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Comment On Energy-Efficient Alternative for Different Types of Traditional Soil Binders

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Abstract: Due to urban sprawl, the demand for land has increased for the purpose of construction. It is unlikely that soil available at different construction sites will be suitable for designed structures. For improving the load-bearing capacity of the soil, different soil binders are used, which are present in distinct states. In this review, the authors have collected details about various binders, which are generally used in the soil stabilization, and their effect as a binding agent on the soil. In this article, the authors tried to review different traditional binders. After studying various research articles, the authors found that lime, ground-granulated blast slag (GGBS) polypropylene, polyurethane grouting, and asphalt mix are frequently used binders. However, the authors also gathered information about the negative environmental impact of these traditional soil binders, which led to the need for alternatives to these commonly used soil binders. To diminish this issue, different alternate hydraulic and non-hydraulic binders are discussed. The authors found alternatives to cement and lime with the alkali-activated material consisting of Na_2O and silica modulus and belite-calcium sulfoaluminate ferrite, which is also known as "Aether™." According to the research, both alternatives emit 20–30% less CO_2 into the environment and also improve the compressive strength of the soil. The various studies promotes bitumen modification. Incorporating 20-mesh crumb rubber and bio-oil into the bitumen reduces its viscosity and improves its fatigue value. When waste oil is mixed with asphalt, it revitalizes the bitumen, improves fatigue resistance, and increases compressive strength. The soil particles treated by Eko soil are held together by enzymes, which give them the same strength as cement. Apart from that, low-carbon binders such as basic oxygen furnace slag, bamboo fiber, enzyme-based soil treatment, zebu manure for stabilization, and lignin-contained biofuels and coproducts are discussed. Replacing these traditional binders helps with energy savings. All waste products are recycled, and energy is saved by not manufacturing traditional binders. Additionally, energy is saved, which is required to avoid the detrimental effects of these conventional binders, making them energy-efficient alternate binders. The authors also summarize the methods used, impacts, and changes that occur in soil properties after using substitutes in place of traditional binders. From the review, the authors determined that different binders have various properties in terms of chemical and physical compositions, and they show different variations in terms of strength when added to soil with low bearing capacity or poor stability.

Keywords: binders; soil stabilization; biochar; BOFS; enzyme; Eko soil; lignin; zebu manure.

1 Introduction

Soil stabilization is a technique used to improve soil stability. Stability can be accomplished either by mechanical methods, i.e., compaction, geo-synthesis, and vibration anchors, or by chemical means, i.e., mixing some chemical binder, e.g., polymers, bentonite, amines, etc. [1]. In this article, the authors only consider chemical binders for review.

Soil binders are chemical compounds added in a controlled manner to improve the stability of the soil [2]. The first known application of chemical binders by mixing weak soil of path subgrade with a stabilizing agent such as limestone and calcium was done by the Mesopotamians and Romans [3].

To achieve the desired level of strength, chemical binders depend on admixtures [4]. Soil binders function by penetrating into the surface of the soil. They stick to soil particles. Binders have adhesive properties. So, they improve the attraction between particles. Since

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most of the binders are generated by chemical reactions and are soluble in water, they only provide temporary solutions against weak soil and require reapplication after being washed away. In addition, for dense soil, they are ineffective since it is difficult for them to penetrate the soil [5].

Numerous chemical compounds are used as soil binders in the construction industry; some are known and others are still unknown to most of the world. Through the study of past papers, the authors found that cement and lime are the most commonly used soil binders. The choice of cementitious binders is based on how well they improve the soil's plastic limit. A plasticity index (PI) of 10 is accepted as the threshold. Cement generally reaches a threshold, which is why cement is preferred over lime, ignoring the cheapness of lime. In addition, the application rate affects the selection of a stability agent [3, 6].

Although various research studies have been done on chemical stabilization, there has been no collective review. Hence, by going through different past research studies, the authors intended to: (i) provide a brief overview of different traditional soil binders, including hydraulic and non-hydraulic binders systematically; (ii) assess the need for alternatives to these traditional soil binders and their ecological impact; (iii) provide a collective review of different novel binders that are alternatives to traditional binders under different categories (i.e., categorization is done on the basis of the material they are made of); (iv) discuss the properties, working method, and effectiveness of different novel soil binders; (v) assess the effect of these binders on the environment; and (vi) review the pursuit of energy-efficient alternatives to these traditional binders. The authors believe that the significance and uniqueness of this review will help the forthcoming contributors to the scientific society.

2 Discussion

2.1 Traditional binders used for stabilization

The chemical method of soil stabilization relies on the addition of an exogenous stabilizer. The different soil stabilizers having distinct working approaches, benefits, and harmfulness resulted in improving mechanical properties, durability, and impermeability in problematic soil [7]. In this part of the review, traditionally available stabilizers are categorized under different captions and their stabilizing capacity, methodology, and so on are discussed.

2.1.1 Mineral binders

Mineral binders are those chemical compounds that have organic or inorganic minerals, and they react either with water or with air to develop some binding properties. The mineral binders are subcategorized into the following categories.

2.1.1.1 Hydraulic binders

Hydraulic binders are minerals that need water to react in order to develop cementation properties. The process is known as hydration. They are generally available in fine powder form, and their large surface area helps in a more rapid, effective, and complete chemical reaction. They produce energy during hydration in the form of heat. Following some previous work on binders, the authors discovered some of the most commonly used hydraulic binders, which are described in the following subsections.

