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Review

Emerging trends in expansive soil stabilisation: A review

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ABSTRACT

Expansive soils are problematic due to the performances of their clay mineral constituent, which makes them exhibit the shrink-swell characteristics. The shrink-swell behaviours make expansive soils inappropriate for direct engineering application in their natural form. In an attempt to make them more feasible for construction purposes, numerous materials and techniques have been used to stabilise the soil. In this study, the additives and techniques applied for stabilising expansive soils will be focused on, with respect to their efficiency in improving the engineering properties of the soils. Then we discussed the microstructural interaction, chemical process, economic implication, nanotechnology application, as well as waste reuse and sustainability. Some issues regarding the effective application of the emerging trends in expansive soil stabilisation were presented with three categories, namely geoenvironmental, standardisation and optimisation issues. Techniques like predictive modelling and exploring methods such as reliability-based design optimisation, response surface methodology, dimensional analysis, and artificial intelligence technology were also proposed in order to ensure that expansive soil stabilisation is efficient.

1. Introduction

In civil engineering structures, various kinds of soils are used; however, some soil deposits in their natural form are suitable for construction purposes, whereas others are unsuitable without treatment, such as the problematic soils. These soils need to be excavated and then replaced, or their properties should be modified before they can sustain the applied loads by the upper structures. Typical of problematic soils are the expansive soils, which are frequently observed due to their existence worldwide, except the arctic regions (Steinberg, 2000). This kind of soil has caused a significant amount of damage in the United States (Jones and Holtz, 1973), due to its high susceptibility to volume change, sensitive to moisture content. The inherent volume change characteristics of expansive soils are mainly resulting from their fine-grained clay mineral content. Due to cost implication, geotechnical engineers often prefer modifying the properties of fine-grained soils in situ via stabilisation in comparison with the soil replacement in practice (Buhler and Cerato, 2007; Hussey et al., 2010). Generally, the typical expansive soils can be easily identified from their high plasticity, excessive heave, and high swell-shrink potential which are made up of clay, shale or marl (Steinberg, 2000; Abiodun and Nalbantoglu, 2015). A well-known expansive soil with high volume change tendency is the black cotton soil (BCS), which occurs mainly in areas with lacustrine and basaltic geologic origin like the Lake Chad basin and India (Uppal and Chadda, 1967; Ackroyd and Husain, 1986). Ackroyd and Husain (1986) stated that the expansive nature of BCS is due to the presence of montmorillonite group, which dominates its clay fraction.

Due to the adverse nature of expansive soil, geotechnical engineers are persistently searching for various options to mitigate its objectionable characteristics via soil stabilisation technologies. The aim of the engineers in stabilisation of expansive soil is more or less to normalise the volume change and plasticity or workability characteristics, whilst significantly improve the strength properties (Petry and Little, 2002; Soltani et al., 2017a, 2018a). Research that attempts to improve the properties of expansive soils has resulted in a vast repository of technical knowledge available. The information obtained from these repositories seems to be somewhat divergent. Rather than providing mature solutions, the information available from stabilisation researches may only serve to complicate issues for the construction engineer. In some cases, the results are only suitable for limited applications, as indicated by various studies (Uppal and Chadda, 1967; Ola, 1981; Puppala et al., 2001;

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Kate, 2005; Dafalla et al., 2015; Zhao et al., 2015), and in other cases, the application may prove to be reserved in practice or unfeasible in situ (Ola, 1981; Cokca, 2001; Kate, 2005; Inyang et al., 2007; Jayasree et al., 2015; Dutta and Mandal, 2016; Ikeagwuani et al., 2017). These issues are likely intractable, pending the development of standards for the application of soil stabilisation results, using various additives and their respective composites.

For this, there is a need for both geotechnical engineers and researchers to reconcile theory and practice with respect to expansive soil stabilisation. This paper presents a review on the stabilisation of expansive soils using various techniques. State-of-the-art in practice of expansive soil stabilisation is discussed with respect to the effect of various additives and techniques on engineering properties of the stabilised soil. Then, possible approaches to transit from state-of-the-art to state-of-the-practice are explored, in an attempt to raise issues in applying the results of soil stabilisation to expansive soils and possible studies needed in order to address the raised issues. Finally, this paper discusses the stabilisation results of various additives to expansive soils, which might be useful in addressing the issues associated with the practical application of expansive soil stabilisation.

2. Expansive soil behaviour

2.1. Characterisation of expansive soil behaviour

2.1.1. Expansion mechanism

It is known that due to isomorphous substitution, clay particles consist of superficial negative charges (Schmitz, 2006; Sridharan and Choudhury, 2008). As a result, electrostatic forces exist between the negative clay surface and exchangeable cations within the clay-pore fluid media whose strength is dependent on the chemistry of the exchangeable cation (Schmitz, 2006). In order to maintain neutrality within the clay-pore fluid media, there is a natural affinity for the counter ions to be attracted onto the surface of clay particles, thereby decreasing their concentration with distance from the clay surface. This change in concentration produces the surface electrostatic property known as the diffuse double layer, and the amount of cations needed for maintenance of neutrality on the clay surface is the cation exchange capacity (Yadav and Tiwari, 2017a). The double layer consequently causes a separation between the minerals and particles, accompanied by swelling behaviour (Schmitz, 2006) for expandable clay minerals like montmorillonite. It is obvious that the diffuse double layer significantly influences all the engineering properties of clayey soil, especially the hydraulic conductivity (Besq et al., 2003; Sridharan and Nagaraj, 2005; Schmitz, 2006). Expansion of the diffuse double layer thickness is expected to reduce the hydraulic conductivity and the converse is the case when the double layer is decreased (Sridharan and Choudhury, 2008). This in essence provides the framework for the swell-shrink behaviour of expansive soils with moisture variation.

The influence of diffuse double layer on volume change behaviour of an expansive soil is inherent due to its expandable clay mineral, e.g. montmorillonite, whose morphology is characterised by an expanding clay lattice. Expandable clay minerals are known to have weak intermolecular forces of attraction between adjacent unit cells, but significant isomorphous substitution during mineral formation that displays negative surface charges, considerable cation exchange capacity, and huge specific surface in terms of mass.

2.1.2. Clay mineral identification

In a recent study by Sridharan and Keshavamurthy (2016), two methods were proposed for identifying the presence of the expandable clay lattice in an expansive soil, namely inferential testing and mineralogical identification methods. Inferential testing method consists of direct methods, which are used to calibrate the index properties like liquid limit, shrinkage limit, and particle size distribution, and indirect methods such as oedometer test and free swell tests (free swell value, differential free swell, and free swell ratio). The mineralogical identification method consists of methods such as X-ray diffraction analysis, differential thermal analysis, dye adsorption, chemical analysis, and scanning electron microscopy (SEM).

Although the mineralogical identification methods are capable of recognising the clay minerals in expansive soils adequately, they are somewhat restricted in use when characterising the swelling behaviour due to some drawbacks. Sridharan and Prakash (2000) and Sridharan and Keshavamurthy (2016) suggested that the mineralogical identification methods are not cost-effective in nature, due to their requirements of high-level instrumentation, complexity and expert interpretation of results. This makes the mineralogical identification methods impractical for a wider range of applications.

The inferential testing methods seem to be helpful for clay mineral identification and classification of swelling behaviours since they are based on index properties and direct methods when determining swell potential, which is neither expensive nor sophisticated. However, from literature point of view, the free swell ratio method proposed by Sridharan and Prakash (2000) seems to be the most promising inferential testing method for identification of the dominant clay mineral in expansive soils, in a highly comparable manner to that of mineralogical identification methods, and it has been applied recently (Wubshet and Tadesse, 2014; Soltani et al., 2018a).

Free swell ratio is defined as the ratio of equilibrium sediment volume of 10 g of soil passing 425 μm sieve which has been oven-dried before immersion in water to that in carbon tetrachloride/kerosene (Sridharan and Prakash, 2000). However, due to the nature of some soils consisting of a combination of non-expansible kaolinitic clay mineral and montmorillonite, the free swell ratio is used in conjunction with the liquid limit test using cone method with water and carbon tetrachloride as pore fluids to determine the dominant clay mineral. The knowledge for this stems from the non-polarity of the carbon tetrachloride, which inhibits the formation of the diffuse double layer and permits the formation of flocs, thereby resulting in higher liquid limit values for kaolinitic-rich soils (Prakash and Sridharan, 2004). Using the free swell ratio method, expansive soils are classified, as shown in Table 1.

2.2. Unsaturated soil mechanics conception of expansive soil behaviour

Due to the behaviour of significant volume change in expansive soils, it poses great difficulty on modelling the unsaturated behaviour of expansive soils. The conception of partial saturated behaviour in expansive soils is evident from the bimodal nature of

Table 1
Expansive soil classification using free swell ratio (Sridharan and Prakash, 2000).

Oedometer expansion (%)[a]	Free swell ratio	Clay type	Soil expansivity
<1	≤ 1	Non-swelling	Negligible
1–5	1–1.5	Mixture of swelling and non-swelling	Low
5–15	1.5–2	Swelling	Moderate
15–25	2–4	Swelling	High
>25	>4	Swelling	Very high

[a] From air-dried to saturated condition under a surcharge of 7 kPa.

the soil-water characteristic curve. Whilst this could hold on a macroscopic scale when the soil mass is observed superficially, it is noteworthy to consider the intrinsic constituents of an expansive soil mass, made up of saturated soil peds with high suction values preceding the air entry value threshold (Cui et al., 2006; Buzzi et al., 2007). Fityus and Buzzi (2009) pointed out that the unsaturated soil mechanics framework attributing to expansive soils does not match their basic volume change processes during constitutive modelling; as a consequence of their coarse granular nature, due to the soil porosity realised by way of macroscopic desiccation cracks.

2.2.1. Discussion of the existing framework

From the existing unsaturated soil mechanics framework apparently extended to expansive soils, it can be deduced that soil suction has an inverse relationship with degree of saturation, as described in Fityus and Buzzi (2009). Since soil suction has a close relation with pore water, which can result in expulsion of the pore water, a corresponding air entry is anticipated. Consequently, Terzaghi's effective stress principle is employed for saturated soils and often extends to expansive soils via the interconversion of suction and its corresponding equivalent stress. In view of permeability and shrinkage behaviours, partially saturated soils exhibit a direct linear relationship between moisture content and permeability. In addition, the attendant desorption trend exhibited by the soil becomes prevalent as observed in the soil-water characteristics curve, when the suction threshold is obtained for filling of the largest pores by air, resulting in little volume change in the residual shrinkage phase (Fityus and Buzzi, 2009).

