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Chemical Soil Stabilization for Improved Load-Bearing of Road Embankment: A Concise Review

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ABSTRACT

Soil stabilization transforms unsuitable materials into usable ones with desirable engineering properties. It can be categorized into mechanical and chemical stabilization. Mechanical stabilization involves processes like compaction and drainage to change soil characteristics, while chemical stabilization uses chemicals to alter soil properties via chemical reactions. Soil properties are modified through chemical reactions like hydration and pozzolanic reactions. This results in higher strength, lower permeability, and reduced plasticity and shrinkage. Chemical stabilization dates back over 5000 years. Ancient civilizations used mixtures like gypsum and lime to construct structures, such as the Egyptian pyramids and the Great Wall of China. In the US, modern research began in the 1930s. In Malaysia, chemical stabilization for road construction started in the 1980s, known as Cold In-Place Recycling (CIPR). JKR Malaysia has conducted numerous pilot projects to assess the feasibility and performance of chemical soil stabilization. Chemical stabilization can be in-situ or ex-situ. In-situ stabilization improves soil on-site and is divided into surface treatment, shallow mixing, and deep mixing. Ex-situ mixing occurs during transportation or in a batch plant. Cement, lime, fly ash, and bituminous chemicals are widely used. Cement improves soil strength but can be brittle. Lime enhances clayey soils' strength and reduces plasticity. Fly ash, a by-product of coal power plants, modifies fine-grained soils. Bituminous chemicals add flexibility and prevent cracking. Innovative chemical stabilizers such as ionic stabilizers, enzyme-based stabilizers, microbial induced calcite precipitation (MICP), biopolymers, synthetic polymers, polymer-modified cementitious stabilizers, and nanotechnology are also explored. These modern solutions offer improved technical effectiveness and commercial efficiency, with potential environmental benefits. In conclusion, chemical soil stabilization significantly enhances the load-bearing capacity of road embankments. This paper provides a critical review of various chemical stabilizing agents and methodologies, highlighting their mechanisms, advantages, and limitations, and underscores the importance of continuous research and development in this field.

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1. Introduction

Soil stabilization is a common engineering method to treat unsuitable materials into usable materials, with desirable properties. In general, soil stabilization can be categorized into mechanical stabilization and chemical stabilization. Mechanical stabilization is the process to change the nature of soil to affect its density, gradation, moisture content, and other characteristics. As stated by Makusa [1], among mechanical stabilization, the simplest processes are compaction (densification) and drainage. Kitazume & Terashi [2] mentioned that other means of mechanical stabilization include altering particle size distribution, replacement, consolidation/dewatering and reinforcement. As mechanical stabilization will not be further discussed since it is not the focus of this research. On the other hand, Barman & Dash [3] highlighted that chemical stabilization utilises various chemicals to alter soil properties, through chemical reactions such as hydration, cation exchange, flocculation and pozzolanic reactions.

This study aims to review the improvement in load-bearing capacity of road embankment application via chemical soil stabilization. This paper reviewed chemical soil stabilization methods, including the history and methodology. Several types of commonly used soil stabilizing agent were assessed in terms of their mechanism, with pros and cons. The critical review from this paper provides insights into chemical soil stabilization.

2. Chemical Soil Stabilization

Chemical stabilization is essentially a modification of soil properties with the addition of a chemical. Kitazume [2] explained that ion exchange at the surface of soil minerals, additional chemical bonding and/or filling up voids by chemical reaction products contributed primarily to such soil properties modification. According to Makusa [1], with the chemical reactions, stabilized soil would present higher strength, lower permeability and lower compressibility compared to the untreated counterpart. Besides, Firoozi *et al.*, [4] emphasized that soil plasticity, as well as swelling/shrinkage potential, can be reduced through chemical reaction, which is other benefits of chemical stabilization. However, chemical stabilization is not to be expected to improve all soil properties. Instead, the outcomes should be focused on key performance indicators, such as volume stability, strength, compressibility, permeability and durability, which are the points of interest for sound road construction.