2.1.1.1.1 Cement

Cement is a synthetic chemical binder extensively used as a building material. Since its first introduction in 1824, the demand for cement has increased dramatically, from 62.4 million metric tons in 1980 to 3.06 billion metric tons per year [8–10], which is expected to exceed the limit of 5 billion tons by the year 2030 [11, 12].

The use of ordinary Portland cement (OPC) is very extensive for binding purposes; OPC is made in a rotary kiln at 1450°C by burning limestone and silica together. The fusion gives clinker (Ca_3SiO_2), which later by hydration takes on a solid form. Dry mixing of OPC in problematic soil at optimum moisture content (OMC) stabilizes the soil by holding soil particles during the hardening process. Curing is also a much-needed process that helps di- and tricalcium silicates (formed during burning in the kiln) form more calcium silicate hydrate (C–S–H) gel, which is responsible for the later strength of the cement [8, 13]. The ease of availability and mass production with little effort to apply it in soil made cement the most demanding soil stabilizer.

2.1.1.1.2 Lime

Lime stabilization is a very appealing stabilization technique used widely to improve soil. A vast range of research studies has been done on lime stabilization of problematic soil [14–21]. Quick lime is shown in Figure 1 [22].

Past papers suggested that lime reacts with fine-grained soil, reduces swelling, decreases plasticity, and increases workability and strength [4, 21, 23, 24]. It is found that lime takes time to develop strength about 14–28 days in hot and cold weather, respectively [4]. An increase in lime content decreases plasticity and increases strength [15, 16, 18, 21].

There are two indicating parameters for the optimum amount of lime mixing for stabilization, which state that the initial design lime content is the lowest amount of lime that achieves a pH of 12.4 and the optimum amount is the lowest amount of lime that decrease plasticity of soil. [4]. Deliberately delaying compaction (by 48 hours) decreases the dry unit weight of treated soil by 18% [25]. As lime is a key ingredient in cement; hence it is obvious that lime is widely used as a stabilizer prior to cement.

Figure 1: Quick lime.

Figure 2: Hydrated lime.

2.1.1.1.3 Other hydraulic binders

Mixing lime and cement can provide a balanced soil binder as they are both good binder materials, and adding lime reduces the cost of the overall stabilizer mix. Cement and lime are both capable of providing soil stability, but cement meets the threshold of PI of 10, hence it is preferred over lime. Apart from these two binders, there are some other hydraulic binders that are used in the construction. Other than that, a mix of pozzolanic rock dust and hydrated lime makes a hydraulic binder. Hydraulic binders show great affinity for water and should be stored in a dry place to avoid premature hardening. However, hydrated lime is non-hydraulic in nature, and when combined with pozzolana, it forms a new hydraulic binder [26, 27].

2.1.1.2 Non-hydraulic binder

Clay is the most common non-hydraulic binder, which causes soil to harden and get soft according to the availability of moisture, respectively. Non-hydraulic binders are those minerals that do not require water to impart cementation properties. This review provides information about some traditionally used non-hydraulic binders.

2.1.1.2.1 Hydrated lime

The hydrated lime {$Ca(OH)_2$} formed after quick lime combines with water is called as slacking.

$$2CaO + 2H_2O–2Ca(OH)_2 + Heat$$

It is inorganic in nature and is a fine white powder as shown in Figure 2 [28].

Hydrated lime is convenient to use as it does not require a slacking agent, i.e., water. A binder addition of 2% of hydrated lime into the soil (dry wt.) makes the soil nonplastic because hydrated lime minimizes the 0.0002 mm particle and therefore stabilizes the soil [17, 29].

Hydrated lime is also referred to as portlandite due to its crystalline structure, and thus has thermal stability (against 500°C). Hydrated lime is also used for heavy metal absorption in contaminated soil. The smaller the size of absorbents (i.e., hydrated lime), better the heavy metal absorption [30]. Due to rapid carbonation, newly generated $Ca(OH)_2$ accelerates cement hydration; when 50% of cement is replaced with hydrated lime, it fills the pore, but there is a decrease in flexural and compressive strength with increasing hydrated lime percentage [31]. In addition,an other studyfound that nanohydrated lime fills the pores and provides better results against fatigue [32].

