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Chemical Stabilisation of Sandstone Road Aggregate Layers: A Literature Review

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Abstract. The increasing demand for aggregates for road construction and development has led to increased exploitation of mineral resources, resulting in their scarcity. This has an adverse effect on the environment as well as the cost of road development, especially when local aggregates are of poor quality and not suitable for road construction, requiring long-distance transportation or importation from another country. An approach that could be more cost-effective is the chemical stabilisation of locally available weak aggregates such as sandstone. This paper reviewed the most commonly used traditional and non-traditional additives for the stabilisation of road aggregate layers. The literature review focused on the type of soil for which each additive is best suited, the binding mechanism involved and the advantages and limitations of using each additive for soil stabilisation. It was found that the majority of the existing literature had focused on the chemical stabilisation of conventional road materials and demolition and waste aggregates for use in pavement base and/or subbase layers, but only a few looked into sandstone chemical stabilisation. Sandstone aggregate investigations have been limited to either cement and/or polymer stabilisation for road aggregate layers or cement concrete mixtures for building construction. As a result, this paper revealed a knowledge gap regarding the strength development of sandstone road aggregate layers after stabilisation with fly ash and lime, either separately or in combination, which is predominantly measured in terms of the unconfined compressive strength, indirect tensile strength, and California Bearing Ratio. Future research to address the gap in knowledge will provide an insight into a potentially cost-effective alternative and sustainable road construction by utilising locally available sandstone aggregate and fly ash waste material.

Keywords. *Sandstones; aggregates; soil stabilisation; cement; lime; polymer; fly ash; pavement; base; subbase*

INTRODUCTION

Pavements are an essential component of any road system. Its primary function is to transfer the imposed wheel load from traffic to the underlying pavement layers without exceeding the subgrade soil's bearing capacity [1]. It should also provide a satisfactory ride quality, sufficient skid resistance, good light-reflecting properties, and minimal noise pollution [2]. The subgrade is the bottommost layer of pavement structure which is made of naturally compacted soil and serves as the foundation for the whole pavement. It bears a crucial role in supporting the pavement structure during its service life span [3]. Pavement performance is reflected from the characteristic of the subgrade soil [4]. The construction of highways and runways over weak subgrade soil has become a common problem worldwide [5]. Weak subgrade swells and shrinks when it comes into contact with water, allowing for more deformation before carrying ultimate load [6], so it is usually stabilised using various mechanical and chemical methods to improve its engineering properties or it is replaced with better subgrade materials. Aggregates can be found in all pavement layers, but they are most commonly found in the base and subbase courses, also known as the pavement aggregate layers. These layers are normally needed to be constructed using higher quality aggregates since they serve as the structural component of the pavement system (such as using granites or diorites). The growing demand for road construction and development has contributed to increased mineral resources exploitation, resulting in scarcity. Aside from the environmental effect, construction costs are a concern, especially when strong aggregates are not readily available near the construction site and must be transported a long distance or imported from another country. Stabilising locally available but sometimes weaker aggregates could be a more cost-effective alternative.

Road base and subbase layers are usually constructed as unbound materials. As a result, its stability is highly affected by the maximum packing density [7]. When the materials are compacted to their maximum packing density at the optimal moisture content, they attain the highest stability. If all grain sizes are present and evenly distributed throughout the material, the aggregate interlocking and particle contact during compaction will be improved, resulting in a tightly packed structure [8]. However, when compaction is applied to lower-quality aggregates, such as sandstones, the aggregate degrades and breaks down, resulting in additional fines. After that, loads get transferred to the fines since they dominate the aggregate matrix, reducing road base and subbase layers' stiffness, stability and durability. Due to its great water absorption capacity, pavement with sandstone aggregates layer may also suffer from rutting and shoving. Since high-quality aggregates, such as granite, are costly to import, this paper aims to evaluate potential chemical stabilising agents for improving the engineering properties of marginal aggregates for the construction of pavement aggregate layers. Soil engineering properties such as its density, water content, plasticity, and strength can be improved by adding chemical additives through chemical stabilisation. Chemical soil stabilisers are generally categorised into traditional and non-traditional additives [9]. Traditional additives such as cement, lime, and fly ash are the most well-known traditional stabilisers [10], while the polymer is the most well-known non-traditional stabiliser [9]. The findings of this state-of-the-art review will identify potential areas that will require further research.

