, V., Gauvin, F., Schollbach, K., & Brouwers, H. J. H. (2019). MSWI bottom ash as binder replacement in wood cement composites. *Constr. Build. Mater.*, *196*, 672-680. https://doi.org/10.1016/j.conbuildmat.2018.11.153.

Caprai, V., Schollbach, K., & Brouwers, H. J. H. (2018). Influence of hydrothermal treatment on the mechanical and environmental performances of mortars including MSWI bottom ash. *Waste Manag.*, *78*, 639-648. https://doi.org/10.1016/j.wasman.2018.06.030.

Chang, I. & Cho, G. C. (2019). Shear strength behavior and parameters of microbial gellan gum-treated soils: from sand to clay. *Acta Geotech.*, *14*, 361-375. https://doi.org/10.1007/s11440-018-0641-x.

Chavali, R. V. P. & Reshmarani, B. (2020). Characterization of expansive soils treated with lignosulfonate. *Int. J. Geo-Eng.*, *11*(1), 17. https://doi.org/10.1186/s40703-020-00124-1.

Chen, L., Wang, L., Cho, D. W., Tsang, D. C., Tong, L., Zhou, Y., Yang, J., Hu, Q., & Poon, C. S. (2019a). Sustainable stabilization/solidification of municipal solid waste incinerator fly ash by incorporation of green materials. *J. Clean. Prod.*, *222*, 335-343. https://doi.org/10.1016/j.jclepro.2019.03.057.

Chen, L., Wang, Y. S., Wang, L., Zhang, Y., Li, J., Tong, L., Hu, Q., Dai, J. G., & Tsang, D. C. (2021). Stabilisation/solidification of municipal solid waste incineration fly ash by phosphate-enhanced calcium aluminate cement. *J. Hazard. Mater.*, *408*, 124404. https://doi.org/10.1016/j.jhazmat.2020.124404.

Chen, P., Zheng, H., Xu, H., Gao, Y. X., Ding, X. Q., & Ma, M. L. (2019b). Microbial induced solidification and stabilization of municipal solid waste incineration fly ash with high alkalinity and heavy metal toxicity. *PloS ONE*, *14*(10), e0223900. https://doi.org/10.1371/journal.pone.0223900.

Chen, Z., Tang, X., Zhao, H., Zhou, Y., & Liu, R. (2023). A compact system for accurate measurement of true stress-strain curves in transparent materials subject to extensive deformation. *Measurement*, *223*, 113799. https://doi.org/10.1016/j.measurement.2023.113799.

Chhabra, V., Bhattacharya, S., & Shastri, Y. (2019). Pyrolysis of mixed municipal solid waste: Characterisation, interaction effect and kinetic modelling using the thermogravimetric approach. *Waste Manag.*, *90*, 152-167. https://doi.org/10.1016/j.wasman.2019.03.048.

Chu, C., Zhan, M., Feng, Q., Li, D., Xu, L., Zha, F., & Deng, Y. (2020). Effect of Drying-Wetting Cycles on Engineering Properties of Expansive Soils Modified by Industrial Wastes. *Adv. Mater. Sci. Eng.*, *2020*(1), 5602163. https://doi.org/10.1155/2020/5602163.

Dang, L. C., Khabbaz, H., & Fatahi, B. (2017). An experimental study on engineering behaviour of lime and bagasse fibre reinforced expansive soils. *In ICSMGE 2017-19th International Conference on Soil Mechanics and Geotechnical Engineering*, 2497-2500.

Dontriros, S., Likitlersuang, S., & Janjaroen, D. (2020). Mechanisms of chloride and sulfate removal from municipal-solid-waste-incineration fly ash (MSWI FA): Effect of acid-base solutions. *Waste Manage.*, *101*, 44-53. https://doi.org/10.1016/j.wasman.2019.09.033.

Du, B., Li, J., Fang, W., Liu, Y., Yu, S., Li, Y., & Liu, J. (2018). Characterization of naturally aged cement-solidified MSWI fly ash. *Waste Manage.*, *80*, 101-111. https://doi.org/10.1016/j.wasman.2018.08.053.

Firoozi, A. A., Guney Olgun, C., Firoozi, A. A., & Baghini, M. S. (2017). Fundamentals of soil stabilization. *Int. J. Geo-Eng.*, *8*, 26. https://doi.org/10.1186/s40703-017-0064-9.

Frouz, J. (2018). Effects of soil macro-and mesofauna on litter decomposition and soil organic matter stabilization. *Geoderma*, *332*, 161-172. https://doi.org/10.1016/j.geoderma.2017.08.039.