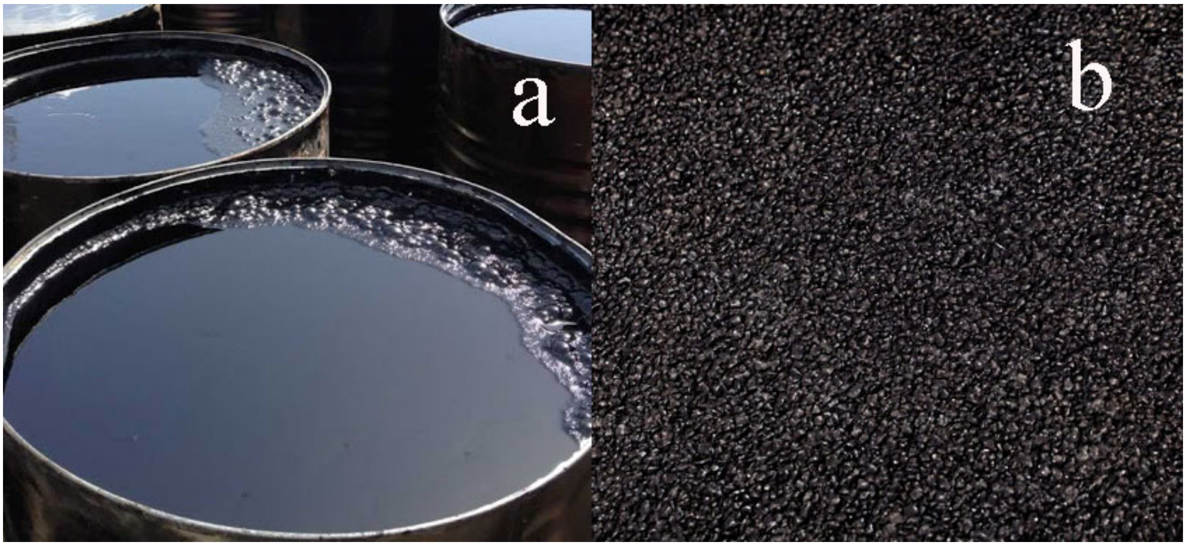

Figure 3: (a) Bitumen; (b) asphalt.

2.1.1.2.2 Gypsum

Calcium sulfate dihydrate ($CaSO_4.2H_2O$) is a non-hydraulic binder having a soft, crystalline form commonly known as gypsum. It is an industrial by-product generated from the evaporation of sea water during fertilizer manufacturing from phosphate rock (phosphogypsum [PG]). Gypsum is used as a retarder to delay setting in all hydraulic cements. Several previous studies suggest that gypsum can help to stabilize clay soil [33]. Mixing gypsum can improve CBR and compaction, whereas PG improves index properties and strength after 40% addition in expensive soil [34]. However, the poor performance of gypsum in water limits its use [35].

2.1.1.3 Thermoplastic binder

Traditionally, the only thermoplastic binder used was sulfur. A study from the past states that there were 70 million tons of sulfur in the world in 2012, and only Iran's petroleum refinery produced 2 million tons of waste sulfur. To mitigate this problem, the use of sulfur waste as a binder is a very good move. A mixture of aggregate and elemental sulfur without cement and water is known as sulfur concrete, which is used as a binding agent [36, 37]. There are numerous research studies that try to improve the mechanical and physical properties of sulfur concrete [38–42]. Sulfur is modified with Syed Mohammed Zargham polymer by mixing it with the melted sulfur at 120°C in order to stabilize the soil. In all, 180 days of curing show that modified sulfur decreases the dry unit weight. Additonally, compressive and direct shear strengths are increased [37].

2.1.2 Bituminous binder

Low-grade crude oil with a complex hydrocarbon structure is called bitumen. It is a highly viscous, black, sticky, and semisolid form of petroleum [43, 44]. In general, penetration-grade bitumen (made from the destructive distillation of crude oil) is used. The other form of bitumen is gilsonite, which is naturally occurring, shiny, smooth, and hard bitumen. It is soluble in organic solvents, hence its use in powdered form.

For soil stabilization, thoroughly mixed soil and stable base or wearing surface of bitumen material are prepared. The stabilization can be performed by selecting one of the bitumen types, i.e., asphalt cement, asphalt cutback, or asphalt emulsion. Results show that bitumen imparts load-bearing capacity and also improves cohesion [6]. Weather conditions such as temperature and water affect bitumen. Temperature increases the penetration, and water causes the loss of adhesion between binder and aggregate and causes separation [45].

2.1.2.1 Difference between bitumen, asphalt and tar

Bitumen is obtained from refined crude oil and has hydrocarbon substances. Tar is also a hydrocarbon, but it is obtained through the distillation of wood or coal. It contains high levels of benzene and is carcinogenic. However, asphalt is considered as a mixture of aggregate and bitumen. Figure 3 [46] shows bitumen and asphalt. Generally, tar is used in pavement construction.

2.2 Need of alternatives

If there is any gap in the existing technique, the need of advancement is required. The traditionally used binders impart good strength to soil stabilizing the expensive soils, but there are some major issues that drive researchers around the world to seek alternatives to these traditional and widely accepted binders. There are four major factors listed here that necessitated looking beyond traditional binders.

2.2.1 Environmental impact of traditional binders

The widely accepted binder is cement. The rapid growth in the demand for cement is causing industries to produce more and more cement. Cement is made in a kiln where raw materials (such as lime and silica) are burned at 1450°C.. The carbonation caused lime to release CO_2, which is a major contributor of greenhouse gases. Estimating that cement plant causes 5–7% of CO_2 emission. Each ton of cement produced emits 0.89 tons of CO_2 [11, 47, 48]. Since cement manufacturing requires heating up the clinker at 1500°C, it is a very energy-consuming sector [49]. Gases emitting from the manufacturing of nitrogen and sulfur are also a concern for health [50, 51]. The use of lime also causes air pollution [18, 52]. Bitumen's benzene causes cancer and also pollutes the air. Hence, using an alternative to this traditional binder can actually assist in saving the environment.

2.2.2 To manage the waste from different industries

The demand for different useful materials causes industries to produce more waste day by day. Since most of the alternate binders are made of waste, there is a good chance of taking care of the masses of waste. Reusing industrial by-products and waste, such as coal fly ash, blast furnace slag, cement kiln dust, carbide lime, resulted in an environmentally friendly option [18]. By utilizing the waste, it may be possible to minimize the hazardous and health-threatening waste to remove from our environment.