2.1 History of Chemical Soil Stabilization

McDowell [5] reported that the history of chemical stabilization can be traced back to 5000 years ago, as exemplified by similar technique was used to construct the pyramids of Shensi in the Tibetan-Mongolian, dating back more than 5000 years. Chemical stabilization can also be found in other ancient civilizations. Rodríguez-Navarro [6] outlined that the Egyptian constructed pyramids (Figure 1) with mixtures consisted of gypsum and lime during 4000 BC while Zhao *et al.,* [7] indicated that the Chinese used lime binder to construct the Great Wall (Figure 2) between 221 BC and 1644 AD and the Indian used lime-clay-sand mortars to build masonry dams. It was found that ground pottery shards or fine powders of natural materials were used to make cement, such as those used to build the 4000-over-year-old Great Pyramids of Giza as discovered by Day [8]. In addition, studies by Hobbs & Siddall [9] revealed that lime and gypsum were produced as early as 700 BC for wall and building construction. Indeed, way back 2000 years ago, the Roman adopted chemical soil stabilization in road construction, specifically for the sub-base course. McDowell [5] further explained that in the United

States, modern research in chemical stabilization started in the 1930s', which eventually expanded to other parts of the world, such as Japan and the Nordic countries.

Fig 1. Egyptian Pyramids

Fig. 2. Great Wall of China

2.2 Overview of In-Situ Chemical Stabilization in Malaysia

The history of chemical stabilization for road construction in Malaysia was recorded as early as 1980s'. In Malaysia civil construction industry context, in-situ chemical stabilization process involving stabilization of existing asphalt concrete together with underlying materials with the addition of stabilizing agent, a technique often known as Cold In-Place Recycling (CIPR). Sufian [10] mentioned CIPR technique has been applied in Malaysia as early as 1985 for rehabilitation of the 15 km long stretch of FT002 in Pahang. Since then, CIPR method has been applied in roads throughout Malaysia, with traffic volume ranging from high to very low, mainly for the rehabilitation of badly deteriorated roads.

In the past decades, Malaysia Public Work Department (JKR) has engaged in research collaboration via testing and experimental work to ascertain both the technical (design and performance) and commercial (cost-effectiveness) aspects of chemical soil stabilization. Sufian [10] further summarized that, ever since then, in-situ chemical stabilization technology has been applied throughout Malaysia for various categories of roads, ranging from tolled expressways, highways to rural access. Up to 2010, it was estimated by Mohd Hizam [11] that approximately 10% of federal roads in Malaysia, which equal to 18,580.73 km, have been treated using the CIPR technique.

The adoption of chemical soil stabilization method in Malaysia has likely been influenced by the government's initiatives to promote sustainable construction practices. Sufian *et al.,* [12] stated that JKR Malaysia has conducted several trial or pilot projects at various locations, such as the federal road at Klang, Kemaman and Kemahang plantation road at Felda Pekoti Timur (Figure 3) and Felda Krau (Figure 4) [13]. Razali [14] also reported pilot study of a rural road at Pos Sinderut (Figure 5) to assess the construction feasibility, as well as technical and commercial performance of chemical soil stabilization under local conditions.

Throughout the years, JKR has constantly been updating the specifications and guidelines on chemical soil stabilizing, i.e. from Arahan Teknik (Jalan) 5/85 [15], to Standard Specification for Road Works - Section 4: Flexible Pavement [16], Arahan Teknik 5/85 (Pindaan 2013) [17], till the most recent Standard Specification for Road Works - Section 18: Soil Stabilization [18]. The commendable efforts from both public and private sectors to develop local technical guidelines and specifications for these recycling methods have certainly contributed to the wider implementation of the technique. Additionally, another pushing factor is the method’s apparent cost-effectiveness, which has made CIPR popular among practitioners from both the public and private sectors.