However, for expansive clays in the framework of unsaturated soil mechanics, Fityus and Buzzi (2009) highlighted the fundamental behaviours of expansive soils, but cast doubt on the aforementioned unsaturated soil mechanics framework for expansive soils. It can be inferred that the widely accepted capability of unsaturated soil models in precisely describing expansive soil behaviour is due to higher pore size resulting from structural rearrangement caused by compaction-related activities, which converges the soil towards a partially saturated behaviour and is more likely to be the case in remoulded samples. In contrast, for undisturbed samples in natural soil deposits, air entry is delayed by the small pore size of smectite clays, which maintains the soil in a saturated state within the suction values observed under field conditions that are of engineering significance.

Furthermore, volume change behaviour of expansive soils conceived to be a consequence of partially saturated behaviour actually occurs within the saturation range, owing to the adjustment in both the soil particles and pore size within the adjacent particles of the soil peds. This adjustment ensures water expulsion whilst excluding air entry despite the increase in soil suction, which continues until the value of air entry, is attained.

Consideration of effective stress applied in unsaturated soil models can be undermined in the case of expansive soils due to the chemistry of the ion layer of clays, which exhibits the well-known electrostatic property of diffuse double layer. This also plays a significant role in the volume change behaviour of expansive soils and the effective stress principle is improper to account for this intrinsic property that affects the soil mechanical equilibrium. It becomes apparent that the framework of unsaturated soil mechanics does not apply properly to expansive soils and as stated by Adem and Vanapalli (2015), the suction-based methods for predicting transient volume change behaviour of unsaturated expansive soils are dependent on the proportionality between suction variation and volume change.

Considering the basic mechanisms of soil expansion, the double layer theory is well established in approximating the volume change mechanism of expansive soils. However, some researchers argued the validity of the theory, having provided both empirical and experimental evidences to elucidate the negligence of the double layer theory to incorporate other factors which significantly affect the expansion of swelling soils. These factors were highlighted in Gens and Alonso (1992) to include anion adsorption, ion size effect, modification of interlayer water potential and others, which are regarded as the direct mechanical influence of water in tension. As a result, various theories have been proposed to incorporate some of the aforementioned factors, rendering the microstructural framework for description of volume change behaviour of expansive soils irresolute and open-ended. Although Gens and Alonso (1992) put forward a framework for the behaviour of unsaturated expansive clays, in which it was explicated that the framework is independent of the microstructural theory adopted, it would be more appropriate if expansive soils were truly unsaturated within their considerable volume change range.

3. State-of-the-art in expansive soil stabilisation

3.1. Historical perspective

Over the years, various results have been achieved in the area of expansive soil stabilisation, probably due to deeper insight and knowledge of expansive soil behaviour. Geotechnical engineers have already made huge effort towards understanding the behaviour of expansive soils under loading condition using scientific principles, and several laboratory experiments have been thus designed.

Within the second half of the 20th century, many attempts were made by the geotechnical community to explain the fundamental behaviour of expansive soils and their proper identification. A method by Palit (1953) was reported to definitely ascertain the swelling pressure of BCS, where it was pointed out that an increase in height of the sample during the test causes an increase in swell pressure, although the relationship remains immature. Information obtained from oedometer test by Jennings and Knight (1957) was used to understand the phenomenon of heave. Further efforts led to the determination of swell potential of expansive clays using laboratory, predictive and field observations (Lambe, 1960; Jennings, 1961; Seed et al., 1962). In order to clarify hydro-mechanical behaviour in clays, a negative pore water pressure resulting from its moisture demand is known as soil suction (Petry and Little, 2002). Soil suction in clay subgrade as stated by Petry and Little (2002) has been established to be related to swell when moisture is present. As a result, many researchers then developed concept as well as methods to measure and apply it for determining expansive soil characteristics like swell and resilient modulus (Vijayvergiya and Ghazzaly, 1973; Snethen et al., 1975; Johnson, 1977; Johnson and Snethen, 1978; McKeen, 1980; Snethen, 1984; Dempsey et al., 1986). Laboratory experiments like Atterberg's limits, particle size distribution (sieve analysis and hydrometer), moisture content and dry density, were used by Lytton (1994) to describe some important properties of expansive clays. These works briefly clarify a basic understanding and various laboratory methods of identifying expansive soil behaviour.

3.2. Techniques for expansive soil stabilisation

For soil stabilisation, two methods are often employed which are mechanical and chemical stabilisations (Estabragh et al., 2013a, 2014; Radhakrishnan et al., 2017; Soltani et al., 2018b). Each of the two methods may be used independently or simultaneously, in an attempt to optimise each benefit. For expansive soils like clay, engineers prefer physicochemical modification of the soil to achieve durability (Petry and Little, 2002). That is, the swell-shrink-

Table 2
Summary of various natural/synthetic fibres used for soil reinforcement.

Fibre source	Fibre type	Dosage/optimal content (%)	Fibre configuration (length)/optimal length (mm)	Information source
Natural	Coir fibre	0.2–1	>4.75	Jayasree et al. (2015)
	Coir pith	0.5–3	<4.75	Jayasree et al. (2015)
	Sisal fibre	0.25–1	10–25	Prabakar and Sridhar (2002)
	Palm fibre	0–1	20–40	Marandi et al. (2008)
	Jute fibre	0.3–0.9	6–18	Wang et al. (2017)
	Flax fibre	0.6[a]	85[a]	Segetin et al. (2007)
	Barley-straw fibre	0–3.5	10–500	Bouhicha et al. (2005)
Synthetic	Carpet waste fibre	1–5	2–20	Mirzababaei et al. (2013a)
	Polypropylene fibre	0.5–1.5	10–30	Estabragh et al. (2014)
	Waste rubber fibre	0–10	≤15	Yadav and Tiwari (2017b)
	Polyester fibre	0–2	3–12	Kumar et al. (2006)
	Glass fibre	0.25–1	10–30	Patel and Singh (2015)
	Polyethylene fibre	0–4	12–36	Choudhary et al. (2010)
	Polyvinyl alcohol fibre	1[a]	12[a]	Park (2011)

[a] The optimal values.

consolidation volume changes are calibrated by either maintaining or improving the strength-related properties for an extended period, which is usually achieved through chemical stabilisation. Hence, the use of various additives was mainly discussed in this review, although other techniques for stabilising expansive soils were also described in brief. In this case, the relationship between various techniques used for soil stabilisation should be considered.

3.2.1. Mechanical/physical technique

(1) Compaction

Compaction is a widely used method for expansive soil treatment. It uses a mechanical means for expulsion of air voids within the soil mass thus the soil can bear load subsequently without further immediate compression, which is different from those initiated by long-term consolidation of soft clays. Therefore, it is very important for obtaining the moisture–density relationship of soils, in which the optimum moisture content (OMC) is obtained at a corresponding maximum dry density (MDD). However, in some cases, the soil could be preferably compacted in the vicinity of OMC, depending on the site-specific conditions and the aim of the compaction process. Soil-dependent factors that significantly influence the OMC and MDD include grain size distribution, shape of the soil grains, soil specific gravity, and amount and type of clay minerals present in the soil (Das, 2002). The effects of varying moisture content and density on expansive soils have been studied in recent years.

Experimental studies conducted on expansive soils by Yan and Wu (2009) showed the influence of moisture and density on expansive force. A positive exponential relationship was established between dry density and expansive force whereas the exponential relationship was negative between moisture content and expansive force. This result is in agreement with other studies that swelling potential generally increases with increase in dry density and decrease in water content (Marinho and Stuermer, 2000; Ferber et al., 2009). The effect of compaction process on expansive soil mass is more perceptible on a macroscopic scale than the microstructure. Microstructural studies conducted on compacted bentonite-sand mixtures using mercury intrusion porosimetry showed that the intra-aggregate pores with mean size diameter less than 0.2 μm were not affected by the soil dry density whilst the inter-aggregate pores varied at different dry densities (10 μm at 1.67 Mg/cm^3 and 50 μm at 1.97 Mg/cm^3) (Wang et al., 2013; Cui, 2017). The relevance of compaction control in expansive soil stabilisation is evident since the moisture fluctuation is the driving force behind the volume change behaviour exhibited by the soil.

(2) Pre-wetting

Pre-wetting is an ancient method, popularly applied in the past for mitigation of swelling in expansive soils. In this method, expansive soils are deluged by creating a moisture-rich environment, which causes the soil to sorb water and swell, creating a preconstruction heave. The fundamental concept behind this method is that saturation of the soil causes it to swell so that subsequent wetting of the soil would be incapable of engendering harmful heaving, thereby maintaining constant volume at such a high moisture content. However, under field conditions, maintaining the soil at high moisture levels constantly is far from attainable and thus, as stated by Nelson et al. (2015), the results of pre-wetting are not reliable and not usually recommended.

Notwithstanding, this method has proven to be successful in cases where the pre-wetted soils have high hydraulic conductivity to enable the soaking process to be executed within a short time period. For expansive soils, low values of hydraulic conductivity cast doubt on the efficiency of pre-wetting technique, although the conventional practice is to use materials like organic compounds with hydrophilic head and hydrophobic tail popularly known as surfactants to expedite water seepage process through the expansive soil layer (Das, 2010). In view of this, instances of successful application of pre-wetting have been recorded in the cases of Yazoo clay formation in Mississippi and Hawthorne clay formation in Gainesville, Florida, USA (Nelson et al., 2015).

(3) Wetting-drying cycles

Due to the nature of expansive soil volume change behaviour, wetting–drying cycles of the soil are often used for investigation of equilibrium conditions in field. A wetting–drying cycle basically involves inundating expansive soil with water until full swelling is obtained, followed by a corresponding drying of the soil to its initial water content. The cycle is repeated until an equilibrium state is reached in which plastic deformation gradually disappears.