2.2.3 To improve the utility of existed binders

Normal lime takes several weeks or months to attain its strength, and when used alone, it does not provide sufficient strength [18, 52]. However, combining an additive or a waste material in an optimal amount can improve lime. Mixing additive precursors and activators helps the binders increase the soil's strength-bearing capacity. In addition, some modifications can be made to stabilize some unstable hazardous matter to make it useful for stabilization. For example, bitumen shows oxidation when exposed to weathering conditions, which causes a reduction in flexural strength and fatigue and allows thermal cracking. However, adding some rejuvenating agents restores asphalt's flexibility and improves its utility [53].

2.2.4 To make stabilization process cost-effective

One of the major factors in producing alternatives to these long-established binder materials is to make them cost-effective. Alternatives not only make it a better stabilization agent but also cut the cost. Cement, bitumen, and other traditional binder materials are expensive. However, mixing the usual binders with additives or waste significantly reduces the cost [54]..

2.3 Advancements on different alternative and modification of traditional binders

The discussion in the previous section justifies the requirement of alternative and modification on different traditional binders. With the help of previous studies, the author tried to collect and compile information about various alternate options under different following captions.

2.3.1 Alternatives and modifications on cementitious binders

In general, lime and cement are used as soil binders around the world, but CO_2 emissions during production from both binders raise concerns. The required energy is also high to produce them. The authors try to take a glimpse at different cementitious binder alternatives in this review.

2.3.1.1 Alkali-activated material (AAM)

AAMs are waste materials in general mixed with alkali-activating agents. Alkali activator can be either a calcium-rich or aluminum-abundant precursor [55]. AAMs require less energy and emit less CO_2 [56]. The main aspect of this

Figure 4: Used bio-oil and crumb rubber.

work is activating media such as sodium oxide content (Na_2O %) and silica modulus (MS). Results show that Na_2O% improves setting time and compressive strength. However, the MS value affects the heat of hydration and drying shrinkage [57].

2.3.1.2 Use of GGBS on sulfate containing soil

Soils having sulfate content cement cannot be used directly as it can cause the sulfate to move. GGBS is a great alternative in this situation to count. It can show great results as it allows soil to swell less (≤5%) and also holds 89% of sulfate and does not allow them to mobilize [58].

2.3.1.3 Two novel binders for stabilizing zinc (Zn) and chlorine (Cl) in soil

GM and KMP are considered new binders to stabilize soils containing Zn and Cl. GM is a mixture of GGBS and MgO (reactive agent) in the ratio of 9:1 in dry mass, respectively. And KMP is a mix of KH_2PO_4, MgO (reactive agent) and phosphate rock powder in the ratio of 1:2:1 in dry mass, respectively. These ratios help minimize the level of leaching ability and impart high strength to the soil [59–61]. The use of 6% of GM-KMP and 23% of water allowed soil to stabilize the Zn and Cl after 28 days of curing. It also increased strength by five times [59, 62].

2.3.1.4 Belite-calcium sulfoaluminate ferrite (BCSAF) cements

The production of BCSAF cement emits 20–30% less CO_2 with similar performance to OPC. Hence, it is a very good substitute for cement, considering environmental aspects. Lafarge recently gave the name “Aether™” to this kind of cement [13, 54].

2.3.2 Modification on bituminous binders

To improve the performance of bitumen, some modifiers are added to it. These additives alone are not capable of replacing bitumen, but with bitumen, they improve stability against weathering action and also cut the cost.

2.3.2.1 Bitumen mixed with crumb rubber (CR) and bio-oil

Compatibility analysis shows that bitumen can be mixed with CR with the help of the CR crossed-link network. Surface activation and additive grafting are useful in linking. The virgin binder’s lower rutting resistance does impact the mixing of bitumen and CR. Since the difference in densities of these two materials can cause phase separation [63, 64]. Hence, bio-oil is introduced to the bitumen CR mix; it improves the binding properties. In Figure 4 [65], used crumbed rubber and bio-oil are shown. Results show that 20-mesh rubbers impart greater viscosity to the mix. Bio-oil enhances the performance of the mix at high temperatures [65].

2.3.2.2 Virgin bitumen binder is mixed with the waste cooking oil

Waste cooking oil from the restaurants after frying process can be mixed with virgin binder. The properties of waste cooking oil are presented in Table 2 [53, 65, 66]. According to Bailey and Philips [53], the mixing of waste oil decreases the viscosity of the binders. The viscosity after the addition of waste oil is discussed in Table 1 [66]. The mixing of waste cooking oil with bitumen added the same penetration value as the virgin bitumen [66].

2.3.3 Polymer-based binders

Soil stabilization using polymers has to attract the attention of the researchers by aiming to provide a better and complete understanding related to the assumed behavior of the polymer-treated soils. In general terms, polymers are large molecules composed of repeating units called monomers. A polymer is usually formed through the polymerization of monomers and exhibits physical and chemical properties that are different from the monomers. Both natural and synthetic polymers have reportedly been used to stabilize soils [1, 68–70]. Polymer and emulsion are novel binders that can be used to bind soil without the use of water in an emergency. The pertinence of emulsion- and polymer-based binders is high.

2.3.3.1 Use of polypropylene as the binder

The use of polypropylene as the binder in clay particles shows that polypropylene acted as a nano-filler; SEM images of nano-filler are shown in Figure 5 [71]. This decreased the plasticity of the clay and also decreased its compressibility. It improves higher vertical effective yield stress, resulting in the reduction of volumetric shrinkage. It also significantly improves the tensile and shear strengths of clay.