Funari, V., Gomes, H. I., Cappelletti, M., Fedi, S., Dinelli, E., Rogerson, M., Mayes, W. M., & Rovere, M. (2019). Optimization routes for the bioleaching of MSWI fly and bottom ashes using microorganisms collected from a natural system. *Waste Biomass Valoriz.*, *10*, 3833-3842. https://doi.org/10.1007/s12649-019-00688-9.

Gao, J., Dong, C., Zhao, Y., Xing, T., Hu, X., & Wang, X. (2021). Effect of B2O3 on the melting characteristics of model municipal solid waste incineration (MSWI) fly ash. *Fuel*, *283*, 119278. https://doi.org/10.1016/j.fuel.2020.119278.

Gao, N., Sipra, A. T., & Quan, C. (2020). Thermogravimetric analysis and pyrolysis product characterization of municipal solid waste using sludge fly ash as additive. *Fuel*, *281*, 118572. https://doi.org/10.1016/j.fuel.2020.118572.

Gao, X., Yuan, B., Yu, Q. L., & Brouwers, H. J. H. (2017). Characterization and application of municipal solid waste incineration (MSWI) bottom ash and waste granite powder in alkali activated slag. *J. Clean. Prod.*, *164*, 410-419. https://doi.org/10.1016/j.jclepro.2017.06.218.

Gayatri, A. & Verma, A. K. (2020). Geotechnical characterization of expansive soil and utilization of waste to control its swelling and shrinkage behaviour. In *In Recent Developments in Waste Management: Select Proceedings of Recycle 2018* (Vol. 57, pp. 11-21). https://doi.org/10.1007/978-981-15-0990-2_2.

Geng, C., Liu, J., Wu, S., Jia, Y., Du, B., & Yu, S. (2020). Novel method for comprehensive utilization of MSWI fly ash through co-reduction with red mud to prepare crude alloy and cleaned slag. *J. Hazard. Mater.*, *384*, 121315. https://doi.org/10.1016/j.jhazmat.2019.121315.

Ghadir, P. & Ranjbar, N. (2018). Clayey soil stabilization using geopolymer and Portland cement. *Constr. Build. Mater.*, *188*, 361-371. https://doi.org/10.1016/j.conbuildmat.2018.07.207.

Goel, G. & Kalamdhad, A. S. (2017). Degraded municipal solid waste as partial substitute for manufacturing fired bricks. *Constr. Build. Mater.*, *155*, 259-266. https://doi.org/10.1016/j.conbuildmat.2017.08.067.

Gou, H., Sofi, M., Zhang, Z., Zhu, H., Zhu, M., & Mendis, P. (2023). Durability development of lightweight and high-strength engineered cementitious composites subject to combined sulfate–chloride attack under freeze–thaw cycles. *Constr. Build. Mater.*, *408*, 133659. https://doi.org/10.1016/j.conbuildmat.2023.133659.

GuhaRay, A., Mei, G. X., Sarkar, A., Bordoloi, S., Garg, A., & Pattanayak, S. (2019). Geotechnical and chemical characterization of expansive clayey soil amended by biochar derived from invasive weed species Prosopis Juliflora. *Innov. Infrastruct. Solut.*, *4*, 44. https://doi.org/10.1007/s41062-019-0231-2.

Hataf, N., Ghadir, P., & Ranjbar, N. (2018). Investigation of soil stabilization using chitosan biopolymer. *J. Clean. Prod.*, *170*, 1493-1500. https://doi.org/10.1016/j.jclepro.2017.09.256.

Horn, R., Fleige, H., Dörner, J., Zimmermann, I., & Wendroth, O. (2025). Pore rigidity as an undervalued process in soil structure development. *Soil Till. Res.*, *245*, 106280. https://doi.org/10.1016/j.still.2024.106280.

Hu, Y., Yang, F., Chen, F., Feng, Y., Chen, D., & Dai, X. (2018). Pyrolysis of the mixture of MSWI fly ash and sewage sludge for co-disposal: Effect of ferrous/ferric sulfate additives. *Waste Manag.*, *75*, 340-351. https://doi.org/10.1016/j.wasman.2018.01.040.

Huang, G., Ji, Y., Li, J., Zhang, L., Liu, X., & Liu, B. (2019). Effect of activated silica on polymerization mechanism and strength development of MSWI bottom ash alkali-activated mortars. *Constr. Build. Mater.*, *201*, 90-99. https://doi.org/10.1016/j.conbuildmat.2018.12.125.

