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# Recent advances in the stabilization of expansive soils using waste materials: A review

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**Abstract.** The increasing population necessitates infrastructural development, and these civil engineering infrastructures are constructed on soils. Highways, buildings, bridges, railways, and dams need a strong foundation; however, some soils are not suitable for making a strong foundation. An example is expansive or reactive soils. Expansive soils are subjected to volumetric changes, thus the biggest challenge that geotechnical engineers encounter in the field. In an attempt to make these poor soils more appropriate for use in engineering projects, different stabilization techniques are used. However, well-established stabilizers like cement, lime, and bitumen are associated with environmental challenges. This has attracted the attention of the researchers to look for environmentally friendly and sustainable stabilizers. The current study provides a review of the recent trends in improving the geotechnical properties of expansive soils using waste materials, focusing on their efficacy, the optimum percentage, and research gaps. Wastes considered in this study include waste tires, sawdust, and sawdust ash, and fly ash. The review utilized research articles extracted from different databases, such as Science Direct, Google Scholar, Scopus, Web of Science, and Google. This work could give the geotechnical engineers and independent researchers insight into the recent soil stabilization trends that could lead to sustainable development.

## 1. Introduction

Various soils are used during the construction of civil engineering structures. However, some soils are suitable, while others are unsuitable for civil engineering purposes [1]. One example of unsuitable soils that cause severe damage to engineering structures' foundations includes expansive clay [2]. These soils experience massive volume changes due to their high affinity to water. Expansive soils have a record of swelling during the wet season and shrinking during the dry season, and the cause of these behaviors could be the presence of a mineral with an enlarging matrix [1], [3], [4]. In most parts of the world, soils with desirable properties are transported from quarries that are at times far from the construction project site. This raises the construction costs of the project in terms of excavation and transportation costs, and for that matter, there is a need for shifting to locally available stabilization materials.

The history of expansive subgrade soil stabilization can be traced way back to the 1950s, and since then, researchers continued looking for better and sustainable ways of soil stabilization [5]. Dubose [6] experimented using a compaction method to control heaving in clay soils. In 1958, Jones conducted laboratory studies on improving the geotechnical properties of reactive clay soils using hydrated lime



and Portland cement [7]. McDowell [8] defined the processes of treating soils in Texas using lime only, and a mixture of lime and fly ash. Taylor [9] discussed the ion exchange processes in clay soils. Dempsey & Thompson [10] conducted several kinds of research to analyze the properties and behaviors of soils stabilized by lime. Their studies determined the soil's durability properties blended with lime, autogenesis healing of lime-soil blends, and lime's reactivity in soils of Illinois, United States of America [10]. However, well-established stabilizers like lime, cement, and bitumen are associated with many environmental challenges and high costs in different parts of the world. This has attracted the researchers' attention in recent times to conduct more studies on the applicability of waste materials to stabilize soft soils. Some wastes are taken to landfills, and others are simply discarded to the environment without treatment, hence causing health and environmental problems [11], [12]. Instead of mishandling these wastes, they could be re-used for other uses like stabilization, especially the wastes that possess pozzolanic properties. Some wastes that have so far shown the potential of modifying soft soils' engineering properties could be grouped into industrial solid wastes, agricultural solid wastes, mineral solid wastes, domestic wastes, and natural fibers. Industrial solid wastes include; cement kiln dust, fly ash, copper slag, blast furnace slag, silica fume, polyvinyl waste, etc., agricultural solid wastes include; sawdust or sawdust ash, rice husk ash, sugarcane bagasse ash, etc. Mineral solid wastes include; marble dust, quarry dust, granite dust, limestone dust, etc. Domestic solid wastes include; waste tires, incinerator ash, etc., and natural fibers include; jute, coir, coconut, water hyacinth, bamboo, banana, human hair fiber, etc. The applicability of waste materials as stabilizing agents could reduce the usage of traditional stabilizers such as lime or cement, hence minimizing the costs of civil engineering projects [13]. Besides, it helps solve the problem of environmental pollution caused by their poor disposal. The current review paper analyzes the recent trends in the use of waste materials (focusing on waste tires, sawdust, sawdust ash, and fly ash) to stabilize expansive soils. The study is a narrative review that utilized published papers, conference proceedings, and text books extracted from Science Direct, Google Scholar, Scopus, Web of Science, and Google. The study has clarified the future focuses in the use of waste materials. The study could help the readers, especially geotechnical engineers and academicians, understand the latest technologies in solving geotechnical problems that could occur due to poor and compressible soils.