CEMENT STABILISATION

Cement is one of the oldest binders and has been implemented in soil stabilisation since 1960's [4, 11]. It is one of the most popular choices of stabilising agents as it is readily available and is not soil-dependent [12]. Its application covers wide range of materials, including non-cohesive, granular, and poorly cohesive soils [13], as well as by-products such as slag and fly ash, and waste materials, such as crushed concrete [14]. However, soil materials with high plasticity should not be stabilised with cement [15]. Organic soils, clays with high plasticity, soils with medium to high sulfate levels, and sandy soils with a low reaction rate are also exempt [16]. Due to their high exchange capacity, organic soils can slow down the hydration process by retaining the calcium ions released during the hydration of calcium silicate and calcium aluminate in the cement [12]. Soil stabilisation with all calcium-based stabilisers, which include cement, lime, and fly ash has the potential to cause deleterious expansions when soil is exposed to sulfates, particularly when clay minerals are present [16]. High sulfate content in soil-cement mixtures will also cause cracking and reduction in compressive strength and durability [17]. Since it has better sulphate resistance and lower heat of hydration than other varieties of Portland cement, Portland cement Type II is typically used for stabilisation [18]. Although the organic content and pH of soil do not necessarily indicate poor-reacting sand, Reference [19] claimed that sandy soil with an organic content of more than 2% or pH less than 5.3 is ineffective for cement stabilisation. Cement is most preferred when stabilising granular or sandy soil than fine-grained soil [11, 20, 21].

Generally, well-graded granular materials with sufficient fines are good soil candidates to produce a floating aggregate matrix (homogeneous) mixture for Portland cement stabilisation [15]. Cement helps to reduce permeability, resulting in a moisture-resistant material that is highly durable and resistant to leaching over time [14], which is advantageous in pavement stabilisation for decreasing rutting problems [22]. It also offers great stiffness and good serviceability for road construction [23]. Cement stabilisation results in a decrease in void ratio, an increase in unit weight, a decrease in plasticity, a decrease in volume expansion or compressibility, and an increase in the soil's shear strength and bearing capacity [12]. Reference [24] investigated the effect of sandstone aggregate types on concrete strength. It was found that using sandstone aggregates that contained clay cement resulted in a weak bond between aggregate and chemical cement and showed approximately 40-50% reduction in concrete strength when compared to the use of sandstone aggregates which contained carbonate cement. Reference [25] investigated the mechanical properties and durability of sandstone concrete. It was found that sandstones have relatively poor workability when compared with other aggregates like syenite, marble, and basalt, but it is not prone to cause concrete segregation. Despite the lower values for compressive and tensile strengths than those related to basalt aggregate, sandstone met the requirements for crack resistance, frost resistance and fatigue resistance, demonstrating its suitability for use in cement-stabilised road base construction. Past researchers have also used cement to stabilise crushed granite aggregate [18, 23, 26, 27], aggregates recycled from construction and demolition wastes [28, 29, 30] as well as other soil materials such as sandy silt soil with some clay [6], silty sand soil with some gravel [6], sandy clay soil [20, 31], sand and clay soil [8, 20, 32], and peat soil [33].