Fig. 3. Felda Pekoti Timur [13]

Fig. 4. Felda Krau [13]

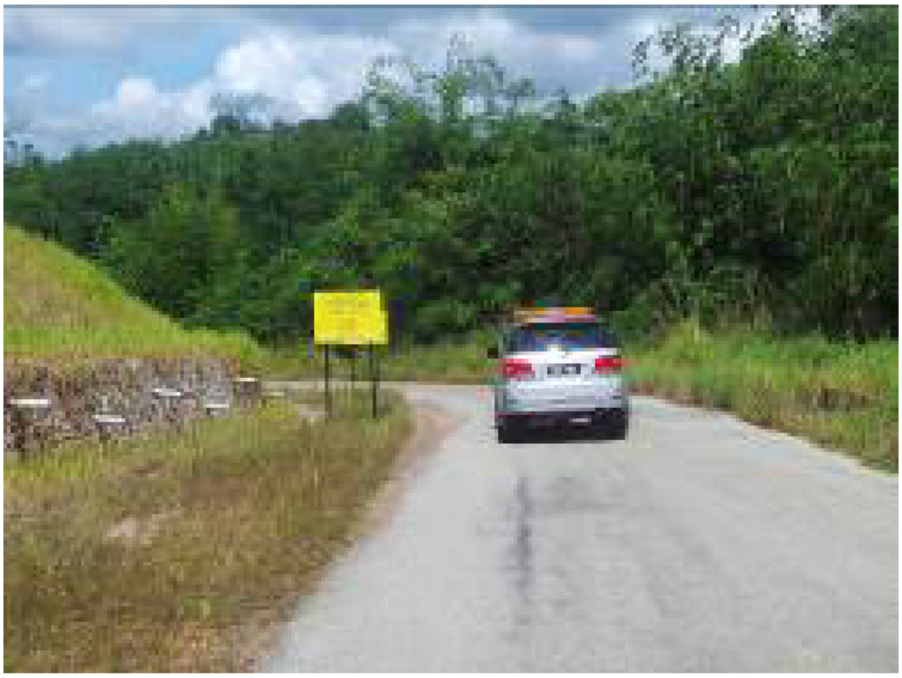

Fig. 5. The condition at Pos Sinderut site after 18 months [14]

3. Methodology of Chemical Stabilization

According to Makusa [1], chemical stabilization can be carried out by either in-situ stabilization or ex-situ stabilization. The advantage of in-situ stabilization is to improve soil properties on-site for both deep foundation and shallow foundation, without transportation of bulk soil and thus minimize logistic activity and associated cost. Depending on the nature of construction and the depth of mixing, in-situ stabilization can be further divided into surface treatment, shallow mixing by mechanical mean, and deep mixing by mechanical mixing and/or high-pressure injection mixing.

On the other hand, Kitazume & Terashi [2] stated that ex-site mixing techniques include mixing during transportation and batch plant mixing, depending upon where mixing of soils and chemical takes place. Ex-situ mixing is applicable when it is impossible or unrealistic to execute in-situ mixing. Furthermore, the authors commented that ex-situ can be beneficial to treat and reuse dredged marine soils, poor quality soils or construction surplus soils.

As shown in Figure 6, soil stabilizer or road recycler/reclaimer is the main machinery used for mechanical mixing for shallow foundation. A soil stabilizer is a specialized construction machinery that comes with a mixing chamber with a built-in powered drum, equipped with paddles or mixing tip, to mix soil and additive. Road recycler/reclaimer is a similar built-up with stronger mixing tips, which is capable of cutting and pulverize the existing asphalt concrete layer. However, the modern stabilizer is usually equipped with carbide tips instead of paddles, simultaneously upgrading the machine's function as a road recycler. During chemical stabilization, the chemical is pre-spread onto the substrate to be treated, followed by the stabilizer. As illustrated by Wirtgen webpage in Figure 7, the stabilizer uses its powerful mixing and/or milling rotor to mix existing soil and/or asphalt concrete with pre-spread chemical. The close-up photo in Figure 8 shows the mixing tips which are responsible for mixing and breaking up existing asphaltic concrete.