## 2. Expansive soil identification

Expansive soils experience swelling and shrinking due to variations in moisture. The identification of reactive or expansive soils is vital during the reconnaissance and preliminary stages of a site investigation. By making such an identification, the geotechnical engineers will easily indicate suitable sampling and testing methods to be used [3]. Identification of the expansive soil can be recognized by conducting physical tests (Atterberg limits, Free swell index, and potential volume change), and conducting mineralogical tests and chemical properties of soils [3]. However, it should be noted that these tests don't reflect the mechanical behavior of expansive soils. Based on physical properties, Holtz & Gibbs [14] developed a general relationship between Atterberg limit tests (shrinkage limit, liquid limit, and plastic limit), and potential volume change for easy identification of expansive soils, as shown in Table 1.

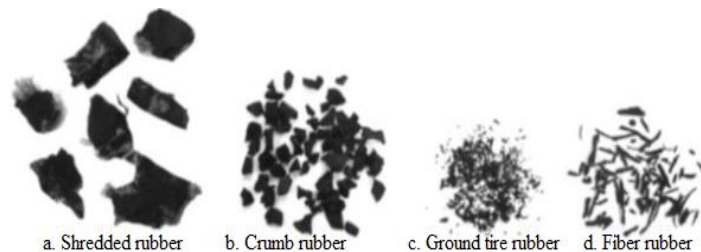
**Table 1.** The relationship between Atterberg limit tests and potential volume change [14].

Shrinkage Limit (SL)	Liquid Limit (LL)	Plastic Limit (PL)	Volume change potential
>15	20-35	<18	Low
10-15	35-50	15-28	Medium
7-2	50-70	25-41	High
<11	>70	>35	Very high

### 3. Stabilization of Expansive Soil Using Waste Materials

#### 3.1. Waste tires

The disposal of waste tires has been a significant challenge throughout the globe and continues to become a challenge until today. Waste stockpiles that are found in most parts of the world impose threats to the environment [15]–[17] and cause health hazards to individuals by producing air pollution from tire stockpile fires [11]. Besides, stockpiles act as breeding places for potential disease-carrying organisms like mosquitoes and rodents [17], [18]. For that matter, dumping waste tires in any way could be dangerous. On the other hand, if the waste tires are handled well, they are useful resources. They can be utilized in different ways, like modifying concrete, highway crash barriers, energy generation, and geotechnical applications [19]. Researchers in the field of engineering are trying to see how best these waste materials could be re-used. Generally, out of the waste tires generated, 25-60% is used for energy recovery, 5-23% are re-used, 3-15% is recycled, and 20-30% landfilled [20]. The appropriate approach to reduce waste tire stockpiles is by recycling and re-use [11]. In geotechnical engineering, waste tires could be used to improve the engineering properties of the soft soils as witnessed by different scholars [17], [19], [21]–[24]. Researchers utilize waste tires in different shapes and sizes, i.e., shredded rubber, crumb rubber, ground tire rubber, and fiber rubber, as seen in Figure 1 [25].