Another application of polypropylene polymer is to use it as a fiber in the soil, which is stabilized with some primary stabilizer. Past research considers soft soil treated with a binder mixture composed of Portland cement and granulated blast furnace slag, with a proportion of 75:25, respectively [72]. The polypropylene fiber has a length of 12 mm and a diameter of 32 μm. If a low number of fibers are mixed, then it shows that it stabilizes the soil structure and reduces stiffness; the compressive and direct tensile strengths also change the structure from brittle to ductile. Research also shows that in flexural strength tests, fiber does have utility, but in direct tensile tests, fiber does not have any impact [72].

Table 1: Viscosity changes in different temperature of bitumen source [66].

Oil content (%)	Viscosity (Pa.s)		
	120°C	**150°C**	**180°C**
0	1.074	0.231	0.074
2	0.844	0.200	0.064
4	0.723	0.172	0.060
6	0.607	0.151	0.053
8	0.504	0.131	0.046
10	0.429	0.117	0.044

Table 2: Chemical properties of used cooking oil source [66].

Type of free fatty acid	% of waste cooking oil
Oleic acid	43.67
Palmitic acid	38.35
Linoleic acid	11.39
Stearic acid	4.33
Myristic acid	1.03
γ-Linolenic acid	0.37
Lauric acid	0.34
Linolenic acid	0.29
Cis-11-eicosenoic acid	0.16
Heneicosanoic acid	0.08
Total	**100.00**

2.3.4 Enzyme-induced binder

Sustainable option for binding agent is a matter that draws attention of researchers toward enzyme-induced binder.

2.3.4.1 Enzyme-induced carbonate precipitation (EICP)

EICP is a method based on a principle to make use of urea presented in soil by ureolysis, which helps precipitate carbonate inside the pores of the soil. Studies show that the unconfined compressive strength of EICP-treated sand is greater than 10% of that of OPC-treated soil [73].

2.3.4.2 Eko soil (ES) enzyme

ES enzyme is a man-made model of termite saliva. When contacted with clay particles, it accelerates a standard compacting process to create a surface with the same

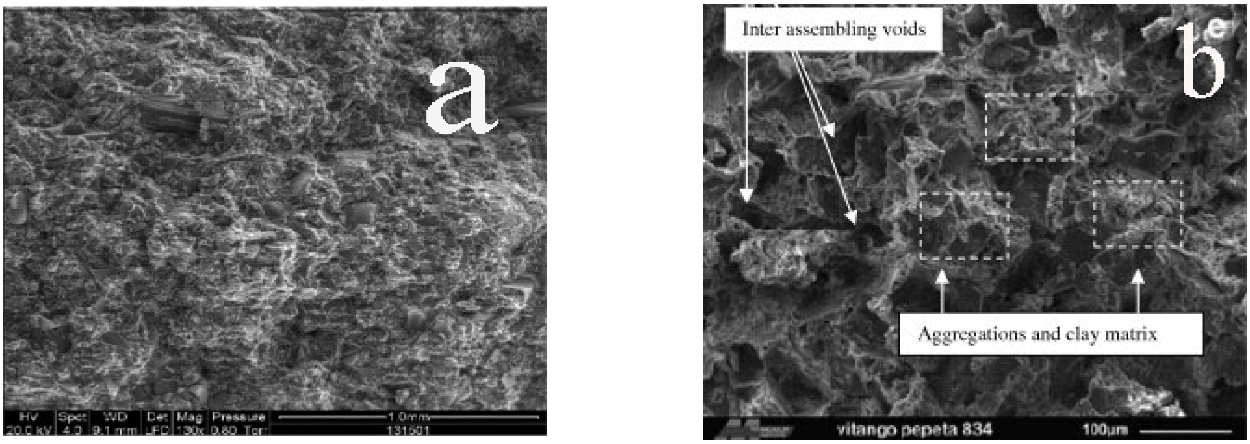

Figure 5: (a) SEM image of tested clay without stabilization and the microstructure. (b) SEM image of the fractured surface of a clay–polymer nanocomposite.

Table 3: Physical and chemical properties of Eko soil enzyme source [74].

S.N.	Properties	Value
1	Specific gravity	1.05
2	Boiling point	212°F
3	Evaporation rate and vapor pressure	Same as water
4	Appearance and Odor	Liquid, brown color, slight ferment
5	Solubility in water	Infinite
6	pH	4–5.5

strength as concrete. Physical and chemical properties of the ES enzyme are represented in Table 3. It is used to stabilize red mud and waste generated from aluminum production. The properties of red mud are discussed in Table 4 [74].

The study shows that 4% of ES addition increases the dry density of the red mud. In addition, after 45 days of curing, it increases the soaked CBR to 580.9% and the unconfined compressive strength (UCS) to 578% [74].

2.3.5 Green and low-carbon binder

Low-carbon binders are binders that emit low-carbon content when used. And green binders are the binders that emit less greenhouse gases when in use. They are safe for the environment as they are mostly by-products or plant-based binders. The increase in environmental concern attracts the attention of the researchers, who take a deep dive into the related field.

Table 4: Geotechnical property of red mud [74].

