# Comprehensive review of soil stabilization agents

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**Abstract**. Soil stabilization is a technique that is used in most construction projects to enhance the geotechnical and engineering properties of soil. There is a wide range of research studies related to soil stabilization techniques and agents, these studies discussed the effects of the different types of soil stabilization on soil, the most suitable agent type regarding soil classification, and the challenges that were founded during the application of these processes. Stabilization agents include traditional and non-traditional additives with their different categories were reviewed and discussed in this paper by presenting the results of the recent studies concerned with various types of soil stabilization agents in different laboratories and project tests with highlights on the enhancement of soil properties. In addition to increasing the compressive and shear strength parameters, Maximum Dry Density (MDD), and California Bearing Ratio (CBR) of the soil, the soil stabilization agents play a great role in decreasing the soil plasticity index, swelling, compressibility, porosity, permeability, and Optimum Moisture Content (OMC).

## Introduction

Soil is one of the most essential and plentiful construction materials, its role cannot be ignored and should be employed acceptably. Some of the soil's engineering and geotechnical properties have to be improved to participate in the position in which it is involved such as; sub-grade and sub-base constructions, embankments and foundation constructions, road and rail constructions, backfill for retaining walls and bridges abutments, etc. Soil properties enhancement is signified by improving soil engineering properties and overcoming some of their flaws to avoid replacing them with others that satisfy the required engineering standards for the purpose it is used for. Particularly, the main engineering properties desired from the engineering material are dependent on their functions, type of load which they will withstand, and the environment which they will face. The most central soil engineering properties is soil mechanical strength (shear strength and compressive strength) which is the most important property for soil stabilization, on the other hand, soil density, permeability, durability, plasticity, and compressibility are extremely significant properties [1].

The additives which were studied in civil engineering research related to soil stabilization are categorized as traditional and non-traditional additives. Traditional additives include lime, cement, bituminous, waste/ recycled materials (e.g., shredded tire, plastic bottle strips, crushed glass, etc.), fly ash, slag, etc [2-4], While non-traditional additives consist of various combinations such as nano additives, acids, ions, liquid polymers, fibres, enzymes, resins, petroleum emulsions, silicates, and lignin derivatives. Some of the additives are more common than others, simultaneously, the type of additive added to the soil depend on many factors, such as; the soil

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characteristics ( eg. Plasticity behaviour, organic matter content, grain size distributions, mineralogy and chemical compositions, etc.), stabilization agent characters and the quantity required, and the quality and method of construction. Furthermore, the proper use of additives including the curing time and effective compaction of soil affected the efficiency of the soil stabilization.

The main objective of this paper is to introduce a comprehensive review of the following subjects: (a) present the most common types of soil additives and their compositions, (b) provide how these stabilizer agents assist to enhance the soil geotechnical and engineering properties depending on the findings of recent researches and studies, and (c) introduce the difference between the traditional and nontraditional soil stabilization agents. This paper is provided to display the importance, processes, and types of soil additives in one paper by consolidating the recent studies on this field to be a reference for professional researchers who are concerned with this type of research to improve the knowledge of soil additives and to help in selecting the accurate type of additives for different types of soils.

## General types of soil stabilization agents

Soil stabilization can be defined as the process in which natural soil and cementing materials are added to advance one or more of its engineering properties. physically mixing the desired soil with stabilizing agents together to reach a homogeneous mixture or by mixing stabilizing material to in-situ soil deposits and making interaction by letting it saturate through soil voids [5].

Stabilizing agents lay under many categories which differ from each other by their compositions, cost, availability as a natural material or artificial material, and the ease of usage due to required experts in the construction site. Table 1 shows the most common types of soil stabilizers, their composition, and if they are natural or artificial.