Its stabilisation mechanism in the soil-cement matrix is achieved through the hydration process. Water and Portland cement combine to form calcium silicate hydrates (C-S-H) and calcium aluminate hydrates (C-A-H), as well as calcium hydroxide (free lime). Calcium hydroxide undergoes a pozzolanic reaction with soil when it comes into contact with it in a high pH environment [4]. The C-S-H and C-A-H cementitious compounds are essential for mineral particle bonding and strength development. Cement also shows better performance in stabilising tropical peat soil when compared to lime additive [33]. Strength development of cement-stabilised soil is affected by several factors such as the presence of foreign matters or impurities, water-cement ratio, curing temperature, presence of additives, and specific surface of the mixture [11]. Water in cement stabilisation is important in order to lubricate and bind the soil into a uniform mix [32]. For cement stabilisation to become effective, a large amount of cement may be required to successfully bond most of the material particles [12], in addition to the fact that the curing period is quite extensive and the compaction process is time-limited, all of which combine to contribute to the high construction cost of soil stabilisation using cement [34]. Global cement production has a detrimental influence on the environment because it is the third-largest source of anthropogenic carbon dioxide emissions [35]. According to Reference [36], a well-graded mixture of stone fragments or gravel, coarse sand, and fine, with or without small amounts of slightly plastic silt and clay material, requires no more than 5% cement by weight. However, Reference [31] discovered that a well-graded mixture of sand and fine required approximately 5.36% and 6.48% to achieve the California Bearing Ratio standard for sub-base and base courses, respectively. Additionally, caution should be used when the cement concentration exceeds 8% [22], as this may result in drying shrinkage cracking, which is always a concern with cement-stabilised bases. Over time, cracks will eventually propagate, causing reflective cracking to the asphalt wearing course, which will cause pavement distress [7].

LIME STABILISATION

Lime is one of the oldest binders used for stabilisation. In contrast to cement, which is recommended for granular soil, lime is excellent and most successful for clayey soil stabilisation [13, 37, 38], with a plasticity index of more than 15-18%, a volumetric change of greater than 20-30%, and clay concentration of greater than 25-30% [39]. These soils contain silica and alumina which allows a pozzolanic reaction to take place [7]. It is also used to stabilise aggregate bases contaminated with clay as well as calcareous bases that have little or no significant clay content [14]. The soil-lime stabilisation mechanism is complex. It consists of two processes: short-term modification process and long-term stabilisation process [40]. The former involves a cation exchange reaction that produces calcium ions [41], followed by a flocculation-agglomeration reaction in which soil particles become friable and granular [42], and a lime carbonation reaction [38]. However, lime carbonation is a limitation because it results in calcium carbonate which is a weak cementing agent that can easily dissolve and precipitate under physical and chemical conditions prevailed on and within the earth [43]. During the short-term modification process, reduction in soil plasticity index, increase in workability [40] and shrinkage limit can be observed [33]. Due to the decrease in maximum dry density and increase in optimal moisture content, soils may even become non-plastic following lime stabilisation [39]. During a pozzolanic reaction, the C-S-H and C-A-H compounds are formed, which is responsible for the long-term stabilisation process [41]. This pozzolanic reaction has the potential to last for a very long period of time [33], provided the lime content is sufficient, and the pH is consistently above 10 [38], in order to achieve high and long-lasting strength gain and stability [42]. This process increases the unconfined compressive strength and moduli of the soil [40]. Typically, 1-3% of lime is required for the soil modification process, and 2-8% for the actual stabilisation [43]. Lime in the range of 5-10% may be used to stabilise sediment soil, such as inorganic soil [33].

Lime is beneficial for soil stabilisation because it increases strength [41], decreases plasticity index [37], improves resistance to fatigue and permanent deformation, reduces swelling, and increases resistance to moisture-related damage [14]. Additionally, it has been shown to be useful in stabilising low plasticity clay in wet condition tests [9]. Lime additives such as hydrated calcium lime, monohydrated dolomite lime, quick calcite lime, and dolomite lime can be utilised to stabilise soil [12, 33]. Quicklime is the most frequently utilised lime, especially in wet soils due to its higher free lime content which allows the acceleration of strength gain and largely reduces moisture content [11]. However, quicklime may be hazardous because it is capable of destroying living tissues [33]. The presence of deleterious compounds in soils may inhibit the lime stabilisation process. An example is sulphur which causes the formation of ettringite that leads to excessive swelling, and chlorides which retards the hydration of lime [44]. Moreover, since lime stabilisation takes a long time and has a slow pozzolanic reaction, it may not be suitable for roads that are scheduled to open soon. Elevation of ground water levels and infiltration of surface water should also be considered before using lime for stabilising pavement aggregate layers as these may leach calcium ions from lime stabilised layers, and hence reducing the stabilisation benefits of the added lime [37]. Lime stabilisation was mostly used by past researchers for stabilising fine-grained soils like clay, silt, and peat soils [20, 21, 33, 37, 40, 44], while only a few used lime to stabilise recycled aggregates from construction and demolition wastes [30, 45, 46] and limestone aggregates [47].