Investigations into the effect of wetting–drying cycles on expansive soils have shown conflicting results. Soltani et al. (2017a) recently investigated the impact of wetting–drying cycle on the swelling behaviour of an expansive soil. The results of the axial deformation curve clearly showed about 50% decrease in swelling potential, 30% increase in shrinkage potential, and plastic deformation range of 6.8% from an initial value of 7.1% at the 1st cycle to 0.3% at the 5th cycle representing the equilibrium condition. Several researchers have also reported similar reduction in swelling potential with increase in number of wetting–drying cycles, including Yazdandoust and Yasrobi (2010), Ahmadi et al. (2012), Thyagaraj and Zodinsanga (2014), and Estabragh et al. (2013a, 2015), while others have recorded contradictory results (Tawfiq and Nalbantoglu, 2009; Estabragh et al., 2013b, 2014, 2018). For partial shrink-swell cycles in which the soil is dried to moisture content greater or equivalent to its shrinkage limit, significant reduction in swelling potential is also recorded, although it is considered to be pragmatically inept in situ (Tripathy et al., 2002; Soltani et al., 2017a). Wetting-drying cycles are also used for durability studies of chemical additives used in soil stabilisation to understand the long-term performance of such additives under field conditions by alternating wetting and drying on the stabilised soil.

(4) Reinforcement

Soil reinforcement as a mechanical means of stabilising weak soils involves the use of fibrous materials which can be in the form of geosynthetics (geogrid, geotextile, geocomposite, geonet, and geocell) or randomly distributed fibres of natural or synthetic origin (Hejazi et al., 2012). In other words, it often requires the placement of the aforementioned randomly or specifically engineered components in the soil regime, and it engenders a spatial three-dimensional (3D) reinforcement network in favour of weaving (or interlocking) the soil grains into a unit mass of improved mechanical performance. Different types and configurations of natural and synthetic fibres used for soil reinforcement are shown in Table 2. A comprehensive review of natural and synthetics fibres for soil reinforcement has been done by Hejazi et al. (2012), describing the effects of some randomly distributed fibres on engineering properties of soils. However, discussion on stabilisation effects of carpet waste fibre and waste rubber fibres was not included in the review work by Hejazi et al. (2012).

Yadav and Tiwari (2017b) investigated the effect of waste rubber fibres on the geotechnical properties of clay. The rubber fibres were added at contents of 0%–10% with 2.5% constant increment by weight of the dry soil. The result of the moisture–density relationship showed progressive reduction in both OMC and maximum dry unit weight (MDU) from 20.1% to 18.25% and from 16.35 kN/m^3 to 14.78 kN/m^3, respectively. The uniaxial compressive strength (UCS) of the soil showed a slight increase from 60.59 kPa to 62.69 kPa at 2.5% rubber fibre content. However, further addition of rubber fibre reduced the peak axial stress with a maximum reduction of about 21.7% at 10% rubber fibre content. The result of the split tensile strength test conducted on the soil showed progressive increase in the split tensile stress with volumetric strain until the peak value was obtained for all percentages of the rubber fibre addition. The peak tensile strength increased by 8.6% at 2.5% rubber fibre content but decreased at higher contents of rubber fibre, with a maximum drop of approximately 7.3% at 10% rubber fibre content. The soaked California bearing ratio (CBR) gradually dropped with rubber fibre content, while the unsoaked CBR attained a peak rise of about 38.6% at 2.5% rubber fibre addition. The swelling pressure of the soil progressively reduced with increase in fibre content from 70.12% for the natural soil to 39.58% at 10% rubber fibre content.

Mirzababaei et al. (2013a) studied the effect of two types of carpet waste fibres from different sources on the swelling properties of two compacted clays. Type 1 was solely made of short nylon fibres from sheared carpet piles, whereas type 2 was a mixture of polypropylene, polyester and wool obtained from carpet edge trimmings. The additives were added at contents of 1%, 3% and 5% by weight of the dry soil. The result showed that for compacted clay with 10% activated sodium bentonite content at MDU and OMC, the swelling pressure dropped by about 20% at 1% type 1 fibre content but increased for the other fibre contents. On the other hand, for type 2 fibre, the swelling pressure of the soil increased significantly, attaining a peak rise of about 83% at 3% fibre content. The effects of varying moisture content at fixed dry unit weight and varying dry unit weight at constant moisture level were also investigated. The results show that the swelling pressure dropped with the increase in moisture content at constant dry unit weight, but increased with increase in dry unit weight at fixed moisture content. Similar results for fibre reinforced soils were also reported by Mirzababaei et al. (2013b, 2018).

(5) Solid wastes

Solid wastes often produced in large quantities are quite common in municipal areas. Such wastes are basically made up of paper, glass, wood, plastics, reusable goods, rubber scraps, plant debris, metals and others with organic material as the major constituent (Puppala et al., 2007). The disposal and management of such wastes produced in large quantities are of environmental challenges, e.g. landfills. However, in recent years, some of these materials are proven to be suitable in soil stabilisation application.

Signes et al. (2016) studied argillaceous marlstone to determine the effect of rubber particle crumbs addition on swelling potential of the soil and recorded a reduction from 3.71% to 1.37% at 25% addition of the rubber crumb particles. Recycled basanite, a solid waste derived from gypsum waste plasterboard, was used by Kamei et al. (2013) to study its effect on durability of cement-modified soft clay. They reported the stabilised soil to be durable since the soil lost a small amount of its UCS from the 1st to the 3rd cycle which was almost regained at the 5th cycle with basanite-soil ratio of 10% at cement-soil ratios of 5% and 10% applied. In a similar study, Ahmed et al. (2011) stabilised clayey soil with gypsum waste plasterboard and recorded about 700% increase in 28-d UCS of the soil. Similarly, other studies have demonstrated promising results in the use of various solid wastes for soil stabilisation (Seda et al., 2007; Dunham-Friel and Carraro, 2011).

3.2.2. Chemical technique

(1) Traditional agents

Pre-existing and well-established chemical additives used in stabilisation of expansive soils are often referred to as traditional agents. These agents include lime, cement and fly ash, and they are usually calcium-based. As a result, in the presence of water, they undergo both instant and prolonged time-dependent chemical reactions with the soil or other additives, resulting in overall enhancement of the soil matrix in terms of swell reduction, shear strength improvement and resistance to influence of wetting and drying (Soltani et al., 2017a).

Cation exchange, flocculation and agglomeration, pozzolanic reaction, and carbonate cementation have been identified as the mechanisms of stabilisation for traditional agents (Little, 1999; Al-Swaidani et al., 2016; Firoozi et al., 2017). However, Le Chatelier's crystalline theory and Taylor's gel theory represent the most widely known stabilisation mechanisms (Le Chatelier, 1919; Taylor, 1971). Various curing phases are better depicted using a combination of the two aforementioned theories (Firoozi et al., 2017).

Table 3
Summary of advantages and disadvantages of mechanical and chemical soil stabilisation techniques.

Technique	Advantages	Disadvantages
Mechanical	(i) The process application is relatively easy and does not require highly skilled personnel; (ii) It does not require time-consuming laboratory standardisation tests when additives are not involved; (iii) It does not pose the risk of imparting an adverse environmental effect from release of potential harmful compounds; (iv) It can serve as an effective waste management alternative to landfills when waste materials are used; (v) It can be readily applied when the soil engineering properties are not considered critical	(i) It involves prolonged physical activity to execute in situ when quality control is essential and thus could be time-consuming; (ii) The expected outcome may be unpredictable especially in the case of pre-wetting/wetting–drying cycles; (iii) It may not be considered sufficient when the soil condition is very critical as in the case of expansive soils; (iv) Mechanical methods are not usually sufficient stand-alone methods and often requires to be supplemented with chemical stabilisation
Chemical	(i) Expected outcome is obtained from laboratory standardised tests; (ii) Most often, the quantity of required chemical additive needed to effectively achieve stabilisation is usually small, making it a desideratum in terms of cost; (iii) Since the process is based on time-dependent chemical reaction which occur spontaneously after initial mixing, it is not regarded to be time-intensive; (iv) Also serves as a waste management strategy to recycle industrial by-product materials; (v) Considered effective irrespective of the soil engineering properties	(i) Application in situ may be pragmatically inept if field conditions vary considerably from that simulated during the laboratory controlled experiments; (ii) The release of harmful compounds are often associated with the production and reaction of some traditional agents and also the risk of groundwater contamination through leachate of toxic elements/compounds; (iii) May not be suitable when the cost of obtaining the chemical additive becomes prohibitive in relation to the quantity needed to achieve effective soil stabilisation; (iv) When unfavourable conditions are prevalent, the effect of chemical stabilisation may become adverse, for instance soil–lime–sulphate reactions, stabilisation induced-cracking, etc.

The ability of traditional additives for expansive soil stabilisation is well studied and their efficiency was proven as sole stabilisation materials (Zhao et al., 2013, 2015; Tran et al., 2014; Dafalla et al., 2015; Nweke and Okogbue, 2017). However, issues like heaving-induced sulphate attack resulting from soil–lime–sulphate reactions, effect of organic materials which inhibits reaction of calcium-based additives, environmental impacts of cement manufacture process and carbonation reactions, question the sustainability of using traditional agents (Jayanthi and Singh, 2016; Firoozi et al., 2017). Consequently, researchers are in continuous search of alternative sustainable and efficient materials for expansive soil stabilisation.

(2) Non-traditional agents

Other additives that chemically react with the soil and/or other additives, often in the presence of sufficient moisture to engender physicochemical interactions in the soil matrix, can be referred to as non-traditional agents. These materials include but are not limited to industrial by-product materials (such as cement kiln dust, lime kiln dust, ground granulated blast furnace slag, pulverised coal bottom ash, steel slag, mine tailings, and others), other waste products with calcium oxide content (such as waste paper sludge ash), sulphonated oils, ionic compounds, and polymers (Petry and Little, 2002; Alazigha et al., 2016; Fasihnikoutalab et al., 2017; Soltani et al., 2017b, 2018a; Estabragh et al., 2018).

The mechanism of soil stabilisation for each category may guide engineers in making predictive selection of any type of material based on the level of physicochemical modification desired. Petry and Little (2002) considered that the by-product materials rely on similar mechanism as the traditional stabilisers, whereas the other materials use a different process for stabilisation. For instance, Onyejekwe and Ghataora (2015) highlighted that the mechanism involved in the use of sulphonated oils and polymers involves alignment of clay particles, and changes of clay surface charge polarity, which increases the inter-particle cohesive strength, modifies the clay lattice, and coats the diffuse double layer zone of influence. This eventually leads to improvement in binding of the soil particles to reduce moisture sensitivity. Sulphonated oils have also been identified to react similarly to anionic polymers, in which the negatively charged hydrophilic head attracts the cations within the clay-pore fluid media, thereby reducing the base ion exchange capacity of the negatively charged clay surface, and thus it makes the soil hydrophobic (Soltani et al., 2017b). This ensures the reduction in sensitivity to moisture fluctuation. The chemical process governing the chemical reactions involved in the stabilisation mechanism of some non-traditional agents is subsequently explicated in Section 3.4.2.

