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Abstract. This paper presents a literature review of the application of cement, lime and polymer emulsion in road construction. The focus is mainly on the soil candidates, binding mechanism, the reported strengths and weaknesses for each chemical stabiliser used in soil stabilisation. While it is generally agreed that cement is best suited for sand-sized to gravel-sized soil mixtures (well-graded), lime is mainly used for wet heavy-clay soil mixtures. Polymer emulsion is more suitable for silt-sized to fine gravel-sized soil mixtures (well-graded). Organic soils are the most difficult soil type to stabilise, and for any kind of chemical stabiliser used, the strength gain is relatively minimal. Cement undergoes hydration reaction which is rapid, and results in high compressive strength, while lime undergoes a slower pozzolanic reaction is slower, and provide lower compressive strength. Polymer emulsion depends on the rate of evaporation for the film formation to complete, and results in ductile polymer-soil matrix. Like lime, polymer does not provide significant compressive strength but does provide great flexural strength that prevents crack propagations. The outcomes from this paper provide an insight into recent and upcoming research trend using chemical soil stabilisers on local soil mixtures to improve the engineering properties of pavement layers made of these soil mixtures.

1. Introduction

Soil stabilisation is an important work package in road construction. It is performed when the sub-grade soils are soft and have low bearing capacity, when the local natural aggregates are of poor quality and importing them is costly, and/or when excavating the sub-grade soils and replacing them with granular materials are expensive. Soft and weak soils such as peats and soft clays typically represent the most problematic spectrums of soils encountered in road construction as they are not sufficiently strong to support the overlying road structure; causing structural damages and premature failures. Expansive soils that contain smectite clay minerals are known to be significantly problematic due to the swelling-shrinking behaviour caused by moisture variability [1, 2]. Peat soils deform greatly when subjected to loads on the account of the soils' exceptionally high water and organic contents [3, 4]. Roads built on raised embankment over soft and weak soils (compressible soils) will give rise to instability problems during construction, and long-term and persistent settlement after construction [5].

In some geological regions, the locally sourced natural aggregates of poor-quality lack the hardness and strength to withstand loads, thus may deform excessively. Stabilising the poor-quality aggregate allow these regions to use their local resources to reduce the dependency of importing expensive high-quality aggregate. Groundwater and floodwater are known to cause moisture-related damages to the unbound and bound layers of the roads, especially when the road is submerged frequently. The road will

eventually experience serviceability problems and structural failures. Soil stabilisation, when performed optimally to the underlying granular layers and/or sub-grade soils, offers significant support to the road, and protection against damages caused by traffic loading, and exposure to climatic and ground conditions.

Although there are many different types of soil stabilisation methods, the choice of method are governed by several important factors such as the soil and aggregate types (e.g. clayey soils, silty soils, sandy soils, siliceous aggregate or calcareous aggregate) and their respective gradations (i.e. well-graded, poorly-graded and gap-graded), the geotechnical layer to be stabilised (i.e. sub-grade, sub-base or base), the degree of improvement of soil properties, the climate conditions (e.g. tropical, dry and mild) and ground conditions (e.g. sandy soils underlain by very soft clay and alluvial deposits overlain by thick peat). Generally, in order to improve the soil's gradation, workability and plasticity, small amount of chemical stabiliser will be sufficient. When it is desired to improve the soil's strength and durability, larger amount of chemical stabiliser will be needed. Generally, fine-grained soils have smaller load bearing capacity than coarse-grained soils, while the former also have greater degree of compressibility [6].

The objective of this paper is to present a literature review of three types of chemical stabiliser, i.e., cement, lime and polymer emulsions used in stabilising the soil or soil-aggregate defined by its effective sizes. The primary binding mechanism for each of the three chemical stabilisers is also reviewed in this paper. The outcome from the paper is expected to lead to an improved insight into recent and future research trend related to the application of the chemical stabilisers on the local soil or soil-aggregate and subsequently, the development of recommendation, guideline and/or general specification for local soil or soil-aggregate stabilisation in road construction.

2. Chemical soil stabilisation

The main purpose of soil stabilisation is to alter the geotechnical properties of natural soils to meet specific engineering purposes. The soil's geotechnical properties can be improved by enhancing the shear strength parameters [7], increasing the tensile strength [8], and improving stiffness [9]. It also aims to reduce plasticity [10], and minimise volumetric changes in expansive or fine-grained soils caused by moisture variability [1]. Chemical stabilisation through the use of chemical compounds or mixtures is very common. It is regarded as a cost-effective, performance-efficient and environmental-friendly method of soil stabilisation [11, 12]. Chemical modification involves soil particles bound together through the use of chemical compounds or mixtures, and the changes in the geotechnical properties normally more complex than mechanical modification. Chemical modification, nonetheless, is the preferred choice when roads are to be constructed under the adverse prevailing traffic loading, climatic and ground conditions.