Fig 6. Soil stabilizer from MTS Fibromat (M) Sdn. Bhd

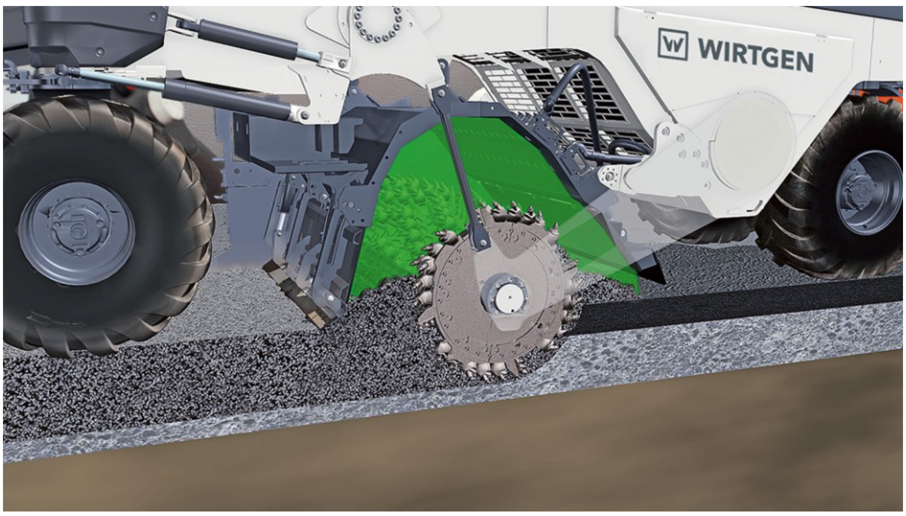

Fig. 7. Illustration of mixing chamber from Wirtgen webpage

Fig. 8. Close-up mixing tips in the mixing chamber from MTS Fibromat (M) Sdn. Bhd.

Nevertheless, such specialized machinery may not be readily available throughout Malaysia. In such an instance, as shown in Figure 9, the rotavator is often used as an alternative machinery to stabilizer. Rotavator is a universal tractor attached with a mixing chamber, while the mixing chamber is driven by the power take-off shaft of the tractor (Figures 10 and 11). Due to the relatively lower machine horsepower, mixing quality is expected to be lower than that of the stabilizer. Therefore, additional mixing passes are often carried out to compensate for the minor shortfall.

Fig 9. Tractor with rotavator attachment from MTS Fibromat(M) Sdn. Bhd.

Fig. 10. Rotavator attachment from Richardson Machinery Sales Ltd. webpage

Fig 11. Close-up mixing chamber of rotavator at work from MTS Fibromat(M) Sdn. Bhd.

4. Commonly Used Chemical Stabilizer

In modern days, cementitious materials are widely used in chemical soil stabilization. Tastan *et al.,* [19] pointed out that traditional chemicals include Ordinary Portland Cement (OPC), lime and fly ash. Kitazume *et al.,* [2] explained that in the 1960s, to improve road base course and sub-base course paving materials in road construction, highway engineers carried out extensive studies on the mechanisms of chemical stabilization using cement and lime. Besides, Harun *et al.,* [20] reported that emulsion, foamed bitumen and liquid-form chemicals are other stabilizing agents used as highlighted by Lim et al. [21]. Some of the commonly used stabilizing agents are reviewed in the following section.