Huang, G., Yang, K., Sun, Y., Lu, Z., Zhang, X., Zuo, L., Feng, Y. Q., Qian, R. C., Qi, Y., Ji, Y. S., & Xu, Z. (2020). Influence of NaOH content on the alkali conversion mechanism in MSWI bottom ash alkali-activated mortars. *Constr. Build. Mater.*, *248*, 118582. https://doi.org/10.1016/j.conbuildmat.2020.118582.

Huang, Y., Deng, P., Wang, G., & Zhang, H. (2024). Effects of vetiver root on cracking of expansive soils and its mechanistic analysis. *Sci. Rep.*, *14*(1), 19737. https://doi.org/10.1038/s41598-024-70934-1.

Huber, F., Laner, D., & Fellner, J. (2018). Comparative life cycle assessment of MSWI fly ash treatment and disposal. *Waste Manag.*, *73*, 392-403. https://doi.org/10.1016/j.wasman.2017.06.004.

Ikeagwuani, C. C., Obeta, I. N., & Agunwamba, J. C. (2019). Stabilization of black cotton soil subgrade using sawdust ash and lime. *Soils Found.*, *59*(1), 162-175. https://doi.org/10.1016/j.sandf.2018.10.004.

Jagaba, A. H., Shuaibu, A., Umaru, I., Musa, S., Lawal, I. M., & Abubakar, S. (2019). Stabilization of soft soil by incinerated sewage sludge ash from municipal wastewater treatment plant for engineering construction. *Sustain. Struct Mater.*, *2*(1), 32-44. https://doi.org/10.26392/SSM.2019.02.01.032.

Jethwa, R. H., Momin, S. S., Devi, B. M., & Chore, H. S. (2023). Evaluation of bagasse ash in stabilization of pavement sub-grade. In A. K. Agnihotri, K. R. Reddy, & H. S. (eds) Chore (Eds.), *Proceedings of Indian Geotechnical and Geoenvironmental Engineering Conference (IGGEC), Lecture Notes in Civil Engineering* (Vol. 280). https://doi.org/10.1007/978-981-19-4739-1_44.

Kami, V. B. & Mishra, A. (2024). Microstructural analysis of creep behavior in soft clays during cyclic loading and unloading. *Geotech. Geol. Eng.*, *42*, 7597-7615. https://doi.org/10.1007/s10706-024-02941-y.

Kaur, H., Siddique, R., & Rajor, A. (2019). Influence of incinerated biomedical waste ash on the properties of concrete. *Constr. Build. Mater.*, *226*, 428-441. https://doi.org/10.1016/j.conbuildmat.2019.07.239.

Khazaei, J. & Moayedi, H. (2019). Soft expansive soil improvement by eco-friendly waste and quick lime. *Arab. J. Sci. Eng.*, *44*(10), 8337-8346. https://doi.org/10.1007/s13369-017-2590-3.

Kulkarni, S. & Ranadive, M. (2024). Optimizing perpetual pavement design in India: stabilized soil and polymer-modified bitumen approach for cost and carbon efficiency. *Multiscale Multidiscip. Model. Exp. Des.*, *7*(2), 1185-1196. https://doi.org/10.1007/s41939-023-00275-5.

Kumar, P. R., Kumar, P. S. P., & Maheswari, G. (2017). Laboratory study of black cotton soil blended with copper slag and fly ash. *Int J. Innov Res Sci. Eng Technol.*, *6*(2), 19601967.

Latifi, N., Eisazadeh, A., Marto, A., & Meehan, C. L. (2017a). Tropical residual soil stabilization: A powder form material for increasing soil strength. *Constr. Build. Mater.*, *147*, 827-836. https://doi.org/10.1016/j.conbuildmat.2017.04.115.

Latifi, N., Horpibulsuk, S., Meehan, C. L., Abd Majid, M. Z., Tahir, M. M., & Mohamad, E. T. (2017b). Improvement of problematic soils with biopolymer—An environmentally friendly soil stabilizer. *J. Mater. Civ. Eng.*, *29*(2), 04016204. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001706.

Le, N. H., Razakamanantsoa, A., Nguyen, M. L., Dao, P. L., & Nguyen, D. H. (2018). Evaluation of physicochemical and hydromechanical properties of MSWI bottom ash for road construction. *Waste Manag.*, *80*, 168-174. https://doi.org/10.1016/j.wasman.2018.09.007.

Li, H., Gao, P., Zhang, C., Guo, S., & Zhang, J. (2023). Effect of polymeric agent on the strength and water stability of cement-stabilized construction waste soil. *Sustainability*, *15*(21), 15571. https://doi.org/10.3390/su152115571.