The most frequently used traditional chemical stabilisers are the calcium-based powdered cement and lime. The common issues when using these stabilisers are the lengthy curing times and large quantity required for soil strength improvement [13]. Another major concern is the brittle behaviour of calcium-treated soils [14], which can cause cracks when subjected to dynamic loading. Soils containing a high level of sulphate ions (SO_4^{2-}) treated with calcium-based stabilisers will cause swell/heave problems as well as having a deleterious impact on the cementitious stabilisation mechanisms [15]. In spite of the limitations, traditional stabilisers remain widely used in countries where the supply is consistent and the procurement cost is low.

The non-traditional type of chemical stabilisers can be categorised into various groups [13], but the most popular ones are polymer emulsions. Soil amendment using polymer emulsion is a growing industry and it receives great interest in applications for improving various soil properties. Polymer emulsions have an advantage as their chemical formulations to treat a wider range of soil compositions.

They also have faster curing period, and lesser quantity is required [13]. Water-soluble polymers have the advantage of easier access to the surfaces of soil particles than the powdered stabilisers; and water-soluble polymers do not produce excessively viscous liquids [16]. They also do not require a solvent carrier and do not pose environmental concerns when used in bulk [17]. In contrast to calcium-based stabilisers, polymer-stabilised soils exhibit flexible [18] or ductile [14] behaviour.

2.1. Cement stabilisation

Cement is the single largest calcium-based soil stabiliser used in road construction. It contains 21.9% silicon oxide (SiO), 6.9% aluminium oxide (Al_2O_3), 3.9% iron oxide (Fe_2O_3) and 63% calcium oxide (CaO) [19].

Cement is the preferred choice for granular and sandy soils [20, 21] but its applications have been extended to include clayey soils [22, 23] and peat soils [3, 24]. Acceptable soil candidates for cement stabilisation are poorly cohesive granular soils [25] and/or soils whose fines fraction is less than 0.074mm but plastic soils should be avoided [26]. Generally, well-graded granular soils that possess sufficient fines that produce a homogeneous mixture (floating aggrege matrix) are best suited for cement stabilisation [26]. Reference [21], on the other hand, stated that the optimum proportion of soils for cement stabilisation is 75% sand with 25% silt and clay. Clay soils that are suitable for cement stabilisation are kaolinitic and illitic clay soils [23], and cement is found to be effective in stabilising low-plasticity clay under wet test conditions [13]. Though peat soils lack the silica (SiO_2) and alumina (Al_2O_3) that are found in clay soils to allow for pozzolanic reaction to take place, the primary hydration reaction is sufficient to create the cementitious bond for peat soils. While it is almost apparent that all types of soils can be stabilised with cement, there are several exceptions. Some types of organic soils, high plastic clays, soils with medium to high levels of SO_4^{2-} and poorly reacting sandy soils are not suitable for cement stabilisation [27]. Organic soils can retard the primary hydration reaction due to the high organic content, and the low content of pozzolans and silts makes cement alone insufficient to provide the desired stabilisation strengths, unless cement is added in large dosage [28, 29]. Soils containing organic matters greater than 2%, and with pH less than 5.5, are considered unacceptable soil candidates for cement stabilisation [27] as lower pH values will negatively affect the rate of hydration reaction, resulting in slower strength gain [29]. Soils with 10% of clay content (an effective minimum for soils to be cohesive) may require only 5% cement for stabilisation, but the cement content will increase to 10% or more when the clay content increases to 30% [30]. Cement content between 6% to 10% would start to cause shrinkage cracking [31], and cement content greater than 10% is not economical [30]. Shrinkage cracking relates to the drying of the cement paste at atmospheric temperature and pressure drying.