4.1 Cement

Cement is a conventional chemical used in soil stabilization. Mazuka summarized several types of cement commonly seen in the industry, including Ordinary Portland Cement (OPC), blast furnace cement, sulfate resistant cement, as well as high alumina cement. Mason & Lea [22] stated that major chemical components found in OPC include tricalcium silicate ($3CaO \cdot SiO2$), dicalcium silicate ($2CaO \cdot SiO2$), tricalcium aluminate ($3CaO \cdot Al2O3$), and a tetra-calcium aluminoferrite

($4CaO \cdot Al2O3Fe2O3$). In general, Basha *et al.,* [23] outlined shear strength of soil can be improved with the addition of cement. Besides, geotechnical problems such as settlement and swelling can be effectively addressed.

When in contact with water, the hydration process of cement takes place. Calcium silicate and calcium aluminate in cement react with water, and produce cementing compounds including calcium-silicate-hydrate (C-S-H) and calcium–aluminate–hydrate (C-A-H). At the same time, excess calcium ions will react with water and produce calcium hydroxide. Katz [24] outlined as the main product during the hydration process, calcium-silicate-hydrate is the main source of strength development in cementing. Meanwhile, Sherwood [25] stated that excess calcium hydroxide produced will further react. Firoozi [4] outlined that the use of cement as the stabilizing agent for granular materials has proven to be effective. However, mixing cement with highly plasticity soil (plasticity index, PI > 30) is difficult, which limits the application range for cement stabilization. Besides, Lim *et al.,* [21] emphasized that after treatment with cement, soil tends to exhibit brittle behaviour and tends to crack under traffic loading, which makes cement-treated soil rarely used as a surfacing material. In general, Kennedy *et al.,* [26] stated cement stabilization is preferred for treating granular soil.

4.2 Lime

Al-Swaidani, Hammoud, & Meizab [27] cited that lime is the oldest traditional chemical used in soil stabilization. With the addition of lime, the strength and stiffness of the soil can be improved. Besides, geotechnical properties of clayey soils, such as plasticity index (PI), California Bearing Ratio (CBR) and workability can be significantly modified. Traditionally, lime stabilization is primarily used for the stabilization of clayey soils. From the research, Kennedy *et al.* [26] reported that for high plasticity soil treated with lime, the compressive strength attainment surpasses cement-stabilized counterpart. However, the result obtained for low plasticity sandy clay was the other way round.

In chemical stabilization, lime always comes in the form of either quicklime (calcium oxide - CaO) or hydrated lime (calcium hydroxide - Ca(OH)2). Quicklime is the product of the calcination of limestone (calcium carbonate – Ca(CO3)2), where calcination is the thermal treatment below the melting point, to drive out carbon dioxide. Hydrated lime is the product of adding water to quicklime, which can be either in powder form or in slurry form. Upon reaction, hydrated lime ionizes and turns into calcium and hydroxide ions, major constituents in lime stabilization.

$$Ca(OH)_2 \rightarrow Ca^{2+} + 2OH^- \qquad (1)$$

Since hydrated lime can be obtained by mixing quicklime with water, therefore quicklime has been used as a soil stabilizing chemical. Additional advantages of using quicklime as the stabilizing agent are that quicklime absorbs water to form hydrated lime on site. Excessive moisture can be removed from the soil to be treated. Besides, quicklime can be more reactive than hydrated lime. Furthermore, Makusa [1] and Firoozi *et al.,* [4] at the same unit mass, quicklime provides more calcium ions, which are responsible for further chemical reactions. Nevertheless, McDowell [5] outlined that since hydration of quicklime is an exothermic process and substantial amount of heat being generate, extra precaution should be taken during application of quicklime. Makusa [1] also mentioned that hydrated lime in slurry form is suitable for mixing with dry soil, where additional water is required for compaction purposes.

Upon calcium cation produced, it will replace sodium ion and hydrogen ion available on the surface of clay mineral. Firoozi *et al.,* [4] said that the alteration in clay structure reduces soil plasticity, thus reduces potential of swelling and shrinkage. Then, it is further explained that with adequate amount of lime, pH of soil substrate increases to alkaline condition (pH = 10.5), clay particles would breakdown and produce silica and alumina. Silica and alumina are then reacting with calcium ion from lime, to form calcium-silica-hydrate (C-S-H) and calcium-alumina-hydrate (C-A-H). These are the similar cementitious compound found in cement hydration process, and contribute to strength increment in lime stabilization.