**Figure 1.** Different shapes and sizes of the waste tire [25].

It is believed that waste tires possess desirable properties (such as good vibration damping, low unit weight and earth pressure, and good thermal insulation) for improving the conditions of problematic soils [24]. Moreover, shredded waste tires are easily compacted, consolidated, non-biodegradable, and less costly [22]. Besides, shredded tires' angular shape and excellent friction characteristics allow the individual tire shreds to lock together entirely. Several scholars have noted increased strengths in soils modified by waste tires. For example, Mittal & Gill [24] used manually cut waste tire chips (12-14 mm) and geogrid to improve granular soils' load carrying capacity. They found out that soils stabilized by waste tire chips had better performance results (better bearing capacity) than those stabilized by geogrid, with an optimum of the waste tire of 20% by weight. Bekhiti et al. [2] analyzed the influence of waste tire rubber fibers on the engineering properties of cement stabilized bentonite clay soil. They concluded that the maximum UCS and ductility behavior was achieved after adding a proportion of 2% rubber fibers. The study conducted by Srivastava et al. [22] on improving the geotechnical properties of expansive black cotton soil with both fine ( 2.0 mm – 0.075 mm) and coarse (4.75–2.00 mm) shredded tire waste shows that shredded tire waste of size 4.75–2.00 mm greatly improved the geotechnical properties of expansive soil. The study indicates that the coarse shredded tire brought better improvements to expansive soil than the fine shredded tire. The coarse shredded tire (30-50%) content reduces the plasticity index, thus decreasing the expansive soils' swelling potential. Tafreshi & Norouzi [21] investigated the bearing capacity of a square model footing on sand reinforced with a shredded tire. Their results yielded success, whereby the bearing capacity of shredded tire reinforced soil was 2.68 times that of non-reinforced soil after reinforcing the soil by 5% of the total volume of soil-shredded tire mixture. After adding 5% of the soil-shredded tire mixture, a decline was observed. The decrease could be attributed to the high percentages of shredded tire added to the soil, thus creating voids that increase the footing settlement. Priyadarshee et al. [19] determined the compaction and strength behaviour of kaoline clay soils stabilised with different contents of tire crumbles and fly ash tire. The

compaction characteristics of tire crumbles and fly ash stabilised soil showed that the increase in the content of fly ash and tire crumbles leads to a decrease in maximum dry density of the soil. On the other hand, the increase in the range of fly ash and tire crumbles leads to an increase in optimum moisture content. The study revealed that the ratio of fly ash and tire crumbles that gives maximum bearing capacity was 20 and 5% respective, thus taken as the optimum value for adequate stabilization of kaoline clay. The recent study conducted by Abbaspour et al. [17] on the stabilization of clay and sand soil using waste tire textile fibers (0.5%, 1%, 2%, 3%, and 4%) also showed promising results by increasing bearing capacity. Similarly, Al-neami [26] conducted a study on stabilizing sandy soil using recycled waste tire chips and noticed good progress, as far as shear strength and CBR of the stabilized soil are concerned.

It has been noted that waste tires crushed into small pieces could be blended with soft soils to produce better engineering properties like increased strength, permeability, and other physical properties of soils [27]. However, more studies are still needed to know the exact size and the optimum content of the waste tire used to stabilize soils effectively.

### 3.2. Sawdust and Sawdust ash

Sawdust is a by-product that is obtained after cutting or pulverizing wood (as shown in Figure 2) using a saw or any other blade in the sawmill or lumbering industries. When sawdust is set to fire, the end product is sawdust ash (see Figure 3). Dry wood mainly consists of cellulose, lignin, hemicelluloses, and small amounts (5-10%) of other materials [28]. These components possess some cementitious properties [29]. Since trees are needed in large numbers for different purposes, then their cutting leads to high proportions of sawdust produced [13], [30]–[32]. Sawdust is regarded as industrial waste from timber, and it is usually dumped along the roads or near sawmills, or transported to sanitary landfills. When treated in the wrong way, it can lead to serious environmental problems, especially when it is open-dumped [33]–[35].

On the other hand, it can be a useful raw material in different ways when treated well. According to Koteswara [36], sawdust can be used for various functions, including soil stabilizer, because of its pozzolanic properties. Also, sawdust is used in the manufacturing industries as a raw material for wood boards and, at times, used as fertilizers in agriculture [34], [37].