Cementitious hydration is a chemical process primary and unique to cement. The phase compounds found in the cement are tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A) and tetracalcium aluminoferrite (C_4AF) [32]. When C_3S and C_2S react with water, the hydration reaction produces tricalcium silicate hydrate (CSH) and crystallised calcium hydroxide (CH); it is these hydration products that give the hardened cement paste (HCP) most of its engineering properties such as strength and stiffness [32]. The rate of reaction of C_3S is fast and the slowest being C_2S [33]. C_3A is particularly important in the early stage of the hydration as it reacts very violently with water resulting in an immediate stiffening of the cement paste [32], and it reacts faster than C_3S. This reaction, albeit important, has be to delayed so gypsum is added to prevent the immediate stiffening [32]. C_3A and gypsum react with water to produce ettringite. When gypsum is exhausted, C_3A reacts with water to produce tricalcium aluminate hydrate (CAH) [32]. The CSH and CAH form a gel network that serves as binder to the soil particles, thus resulting in a soil-cement matrix [22], and when the cement paste hardened the strength is established. As a result, the HCP becomes tough and insoluble, which gives the soils the required compressive strength. Strength gain occurs from day 1 to day 27 [22]; after that, the

strength gain gradually slows down until the cement grains are completely hydrated. The rate of cement hydration is influenced by cement fineness, water-to-cement ratio and curing temperature [34].

Leaching of calcium is minimal when cement is used [22]. However, the single use of cement in soil stabilisation is highly discouraged, and this is mainly due to the negative environmental impacts associated with cement production in terms of high energy consumption and emission of carbon dioxide (CO_2) [35-37].

2.2. *Lime stabilisation*

After cement, lime is the next most used calcium-based soil stabiliser. The two types of lime used in soil stabilisation are quicklime (CaO) and hydrated lime (Ca(OH): calcium hydroxide). Apart from the difference in chemical compositions, their reactivities are also different. CaO is denser, and more readily reactive than $Ca(OH)_2$. Quicklime appears to be a more effective soil stabiliser than hydrated lime, and quicklime in a slurry state produces higher strength in soils than when it is a dry state [38]. Quicklime has also a higher drying effect on wet soils, but quicklime is very caustic, posing health risks [39].

Lime stabilisation is common for clayey soils as lime works better with the clay minerals [30]. A good soil candidate for lime stabilisation is generally fine-grained clayey soils (reactive clays) with a minimum of 25% by mass passing the 74μm sieve, and a PI of greater than 10 [40, 41]. In order words, low-plasticity soils are not suitable. Soils of medium to high plasticity can also be treated with lime to decrease plasticity, increase workability, reduce swell and increase strength [26]. Lime stabilisation is less suitable for granular soils (non-plastic soils) [10, 20, 30, 38, 42]. The efficacy of lime in low-cohesion or cohesionless soils is poor without the addition of pozzolans [43]. Lime is use only as construction expedient to improve the workability of wet clayey soil with little regards given to time and strength gain [39]. The assumption that lime is more suitable than cement to stabilise clay soils is not true, and cement is as good as lime to stabilise clay soils with PI value between 20 and 50, if not better as cement offers higher strength gain [22]. In order words, lime does not contribute strength to the soils. Hence, it is relatively common to see that lime is mixed with cement. The success of the lime-cement stabilisation depends on the properties of soils, the ratios of lime to cement and curing time.

Cation exchange and flocculation-agglomeration are a two-phase chemical process unique to lime. These reactions cause textural changes within the soils which subsequently improve workability and moisture stability [40]. A small amount of lime will increase the PI, but lime has less pronounced effect on the liquid limit (LL) [39]. They are considered the short-term benefits of lime stabilisation. Most clays are reactive and when stabilised with lime, the soils' strengths may triple or quadruple, and in some unique instances, the strengths improved by an order of ten or more [40]. Clay is a pozzolan, and is a source of silica (SiO_2) and alumina (Al_2O_3) for the pozzolanic reaction, and is regarded as the long-term benefit of lime stabilisation. Pozzolanic reaction is slower than cement hydration [33]. The soluble clay-silica and clay-alumina react with the calcium ions (Ca^{2+}) and hydroxide ions (OH^-) to produce CSH and CAH [40]. They are essentially the same cement hydration products. The pH of water saturated with lime is 12.45 at 25°C, and as long as there is sufficient residual Ca^{2+} in the soil system to react with clay-silica and clay-alumina, the pozzolanic reaction will continue [40]. The continuing pozzolanic reaction can result in self-healing of cracks [39]. The high alkalinity of lime can neutralise acidic soils [39]. The pozzolanic reaction is temperature-dependent, and for temperature between 25°C to 30°C, there is a large increase in strength for every degree increase, thus, making lime stabilisation attractive than cement in countries with warm climate [39]. It is worthwhile to note that CaO consumes considerably larger amount of water when it hydrates in an exothermic reaction [22].