4.3 Fly Ash

Fly ash is the by-product of coal-fuelled power plant, after combustion. In general, fly ash consists of pozzolans-siliceous or siliceous and aluminous materials, which exhibit cementitious behaviour, either self-cementing or during presence of activator (mainly cement or lime). In commercial application, fly ash can be broadly classified into Class C and Class F. Bhatt *et al.*, [28] explained that ash containing 70% and above of SiO2 + Al2O3 + Fe2O3 by weight is classified as Class F, while the ash with having 50% to 70% of SiO2 + Al2O3 + Fe2O3 by weight is categorized as Class C. Typically Class C fly ash contain more than 15% CaO, which is higher than 5% or less CaO in Class F. Higher CaO content in Class C fly ash leads to better self-cementing properties. Therefore, Class C fly ash can be used as a stand-alone soil stabilizing agent, while Class F fly ash acts as a co-stabilizer together with other cementitious chemicals. Fly ash is often used to modify fine grain soil. Bidula [29] reported that fly ask stabilization is an effective treatment for expansive soil., where the Atterberg limits of liquid and plastic limit as well as plasticity index of fly ash treated soil were found to decrease, while the shrinkage limit was increased. Saeid *et al.,* [30] also found that the strength property and bearing capacity of soil could be greatly improved through fly ash treatment.

4.4 Bituminous Chemical

Generally, Mrugala [31] chemical stabilization increases compressive strength of soil substrate, however, it also increases rigidity and shrinkage deformation, which are unfavourable in road construction because this would lead to cracking across stabilized layer, thus eventually reflect cracking on the road surface. With viscoelastic property, bitumen stabilization does not increase rigidity, therefore cracking problem can be resolved. However, in general Kendall *et al.,* [32] stated cost of bituminous stabilization is higher than other conventional stabilizer such as cement or lime.

Two types of bituminous chemicals are used in chemical soil stabilization, namely bitumen emulsion and foamed bitumen. Bitumen emulsion is a mixture of bitumen and water. Linsha *et al.,* [33] mentioned as bitumen is hydrophobic and it does not dissolve in solvent, therefore emulsifier is added to solvent before adding in bitumen, to keep bitumen dispersed and suspended in water. Sufian [12] found that bitumen emulsion is delivered in liquid form in ambient temperature, therefore it can be readily mixed with soil without addition of heat, to deliver similar effects of asphaltic concrete. Sometimes, bitumen emulsion is used together with co-binder, such as cement in soil stabilization. It also summarized advantages of such practice included better bitumen-to-aggregate adhesion, leading to higher initial and ultimate strength.

Foamed bitumen is product in-situ by adding a small amount of water to a heated-penetration grade bitumen. Huan *et al*., [34] mentioned that during foaming process, heated bitumen, small water of cold water, and compressed air are injected into mixing chamber. Bitumen is then expanded and a fine mist/foam is formed. Sufian [12] explained that foaming process enables mixing of bitumen with cold and moist soil substrate, without using an emulsifier. Besides, foamed bitumen requires less moisture content than bitumen emulsion and therefore reduces wet spots in the mixture as stated by Kendall *et al.,* [32].

4.5 Innovative Chemical Soil Stabilizer

Apart from the traditional chemical stabilizing agents mentioned above, road practitioners have put in continuous effort to research and develop innovative chemical stabilizing agents, to provide better technical effectiveness and commercial efficiency. Following are several types of innovative chemical soil stabilizers reviewed.