3.3. *Comparative analysis of various stabilisation techniques*

The above-mentioned stabilisation techniques offer engineers an alternative for strengthening weak soils in situ. Some factors, which are likely to guide engineers whether to select a particular stabilisation method after geotechnical site investigations and testing programmes, include expansion potential for the site, design active zone, degree of soil fracturing, heterogeneity or uniformity of soils on-site, chemical reactivity of soil, presence of undesirable chemical compounds, heterogeneity of water and hydraulic conductivity of soil, and the required soil strength (Nelson et al., 2015). The engineers are required to utilise their knowledge and experience to make engineering judgement about the optimal technique to be applied. Comparative analysis of some advantages and disadvantages of various stabilisation techniques is presented in Table 3.

3.4. *Engineering properties of stabilised soils using various techniques*

Soil stabilisation for expansive soils was initiated in the 1950s (Petry and Little, 2002). Since then, various works have been done. However, with the technological advancement in the 21st century, it is crucial for engineers to update their knowledge upon the recent trends in the stabilisation of expansive soils, since there is no generally acceptable standard for applying soil stabilisation in situ.

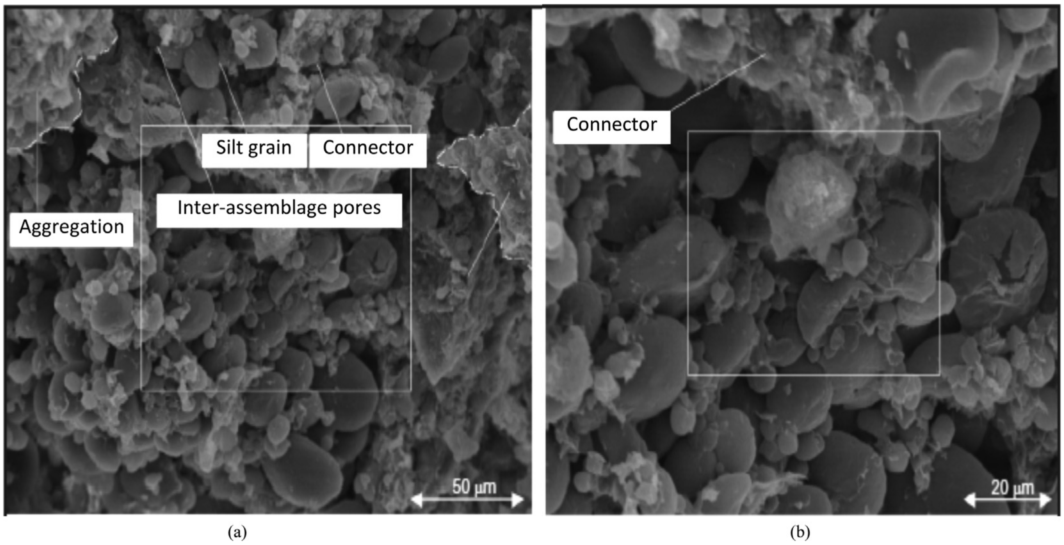


Fig. 1. Microfabric of natural soil: (a) 500× magnification, and (b) 1000× magnification (modified from Mirzababaei et al., 2009).

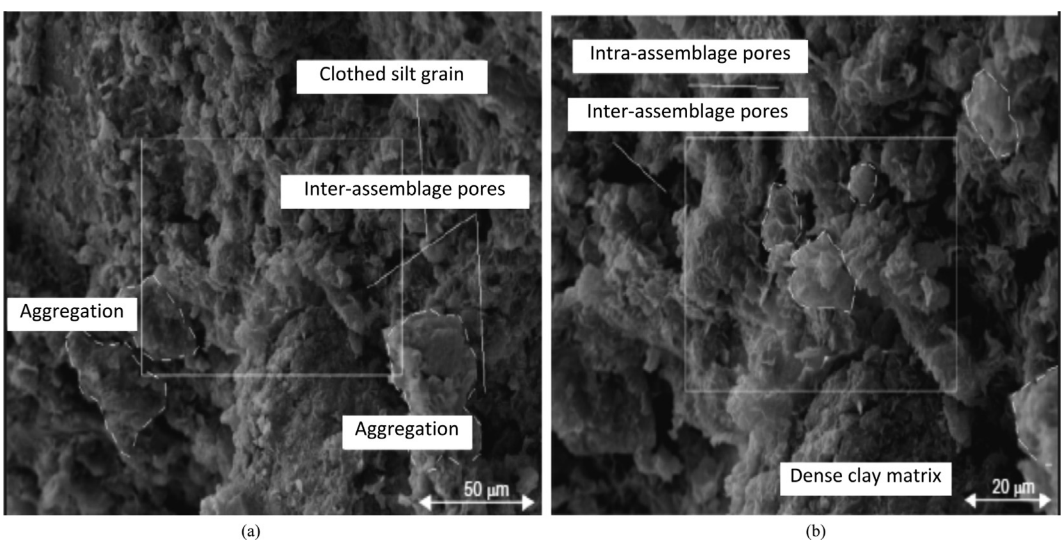


Fig. 2. Microfabric of Soil with 5% furan: (a) 500× magnification, and (b) 1000× magnification (modified from Mirzababaei et al., 2009).

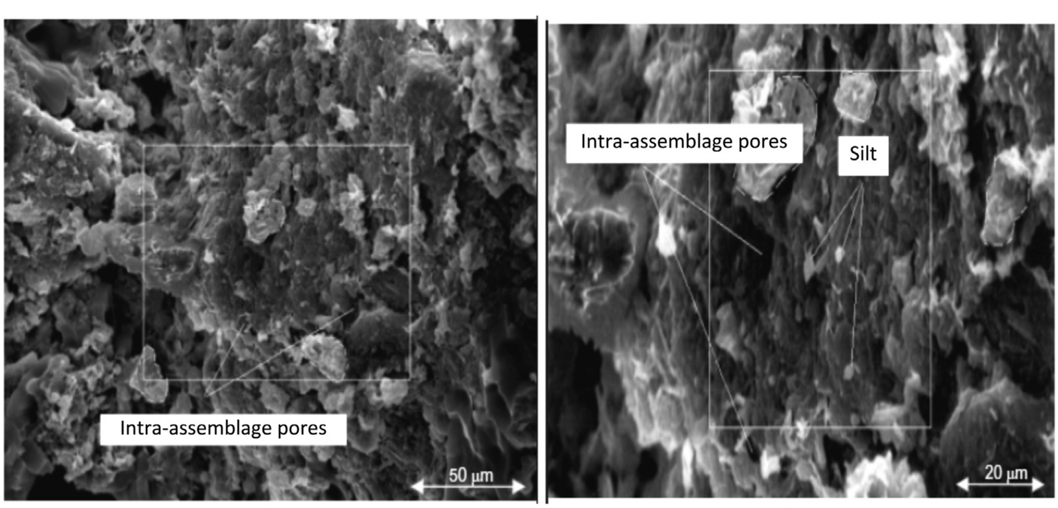


Fig. 3. Microfabric of clayey soil with 10% furan: (a) 500× magnification, and (b) 1000× magnification (modified from Mirzababaei et al., 2009).

3.4.1. Emphasis on microstructural interaction

The knowledge of the physicochemical changes of the stabilised soil is crucial to the engineers. In view of this, microstructural analysis provides a convincing explanation to the physicochemical changes. Such analysis can be presented in the form of qualitative digital image analysis, e.g. SEM, or quantitative charts as in X-ray diffraction (XRD). They help to clarify the impact of stabilisation on the soil constituent, microfabric and pore structure.

Mirzababaei et al. (2009) investigated the effect of polymers on soil microfabric microstructurally. The polymer, furan, added at 3%, 5% and 10% by weight of the soil, progressively reduced the free swell percentage of three expansive soils compacted at OMC and MDD with an average maximum drop of about 83.5%. The changes that occurred in the soil microfabric as a result of addition of the furan at 5% and 10% are presented in Figs. 1–3. From the different image magnification ratios (×500 and ×1000), the natural soil mainly consists of discrete granular in combination with sparse aggregations, few silt grains, and some connectors. The inter-assemblage pores between the discrete and sparse aggregations are obvious. However, on addition of furan at 5% and 10%, the soil fabric changes to dense aggregations with the formation of intra-assemblage pores coming from the formation of dense aggregations, with the inter-assemblage pores becoming less evident, indicating the reduction in pore sizes. Also clothed silt grains become more obvious than that in the natural soil. The changes in the soil fabric and pore structure are responsible for the observed reduction in swelling properties of the soil. However, the microstructural investigation conducted here was only qualitative.

In a recent study by Osinubi et al. (2015), the changes in pore size in addition to image observations (Fig. 4) are confirmed quantitatively, which shows the variation observed in the soil fabric and pore sizes. This was done using fibremetric analysis (a statistical package incorporated in SEM used for pore ranges from 40 μm to 100 nm), and the fibre and pore histograms are shown in Figs. 5 and 6. It can be inferred that a reduction in both soil fabric and pore sizes occurred, which can further be consolidated by observing the histograms. The fibre histogram shows a reduction in the mixture fabric from 2.23 μm for the natural soil to 875.16 nm for the modified soil, while the pore histogram confirms a surface area reduction of the natural soil pores from 2.75 μm^2 to 0.84 nm^2 for the modified soil.

Similarly, many works (Rao et al., 2000; Sarker et al., 2000; Al-Rawas, 2002; Sharmer and Sivapullaiah, 2012; Salahudeen et al., 2014; Osinubi et al., 2015; Zhao et al., 2015; Fasihnikoutalab et al., 2017; Mousavi, 2017) provided microstructural analysis for the stabilised expansive soils, using tests like Fourier transform infrared spectroscopy (FTIR), zeta potential, environmental SEM, transmission electronic microscopy (TEM), fibremetric analysis and others. These tests explain the physicochemical changes which modify the soil to produce desirable engineering properties. A summary of various microstructural analyses conducted on expansive soils is presented in Table 4.