POLYMER EMULSION STABILISATION

Polymer emulsion is considered to be one of the most environmentally friendly methods of soil stabilisation, and its application in the construction sector is gradually increasing. It offers a more cost-effective option to other methods while also promoting sustainability at the same time. Polymer emulsions are essentially a “glue” used in soil stabilisation to bond the soil-aggregate particles together physically. The formation of a soil-polymer matrix occurs after the water in the emulsion evaporates [26]. Since bonding occurs on the surface of soil particles, the amount of the soil’s surface area is of great importance. Polymer stabilisation can be applied to various soil types but the bonding is more effective with fine clay particles than with large sand- and silt-sized soil particles. However, the large specific surface area of fine-grained soils could reduce their mixing efficiency with polymer by inhibiting it from sufficiently coating the soil particles [48]. Therefore, the optimum soil gradation for mixing with polymer emulsions, and forming a proper soil matrix, is well-graded with adequate fines [48]. Polymer stabilisation can also be used for soils having a plasticity index up to 12% [49]. Polymer emulsion has been utilised in previous studies for various soil materials such as clayey soil [50], silty sand soil [51], subgrade soil [52], subbase material [53], crushed granite aggregate [26, 27], and crushed sandstone aggregate [54].

The standard types of polymer emulsions are vinyl acetate, acrylic-based copolymer latexes, and styrene-butadiene (SB) copolymer [55]. Polymer stabilisation offers many advantages, such as the minimisation of soil and water erosion and the shortened curing time that is superior to that of traditional additives. It also provides soil with ductile characteristics, is natural eco-system friendly [9], and is suitable for treating soils, especially in regions where flooding occurs on a regular basis [53]. The risks of dust dispersion caused by dry soil stabilisers in powder form can also be mitigated with liquid soil stabilisers [53]. Polymer can give almost the same results as stabilisation using traditional additives [9]. Reference [51] reported significant improvements in soil strength after stabilisation with a small polymer content that were comparable to soil improvements after stabilisation with typically high cement content. This can also be seen in Reference [56] where soil stabilisation with 40%, 30%, and 20% cement contents resulted in the same strength as that of soil stabilised with 4%, 3% and 2% polymer contents, respectively. The polymer can also be added to a soil-aggregate-cement mixture to increase their workability and mechanical properties [26]. The polymer was first used in concrete mixtures in the 1950s, and by the 1960s, it became well-known [57]. Polymer film formation occurs during cement hydration when a polymer is added to soil-aggregate-cement mixtures, resulting in a co-matrix with polymer film intermingled with cement hydrates [58]. Due to its very low permeability, the use of polymer in concrete mixtures results in favorable gains in compressive, tensile, and flexural strength with excellent durability, particularly freezing and thawing and acid resistance [57]. However, leaching of polymer emulsions may occur during inclement weather conditions such as rainfall during field application [7].

FLY ASH STABILISATION

Fly ash is a finely divided by-product of coal power generation [59] that has less cementitious properties in comparison to lime and cement [12]. With silt- to clay-sized particles ranging in size from 10 to 100 microns, it is finer than Portland cement and lime [60]. It is traditionally disposed of at landfills. Numerous research studies have been conducted around the world on the reuse of waste materials in engineering projects due to the economic benefits it offers [61] while reducing disposal costs and is therefore environmentally friendly [62]. When mixed with other construction materials, fly ash can be used to improve their properties [38] such as improving soil's bearing capacity [63], controlling shrink swell properties of expansive soils [5, 63], reducing moisture content [63], and stabilising embankments for slope stability [60]. Since it has been proved to improve the ride quality and serviceability of roads [64], with considerable improvements in strength and durability, fly ash has also become a popular alternative for soil and pavement bases stabilisation [14]. According to ASTM C 618, fly ashes are classified into two primary classes based on their chemical composition: Class F and Class C fly ashes. Because of its high free lime concentration, Class C fly ash has self-cementing characteristics and will chemically react with water alone to produce a cementitious compound [11]. Class F fly ash, on the other hand, is incapable of achieving the desired effect on its own and so requires the addition of activators such as cement or lime to make cementitious products known as pozzolan stabilised mixes [62]. For soil stabilisation, both non-self-cementing and self-cementing fly ashes can be used [14]. Several research efforts have looked into fly ash as a soil stabilisation additive which includes using off-specification fly ash which is not Class C or Class F with various additives, including cement [62, 65, 66, 67], lime [62, 68], cement kiln dust [59], lime kiln dust [69], marble dust [70], geopolymer [71, 72], and without additives [61, 73]. These past studies involved the use of different soil materials such as sandy soil [62, 65], gravel soil [70], lateritic soil [72], expansive soft soil [4, 5, 38], recycled asphalt pavement [71], conventional road base materials [66, 69], road surface gravel [64], and aggregates recovered from construction and demolition wastes [59, 73].