**Figure 2.** Sawdust [4]



**Figure 3.** Sawdust ash [30]

Sawdust mainly consists of a high percentage of carbon (60.8%) and Oxygen (33.3%), and low percentages of other chemical elements such as hydrogen and nitrogen [37]. Therefore, it has inadequate cementitious properties, but it can react chemically in moisture and forms cementitious compounds [30]. This reaction can be paramount significant to the improvement of the strength and compressibility characteristics of subgrade soils. The effective utilization of sawdust will help improve soil strength properties, making them suitable for road construction.

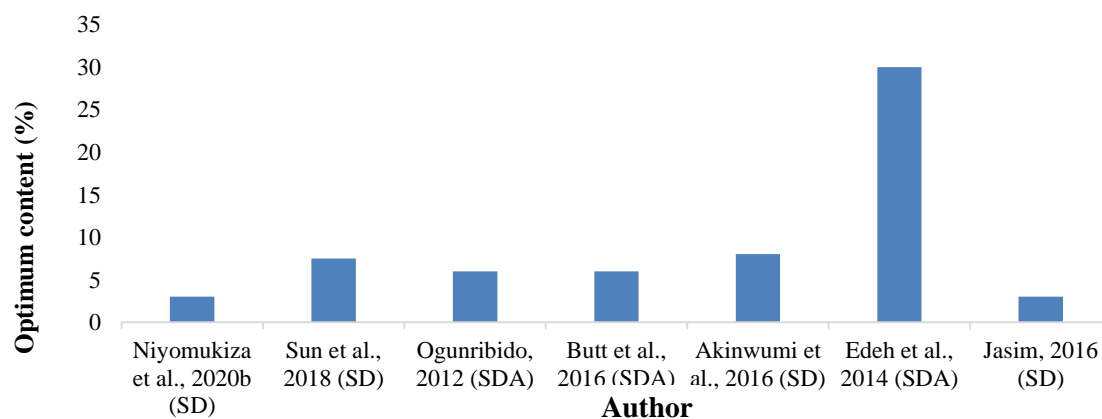
Various researchers have conducted extensive studies. They have shown promising results when sawdust, sawdust ash, the mixture of sawdust, or sawdust ash, and other cementitious stabilizers like lime and cement stabilize the soil. For example, Niyomukiza et al. [4] conducted a study on the influence of *Keruing* sawdust on geotechnical properties of expansive soils. Their results showed that 3% of sawdust improved the properties of expansive soils; however, they recommended conducting durability tests. Sun et al. [38] carried out a research to improve the geotechnical properties of expansive soil using

different percentages of sawdust (0, 2.5, 5, 7.5, 10, and 12.5%) of the dry unit weight of soil. They concluded that swelling potential and swelling pressure decreases with the increased percentages of sawdust addition.

In comparison, strength properties such as unconfined compressive strength (UCS) increased up to 7.5% sawdust addition; beyond that, they started reducing. However, their research did not test the California Bearing Ratio (CBR) of the sawdust stabilized soil, which is a substantial factor in determining the pavement's thickness. Similarly, Jasim [39] conducted studies on the stabilization of expansive soil using different quantities of sawdust (1, 2, 3, and 5%) and found that smaller percentages of sawdust brought a tremendous increase in the strength of the stabilized soils. Their study found out that the optimum portion of sawdust to effectively stabilize expansive soil is 3%; beyond that, a decline in strength was observed. They later concluded that sawdust could be used to fill the voids in soils. Ogunribido [40] tested the geotechnical properties of the South-western Nigerian soils using 0, 2, 4, 6, and 8% sawdust ash (SDA), and confirmed that 6% SDA gave optimum results and concluded that SDA is an effective soil stabilizer for lateritic soil, and therefore can increase on road quality.