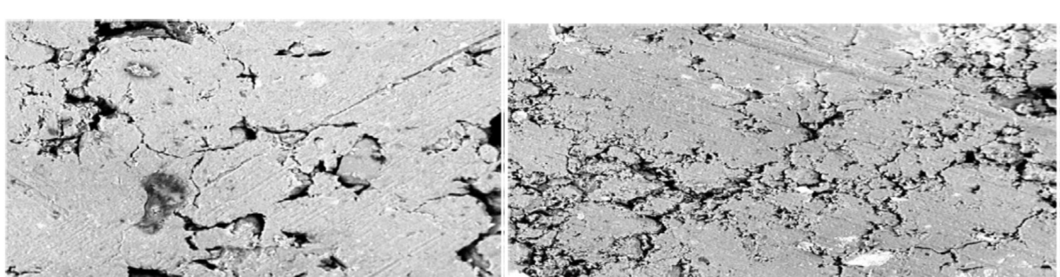
3.4.2. Emphasis on chemical process

An in-depth understanding of the chemistry behind soil stabilisation can help engineers to alter soil characteristics in order to obtain specific properties. For instance, Soule and Burns (2001) used four Quaternary ammonium cations (benzyltriethylammonium chloride, tetramethylammonium bromide, decyltrimethylammonium bromide, and hex-adecyltrimethylammonium bromide) to replace the cations in Wyoming bentonite by synthetically using cation exchange capacity. The knowledge for this particular application stems from the cation exchange capacity of the original clay material that determines the ability of organic cations to be exchanged onto the mineral surface (Jaynes and Vance, 1996). This substitution resulted in the reduction in specific gravity, improvement of swell-shrink characteristics, and increase in shear friction angle of the soil.

The absence of strong Si–O–Si bond in olivine (Mg_2SiO_4) was exploited by Fasihnikoutalab et al. (2017), who used a strong alkaline compound (NaOH) to break the bond between MgO and SiO_2, which ultimately results in production of silica gel. The alkali-activated olivine (added at 5%, 10%, 15% and 20%) improved the UCS of the untreated soil. The natural soil has a peak UCS value of 103.4 kPa at about 1.8% strain value, which depicts a ductile behaviour. At 20% additive content, the soil attained the maximum values of UCS with percentage increase of approximately 720%, 880%, 1070% and 3730% at curing periods of 7 d, 14 d, 28 d and 90 d, respectively.

Radhakrishnan et al. (2017) used strong electrolytes characterised by high solubility in water, ease of mixing with the soil and supply of adequate cations for ready cation exchange. Thus, they can readily be used as a substitute for lime in soil stabilisation. The researchers further studied the effects of three kinds of chloride compounds (ammonium chloride, NH_4Cl; magnesium Chloride, $MgCl_2$; and aluminium chloride, $AlCl_3$) on geotechnical properties of an expansive soil. Each of the compounds was added from 0 to 2% at 0.5% constant increment. The compounds each resulted in a monotonic reduction in plasticity index (PI) of the soil, achieving the minimum PI at 2% content (maximum reduction in PI was about 42.3%, 46.2% and 57.7% for NH_4Cl, $MgCl_2$ and $AlCl_3$, respectively). The result was similar for swelling pressure with maximum reduction of about 59.3%, 67.5% and 79.7% for NH_4Cl, $MgCl_2$ and $AlCl_3$, respectively. The CBR of the soil also increased monotonically from 2.02% for the natural soil to 3.25%, 3.925% and 4.21% for NH_4Cl, $MgCl_2$ and $AlCl_3$, respectively, at 2% additive content.

Horpibulsuk et al. (2012) detected the similarities in chemical compositions of calcium carbide residue and hydrated lime by conducting XRF test and studying the XRD pattern of the stabiliser. Based on the knowledge of the chemistry involved in stabilisation with hydrated lime, they stabilised problematic clay using a



(a) (b)

Fig. 4. Microfabric of black cotton soil at 28-d curing: (a) Natural soil, and (b) Optimal modified soil (modified from Osinubi et al., 2015).

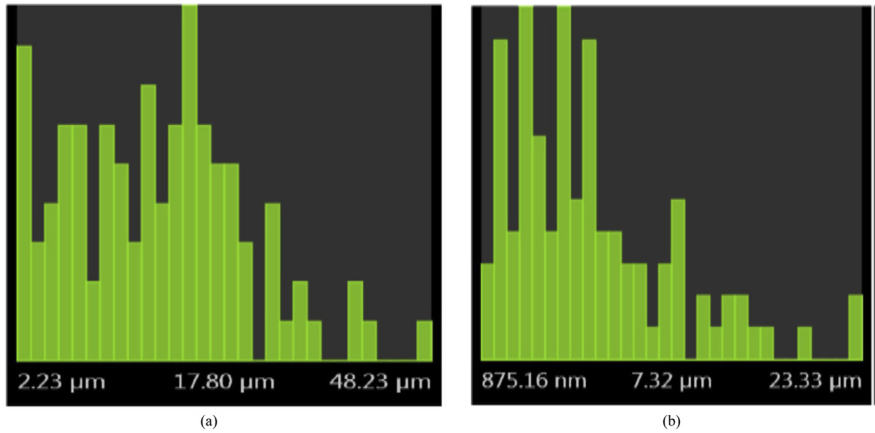


Fig. 5. Fibre histogram of black cotton soil: (a) Natural soil, and (b) Optimal modified soil (modified from Osinubi et al., 2015).

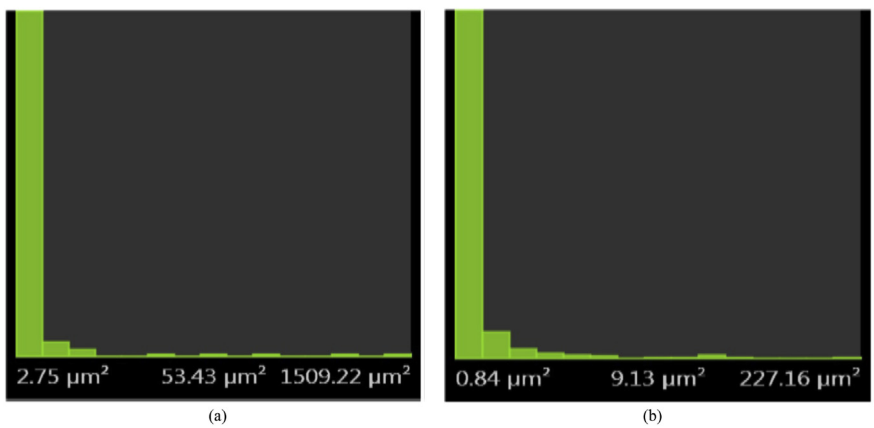


Fig. 6. Pore histogram of black cotton soil: (a) Natural soil, and (b) Optimal modified soil (modified from Osinubi et al., 2015).

combination of calcium carbide residue and fly ash. In a comparable fashion, Kamei et al. (2013) used recycled basanite in conjunction with cement for stabilisation of expansive clay as the cement will positively affect both the solubility of recycled basanite and the seepage of heavy metals from the recycled basanite into the soil.

Miao et al. (2017) used geopolymerisation to successfully stabilise BCS in Kenya. The basic chemistry involves the alkaline polymerisation of kaolinite, which gives rise to a material with properties similar to that of concrete (Davidovits, 2013). Furthermore, they used calcium and potassium hydroxides as alkaline activators in their work, and then added volcanic ash to reduce the soil plasticity. Also, the mechanisms in which the geopolymerisation process modified the engineering properties of the soil were also discussed.

Similarly, some researchers (Rao and Venkataswamy, 2002; Madhyannapu et al., 2009, 2010; Abiodun and Nalbantoglu, 2015) have illustrated in detail the reactions that occur deep inside the soil strata to improve expansive soil properties using deep soil mixing (DSM) technique.

(1) Deep soil mixing

This technique serves to either stabilise weak soils or repair contaminated ground on site (Porbaha, 2000). It involves mixing soil with cement, lime or other stabilisers using auger at a great depth (Madhyannapu and Puppala, 2014). DSM columns are often used for boring through the ground at a considerable depth in a similar fashion to piling techniques. As a matter of fact, lime pile treatment is a widely applied deep mixing technique for stabilisation of expansive soils.

Lime pile treatment method consists of holes drilled downwards containing quicklime, having a depth of 10 m or greater with approximately 0.5 m diameter (Abiodun and Nalbantoglu, 2015). Abiodun and Nalbantoglu (2015) stated that on site, the void created in the ground during lime pile treatment is filled with calcium oxide without being combined with displaced soil in a mechanised hollow tube. The mechanism of stabilisation involves diffusion of calcium ion into the soil under favourable moisture condition, which ultimately modifies the physicochemical properties by ionic exchange (Little, 1995; Nalbantoglu and Gucbilmez, 2002; Tonoz et al., 2003).

The design of DSM has been summarised by Madhyannapu and Puppala (2014) to include the following procedures: use of laboratory mix design and analysis to choose the type of additive required and the quantity that will be most effective; determination of the ratio of water to additive, for which the DSM columns achieve optimal performance, and selection of the DSM column geometry using inference from the results of laboratory test, installation method and column configuration. These procedures were classified into two by Porbaha (2000) as material and geometry designs. The improvement in engineering soil properties in DSM is dependent on the conditions and characteristics of soil strata, the binder's mixing environment or method, and the conditions of curing, as stated by Holm (2001).

Table 4
Summary of various microstructural methods used for analysis in expansive soil stabilisation.