The greatest concern of lime stabilisation is calcium leaching, and it negatively impacts the durability of lime-treated soils. It is resulted from cyclic wetting and drying conditions that are caused by periods of wet and dry seasons, fluctuating groundwater tables and water runoffs followed by dry spells [40].

When clayey soils containing high SO_4^{2-} content are treated with calcium-based stabiliser, the soils will experience heaving problems, and SO_4^{2-} interfere with the pozzolanic reaction [15]. For the same mass of lime and cement and same, the calcium oxide in quicklime (100%) is more than cement (63%), thus quicklime will cause more heaving than cement, and this have been validated by [44]. The heave-induced failure to the road is caused by the highly expansive crystalline ettringite and thaumasite, which are formed when SO_4^{2-} react with Ca^{2+} [45, 46]. The pressure exerted by the calcium-sulphate-aluminate-hydrates can reach to approximately 241 MPa within the crystal [40]. In principle, calcium-sulphate-aluminate-hydrates is not a problem if they are form before compaction, but when they are formed after compaction, and the road is in service, the resulting heave can be destructive [40]. Shrinkage cracking is common in both lime and cement stabilisation, but the effect is less pronounced in lime stabilisation [39].

2.3. Polymer emulsion stabilisation

The use of polymer emulsion for soil stabilisation has been studies as early as the late 1960's [47]. Polymer latexes/dispersion/emulsions consist of very small (0.05μm to 5μm in diameter) polymer particles dispersed in water, and are usually produced by emulsion polymerisation [48]. In general, polymer emulsions are copolymer systems of two or more different monomers, and the total solid particles are between 40% to 50% by mass [48]. However, not all monomers can be copolymerised as there must be compactability among the monomers to form copolymer [49]. Polymer emulsions are regarded as a successful stabiliser for the following reasons: strong adhesive strength with soil surface, strong cohesive strength, low shrinkage during setting, low-water susceptibility after cure, resistance to solar radiation, atmospheric oxygen (oxidation) and biological degradation, non-toxic, non-polluting and inexpensive [49]. The elastomeric or thermoplastic water-based polymers form a continuous polymer film when water completely evaporated off [48]. As water has higher latent heat of vaporisation, it takes a longer time and higher temperature to evaporate, and give the final cured product [49].

The typical polymer-based admixtures are vinyl acetate (homo and copolymer latexes), acrylic-based copolymer latexes and styrene-butadiene (SB) copolymer latex [48]. In general, polymer emulsions can stabilise a greater range of soils as the formulations can be altered. Nonetheless, a majority of published papers has reported on the success of using polymers on granular soils, but the use of polymers of fine-grained soils has mixed results [50]. This could be resulted from the interaction between clay minerals and polymers as the water provides a medium in which clay and polymer react chemically to form clay-polymer complex [49]. References [13] and [51] used proprietary polymers to stabilise clay soils and silty sand respectively, and Reference [52] found that soil stabilisation using polymer emulsion is suitable for granular soils; and is less effective for fine-grained soils due to reduced mixing efficiency and insufficient ability to coat the soil particles, both resulted from high specific surface area. Little or no improvement would be observed if non-plastic crush rocks and poorly-graded soils containing large amount of gravel-sized soils are used with polymer emulsion, and this is simply due to the presence of intergranular air voids even after compaction [53]. A well-graded soil with sufficient fines is the ideal gradation for polymer emulsion to effectively form a soil-polymer matrix [54]. Polymer emulsion is also used to treat peat soils to improve strength but the increase may not be as significant [55, 56].

Cement is commonly added to polymer to further enhance the engineering properties of natural soils. The polymer-cement matrix reduces the propagation of microcracks that are prevalent in cement-stabilised soils [57]. The polymer-cement matrix also provides the stabilised soils with increased flexural and tensile strength and fracture toughness [57]. Similarly, polymer-lime matrix provides the stabilised soils with decreased PI and increased UCS [58]. The commonly used SB polymer is less water sensitive, and has better adhesive property than polyvinyl acetate and acrylic polymers [18]. SB polymer is also suitable for treating non-cohesive sandy soils without significantly reducing the permeability of the treated soils [18]. The non-cohesive sandy and silty sands can be better treated with carboxylated

SB polymer [18], but when either powdered or liquid carboxylated SB is used with cement, there was a significant retardation of the cement hydration reaction as the anionic SB particles strongly retard or suppress the silicates and aluminates in the hydration reaction [59]. Similarly, when cement is added with SB polymer to treat granular soils, the rigid styrene chains and flexible butadiene chains provides the treated soils with good mechanical properties, waterproofing properties and chemical resistance [57, 60]. The flexural strength and modulus of rupture of soils treated with SB polymer and cement [61]. The addition of SB polymer, however, creates a polymer film on the surface of the C_3S that retards or slows down the hydration reaction of silicates to produce CSH [62] and $Ca(OH)_2$ [63]. SB polymer is also used with hydrated lime to stabilise lateritic residual soils to reduce the PI values [58].