S.N.	Laboratory test	Numeric value
1	Specific gravity	3.02
2	Gravel (%)	0
3	Sand (%)	8
4	Silt (%)	75
5	Clay (%)	17
6	Color	Red
7	Liquid limit (%)	45.5
8	Plastic limit (%)	3204
9	Plasticity index (%)	13.01
10	Shrinkage limit (%)	2.78
11	Indian standard soil classification	MI
12	Maximum dry density (%)	1.59
13	Optimum moisture content (%)	33
14	CBR, soaked (%)	1.422
15	CBR, unsoaked (%)	6.219
16	UCS (MPa)	0.0143
17	Permeability	$5.786e^{-7}$
18	pH	11.3

2.3.5.1 Basic oxygen furnace slag (BOFS)

The usage of BOFS activated with mixed calcium carbide residue (CCR) and PG is used to stabilize the heavy metals resulting from industrial contamination. The results indicate that the inclusion of the BCP binder increases the pH of the soil, the UCS, and the relative binding intensity index (*I*R) and also mitigates heavy metals such as nickel

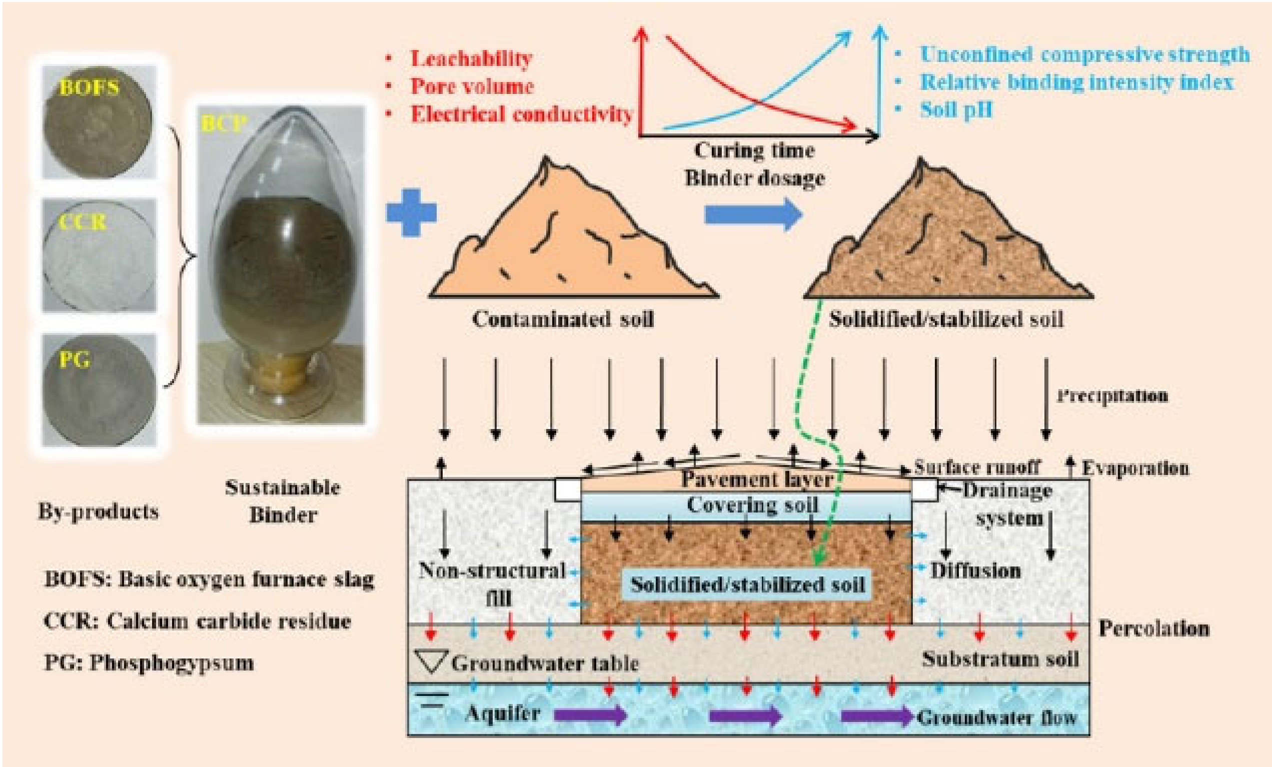

Figure 6: A graphical representation of the BCP binders.