Method	Application	Source
Scanning electron microscopy (SEM)	Presents digital images of high resolution, showing changes in the soil microfabric	Al-Rawas (2002), Mirzababaei et al. (2009)
Environmental SEM (ESEM)	Similar to SEM but capable of examining samples which are in moist or slurry form unlike the conventional SEM, which requires samples to be in dry form	Sarkar et al. (2000), Romero and Simms (2008)
Transmission electronic microscopy (TEM)	Similar to SEM but capable of achieving a much higher resolution because of its much higher acceleration potential (200 kV) and use of ultrathin specimen	Sarkar et al. (2000)
X-ray diffractometer (XRD)	Assessment of active minerals present in the soil matrix and identification of their peak intensity	Rao et al. (2000), Zhao et al. (2015)
X-ray fluorescence (XRF)	Quantitative determination of chemical oxide composition of materials	Mousavi (2017)
Energy-dispersive X-ray spectroscopy (EDS)	Capable of elemental analyses for determination of type and quantity of particular elements present in minerals	Salahudeen et al. (2014), Osinubi et al. (2015)
Zeta potential	Provides data on the nature and magnitude of charge on particulate surfaces	Sarkar et al. (2000)
Fibremetric analysis	Presents fibre and pore histograms for quantitative determination of changes in soil fabric and pore sizes	Osinubi et al. (2015)
Fourier transform infrared spectroscopy (FTIR)	Analysis of bond interaction (formation and breakage) via transmittance-wavenumber charts, identifying particular band ranges for various bond interactions	Fasihnikoutalab et al. (2017), Alazigha et al. (2016)

The investigations using DSM include either one or a combination of laboratory and in situ tests, usually done over time to ensure durability and sustainability of the method. The chemistry involves the migration of calcium cations from lime and/or lime-cement mix onto the clay mineral ions and increased pore salinity, which apparently impact the diffuse ion layers and thus alter the soil engineering properties (Glendinning and Rogers, 1996; Rao and Venkataswamy, 2002; Madhyannapu et al., 2009, 2010; Abiodun and Nalbantoglu, 2015).

Another method that has been used to accelerate the chemical reaction of additives with the soil is the injection technique.

(2) Injection technique

The injection technique basically involves injecting stabilisers into the soil to induce chemical reaction and cause physicochemical changes, whilst improving the engineering properties substantially. In the field, hydraulic injection is the principal method used for injecting chemical stabilisers into the soil although their stabilisation potential is questionable under hydraulic gradient (Ozkan et al., 1999). Electrokinetic injection can also be used, which uses electro-osmosis as the fundamental principle for the transportation of chemicals into the soil (Ozkan et al., 1999).

Electrokinetic injection uses electrochemical effects for improving strength of clays. These effects include electrolysis, redox reaction, hydrolysis, formation of osmotic and pH gradient, ion diffusion and exchange, heat formation across electrodes leading to dehydration, salt and secondary mineral precipitation, mineral decomposition, physical and chemical adsorption and fabric changes (Mitchell, 1993). Several researchers (Esrig and Gemeinhardt, 1967; Gray, 1970; Mitchell, 1993; Ozkan et al., 1999; Sarker et al., 2000) have successfully applied this technique to improving the engineering properties of expansive soils.

The dependence of expansive soil stabilisation on the chemistry between the soil and stabilisation material can easily be detected from the works of many other researchers (Inyang et al., 2007; Huang and Liu, 2012; Zhao et al., 2015; Fasihnikoutalab et al., 2017; Qiu et al., 2017; Soltani et al., 2017b).

3.4.3. *Emphasis on economic implication*

Even though it is necessary to improve soil properties in order to obtain certain predetermined values during stabilisation, the engineer's task is not only to provide geotechnical modification of soils, but also to achieve the desired properties in a cost-effective manner. In an attempt to achieve this, researchers often carry out comparative analysis to determine both the economy and the efficacy obtainable using various additives. From the investigations within the 2000s, it is vivid that traditional stabilisers, which are more widely employed, are used as stand-alone materials for expansive soil stabilisation (Cokca, 2001; Buhler and Cerato, 2007; Sirivitmaitrie et al., 2008; Zhao et al., 2013, 2015; Tran et al., 2014; Dafalla et al., 2015; Nweke and Okogbue, 2017; Soltani et al., 2017b). However, some issues associated with them as pointed out by Jayanthi and Singh (2016) and Firoozi et al. (2017) create room for potential alternatives. Despite this, the stabilisation effects of traditional agents still surpass those of other stabilisers during comparative analysis (Puppala et al., 2001; Rao et al., 2000; Punthutaecha et al., 2006; Oza and Gundaliya, 2013; Ranga, 2016), especially with respect to the soil plasticity, except in a case in which electrolytic lignin performs slightly better than fly ash (Lekha et al., 2015). Nevertheless, amongst the traditional agents, fly ash seems to edge out both lime and cement in terms of economy since it is a waste product.

Aside from traditional agents, other non-traditional agents are equally used in the comparative analyses. These have been greatly applied in soil cushions. Since it is known that the instability of expansive soils is the result of fluctuations in water content in the presence of moisture, soil cushioning techniques are often adopted to prevent changes in moisture content of expansive soils. The method employs a cohesive non-expansive soil cushion to mitigate the swelling behaviour of expansive clays (Rao and Sridevi, 2011). Materials used for cushioning are usually laid over expansive soil beds in a form of layer of mattresses to strengthen the overlain soil. Different materials are used for this application including sand beds, geocell and so on as obtainable in the works of Ikizler et al. (2009), Rao and Sridevi (2011), Asha et al. (2012) and Dutta and Mandal (2016). The primary constituents of some cushioning materials include industrial by-product waste, polymers, geotextiles and others.

Geocell is a form of rigid geosynthetic material consisting of intricately blended cells which have 3D honey comb structures, with desirable confining effect (Asha et al., 2012). Dutta and Mandal (2016) suggested that the shear strength of confined materials is significantly improved as a result of the boundary effect of geocell system. They further stated that settlement is reduced when geocell confinement is used to distribute footing load in comparison to

Table 5
Summary of findings on use of some waste materials in expansive soil stabilisation.

Sources	Material (content (%))	Optimal content (%)	Findings
Sharmer and Sivapullaiah (2012)	GGBS (10–90)	20	UCS at 28 d increased by about 100%, and initial tangent modulus increased from 20 MPa to 60 MPa
Gobinath et al. (2016)	Precipitated silica (10–70)		UCS and unsoaked CBR attained peak values at 10% additive content, soaked CBR reached the peak at 50% content, and consolidation coefficient increased from about 0.3×10^{-3} cm^2 s^{-1} to 2.7×10^{-3} cm^2 s^{-1}
Shukla and Parihar (2016)	Micro fine slag (3–15)	6	UCS at 7 d and unsoaked CBR increased by approximately 325% and 186%, respectively; while increase in soaked CBR was marginal
Dharan (2016)	Waste paper sludge ash (4–12)	8	CBR at 14 d increased from 5% to 25%, while UCS at 28 d increased from 150 kPa to about 450 kPa
Latifi and Meehan (2017)	Calcium carbide residue (3–15%)	9	Natural soil UCS of about 200 kPa increased by approximately 250%, 1000% and 1800% at respective curing periods of 7 d, 28 d and 90 d
Al-Sharif and Attom (2000)	Burned sewage sludge (2.5–15)	7.5	UCS marginally increased at 7 d curing, while the swelling pressure reduced by 60% and 28 d curing had no effect on UCS
Anupam et al. (2014)	Rice husk ash, RHA (5–35)	25	Tests were performed at various curing periods (7 d, 14 d, 28 d, 56 d and 128 d), and all results showed a similar trend. At 28 d, CBR increased from 2% to 13%, and the UCS, cohesion and friction angle increased respectively by 94%, 31% and 150%. Also, the split tensile strength increased from 15 kPa to 23.5 kPa. At stress-strength ratios 0.5 and 0.8, the resilient modulus of the soil increased by 94.5% and 94.2%, respectively
Osinubi et al. (2016)	Locust bean waste ash (2.5–15)		Three compaction energies, British Standard Light (BSL), West African Standard (WAS), and British Standard Heavy (BSH) and also curing periods of 7 d, 14 d and 28 d (for UCS) were used. At all curing periods, UCS significantly improved using BSL, and all peak values of UCS progressively increased with curing period. CBR significantly increased for all compaction energies and a similar trend was observed for the resistance to loss in strength
Butt et al. (2016)	Sawdust ash (SDA) (4–12)	4	UCS and unsoaked CBR increased by 26% and 103%, respectively
Sivasubramani et al. (2017)	Bagasse ash (5–25) and egg shell power (3)	25	CBR increased from 0.58% to 12.23% and cost reduction of 23.4% was obtained after comparative analysis of subgrade pavement design using stabilised and natural soils
Signes et al. (2016)	Crumb rubber particles		Swelling potential reduced from 3.71% to 1.37% while friction angle increased from 28.5° to 48.5°
Ikeagwuani (2016)	SDA (2–10) and lime (4)		Overall improvement in the plasticity and compressibility characteristics of the soil

other two-dimensional (2D) composite materials in mesh form. This statement was supported by the studies conducted by Latha and Somwanshi (2009) and Moghaddas Tafreshi and Dawson, 2010, who reported that geocell reinforcement system produced better performances than material quantity equivalence of a planar reinforcement system.

Experimental studies conducted using soil cushioning technique for comparative analyses purpose show the effectiveness of the method. Rao and Sridevi (2011) used ground granulated blast furnace slag (GGBS) and fly ash, respectively, as cushions on lime-treated expansive soil. Both materials increased the CBR and reduced the swell potential of the expansive soil with the increase in cushion thickness. A similar result was obtained by Ikizler et al. (2009), who used sand and expanded polystyrene (EPS) geofoam as soil cushions, and further discovered that the cushioning technique performs similarly to the additive mixing technique using sand as cushion. However, the EPS geofoam performed better than sand in stabilising the soil. Asha et al. (2012) used finite element method to assess the effectiveness of 3D geocell mattresses and EPS geofoam as soil cushion and fill materials in an embankment, respectively. The geocell and geofoam component materials were modelled using Mohr-Coulomb failure criterion except the concrete and geogrid layers which were modelled using linear-elastic and elastic models, respectively. The analysis results showed reduction in vertical displacement of the geocell-stabilised soil and also a decrease in vertical and horizontal displacements of the geofoam embankment with attendant increase in safety factor. However, more laboratory work is required to calibrate these findings.