***Table 1.*** *Types of soil stabilization agents.*

| Stabilizer | Composition | Natural or Artificial |
|---|---|---|
| Cement | Combination of calcium, silicon, aluminium, iron and other ingredients | Artificial |
| Lime | Combination of oxides, and hydroxide, usually calcium oxide and/ or calcium hydroxide. | Natural |
| Glass Fibers | Consist of numerous extremely fine fibres of glass. | Artificial |
| Chemical Additives | Calcium, sodium hydroxide, zycobond. | Artificial |
| Polymers | Poly (vinyl alcohol) , Butanetetracarboxylic acid. | Artificial |
| Nano additives | Nano silica, nano clay. | Artificial |
| Organic Additives | Coal humate,peat-gel, biochar. | Natural |
| Recycled Materials | Plastic bottles strips, crushed glass, shredded tires. | Artificial |

Selecting the accurate soil stabilization method and stabilizer may be challenging. It is essential to keep in mind that there isn't a gold set in regards to soil stabilization, this indicates that each construction or project and each soil type will have dissimilar requirements for soil stabilization. It is valuable to be acquainted with the different stabilizing agents that are on hand, then the type of soil, the project category longevity of the project, budget, and environmental concerns may help to choose the proper type of soil stabilizing agent. On the other hand, the method of providing the soil stabilizing agent to the soil may differ from one case to another. Ultrasonic dispersion, direct mixing, and solution mixing are the most frequently used methods for this purpose.

Following are explanations of the effect of traditional and non-traditional stabilizer agents on enhancing the soil properties in detail.

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**Traditional soil stabilization agents**

*Chemical soil stabilization agents*

*Cement*

Using cement as a soil stabilizer agent is the most common product used among many projects due to its availability, cost efficiency, long-term performance record, and its effectiveness in bonding the soil particles by the hydration process, the cement grows as crystals then these crystals interlock to give a high compressive strength. To achieve a strong bond the cement particles should coat most of the soil particles and assure good contact between cement and soil particles; proficient soil cement stabilization, mixing soil and cement properly is extremely necessary [6].

The chemical reaction between the Portland cement which is considered a calcium-based stabilizer and soil (mainly clayey soil) begins once the Portland cement is mixed with soil and may take a specific time to finish, the reaction starts with hydration which may be obtained by one month after mixing, and once the concentration of ($OH^-$) increase the alkalinity of the soil increase and led to develop the pozzolanic reaction. The results of the pozzolanic reaction are seen by increasing the concentration of ($Ca^{+2}$) (which is supplied from the Portland cement stabilizer) and then reacting with (Si and Al) to create a cementitious material as calcium aluminate hydrates (CAH), calcium alumino-silicate hydrates (CASH), and calcium silicate hydrates (CSH) [7]. [8] provided a study on improving the engineering properties of soils taken from Modinagr UP, ABU PUR, in India. The soil samples were tested before and after adding cement as a soil stabilizer for the projects related to railway track base courses, sub-grade, and sub-base courses. Cement was mixed with the soil to reach the preferred properties. The experimental tests which were obtained to study the effect of soil stabilizer (cement) are; grain size distribution, Atterberg'slimits (Liquid, Plastic, and Shrinkage) limits, Proctor Compaction Test, California Bearing Ratio Test, and Direct Simple Shear test. The soil understudy was Silty Sand/ Clayey Sand (SC/SM) soil, the tests showed an improvement of the engineering soil properties after using cement agents with percents (2%, 4%, and 6%) as shown in Table 2.

*Lime*

Lime material is used for both soil modification and soil stabilization depending on two main reactions between the soil and lime, the first one is short-term or quick reactions and the second one is a pozzolanic or long-term reaction which needs time to present the results of improving the engineering soil properties [9]. The reaction between the soil particles and lime require water to occur accurately and the mechanism is completed within four parts; 1. Cations/ions exchange; 2. Agglomeration and flocculation; 3. Pozzolanic reaction; and 4. Carbonation. It is worth mentioning that the carbonation process is not mostly needed because it does not have a significant effect on improving the soil strength. The exothermic reaction between the soil-water system and quick lime (CaO) forms hydrated lime ($Ca(OH)_2$) and increase the workability of the soil, on the other hand, the cations and anions ($Ca^{+2}$, $OH^-$) appear after this reaction, then the cations and anions exchange with clay lattice take place to enhance the clay properties by increasing the pH due to increasing the $OH^-$ ions. The quick reactions help to reduce the Diffuse Double Layers (DDL) which make extremely valuable effects in reducing the swelling behaviour of the clayey soil [10].