Li, J. & Poon, C. S. (2017). Innovative solidification/stabilization of lead contaminated soil using incineration sewage sludge ash. *Chemosphere*, *173*, 143-152. https://doi.org/10.1016/j.chemosphere.2017.01.065.

Li, X., Liu, Z., Lv, Y., Cai, L., Jiang, D., Jiang, W., & Jian, S. (2018). Utilization of municipal solid waste incineration bottom ash in autoclaved aerated concrete. *Constr. Build. Mater.*, *178*, 175-182. https://doi.org/10.1016/j.conbuildmat.2018.05.147.

Liang, S., Chen, J., Guo, M., Feng, D., Liu, L., & Qi, T. (2020). Utilization of pretreated municipal solid waste incineration fly ash for cement-stabilized soil. *Waste Manage.*, *105*, 425-432. https://doi.org/10.1016/j.wasman.2020.02.017

Linh, H. N., Tamura, H., Komiya, T., Saffarzadeh, A., & Shimaoka, T. (2020). Simulating the impact of heavy rain on leaching behavior of municipal solid waste incineration bottom ash (MSWI BA) in semi-aerobic landfill. *Waste Manage.*, *113*, 280-293. https://doi.org/10.1016/j.wasman.2020.06.008.

Liu, B., Liu, Y., Zhang, L., & Fan, X. (2024). Mechanical behavior and acoustic emission characteristics of cemented tailings backfill with varied water loss. *Geotech. Geol. Eng.*, *42*(7), 6005-6025. https://doi.org/10.1007/s10706-024-02874-6.

Liu, D. G., Ke, Y., Min, X. B., Liang, Y. J., Wang, Z. B., Li, Y. C., Fei, J. C., Yao, J. C., Yao, L. W., Xu, H., & Jiang, G. H. (2019a). Cotreatment of MSWI fly ash and granulated lead smelting slag using a geopolymer system. *Int. J. Environ. Res. Public Health.*, *16*(1), 156. https://doi.org/10.3390/ijerph16010156.

Liu, J., Hu, L., Tang, L., & Ren, J. (2021). Utilisation of municipal solid waste incinerator (MSWI) fly ash with metakaolin for preparation of alkali-activated cementitious material. *J. Hazard. Mater.*, *402*, 123451. https://doi.org/10.1016/j.jhazmat.2020.123451.

Liu, L., Zhou, A., Deng, Y., Cui, Y., Yu, Z., & Yu, C. (2019b). Strength performance of cement/slag-based stabilized soft clays. *Constr. Build. Mater.*, *211*, 909–918. https://doi.org/10.1016/j.conbuildmat.2019.03.256.

Liu, Y., Clavier, K. A., Spreadbury, C., & Townsend, T. G. (2019c). Limitations of the TCLP fluid determination step for hazardous waste characterization of US municipal waste incineration ash. *Waste Manage.*, *87*, 590-596. https://doi.org/10.1016/j.wasman.2019.02.045.

Ma, W., Chen, D., Pan, M., Gu, T., Zhong, L., Chen, G., Yan, B. B., & Cheng, Z. (2019). Performance of chemical chelating agent stabilization and cement solidification on heavy metals in MSWI fly ash: a comparative study. *J. Environ. Manage.*, *247*, 169-177. https://doi.org/10.1016/j.jenvman.2019.06.089.

Maldonado-Alameda, A., Giro-Paloma, J., Rodríguez-Romero, A., Serret, J., Menargues, A., Andrés, A., & Chimenos, J. M. (2021). Environmental potential assessment of MSWI bottom ash-based alkali-activated binders. *J. Hazard. Mater.*, *416*, 125828. https://doi.org/10.1016/j.jhazmat.2021.125828.

Mao, Y., Wu, H., Wang, W., Jia, M., & Che, X. (2020). Pretreatment of municipal solid waste incineration fly ash and preparation of solid waste source sulphoaluminate cementitious material. *J. Hazard. Mater.*, *385*, 121580. https://doi.org/10.1016/j.jhazmat.2019.121580.

Marieta, C., Guerrero, A., & Leon, I. (2021). Municipal solid waste incineration fly ash to produce eco-friendly binders for sustainable building construction. *Waste Manage.*, *120*, 114-124. https://doi.org/10.1016/j.wasman.2020.11.034.

Miao, S., Shen, Z., Wang, X., Luo, F., Huang, X., & Wei, C. (2017). Stabilization of highly expansive black cotton soils by means of geopolymerization. *J. Mater. Civ. Eng.*, *29*(10), 04017170. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002023.