In comparative analysis, a clear distinction can be made regarding the efficiency of one material over another as seen in the works of many researchers (Puppala et al., 2004; Poh et al., 2006; Yi et al., 2012; Mutaz and Dafalla, 2014). Whereas in other cases, a slight difference is observed on assessing the efficiency of the compared stabilisers (Sharma et al., 2008; Mahasneh, 2016; Dalal et al., 2017). The need for efficient and economically viable stabilisation further led researchers to attempt optimisation based on the information from any of the following two steps: firstly, using a feasible combination of various materials after comparative analysis and secondly, the knowledge provided by the results of various independent works using a single material. This is usually an optimisation technique in order to fully utilise the benefits of various materials. The second step aforementioned seems to be more common and has been applied by so many researchers (Kumar et al., 2007; Osinubi et al., 2009, 2011; Mutaz et al., 2011; Wiechert et al., 2011; El-Aziz and Abo-Hashema, 2013; Amadi and Lubem, 2014; Mudgal et al., 2014; Estabragh et al., 2016; Hassan et al., 2016; Karatai et al., 2017; Yilmaz et al., 2017), while the first step has been used by few researchers (Muthukkumaran and Joseph, 2014; Maneli et al., 2016; Ashango and Patra, 2016).

3.4.4. *Emphasis on waste reuse and sustainability*

Geotechnical engineers often apply soil stabilisation, with particular attention paid to the geoenvironmental implication of the process. The aim is usually to effectively reuse the waste material, whilst improving the engineering properties of the soil and ensuring that harmful compounds are not released in quantities that may induce adverse environmental effect. For this, many waste products, both from agricultural and industrial processes, are used for stabilising expansive soils. Many waste materials have been successfully applied to stabilising expansive soils.

(1) Waste reuse

Waste tire rubbers have shown great potentials in expansive soil stabilisation. Seda et al. (2007) applied the expansive soil-rubber (ESR) technology and proposed that it could greatly reduce heaving in expansive soils in situ, especially where the natural soil deposit is rich in sulphate, which can impede the use of traditional agents; although Dunham-Friel and Carraro (2011) pointed out a major limitation that ESR technology is not suitable where the stiffness of material is crucial. A summary of findings on use of other waste materials in expansive soil stabilisation is presented in Table 5.

(2) Sustainability

Waste reuse in soil stabilisation for effective waste management should ensure that the waste material is sustainable to ensure a green environment. Consequently, stabilisation studies which use waste materials involve assessment of potential environmental impact of the additive to make its application sustainable. However, few researches have considered this as a critical parameter in the application of expansive soil stabilisation.

Ahmed et al. (2011) used recycled gypsum from gypsum waste plasterboard to improve the use of soil as an embankment material and also the strength properties of the stabilised soil, whilst ensuring that the stabiliser had no adverse environmental effect within its dosage of administration. They conducted tests to measure the impact of the recycled gypsum in terms of pH, hydrogen sulphide, and deleterious substances such as fluorine, boron and chromium.

Latifi et al. (2018) utilised low-carbon sodium silicate-based liquid to improve the UCS and compressibility characteristics of expansive clay. This can be seen as a sustainable improvement because of the low-carbon additive used.

3.4.5. Emphasis on nanotechnology application

The use of extremely fine particles (within the nanoparticles range) is another practice which has emerged in recent years. Anggraini et al. (2016) used nano modified coir fibre to improve the tensile strength and shear strength parameters of lime-treated marine clay, whilst ensuring durability by exposing the stabilised soil matrix to increased wetting cycles. Also, in a study by Sharo and Alawneh (2016), nano-clay materials were used to modify an expansive clay soil. The swelling potential of the soil showed a regressive trend with increasing clay content, achieving a maximum reduction of about 65.5% at 3% nano clay content. The UCS attained a peak increment of approximately 42% at 0.6% nano clay content.

Ugwu et al. (2013) used nano material (nano-z) to improve the subgrade strength of a plastic clay soil. The nano material was added at varying nano-z/water ratios of 1:150, 1:200 and 1:300. Increase in the ratio of the material exhibited a monotonic reduction with improvement in the soil properties examined, and as such, 1:150 was found to be the optimal ratio. The additive resulted in the reduction of soil PI by about 74.5% and the CBR increased by approximately 120%. The mechanism of stabilisation using the nano material was explicitly highlighted. The nano-z material was considered to be an organic compound, with a non-functional alkyl group, which forms silanol (Si–OH) group when it undergoes hydrolysis (reaction with water). The reactive silanol is capable of forming siloxane (=Si–O–Si=), which bonds with the surface silanol groups of the soil, imparting molecular-level hydrophobicity to the treated soil. This makes the treated soil surface water-repellent.

4. Transitioning from state-of-the-art to state-of-the-practice

4.1. Brief overview

Apparently, the geotechnical community beholds a tremendous amount of works on expansive soil stabilisation within the 21st century. However, to be more effective and practicable, issues arising in some aspects of the practice need to be addressed. This is not so much a limitation, but possible ways to improve the use of the available techniques, in order to apply expansive soil stabilisation in a sustainable and efficient way.

When such issues are resolved, expansive soil stabilisation will certainly transit from an art to a highly practical tool. The method would be better applied in the field without need for rigorous time-consuming and cost incurring trial tests, which may not be feasible in situ.

4.2. Issues with current practice

4.2.1. Standardisation issue

This is an important issue with the geotechnical community since the inception of soil stabilisation technology. It is not easy relating whether or not the rate of advancement in this technology contributes to this issue. A comprehensive standard manual for application of expansive soil stabilisation using various techniques/materials has not been developed so far. Some efforts have actually been made towards this. American Coal Ash Association (ACAA) published a manual in 2008 which presented guidelines for engineering application of coal fly ash as a sole stabilising agent (ACAA, 2008). American Society for Testing and Materials (ASTM) similarly published a guide in 2011 (ASTM D7762-11, 2011), but it is still limited to the use of fly ash. Other published guidelines are either for a traditional agent or for a particular application and neither for other stabilisation materials nor for a more generalised application (Terrel et al., 1979; White et al., 2005, 2013).

This calls the attention of experts in the area to team up and emerge with the appropriate response to this challenge, which has somewhat undermined the applicability of expansive soil stabilisation in the field. Based on experience, available research results and potential application of artificial intelligence techniques, it could be possible to develop a comprehensive and generally acceptable standard to execute expansive soil stabilisation in various engineering applications.

Artificial intelligence techniques have gained popularity in geotechnical engineering, especially in pile foundations (Fatehnia and Amirinia, 2018). Artificial intelligence techniques have advantages over the physically-based empirical and statistical methods (Fatehnia and Amirinia, 2018). Artificial intelligence techniques like genetic programming, artificial neural networks, neuro-fuzzy based inference systems and others could be indispensable in prediction of stabilisation potential/performance of various additives when combined together to optimise soil stabilisation. Thus, these techniques would be both time- and cost-effective in comparison with the traditional laboratory trial tests.

4.2.2. Geoenvironmental issue

Soil stabilisation technology ought to be applied in such a way that it does not cause adverse effects on the natural environment. For instance, applications which require the use of a high-carbon or hydrogen sulphide producing additive are highly discouraged. It is well known that emissions from such compounds cause harmful effects to the environment. Using materials composed of heavy metals which can contaminate the groundwater by leaching is also undesirable. The pH value of the soil should also be taken into account when using any stabiliser. Apparently, there is need for researchers to carry out geoenvironmental assessment as applicable to their researches based on the additive used, for their investigation to be more sustainable.

Ahmed et al. (2011) proposed that the use of gypsum waste plasterboard caused no adverse effect within the dosages applied by assessing the pH of the soil and hydrogen sulphide emission after the stabilisation process. Etim et al. (2017) conducted batch equilibrium studies to ascertain that the level of iron from the additive which could seep into the groundwater fell within the drinking water standard recommended by the World Health Organisation.

Another method applied to inhibit seepage of heavy metals to groundwater is the use of engineered landfills in form of landfill liners. These liners act as barriers to sorb heavy metals and thus prevent them from contaminating the groundwater. Ghosh et al. (2012) used 2% bentonite and 17% rice husk ash (RHA) mixed with clay as a landfill liner to curtail chromium leachate. Similarly, Akinwumi et al. (2016) used sawdust-stabilised clay soil as a landfill liner to contain lead and cadmium leachate.

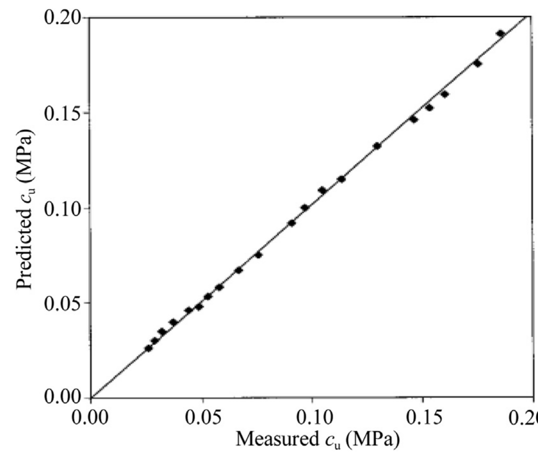


Fig. 7. Correlation of experimental and predicted undrained shear strengths, c_u (modified from Kumar and Sharma, 2004).

4.2.3. Optimisation issue

Researchers often target to attain both economy and efficiency during expansive soil stabilisation. As a result, they use various trial methods to combine various stabilisers in order to maximise the benefits of each. To achieve such optimal performance, their results are often derived from individual works or their knowledge of the chemistry behind the physicochemical changes induced in the soil by a particular stabiliser. However, the traditional trial method is not so sufficient, owing to its cost implication and time-consuming nature. Therefore, the need arises for better approaches towards attaining optimal performance using a combination of stabilisers.

(1) Predictive modelling

Predictive modelling has been proven to be a promising approach towards optimising soil stabilisation procedure. Predictive models assist in prediction of strength properties of stabilised soils with a very high degree of accuracy (Kumar and Sharma, 2004; Patel and Shahu, 2015; Jamsawang et al., 2017; Mamatha and Dinesh, 2017; Naveena et al., 2017). Descriptions of these models are given in Table 6, showing various models used for the modelling, as well as the specific soil parameters which have been predicted. Fig. 7 shows the correlation between the measured and predicted parameters for the model in Kumar and Sharma (2004), in which the correlation coefficient R^2 was not stated (see Table 6).

In the case of pavement design, optimisation for stabilisers can be done using deterministic design optimisation (DDO) or reliability-based design optimisation (RBDO). As explained by Moghal et al. (2018), DDO has a major disadvantage as it drives the design parameters to the limits with no allowance made to

Table 6
Description of various predictive models used in soil stabilisation.