To present the effect of lime as a soil stabilization agent [11], treated an expansive soil from the Belgaum district of Karnataka state in India utilizing the lime material, the clayey soil contained quartz, montmorillonite, and aluminium oxide. Hydrated lime ($Ca\ (OH)_2$); which is available as a commercial soil stabilizer was employed, results on treated soil samples showed significant improvement in the engineering properties of the clayey soil, the plasticity behaviour of the clayey soil was enhanced due to reduction in the thickness of DDL because of the raise of electrolyte concentration of pore water and the substitute of monovalent cation ($Na^+$) with the divalent cation

($Ca^{+2}$), this led to a considerable improvement in the swelling behaviour of the clayey soil. Moreover, testing the strength of the treated soil by lime presents an increase in the Unified Compression Strength (UCS) and raises the alkalinity after curing the lime-treated soil for different periods. Table 3 shows the improvement of the lime-treated soil UCS with different curing periods.

***Table 2.*** *Cement-treated soil tests results [8].*

| Test | Notes |
|---|---|
| Proctor Compaction Test | Maximum dry density increased while the optimum moisture content decreased. |
| Direct shear test | The cohesion and internal friction angles were as; c=1.6, Φ=38. With cement percentage (2%, 4%, 6%) the cohesion and internal friction angle were equal to, (c=1.1, Φ=40), (c=0.6, Φ=41), (c=0.6, Φ=40), representivly. |
| California Bearing Ratio test | Max subgrade CBR values are5.07%, 6.62%, 8.23% and 10.15% for untreated soil sample, 2%, 4%,and 6% cement contents respectively |
| The cement increased the bearing capacity ofSC/SM soil effectively, so it is recommended to be used for subgrade of railway track with 6% cement content or more. | |

***Table 3.*** *Strength and pH of lime-treated soil with curing periods [11].*

| Mixes | Curing periods/day | UCS, kPa | pH value |
|---|---|---|---|
| Soil | - | 312.04 | 6.04 |
| Soil+ 6% lime | 0 | 267.68 | 12.04 |
| | 7 | 634.38 | 11.78 |
| | 14 | 971.80 | 11.77 |
| | 28 | 1350.00 | 11.65 |
| | 90 | 1520.00 | 10.80 |
| | 180 | 1700.00 | 10.75 |
| | 360 | 1656.67 | 10.90 |

*Sodium hydroxide additives*

Sodium hydroxide can be described as an odourless, non-volatile, white solution. Which is a highly reactive material, its reactions with water produce heat which is sufficient to set fire to the nearby flammable materials. The useful property due to sodium hydroxide is reacting with soil containing aluminium in presence of water to increase the density of soil in small efforts [12], [13]studied the effect of sodium hydroxide as a chemical soil stabilization agent on the clayey soil rich with kaolinite clay minerals which were taken from the Odooru area in Ogbomoso, Oyo State. The tests were carried through three parts, first as dried samples, second as soaked samples, and at the end, they carried the tests on the cycling samples. Adding sodium hydroxide to the soil enhance each of the following engineering properties as shown in Table 4; compressive strength, the density of the soil, and soil porosity (soil's water absorption). The results showed that the dry specimen provide better strength than wet and cycled specimens. The water absorption less or more raises with increases in the NaOH percentage. even though the increase is not standardized and is relatively small in contrast with other variations. On the other hand, densities of all specimens increased after moulding with increased with all NaOH percentages, this results from the bonding generated by subsequent isomorphous substitution ofAluminium (Al) and alkaline solution.

*Sodium silicates*

[14] used multistep techniques to rehabilitate and stabilize liners (bentonite clay and sand mixtures) contaminated with hydrocarbon fluids using silicate grout solution and pretreatment under the effect of electrokinetic phenomena. Silica grout formulations were developed and adequate curing periods were established for the electro–silicatization process. Results showed that hydraulic conductivity was reduced fourfold in the case of using three-step electro

rehabilitation for alternative fuels under the pressure of 40 kPa, and reduced threefold in the case of 100 kPa pressure on a liner.