Similarly, Butt et al. [30] have shown the positive impact of sawdust ash as an inexpensive stabilizing agent for soft clayey soils to be used in pavement construction. The optimum quantity of sawdust ash obtained was 4% by dry weight of soil. However, Butt et al. [30] recommended adding other additives such as lime to improve its performance. Edeh et al. [41] substituted the soil with sawdust ash in different ratios to improve lateritic soil's geotechnical properties. Their study found a mixed composition of 70% lateritic soil, and 30% sawdust ash significantly improved the CBR in both soaked and unsoaked conditions. Sawdust also provided excellent results when used to stabilize clay for landfill applications, as witnessed by the study conducted by Akinwumi et al. [42]. They used different percentages (0, 2, 4, 6, and 8% by the dry unit weight of soil), and their results met the standard hydraulic conductivity requirement. However, they concluded that 8% is optimum content. From the above studies, it was noted that the improvement in the geotechnical properties of the soils stabilized by either SD or SDA depends on the content of the stabilizers used. Different optimum values for SD or SDA stabilized soils were proposed by researchers of the selected articles reviewed (see Figure 4). Some stabilized soils showed improvement upon adding small quantities of the stabilizers, and others show improvement upon using large amounts of the stabilizers. The phenomena could be the properties of the soil and minerals present in the soil since soils in different areas possess different properties.

The above studies showed that either sawdust (SD) or sawdust ash (SDA) significantly improved the physical, mechanical, and strength properties of clay soils; therefore, they can be used as cheap stabilizers to reduce the construction costs of civil engineering projects. However, it was noted that some knowledge is still lacking in the durability of the SD or SDA stabilized soils. Therefore, it is recommended to conduct durability tests to know these stabilizers' performance in the long run, since the engineering projects are designed to last for long.



**Figure 4.** Optimum Sawdust or Sawdust ash to stabilize soils

### 3.3. Fly ash

The Fly ash is an industrial by-product that is produced from thermal power plants and factories by combustion or igniting coal for energy production [43]. It has a different chemical composition. The chemical composition of fly ash varies depending on the type of coal. Nevertheless, all fly ash possesses high quantities of silicon dioxide ( $\text{SiO}_2$ ), calcium oxide ( $\text{CaO}$ ), and aluminum oxide ( $\text{Al}_2\text{O}_3$ ). Fly ash is classified as either Class C or Class F based on the quantity of three compositions ( $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{Fe}_2\text{O}_3$ ) [44]. Class C fly ash possesses the sum of  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{Fe}_2\text{O}_3$  that is below 70%, and usually high quantities of  $\text{CaO}$ . On the other hand, the total amounts of  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{Fe}_2\text{O}_3$  is always greater than 70%.

Million tons of fly ash are produced globally every year due to the need for coal-based energy. However, one-quarter of the total production is utilized [45]. This means that a lot of fly ash (around 90%) is either exposed to the environment or dumped in the landfill. The one dumped directly on the environment directly causes environment pollution, while the one taken to the landfill exerts pressure on the landfill. Fly ash has adverse effects on the environment if mishandled, for example, contamination of groundwater and surface water, air pollution, and many others [12]. Fly ash can be seen as a waste product but can also be seen in another way as a useful product if handled well from different perspectives. Cement factories use fly ash to manufacture concrete, geotechnical engineers use it to stabilize soft soils (as stand-alone or mixed with other stabilizers), and farmers use it as fertilizers. Besides, fly ash is used in the treatment of wastewater to remove toxic metals [43].