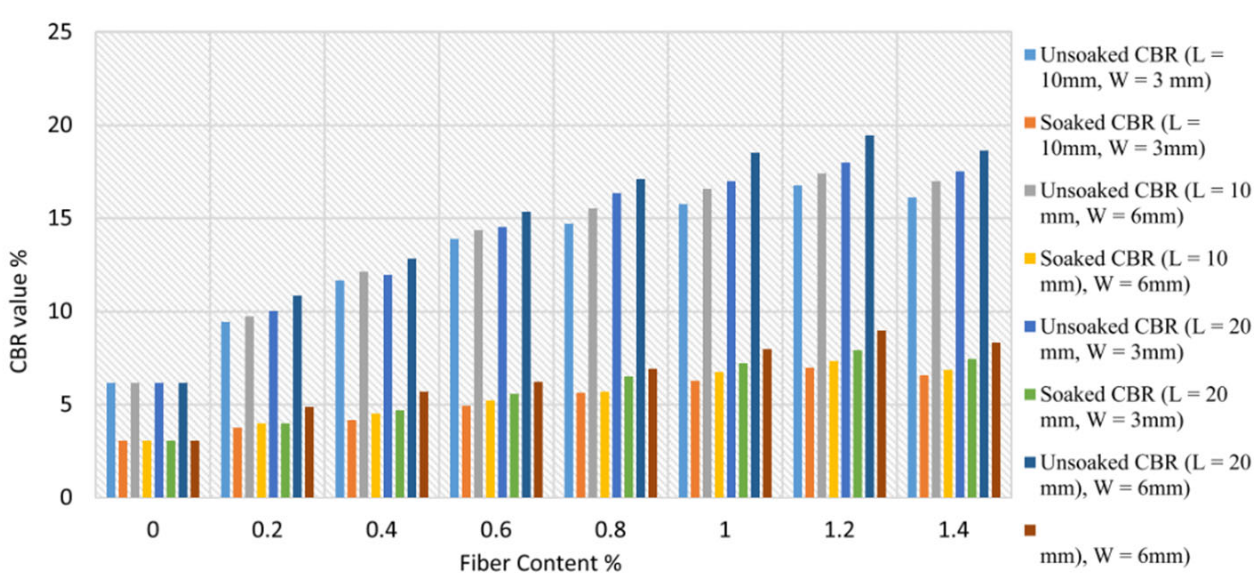

Figure 7: CBR value with different bamboo fiber percentage.

(Ni) and zinc (Zn). However, it reduces the electrical conductivity and leaching ability of the treated soil. The binder forms a C–S–H gel, which stabilizes the heavy metal to mobilize. The process of BCP binder activity is shown in Figure 6 [75].

2.3.5.2 Addition of natural bamboo fiber

The addition of natural bamboo fiber, as shown in Figure 9, improves the soil. According to the research, the inclusion of bamboo fiber of sizes 10–20 mm in length and 3–6 mm in diameter at OMC of soil shows that it holds

Table 5: Comparison between different methodologies applied for using different soil binders by previous researchers and their obtained results source: author.

S.N.	Used binders	Methodology	Obtained result	References
1	Sweet potato, zebu manure, banana leaves, and trunk	Laterite soil mixed with the paste of binding agent by kneading, molding, and curing the compressed earth block (CEB) is obtained.	85:15 of ratio of laterite and LE agents leaf and trunk, respectively, gives the best results among different ratio. Compressive strength of 3.9 MPa and 1.7 MPa is obtained in dry and humid condition, respectively.	[79]
2	FARmLG (fly ash, red mud, lime, and gypsum)	This new binder mix is synthesized with marine dredge soil with different percentages of gypsum and red mud; other components (fly ash and lime) were fixed.	This new mix imparts strength, stiffness, and hydraulic resistance capacity; this new binder is also classified as nonhazardous.	[80–83]
3	Glass fiber-reinforced sulfur mortar made with dicyclopentadiene-modified sulfur	Sulfur modified with dicyclopentadiene and glass fibers of 6 and 12 mm are added to the mix.	Splitting tensile and modules of rapture increased by 147.44 and 83%, respectively. However, compressive strength is unchanged.	[42, 84–87]
4	Volcanic ash-based geopolymer	Making a slurry of volcanic ash and NaOH solution and applying it to a soil specimen.	Shear strength is increased with increased binder percentage. Also, cohesion is increased.	[88–91]
5	SiO_2 used as binding agent with rice husk GGBS fly ash and $CaCl_2$	Silica fume is added to black cotton soil by 20% of the soil's weight, and other binding agents are added in soil accordingly that is presented in the respective paper.	Decrease in the plasticity of black cotton soil also imparts strength and stabilizes the soil.	[92]
6	Combining bio char (BR) with magnesium potassium phosphate cement (MC)	Different percentages of BR:MC are introduced to the Pb-contaminated soil.	BR:MC of 50:50, respectively, shows the best result to help in the immobilization of Pb with 73%. Cost-effective option on heavy metal removal.	[93]
7	Biofuel coproducts (BCPs) containing lignin (complex organic polymer, key structural material to support tissue of plants)	Liquid type and powdered BCP are mixed with soil to determine the physical and mechanical behavior.	BCP increases the compressive strength and, in coarse soil, BCP imparts high strength, freeze-thaw durability, and moisture susceptibility.	[94]
8	Marine soil stabilization with MgO	MgO is added to the soil and dry mixed for 10 minutes with a mixer to ensure homogeneity.	Addition of MgO increases yielding stress; as MgO content increases but drops soon as the initial void ratio changes and the compression index C_c and recompression index C_r increase, MgO solidifies the soil, which continues to gain strength until 28 days after curing.	[61, 95–97]

Continued Table 5: Comparison between different methodologies applied for using different soil binders by previous researchers and their obtained results source: author.

S.N.	Used binders	Methodology	Obtained result	References
9	Alkali-activated material (AAM)	GGBS, sand, and Na_2O are mixed and prepared as a paste, and it is kept for 24 hours. Cubes of 25 × 25 × 150 are made, and alternate curing and resting are done for 2, 7, 28, and 90 days, respectively.	Na_2O increases setting time and compressive strength.	[56, 57]
10	BCASF cement making	Raw mix contained 60.01% limestone, 28.34% clay, 6.58% gypsum, and 5.07% Fe2O3. At 1400℃, good clinker is made having lime % ≤0.2%.	Good cement substitute and environmentally friendly.	[54]
11	Bitumen and crumb rubber with bio-oil	Crumb rubber is stirred into heated asphalt for 30 min at 170℃, after 30-minute bio-oil is mixed in the same manner.	Increase viscosity and improve high-temperature performance of asphalt.	[63, 65]

Figure 8: Bone glue.

the soil particles together and provides control in rapid volumetric change. The ductility and CBR value also get better when adding more fiber to the soil, as shown in Figure 7. The CBR value increases with the size of the fiber. The optimum fiber dose is found to be 1.2% [76].