***Table 4.*** *Tests results [13].*

| **NaOH (%)** | **Compressive strength (MPa)** | | | **Soil porosity (%)** | | **Density (g/cm3)** | |
|---|---|---|---|---|---|---|---|
| | dry | cycling | wet | Water Absorption for Wet Sample | Open Porosity for Wet Sample | Density after Moulding | Density after curing at 80°c |
| **7** | 29.26 | 5.25 | 4.48 | 8.360 | 17.54 | 2,183 | 2,032 |
| **10** | 36.43 | 10.08 | 11.35 | 9.093 | 17.92 | 2,184 | 2,016 |
| **13** | 40.38 | 11.97 | 19.06 | 10.151 | 20.68 | 2,196 | 1,994 |
| **16** | 47.03 | 18.3 | 21.72 | 10.068 | 20.01 | 2,195 | 1,998 |

*Recycled material (waste plastic bottle strips)*
One of the beneficial usages of recycled material is to utilize the harmful material to the environment as an agent provide an important role in another place in the same environment as a reverse reaction, it is obvious that plastic materials are the most common type of materials should be recycled due to our daily massive production and usage of it as an essential need. [15] investigate the effect of adding the waste plastic bottle strips on the improvement of the soil engineering properties. The natural soil utilized in the study is from the plain of Bihar (Patna), they mixed it with plastic bottle strips (15mm*25mm strips size) which mainly consist of Polyethylene Terephthalatewhich which is produced from petroleum hydrocarbons. A series of CBR tests, Direct Simple Shear tests, and compaction tests were made on the natural soil and the reinforced soil with plastic strips, the results showed a considerable improvement of the engineering soil properties as shown in Table 5. the development in shear strength parameters is most favourable at 0.4% plastic content. The shear stress increases due to the allocation of plastic pieces in various directions along the surface of shear linking two halves of direct shear boxes.

**Non-Traditional soil stabilization agents**
*Polymers and glass fibres*
Polymers can be defined as every artificial or natural substance collected from extremely big molecules which are called macromolecules which are consisting of multiples of unpretentious chemical units (monomers). The usage of polymers increased recently due to their high-performance related to structural materials, one of the disadvantages of polymers is their sensitivity to environmental factors such as; exposure to gases, liquids, radiation, electrical field, and temperature. Polymers are one of the stabilization agents added to the soil to develop its engineering properties, their role can be summarized by the adhesion of the clayey soil particles together then the strength of the soil will be improved, the plasticity and swelling behaviour will be reduced, and the workability will be increased due to forming the flocculated particles [16], [17] studied the effect of polymers (Poly(vinyl alcohol)([-CH2CHOH-]n) which is called (PVA) and 1,2,3,4-Butanetetracarboxylic acid ($C_8H_{10}O_8$) which is called (BTCA) ) on the soil samples classified as highly plastic clayey soil and the soil activity ratio is 0.5 with specific gravity equal to 2.71 from Township in Central Queensland of Australia. Adding PVA and BTCA to the clayey soil with different percentages provides a significant effect on improving the UCS and ductility of the soil; treating the clayey soil with 1% of PVA led to a reasonable raise of the UCS of the clayey soil sample with properties (dry unit weigth= 16.2 kN/m3, water content=16.8% and initial void ratio=0.64), on the other hand, by increasing the percentage of PVA up to 1.5% the UCS raise from 10 kPa to 116 kPa, this show that adding PVA as a soil stabilization agent is very effective due to its availability as an organic material and its nontoxicity. It is worth to be mentioned that

the BTCA does not have any reflect on improving the soil strength but was used to make PVA insoluble in water.