Sources	Predictive model	Equation	R^2	Parameter description
Kumar and Sharma (2004)	Sanglerat's relation	$Q_C = N_K c_U + P_0$		Q_C is the penetration resistance; N_K is the penetration constant; c_U is the undrained cohesion, and P_0 is the total overburden pressure
Patel and Shahu (2015)	Three parameter stress-based model	$\frac{M_r}{P_a} = k_1 \left(\frac{\sigma_3}{P_a}\right)^{k_2} \left(\frac{\sigma_d}{P_a}\right)^{k_3}$	0.988	M_r is the resilient modulus; P_a is the atmospheric pressure; σ_3 is the confining pressure; σ_d is the deviatoric stress; and k_1, k_2, and k_3 are the model constants
Jamsawang et al. (2017)	Multiple regression analysis	$q_{u,D} = 0.00106CSH + 0.000667Et + 0.00554D - 1.144e_{0t} + 2.296$	0.9967	$q_{u,D}$ is the UCS of stabilised soil after D days curing, D is the curing time (d), CSH is the calcium silicate hydrate gel intensity, Et is the ettringite intensity, and e_{0t} is the void ratio after curing
Naveena et al. (2017)	Abram's law	$\left\{\frac{q_{(W_c/L)_D}}{q_{(W_c/L)_{28}}}\right\} = \left[\frac{(W_c/L)_{28}}{(W_c/L)_D}\right]^B$	0.95	$q_{(W_c/L)_D}$ is the UCS at curing of D days, $q_{(W_c/L)_{28}}$ is the UCS at 28 d curing, and W_c/L is the clay-water/lime ratio
Mamatha and Dinesh (2017)	Multiple linear regression analysis	$M_r = \frac{K_1 \theta^{K_2} (\gamma_s/\gamma_{opt})^{K_3} (CP)^{K_4} L^{K_5}}{\tau_{oct}^{K_6} (\omega_s/\omega_{opt})^{K_7}}$	0.875	θ is the bulk stress; τ_{oct} is the octahedral shear stress; γ_s is the unit weight; γ_{opt} is the maximum unit weight; ω_s is the molding water content; ω_{opt} is the optimum water content; CP is the curing period (d); L is the lime content (%); and K_1–K_7 are the regression constants

accommodate unforeseen incidents. On the other hand, RBDO takes care of the limitations of DDO and the target RBDO approach based on the reverse first-order reliability method, is a very efficient approach for predicting stabilised pavement performance (Moghal et al., 2018). However, for applications of this technique, more studies are needed in this area upon the use of predictive models to predict the engineering properties of stabilised soils.

(2) Response surface methodology

In recent years, some studies have successfully implemented the response surface methodology (RSM) in optimisation of stabilisers for expansive soils. The RSM is an optimisation technique in which statistical method is utilised to appropriately design experiments and generate models that can predict the influence of some predictor variables on the behaviour of a response variable, and subsequently examine the contributions of each predictor in affecting the behaviour of the response. The method ultimately results in the selection of optimal conditions of the predictors to obtain specifically desired responses.

As explained by Olgun (2013), the RSM involves three procedures. The first stage is the experimental design, in which the predictor data sequence needed for implementation of experiments is generated using statistical methods like full factorial, partially factorial and central composite design (CCD). The second stage involves building the mathematical model, in which an empirical model that explains the predictor–response relationship is chosen. The last stage involves model validation in which the selected model is evaluated in relation to its ability to yield rational estimation of the desired response using statistical analysis like analysis of variance (ANOVA). The interactions between the predictors can then be verified and used optimally to achieve predetermined responses that are physically meaningful.

Olgun (2013) applied the RSM technique to obtain optimal stabiliser content for a combination of lime, RHA and fibre needed to yield maximum value of UCS for expansive clay, while simultaneously attaining specific target values of 3% axial strain and swelling pressures of 1 kPa and 2 kPa for freeze-thaw and non-freeze-thaw subjected samples, respectively. The ranges of additive content for the inputs are 2%–8% lime, 0%–15% RHA and 0%–0.8% fibre. The CCD method was used for the experimental design, and three mathematical models including linear, quadratic and special cubic functions, were proposed to explain the input-response obtained in the experimental design. The result of the optimisation studies showed that the optimal combination of additives at 0.94 and 0.85 desirability levels for freeze-thaw and non-freeze-thaw samples were obtained respectively as 6.46% lime, 14.94%–15% RHA, 0.78%–0.79% fibre, and 7.39% lime, 5.78%–5.91% RHA, 0.8% fibre.

Shahbazi et al. (2017) used the RSM to optimise three input parameters (steel slag and fibre contents, as well as the fibre aspect ratio in ranges of 0%–25%, 0.2%–3% and 5%–45%, respectively) required to maximise UCS and minimise both swell percentage and swelling pressure of an expansive soil. The CCD method was used for the experimental design and a second-order polynomial regression equation was derived to account for the relationship between the inputs and responses, and ANOVA was used for confirmation of the model. The result of the optimisation studies resulted in improving the UCS, swell percentage and swell pressure by 111%, 89% and 84%, respectively, at additive contents of 14% steel slag and 0.78% fibre with fibre aspect ratio of 45.

However, in the discussion of the work by Shahbazi et al. (2017), Soltani (2017) identified two drawbacks of the study. The first was the limited number of design experiments (11) used for the study, which is insufficient for analysis using CCD. This is because replacement of 2^k factorial runs with $k+1$ fraction is undesirable for the small number of inputs (3) used, and also a more accurate prediction of the response is attainable when higher-level designs are adopted for handling a broad range of inputs. The second shortcoming identified was the independent contribution attributed to some physically meaningless parameters derived from the statistical analysis, which would have been sensible for multi-linear regression models; however, a quadratic polynomial mathematical model was adopted by Shahbazi et al. (2017). Furthermore, the sum of squares term used for estimating the percentage contribution of each regression component represents the aggregated effects (both favourable and unfavourable) and therefore counters the objective of optimisation. Soltani (2017) further proposed the partial derivative sensitivity analysis approach to address the later drawback, ignoring the implication of the former.

(3) Dimensional analysis

Dimensional analysis (DA), which is based on the theory of dimensional homogeneity, very pronounced in fluid mechanics applications, has been applied to description of soil swelling behaviour and optimisation of stabiliser additive content. Buzzi et al. (2011) pioneered the DA application to soil swelling behaviour.

In the dimensional model by Buzzi et al. (2011), the soil swelling was assumed dependent on the initial mass of water, mass of solid particles, vertical stress and initial dry unit weight. The Vaschy Buckingham-Π theorem was used to obtain a dimensionless number known as the dimensionless swelling parameter, DSP_w, which was used to describe the swelling strain. Calibration of the model was done using data obtained from literature and an R^2 value of 0.89 was obtained between experimental and predicted values of swelling strain. To avoid mathematical singularity, some simplifications were made, which were noted to adversely affect the model accuracy. Hence, Buzzi (2010) improved the original model by substitution of initial water content by initial suction to derive a new dimensionless number in place of DSP_w. After validation of the model using experimental tests for one-dimensional and 3D consolidation, R^2 values of 0.95 and 0.92 were obtained, respectively.

In a recent study by Berrah et al. (2018), DA was used to predict the swelling pressure of an expansive soil by applying the Buckingham-Π theorem. The swelling pressure was assumed as a function of water content, dry unit weight, liquid limit, plasticity index, percentage of fine fraction (expressed in terms of masses), and the pre-consolidation pressure, giving a total of nine parameters with three fundamental units. Six dimensionless numbers were then derived to show the relationship between the swelling pressure and the previously mentioned soil parameters. The model obtained was calibrated using experimental results, which gave an R^2 value of 0.96 between predicted and measured values of swelling pressure. The study also illustrated marginal superiority of DA over regression analysis, in which the R^2 value was 0.94.

DA has also been applied in optimisation of stabiliser content in expansive soil stabilisation. Williamson and Cortes (2014) obtained a dimensionless ratio known as the *D*-factor through trial-and-error method in the course of calibrating from published data, and four dimensionless terms were obtained by applying the Buckingham-Π theorem. The *D*-factor, which combines the water content, cement content, post-compaction void ratio and specific surface area of the soil and cement, was found to exhibit negative linearity with the UCS of the soil.

5. Conclusions

A review of the recent trends in soil stabilisation technology has been conducted in this paper. The aim was to review the emerging trends in expansive soil stabilisation, laying emphasis on some critical areas such as microstructural interaction, chemical process determining the stabilisation mechanism, economic implication during comparative analysis, the issue of sustainability and waste reuse, and application of nanotechnology.

Methods for studying changes in the microstructure of expansive soils and the stabilised soils have emerged in recent years. These changes are mostly associated with the changes to the soil microfabric, pore sizes and constituents. The commonly known chemical processes between elements and compounds, as well as mixtures, have been identified for various chemical additives used in soil stabilisation. This has been used in combination with some technological processes such as injection techniques and DSM. Furthermore, researchers attempt to conduct comparative analysis of various additives in the absence of capability of sole traditional agents in stabilisation. This is usually done with the motive to optimise the use of various additives to achieve economy. Also, sustainability is very vital. Soil stabilisation technology has provided effective means of waste management and recycling through the reuse of waste materials. In addition, nanotechnology has also been proven to be a practicable method for stabilisation of expansive soils.

Despite the success achieved in expansive soil stabilisation, some insights were provided to address some of the issues that hinder the applicability of the available and emerging technologies. A summary of the critical findings is given:

(1) Geoenvironmental issue could arise after soil stabilisation. Therefore, it is crucial for researchers to carry out necessary tests to ensure that the stabilisation process is sustainable. Based on the type of additive used and its dosage, some parameters which could have adverse environmental effects need to be checked. This includes pH value of the soil, emission of harmful compounds like those of carbon and so on, and leachate of heavy metals to groundwater.
(2) Standardisation issue is prevalent, as a generally acceptable standard for applying expansive soil stabilisation in the field using various additives has not been developed. This issue could be resolved if experts in the field explore the possibility of developing such standard based on experience, available individual stabilisation results and potential application of artificial intelligence techniques.
(3) Optimisation issues arise in the attempt to achieve optimal performance when using a combination of various additives. Techniques like predictive modelling, reliability-based approach, RSM, and DA were discussed. These methods have the potential to substitute the traditional trial test method, which is cost-intensive and time-consuming.

Conflicts of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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