The stabilisation mechanism of fly ash is dependent on many factors such as curing time and temperature, compaction energy, moisture content, and the type of additives used. The strength gain mechanism with fly ash stabilisation is usually discussed with the reaction of the silicon dioxide (SiO_2) component in fly ash, but it was suspected that the aluminium oxide (Al_2O_3) component is also contributing to the hydraulic property of the pozzolanic reaction of fly ash [74]. Similar to other traditional additives, fly ash has a lengthy curing time of up to 28 days for effective stabilisation to occur [52]. This is attributed to the delayed pozzolanic reaction, which generally takes 28 days to complete [32]. The strength of fly ash-stabilised material was found to be less when quicklime was used as an activator than when cement activated the fly ash, with the latter showing continual improvement until 56 days curing time [62]. Low curing temperature also allows the gradual increase in strength resulting in maximal values even when fly ash-stabilised material is cured until 365 days [65]. With the best binder combination, fly ash-stabilisation can increase the strength of material by up to 12-fold [59]. Excessive fly ash causes gradual changes in the soil matrix, and when the soil is in an amorphous state, it changes the initial support of inter-particular force chains and transfers the force flow from the coarse aggregates to the fine fraction of mix, resulting in a reduction in the strength of the soil [73]. From previous studies, effective fly ash content is between 10 and 40%. According to Reference [62], lime has a negative impact on the strong performance of fly ash-soil combinations. It is therefore unsuitable as an activator for the stabilisation of fly ash in road base materials. Another limitation of fly ash stabilisation is the sulfur concentration in soil-fly ash mixtures, which may result in the formation of expansive minerals, thereby reducing the material's long-term strength and durability [63]. Additionally, slaking and strength loss are especially common in soil-fly ash mixtures that have been cured below zero and then soaked in water [63]. Moreover, when fly ash is used in geotechnical applications, trace metals in the ash may leach into the environment [69].

DISCUSSION AND CONCLUSIONS

A critical review of the literature on four methods of chemical soil stabilisation involving cement, lime, polymer emulsions and fly ash is presented. As a result, it can be concluded that both traditional and non-traditional stabilising agents have their own strengths and weaknesses. Based on the literature review, lime stabilisation may not be the best option for stabilising unbound aggregate materials since most researchers have agreed that lime additive should be used to stabilise cohesive soils but there are a few studies that used lime to stabilise demolition and construction waste aggregate and limestone aggregate. While cement, polymer, and fly ash have all been extensively studied for their ability to stabilise a variety of soils and aggregates, far fewer studies on sandstones have been conducted. Stabilisation of sandstone road aggregate layers with cement and/or polymer or cement concrete mixes for building construction were the only studies on sandstone materials. No studies have yet investigated the stabilisation of sandstone aggregates using lime or fly ash. These are the identified gaps in knowledge that should be addressed. Future research should focus on the stabilisation of sandstone road aggregate layers with fly ash or lime or a combination of fly ash and other additives, especially when using non-self-cementing fly ash. These future studies will provide an important insight into a potentially cost-effective alternative and sustainable road stabilisation method by utilising locally available sandstone aggregate and fly ash waste material.

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