***Table 5.*** *Test results of reinforced soil with plastic contents for strip size of (15 mm 9 25 mm) [15].*

| Percent of plastic content for strip size (15 * 25) mm | Compaction parameters | | Shear strength Parameters | | CBR Ratio |
|---|---|---|---|---|---|
| | OMC(%) | MDD(kN/m3) | c (kN/m2) | Φ(degree) | (%) |
| 0% | 16.8 | 16.75 | 19 | 23.1 | 3.3 |
| 0.2% | 16.1 | 17.5 | 28 | 28.7 | 7.1 |
| 0.4% | 14.2 | 18.4 | 34 | 32.8 | 16.5 |
| 0.6% | 15 | 18.1 | 18 | 27 | 13.7 |
| 0.8% | 16.4 | 17.3 | 13 | 25 | 12.5 |

The influences of fibre glass with nanocomposite are can be obvious on the clay distribution, the mixing of clay with different percentages of fibre glass gave a significant effect on the thermal and mechanical properties of the clayey soil [18]. On the other hand [19] investigated the effect of fibre glass on the durability of clay by treating it with nanophase fibre glass in different conditions; cold and wet, dry with high temperature, wet with high temperature, and cold and dry, they observed an increase of flexural strength and fibre glass modulus

*Nano materials*

One of the most recent common used types of soil stabilization additives are nano materials, which may be mixed directly in different percentages with the soil or used as agents with other traditional soil stabilization agents like cement, lime, bentonite clay for improvement the different engineering soil properties such as shear strength of sand [20]. Nano-Clay and Nano-Silica (pozzolanic material), are the most important nano additives, but Carbon-Nanotube, Nano-alumina, Nano-MgO, and Nano-CuO are also used as nano material soil additives and there are research studies concerned with them.

The definition of nano clay can be summarized as the layered silicates material with the double-layer thickness equal to 1nm and single-layer thickness equal to 0.7nm, the modification of the interlayer of the nano clay made for swelling and plasticity behaviour improvement. Nature of surface atoms, interlayer exchangeable cations, and nanosheet charge are the factors that have influenced the properties of the nano clay particles, the negative charge of the nano clay is due to the isomorphous substitution between the silicon and cations ( $Mg^{+2}$and $Al^{+3}$) [21-23]. [24] treated soft soil with three types of nano materials which are; nano clay, nano MgO, and nano CuO, they studied the effect of the nano materials on the clayey soil behaviour and properties such as; Atterberg's limits, shear strength, and compaction parameters ( MDD, OMC). The soil engineering properties are enhanced by adding the nano materials ( there was a reduction in plasticity index and OMC, and increase in the MDD), this improvement was obvious up to exceeding the optimum contents then the clay particles agglomeration which affects negatively. furthermore, adding nano materials with a percent not more than 1% has a significant effect on improving the compressive strength of the tested clayey soil. Clay materials such as bentonite clay are also used to improve and stabilize various engineerings properties of other engineering materials such as asphalt concrete mixtures concrete, and celleular concrete by the addition of clay in optimum amounts which improved stability of asphalt concrete, its resistance to rapid freeze and thaw, and improved the compressive and flexural strengths of concrete and celleular concrete mixtures [24,26].

## Conclusions

This paper presents a comprehensive review of a range of soil stabilization agents. The following conclusions can be drawn:

1. The two major types of soil stabilization agents can be classified into traditional and non-traditional soil stabilization agents which have a large effect by mixing them with the soil in different amounts and efforts, every additive enhances a specific or more than one specific property of the soil some was used to increase the strength of the soil
and others were concerned with other soil properties.
2. Chemical soil stabilization agents (cement, lime, and sodium hydroxide, silicates) provide a considerable enhancement on the soil properties (mainly on the clayey soil), but the Portland cement stabilizer offers the best strength properties in a short curing time in compassion with the chemical soil stabilization agents, because of its rapid hydration reaction.
3. Recycled materials additives enhance the strength of the soil by reinforcing the soil particles. Other recycled materials may be used such as; cardboard, cereal boxes, aluminium cans, steel cans, and used gallons.
4. Polymers and Nano-materials such as; Nano-Clay and Nano-Silica, provide a significant effect on the soil strength properties, permeability, and compressibility of the soil by enhancing the microstructure of the soil, because of their high cation exchange capacity and their high specific surface area which help them to interact with soil particles.

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