When polymer emulsion is used alone to stabilise soils, the binding mechanism involves film formation. When polymer emulsion and cement are added together to the soils, the modification is governed by two processes: cement hydration and film formation [57]. Hydration reaction precedes film formation, except on surfaces where loss of water by evaporation cause the film to form faster than hydration reaction [57]. The process by which the polymer film forms is known as coalescence. With water loss due to the hydration reaction and evaporation, the polymer particles are gradually confined in the capillary pores [57]. As more water is used during hydration reaction and evaporation, the polymer particles flocculate to form a continuous closed-packed film on the surface of the hydration products and unhydrated cement [57]. The film ultimately adheres to all surfaces that it comes in contact with, resulting in a polymeric monolithic network that binds the unhydrated cement, hydration products and soils together. Poorly-formed film will cause weak link or bond between the soil particles, and will soon break apart [49]. The factors that affect the film formation are time, temperature, size and shape of the polymer particles and the physical state of the polymer emulsion [49].

The use of polymer emulsion and cement are often comparable in cost, and both are less expensive than bitumen [53]. In an experimental investigation by Reference [64] shown that 2% to 4% of (acrylic) polymer and 20% to 40% of cement were required respectively to achieve comparable compressive strength of the stabilised sandy soils. This indicates that lesser polymer is required, and the investigation also revealed that the construction cost of 2% polymer content is lower than 20% cement content. Polymer emulsion used in soil stabilisation are often non-toxic and non-polluting [49].

3. Discussion and conclusions

A literature review of three types of chemical stabilisers, i.e., cement, lime and polymer emulsion used for stabilising soil or soil-aggregate defined by its effective size, and their primary binding mechanisms have been presented in the paper. The following are the conclusions drawn from the literature review:

- For cement stabilisation, the ideal soil mixture should be well-graded, consisting of sand-sized to gravel-sized soil particles. If silts and clays are present in sands, they should be less than 25%. Organic soils, high plastic clays and soils with medium to high levels of SO_4^{2-} are the least suitable for cement stabilisation. The primary binding mechanism is hydration reaction, whereby silicates, aluminates and gypsum react with water to from CSH, CAH and CH. CHS and CAH are the main hydration product, and is responsible for the compressive strength in cement-stabilised soils.
- For lime stabilisation, soils with high content of clay (clay rich soils) are the best suited as soluble clay-silica and clay-alumina react with the calcium ions (Ca^{2+}) and hydroxide ions (OH^-) to produce CSH and CAH. Lime is not well suited to treat granular soils, soils with low plasticity and organic soils. When quicklime is added to soils containing high SO_4^{2-}, heaving is greater, though is has good drying effect on wet soils. Though lime is an effective soil stabiliser, but when compared to cement, lime does not provide the much-required strength. Hence, it is not uncommon to find cement added to lime in order to achieve strength.
- For polymer stabilisation, a well-graded soil mixture with sufficient fines is the ideal to ensure a well-established soil-polymer matrix. Soil mixture that contains too much gravel-sized soil

particles are not suitable for polymer stabilisation as high air void content prevents proper coating. Polymer emulsion have negligible chemical reaction with soils as the main binding mechanism is film formation. Similar to lime, polymer emulsion does not provide compressive strength but gives the soil-polymer flexural strength, which is missing for cement-stabilised soil.

While the majority of past researches had focused on cement and lime in soil stabilisation, there has been considerably fewer reported work that investigated the application of polymer emulsion in soil stabilisation. Cement, especially, is easier to procure and it can be used across a wide range of soil mixture than lime. The use of polymer emulsion in soil stabilisation is quickly replacing traditional soil stabilisers due to their lower costs, easy handlings, formula variations and environmental benefits. Nonetheless, for any kind of chemical stabiliser used to stabilise a soil mixture, the target objectives must be clearly stated to obtain optimum results. There will always be future innovative research related to cement and lime stabilisation, while polymer emulsion is expected to receive heightened interest compared to other types of non-traditional chemical stabilisers.

Acknowledgement

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