For a long time, fly ash has acted as a useful resource in stabilizing expansive soils due to its desirable chemical composition. It has shown excellent results both in the laboratory and in the field. Alsafi et al. [46] determined the collapsibility potential of gypseous soil stabilized by the fly ash class F activated with KOH and NaOH. Their study found out that fly ash geopolymer can decrease the collapsibility potential of gypseous soil, where the reduction in the collapsibility potential occurs due to the increase in the percentage of fly ash. Besides, the study noted that geopolymer fly ash has higher sulfate resistance compared to Portland cement. Another study conducted by Yilmaz [47] incorporated 0, 5, 10, 15, 20, 30% fly ash. Their research revealed that the increase in fly ash quantity increases the maximum dry unit, but reduces the optimum moisture content. Considering the strength characteristics, the unconfined compressive strength (UCS) increased with the increase in fly ash content and the increase in curing days, where the highest UCS was achieved at 30% fly ash after 90 days of curing. Nalbantoglu [48] used fly ash Class C to stabilize expansive soils in two places in Turkey (Degirmenlik and Tuzla) having different expansive soils. The expansive soil in Degirmenlik had high swelling potential (19.6%), while Tuzla's expansive soil had low swelling potentials (6.5%). The results showed that fly ash was more effective in stabilizing the expansive soils of Degirmenlik than the expansive soils of Tuzla. It was seen that 25% of fly ash reduced the swelling potential of Degirmenlik expansive soil from 19.6% to 0% at the curing of 30 days.

On the other hand, fly ash reduced Tuzla expansive soil's swelling potential from 6.5% to 2%. From this study, it can be deduced that fly ash class C is more appropriate in stabilizing soils with high swell potentials. Xiao et al. [49] utilized fly ash, and cement to improve marine clay soils. They found out that the strength properties (compressive strength and tensile strength) of cement stabilized soils were higher than those of fly ash stabilized soils in the short-run (7-28 days). However, the prediction model shows that these strength properties will approach cement stabilized clay in the long run. This study indicates that fly ash stabilized soils gain tremendous strength in the long run. Jafer et al. [50] studied the influence of calcium fly ash (0, 3, 6, 9, 12, and 15% of the dry unit weight) and palm oil fuel ash to stabilize soft soils. By considering the chemical composition of the fly ash used in this study, it can be deduced that it is Class C fly ash because the sum of  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{Fe}_2\text{O}_3$  is 27.53, which is below 70%. The Atterberg test results show that fly ash improved the soil by reducing the plasticity index from 20.2% (non-stabilized) to 13.1% stabilized soil with 15% fly ash. The above studies have shown the success brought by fly ash when used to stabilize soils as a stand-alone stabilizer or mixed with other stabilizers.

#### 4. Limitations of usage of waste materials in the field

Waste materials show promising results in the laboratory, but field application is still missing or limited, except the few wastes like fly ash that is utilized in the field by few countries. The limited usage is attributed to the following reasons;

1. There are no clearly documented guidelines by the governing bodies (relevant authorities) on their usage.
2. There is no clear standard or optimum quantity of the wastes documented to stabilize soft soils effectively.
3. There is inadequate data published by independent researchers or organizations concerning the use of the waste materials to stabilize soils.

#### 5. Conclusions

The current study has reviewed the recent trends in stabilizing expansive soils using waste materials, focusing on waste tires, sawdust, and sawdust ash, and fly ash as stabilizing agents for expansive soils. The mentioned waste materials improved index properties, compaction characteristics, strength, and compressibility features of expansive soils. Besides, the use of these wastes as stabilizing agents could reduce the number of wastes discarded directly to the environment or taken to landfills, thus minimizing the health and environmental problems caused by the poor disposal of these wastes. The optimum content of the waste materials to stabilize the soil depends on the properties of the soil. The discussed waste materials showed success in the laboratory, and some of them, like fly ash, demonstrated success in both the laboratory and the field. Therefore, it is recommended to emphasize the field application of these wastes instead of only focusing on laboratory studies. Furthermore, there is a need for collaboration between academicians and government agents to embrace these new technologies. Some of the research gaps identified include; more studies on the microstructural of soils stabilized by waste materials, and mineralogical studies are still needed. There is also a need to conduct durability tests to know these wastes' performance in the long run. Economic analysis between well-established stabilizers (lime, Portland cement, and bitumen) and waste materials is still lacking.

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