Momeni, M., Bayat, M., & Ajalloeian, R. (2020). Laboratory investigation on the effects of pH-induced changes on geotechnical characteristics of clay soil. *Geomech. Geoeng.*, *17*(1), 188-196. https://doi.org/10.1080/17486025.2020.1716084.

Mujtaba, H., Aziz, T., Farooq, K., Sivakugan, N., & Das, B. M. (2018). Improvement in engineering properties of expansive soils using ground granulated blast furnace slag. *J. Geol. Soc. India.*, *92*, 357-362. https://doi.org/10.1007/s12594-018-1019-2.

Murmu, A. L. & Patel, A. (2020). Studies on the properties of fly ash–rice husk ash-based geopolymer for use in black cotton soils. *Int. J. Geosynth. Ground Eng.*, *6*, 38. https://doi.org/10.1007/s40891-020-00224-z.

Murthi, P., Saravanan, R., & Poongodi, K. (2021). Studies on the impact of polypropylene and silica fume blended combination on the material behaviour of black cotton soil. *Mater. Today Proc.*, *39*, 621-626. https://doi.org/10.1016/j.matpr.2020.09.004.

Narani, S. S., Abbaspour, M., Hosseini, S. M. M., Aflaki, E., & Nejad, F. M. (2020). Sustainable reuse of Waste Tire Textile Fibers (WTTFs) as reinforcement materials for expansive soils: With a special focus on landfill liners/covers. *J. Clean. Prod.*, *247*, 119151. https://doi.org/10.1016/j.jclepro.2019.119151.

Nedkvitne, E. N., Borgan, Ø., Eriksen, D. Ø., & Rui, H. (2021). Variation in chemical composition of MSWI fly ash and dry scrubber residues. *Waste Manag.*, *126*, 623–631. https://doi.org/10.1016/j.wasman.2021.04.007.

Nidoni, P. G. (2017). Incineration process for solid waste management and effective utilization of by products. *Int. Res. J. Eng. Technol.*, *4*(12), 378-382.

Nikravan, M., Ramezanianpour, A. A., & Maknoon, R. (2020). Study on physiochemical properties and leaching behavior of residual ash fractions from a municipal solid waste incinerator (MSWI) plant. *J. Environ. Manag.*, *260*, 110042. https://doi.org/10.1016/j.jenvman.2019.110042.

Obaid, S. S., Sayyed, M. I., Alameen, A. S., Gaikwad, D. K., & Mahmoud, K. A. (2024). Extensive analysis of several Indian and Yemeni soils' gamma-ray shielding characteristics: An experimental and simulation approach. *Nucl. Eng. Technol.*, *56*(9), 3558-3565. https://doi.org/10.1016/j.net.2024.04.005.

Oliveira, P. J. V., Freitas, L. D., & Carmona, J. P. (2017). Effect of soil type on the enzymatic calcium carbonate precipitation process used for soil improvement. *J. Mater. Civ. Eng.*, *29*(4), 04016263. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001804.

Pai, R. R. & Patel, S. (2019). Effect of GGBS and lime on the strength characteristics of black cotton soil. *In Ground Improvement Techniques and Geosynthetics: IGC 2016*, *2*, 319-328. https://doi.org/10.1007/978-981-13-0559-7_36.

Paranthaman, R., Azam, S., & Chowdhury, R. H. (2024). Geotechnical evaluation of consolidation and conductivity of synthetic municipal solid waste. *Geotech. Geol. Eng.*, *42*(6), 4401-4415. https://doi.org/10.1007/s10706-024-02787-4.

Phanikumar, B. R. & Nagaraju, T. V. (2018). Effect of fly ash and rice husk ash on index and engineering properties of expansive clays. *Geotech. Geol. Eng.*, *36*(6), 3425-3436. https://doi.org/10.1007/s10706-018-0544-5.

Pusadkar, S., Bakhade, S., & Dhatrak, A. I. (2017). Effect of nano-copper on performance of Black Cotton Soil. *Int. J. Eng. Res. Appl.*, *7*(6), 34-39. https://doi.org/10.9790/9622-0706073439.

Rashid, A. S. A., Latifi, N., Meehan, C. L., & Manahiloh, K. N. (2017). Sustainable improvement of tropical residual soil using an environmentally friendly additive. *Geotech. Geol. Eng.*, *35*, 2613-2623. https://doi.org/10.1007/s10706-017-0265-1.