2.3.5.3 Modification of asphalt with bone glue

Bone glue, shown in Figure 8, is extracted from animals and helps modify asphalt. They are waste-derived materials that can provide green options for stabilization. The addition of bone glue to asphalt minimizes penetration, and an increase in softening point and ductility is noted [77]. Mix imparts great improvements in complex shear fatigue, creep compliance, and shear modulus [78]. In addition, combining bone glue with fly ash and using it as an additive in asphalt results in a more fatigue resistant pavement. The study takes 60/70 grade of binder and mixes fly ash in the optimum percent of bone glue, i.e., 10% mixes; the results show great resistance to fatigue and improved moisture sensitivity [67].

3 Limitations on previous research

By going through various previous works, the authors found that the use of waste material is common practice for alternatives to soil binders, but these are only laboratory studies. There is no in-depth in-situ application study of these alternate binding agents that would give us a real set of data on their effectiveness. In addition, waste from industries is impure, which requires purification, which is a time-consuming practice that costs money too. Since most alternatives are waste products, they require activation by some chemical addition, which is also a money and resource-consuming practice. Some waste material contains hazardous and radioactive substances, which can be harmful and require neutralization before use.

4 Conclusions

This study presents an organized review of numerous soil stabilization methods that use various soil binding agents in the process. This study indicates that there are a number of different soil binders used in different research

Figure 9: Natural bamboo fiber.

studies. Based on previous works, the authors reviewed 97 relevant papers, and by drawing information about different soil binders and discussing their properties, working methodology, and effectiveness, as well as the need for alternatives to traditional soil binders with their environmental impact, the authors achieved thereall goals discussed earlier. By going through all previous works, the authors gain key inputs about alternatives such as various waste materials as binder, e.g., GGBS, GM, KMP, AAMs, BCSAF, they all can utilize as soil binders. In addition, the modification of asphalt by various additives, i.e., CR, bio-oil, waste cooking oil, bone glue, and so on, plays a great role in improving the binder's performance. A green and low-carbon-emitting option and a man-made termite saliva model (Eko enzyme) are discussed.

Discussing about soil binding, there are some specific requirements that should be met, including: (i) better stabilization method, (ii) more economical options for binders, and (iii) a binder that can stabilize soils with specific needs. Various binders and their alternatives are discussed in this review, and the findings of this study are listed as follows:

– The adhesive responsible element C–S–H gel in cement, the carbonation of quick lime and its effect on soil plasticity, the effect of lime with cement combined as a binder, and the influence of mixing pozzolana with hydrated lime as a hydraulic binder are studied and reviewed in this paper. They decrease the plasticity of soil and also help in increasing the ultimate compressive strength of the problematic soil.
– Hydrated lime's portlanite crystalline structure that imparts a non-hydraulic nature after slacking, as well as gypsum's lack of water affinity, are discussed in previous sections of this paper. They are highly unstable binders; hence, they should be mixed with other binders before use.
– Sulfur as a thermoplastic binder and bituminous binder, with their notable roles as binding agents, are discussed in this review. After 180 days of curing, modified sulfur decreases the dry unit weight. In addition, compressive and direct shear strengths are increased. Alternatives to these customary binders and reasons for the requirements of these alternatives in industries are also included.
– By studying past papers, the authors found some binders that are used for different special purposes; for example, GGBS's effect on sulfate-containing soil, GM, KMP is used to mitigate Zn and Cl present in the soil also BCSAF as well as AAM's positive effect on the environment.
– Some modification methods are also found on previously used binders that make them better for stabilization, such as the mixing of CR and bio-oil in bitumen to impart flexibility, the mixing of waste cooking oil in bitumen to improve its compressive strength and viscosity, and the use of bone glue and coal fly are also used to improve fatigue and moisture sensitivity.
– A small number of sustainable and green binders are also briefly discussed, providing insights into the advancements of soil binding selections. Since most of the green binders are retrieved from waste materials, they are both economical and environmentally friendly. The addition of bamboo fiber to problematic soil increases CBR value, the use of BOFS with CCR and PG, and reduces the environmental burden.

5 Future scope

This review required to understand the concept of soil binders and their properties. There should be a dearly effort to understand the soil and their nature, which will provide us with knowledge of the required binder and eventually lead to the selection of suitable binder. This will help us utilize time, energy, money, and materials effectively to achieve our goal of treating problematic soil. In this review paper, we attempted to collect and compile as much information about different soil binders as possible. The authors tried to gather the information about the different alternatives so that future researchers would find this article helpful. It is the best belief of the authors that this work will lead future researchers to the suitable selection of binder according to their needs.

In this review paper, the authors archived various methods of soil binding, which will help people around the globe. The authors found that excessive use of traditional binders resulted in environmental damage. It is not suitable to use these soil binders on a large scale due to the previous reasons alone. Hence, the compliance of the details of these binder's alternatives helps and inspires the researcher's society to give their energy to exploring new, cheap, and sustainable options. The authors suggested that there has not been enough study done on Indian soil. In addition, there are some limitations on the application of various binders obtained from industrial waste. There should be methods that purify and remove the hazardous substances in this waste effectively and quickly with less resource consumption; similarly, other options for binding agents obtained from other waste materials should be taken into consideration apart from this particular waste. Hence, future researchers should make an effort to fill this gap and achieve more environmentally friendly and cost-effective binders in the future.

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