4.5.1 Ionic stabilizer

With the addition of ionic stabilizer, the electrolyte concentration of water content within soil matrix is altered. Tingle *et al.,* [35] explained that changes in electrolyte concentration results in cation exchange that reduces the surface charge of soil particles. Less water molecules being attracted to soil particles leads to reduction in the double-water layer thickness as well as interparticle distance, which leads to flocculation of the clay particles. Therefore, ionic stabilizer is suitable for soil with fine particles such as clays and silts, with interparticle double-water layer which is significantly large as compared to the soil particles. Luo *et al.,* [36] further explained that due to the unique hydrophobic-hydrophilic molecular structure, addition of ionic soil stabilizing agent encourages flocculation of soil particles and significantly increases UCS. Though, the increment does not comply to requirement of bearing capacity of a road, ionic soil stabilizer can act as co-stabilizer and combine with conventional stabilizing agent such as cement or lime, and further improve the strength properties. Through observations with the Scanning Electronic Microscope, Gautam *et al.,* [37] verified the changes in soil morphology before and after ionic soil stabilizer treatment: Post-treatment, flaky edges of the soil particles were not observed, and that the soil particles appeared to be more closely packed.

4.5.2 Enzyme-based soil stabilizer

Enzymes are biomolecules (protein) which catalyse specific chemical reactions to improve the soil properties. Renjith *et al.*, [38] reported the most widely accepted hypothesis on the enzyme-based soil stabilization mechanism is organic encapsulation. It is also explained that clay particles are negatively charged with high affinity for water. In the organic encapsulation process, these clay particles are encapsulated by the positively charged enzyme molecules leading to decreased water affinity, thus reducing the moisture content. The clay particle aggregates would then bind better to close up the voids, hence resulting in lower porosity. Gautam *et al.,* [37] reported that after treatment with enzyme-based soil stabilizer, significant increase in the unsoaked and soaked CBR at 48% and 58% were recorded respectively. As such, through a series of laboratory testing, the authors concluded that the strength and hydraulic properties of soil can be considerably improved with addition of enzyme-based soil stabilizer.

4.5.3 Microbial induced calcite precipitation (MICP)

Bio-cementation or bio-mineralization refers to the generation of particle-binding materials through microbial reaction said by Ramdas *et al.,* [39]. Among the approaches in bio-mineralization, Chang *et al.,* [40] stated that microbial-induced calcite precipitation is one of the most recognized methods. MICP uses microorganisms to precipitate calcium carbonate crystals in the voids, which effectively fill the voids, bind the soil particles and improve strength of the soil. MICP can also be carried out without microbial activities, such as with the use of urea, calcium chloride and urease. However, the MICP process could be time-consuming for calcite precipitation, and the outcome of MICP is largely unpredictable as the precipitation would differ due to changes of in-situ organic compounds, presence of natural bacteria and the chemical conditions; which are indeed the main drawbacks of MICP.

4.5.4 Biopolymer soil stabilizer

Biopolymers are polymers either derived from natural resources, or artificially synthesized from bio-derived monomers or microbial activities. Therefore, biopolymers are considered environmental-friendly. Chang *et al.,* [41] mentioned that applications of biopolymer includes soil stabilization, mainly for soil strengthening or permeability reduction, dust control and erosion control. As opposed to MICP, biopolymers are pre-cultivated with qualitative and quantitative control before the soil stabilization process, therefore the outcome is more predictable than MICP. Ramdas *et al.*, [39] commented that limited literatures regarding cost and benefits are available. However, it was reckoned that due to the lower green-house gas emission incurred as compared to conventional cement or lime, biopolymer soil stabilizer has great potential from the environmental and ecological perspectives.