Rawayau, U. H., Abdulfatah, A. Y., & Shuaibu, R. B. (2019). Stabilization of expansive soil using bauhinia thonningii (KALGO) fruit ash. *Nig. J. Eng. Sci. Technol. Res.*, *5*(1), 35-44.

Reddy, C. S., Mohanty, S., & Shaik, R. (2018). Physical, chemical and geotechnical characterization of fly ash, bottom ash and municipal solid waste from Telangana State in India. *Int. J. Geo-Eng.*, *9*, 1-23. https://doi.org/10.1186/s40703-018-0093-z.

Rissler, J., Klementiev, K., Dahl, J., Steenari, B. M., & Edo, M. (2020). Identification and quantification of chemical forms of Cu and Zn in MSWI ashes using XANES. *Energy Fuels.*, *34*(11), 14505-14514. https://doi.org/10.1021/acs.energyfuels.0c02226.

Rosone, M., Celauro, C., & Ferrari, A. (2018). Microstructure and shear strength evolution of a lime-treated clay for use in road construction. *Int. J. Pavement Eng.*, *21*(9), 1147-1158. https://doi.org/10.1080/10298436.2018.1524144.

Saidi, M., Cherif, A. S., Zeghmati, B., & Sediki, E. (2018). Stabilization effects on the thermal conductivity and sorption behavior of earth bricks. *Constr. Build. Mater.*, *167*, 566-577. https://doi.org/10.1016/j.conbuildmat.2018.02.063.

Saneiyan, S., Ntarlagiannis, D., Werkema Jr, D. D., & Ustra, A. (2018). Geophysical methods for monitoring soil stabilization processes. *J. Appl. Geophys.*, *148*, 234-244. https://doi.org/10.1016/j.jappgeo.2017.12.008.

Sefene, S. S. (2021). Determination of effective wood ash proportion for black cotton soil improvement. *Geotech. Geol. Eng.*, *39*(1), 617-625. https://doi.org/10.1007/s10706-020-01508-x.

Selvaraj, M., Krithigaisrilatha, M., Masoodhu, S. S., & Natarajan, N. (2020). Use of crystalline silica waste for enhancement of engineering properties of black cotton soil. *Nature Environ. Pollut. Technol.*, *19*(3), 1105-1112.

Singh, D. & Kumar, A. (2017a). Geo-environmental application of municipal solid waste incinerator ash stabilized with cement. *J. Rock Mech. Geotech. Eng.*, *9*(2), 370-375. https://doi.org/10.1016/j.jrmge.2016.11.008.

Singh, D. & Kumar, A. (2017b). Performance evaluation and geo-characterization of municipal solid waste incineration ash material amended with cement and fibre. *Int. J. Geosynth. Ground Eng.*, *3*, 16. https://doi.org/10.1007/s40891-017-0094-6.

Singh, D. & Kumar, A. (2020). Factors affecting properties of MSWI bottom ash employing cement and fiber for geotechnical applications. *Environ. Dev. Sustain.*, *22*, 6891-6905. https://doi.org/10.1007/s10668-019-00519-w.

Singh, M. J., Feng, W. Q., Xu, D. S., & Borana, L. (2020). Experimental study of compression behavior of Indian black cotton soil in oedometer condition. *Int. J. of Geosynth. and Ground Eng.*, *6*, 30. https://doi.org/10.1007/s40891-020-00207-0.

Singh, M. J., Feng, W. Q., Xu, D. S., & Borana, L. (2022). Time-dependent compressibility characteristics of montmorillonite clay using EVPS model. *Geomech. Eng.*, *28*(2), 171-180. https://doi.org/10.12989/gae.2022.28.2.171.

Song, J. Y., Sim, Y., Jang, J., Hong, W. T., & Yun, T. S. (2020). Near-surface soil stabilization by enzyme-induced carbonate precipitation for fugitive dust suppression. *Acta Geotech.*, *15*, 1967-1980. https://doi.org/10.1007/s11440-019-00881-z.

Srikanth Reddy, S., Prasad, A. C. S. V., & Vamsi Krishna, N. (2018). Lime-stabilized black cotton soil and brick powder mixture as subbase material. *Adv. Civ. Eng.*, *2018*(1), 5834685. https://doi.org/10.1155/2018/5834685.

Sun, Z., Chen, W. B., Zhao, R. D., Shen, P., Yin, J. H., & Chen, Y. G. (2023). Effect of seawater on solidification/stabilisation treatment of marine soft soil slurry by lime-activated ISSA and GGBS. *Eng. Geol.*, *323*, 107216. https://doi.org/10.1016/j.enggeo.2023.107216.

Tabassum, N., Hashino, T., Phan, B. N., Hayano, K., & Yamauchi, H. (2022). Effects of primary curing conditions and subsequent crumbling on properties of compacted soils treated with paper sludge ash-based stabilizers. *Soils Found.*, *62*(5), 101183. https://doi.org/10.1016/j.sandf.2022.101183.

Tang, J., Petranikova, M., Ekberg, C., & Steenari, B. M. (2017). Mixer-settler system for the recovery of copper and zinc from MSWI fly ash leachates: An evaluation of a hydrometallurgical process. *J. Clean. Prod.*, *148*, 595-605. https://doi.org/10.1016/j.jclepro.2017.02.015.

Tang, P., Xuan, D., Li, J., Cheng, H. W., Poon, C. S., & Tsang, D. C. (2020). Investigation of cold bonded lightweight aggregates produced with incineration sewage sludge ash (ISSA) and cementitious waste. *J. Clean. Prod.*, *251*, 119709. https://doi.org/10.1016/j.jclepro.2019.119709.

Tome, S., Nana, A., Kaze, C. R., Djobo, J. N. Y., Alomayri, T., Kamseu, E., Etoh, M. A., Etame, J., & Kumar, S. (2021). Resistance of alkali-activated blended volcanic ash-MSWI-FA mortar in sulphuric acid and artificial seawater. *Silicon*, *14*(6), 2687-2694. https://doi.org/10.1007/s12633-021-01055-x.

Türköz, M. (2019). Computer-controlled equipment for the direct measurement of the swell potential of expansive soils. *Arab J Geosci*, *12*(23), 743. https://doi.org/10.1007/s12517-019-4987-7

Ukritchon, B., Yingchaloenkitkhajorn, K., & Keawsawasvong, S. (2017). Three-dimensional undrained tunnel face stability in clay with a linearly increasing shear strength with depth. *Comput. Geotech.*, *88*, 146-151. https://doi.org/10.1016/j.compgeo.2017.03.013.

Vavva, C., Voutsas, E., & Magoulas, K. (2017). Process development for chemical stabilization of fly ash from municipal solid waste incineration. *Chem. Eng. Res. Des.*, *125*, 57-71. https://doi.org/10.1016/j.cherd.2017.06.021.

Verbinnen, B., Billen, P., Van Caneghem, J., & Vandecasteele, C. (2017). Recycling of MSWI bottom ash: A review of chemical barriers, engineering applications and treatment technologies. *Waste Biomass Valoriz.*, *8*, 1453-1466. https://doi.org/10.1007/s12649-016-9704-0.

Verma, H., Rudra, E. S. C. K., Rai, R., Pandian, K. A., & Manna, B. (2023). Design of dump slope on weak foundation. *J. Inst. Eng. India Ser. D.*, *104*, 107-118. https://doi.org/10.1007/s40033-022-00396-0.

Wang, B. & Fan, C. (2020). Hydration behavior and immobilization mechanism of MgO–SiO2–H2O cementitious system blended with MSWI fly ash. *Chemosphere*, *250*, 126269. https://doi.org/10.1016/j.chemosphere.2020.126269.

Wang, H., Fan, X., Wang, Y. N., Li, W., Sun, Y., Zhan, M., & Wu, G. (2018a). Comparative leaching of six toxic metals from raw and chemically stabilized MSWI fly ash using citric acid. *J. Environ. Manage.*, *208*, 15-23. https://doi.org/10.1016/j.jenvman.2017.11.071.

Wang, X., Tao, J., Bao, R., Tran, T., & Tucker-Kulesza, S. (2018b). Surficial soil stabilization against water-induced erosion using polymer-modified microbially induced carbonate precipitation. *J. Mater. Civ. Eng.*, *30*(10), 04018267. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002490.

Wang, Y., Guo, P., Li, X., Lin, H., Liu, Y., & Yuan, H. (2019). Behavior of fiber-reinforced and lime-stabilized clayey soil in triaxial tests. *Appl. Sci.*, *9*(5), 900. https://doi.org/10.3390/app9050900.

Wang, Y., Li, R., & Qiao, J. (2023). Solidification of heavy metals in municipal solid waste incineration washed fly ash by asphalt mixture. *Chemosphere*, *343*, 140281. https://doi.org/10.1016/j.chemosphere.2023.140281.

Withanage, K. R., Hayano, K., Kang, X., & Yamauchi, H. (2024). Water immersion induced swelling characteristics and underlying mechanisms of compacted neutralized and un-neutralized-recycled construction sludge. *Case Stud. Constr. Mater.*, *21*, e03746. https://doi.org/10.1016/j.cscm.2024.e03746.