4.5.5 Synthetic polymer stabilizer

Synthetic polymers are artificial polymers, which are by products of the petrochemical process. Tingle *et al.,* [35] explained that polymer stabilizer forms a coating over the soil particles, which creates inter-particles physical bonding. Almajed *et al.,* [42] summarized that synthetic polymer stabilizer comes in either powder, fibre or liquid form; and commonly used synthetic polymer stabilizer includes polyacrylamide (PAM), polyethylene (PE), polypropylene (PP), polystyrene (PS) and styrene copolymer, polyurethane (PU), polyvinyl Alcohol (PVAO), polyvinyl acetate (PVA) and polyvinylchloride (PVC). Since the primary mechanism of polymer stabilizer is physical coating and bonding, the strength improvement of polymer stabilization relies on the ability to coat over soil particles evenly and adequately. Therefore, polymer stabilizer is less effective for fine-grained soil, because of reduced mixing efficiency attributed to the higher surface-volume ratio.

4.5.6 Polymer modified cementitious (PMC) stabilizer

As mentioned earlier, cement and cementitious chemicals are proven effective soil stabilizers. However, brittle behaviour and tendency to crack under traffic loading are the major drawbacks recognised for the treated soils. Furthermore, Louw *et al.,* [43] emphasized that with shrinkage cracks inherited as natural characteristic of cement-stabilized bases, the overall performance of cement stabilized base remains a concern.

By adopting the idea of composite material, pavement technologists utilise various polymers to reinforce cementitious-stabilised soil substrate, and modify the property against internal crack formation. Besides, other bonding or strengthening mechanism of polymers may synergize and compound the stabilization effect admixed with the cementitious base stabilizer. For example, Ateş [44] reported with addition of waterborne polymer to cement as co-stabilizer, the Unconfined Compressive Strength of sandy soil was significantly improved. Besides, Radwan *et al.,* [45] examined the effect of addition polypropylene fiber (PPF) in conventional cement to stabilize peat soil. With addition of PPF, both CBR and UCS were found to be improved as compared to pure cement counterpart. From micrographic analysis, presence of bonding between PPF fiber thread and cement hydration products explained the increased static friction force between the cement-soil and fiber, and eventually leading to improvement in overall strength property.

4.5.7 Nanotechnology for soil stabilization

Poole & Owens [46] explained nanotechnology is a multidisciplinary technology which studies materials' structure and phenomena at nanoscale. Many materials properties change, when material size range measurements made reduce to microscale or nanoscale Nanotechnology enables creation of novel materials and application with unique properties, creating impacts in various industries. In recent years, Majeed *et al.,* [47] outlined much attention has been directed at the application of nanomaterials (with size of 100 nm or lower) in geotechnical engineering, for improving various soil properties, including maximum dry density, unconfined compressive strength and plasticity index Examples of nanoparticles applicable in soil stabilization are nano-alumina, nano-silica, nano-copper, nano-clay, nano-magnesium and carbon nanotube as highlighted by Correia & Rasteiro [48].

5. Conclusion

In conclusion, this study provides a comprehensive review of the advancements and applications of chemical soil stabilization in enhancing the load-bearing capacity of road embankments, as well as general overview on soil stabilization in Malaysia's road construction. The methodology of chemical stabilization, including both in-situ and ex-situ methods, showcases the flexibility of these methods, adapting to various site conditions and project requirements.

Chemical stabilization methods, including the use of traditional agents such as cement, lime, and fly ash, as well as innovative stabilizers like ionic and enzyme-based stabilizers, microbial induced calcite precipitation (MICP), biopolymer, synthetic polymer stabilizers, polymer modified cementitious stabilizers, and nanotechnology, have demonstrated significant improvements in soil properties. These chemicals enhance key performance indicators such as volume stability, strength, compressibility, permeability, and durability, converting previously unsuitable materials for construction purposes. Furthermore, by synthesizing of these innovative chemical stabilizers holds promise for further enhancing the performance and sustainability of soil stabilization practices.

Overall, the findings of this study reinforce the significance of chemical soil stabilization as a vital tool in modern civil engineering, enabling the effective transformation of weak soils into robust, load-bearing materials essential for infrastructure development. Continued research and technological advancements in this field are expected to further optimize the use of chemical stabilizers, contributing to more durable and sustainable road construction solutions.

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