Wongsa, A., Boonserm, K., Waisurasingha, C., Sata, V., & Chindaprasirt, P. (2017). Use of municipal solid waste incinerator (MSWI) bottom ash in high calcium fly ash geopolymer matrix. *J. Clean. Prod.*, *148*, 49-59. https://doi.org/10.1016/j.jclepro.2017.01.147.

Wu, M., Yin, Z. Y., Sun, Y., Li, Y., & Wang, J. (2024). DEM modeling of granular soils reinforced by disposable face-mask chips. *Comput. Geotech.*, *176*, 106804. https://doi.org/10.1016/j.compgeo.2024.106804.

Xu, H., Zheng, H., Wang, J. N., Ding, X. Q., & Chen, P. (2019a). Laboratory method of microbial induced solidification/stabilization for municipal solid waste incineration fly ash. *MethodsX*, *6*, 1036-1043. https://doi.org/10.1016/j.mex.2019.05.006.

Xu, P., Zhao, Q., Qiu, W., Xue, Y., & Li, N. (2019b). Microstructure and strength of alkali-activated bricks containing municipal solid waste incineration (MSWI) fly ash developed as construction materials. *Sustainability*, *11*(5), 1283. https://doi.org/10.3390/su11051283.

Yadav, J. S. & Tiwari, S. K. (2017). Effect of waste rubber fibres on the geotechnical properties of clay stabilized with cement. *Appl. Clay Sci.*, *149*, 97-110. https://doi.org/10.1016/j.clay.2017.07.037.

Yakubu, Y., Zhou, J., Ping, D., Shu, Z., & Chen, Y. (2018). Effects of pH dynamics on solidification/stabilization of municipal solid waste incineration fly ash. *J. Environ. Manage.*, *207*, 243-248. https://doi.org/10.1016/j.jenvman.2017.11.042.

Yang, Z., Tian, S., Liu, L., Wang, X., & Zhang, Z. (2018). Recycling ground MSWI bottom ash in cement composites: Long-term environmental impacts. *Waste Manage.*, *78*, 841-848. https://doi.org/10.1016/j.wasman.2018.07.002.

Yang, Z., Wang, Y., Li, D., Li, X., & Liu, X. (2020). Influence of freeze–thaw cycles and binder dosage on the engineering properties of compound solidified/stabilized lead-contaminated soils. *Int. J. Environ. Res. Public Health.*, *17*(3), 1077. https://doi.org/10.3390/ijerph17031077.

Yin, Z., Li, Q., Zhang, Y., Xu, R., Qu, G. F., Wu, H. T., Liao, L., Yang, Y. B., & Jiang, T. (2024). Stabilization effect of nano-SiO2@ iron-phosphorus on ferrallisols, calcareous soil and organic soil heavily polluted by heavy metals: A fast reaction curing stabilization process. *Sci. Total Environ.*, *954*, 176379. https://doi.org/10.1016/j.scitotenv.2024.176379.

Zhan, X., Hu, C., Gong, J., Xu, T., Li, J., Yang, L., Bai, J. S., & Zhong, S. (2018). Co-disposal of MSWI fly ash and electrolytic manganese residue based on geopolymeric system. *Waste Manage.*, *82*, 62-70. https://doi.org/10.1016/j.wasman.2018.10.014.

Zhan, X., Wang, L., Gong, J., Wang, X., Song, X., & Xu, T. (2021). Co-sintering MSWI fly ash with electrolytic manganese residue and coal fly ash for lightweight ceramisite. *Chemosphere*, *263*, 127914. https://doi.org/10.1016/j.chemosphere.2020.127914.

Zhang, J., Niu, G., Li, X., & Sun, D. A. (2020). Hydro-mechanical behavior of expansive soils with different dry densities over a wide suction range. *Acta Geotech.*, *15*, 265-278. https://doi.org/10.1007/s11440-019-00874-y.

Zhao, K., Hu, Y., Tian, Y., Chen, D., & Feng, Y. (2020). Chlorine removal from MSWI fly ash by thermal treatment: Effects of iron/aluminum additives. *J. Environ. Sci.*, *88*, 112-121. https://doi.org/10.1016/j.jes.2019.08.006.

Zhou, Y., Cai, G., Cheeseman, C., Li, J., & Poon, C. S. (2022). Sewage sludge ash-incorporated stabilisation/solidification for recycling and remediation of marine sediments. *J. Environ. Manage.*, *301*, 113877. https://doi.org/10.1016/j.jenvman.2021.113877.