Cleaner Engineering and Technology 4 (2021) 100159

Contents lists available at ScienceDirect

Cleaner Engineering and Technology

journal homepage: www.sciencedirect.com/journal/cleaner-engineering-and-technology

Understanding the performance of expansive subgrade materials treated with non-traditional stabilisers: A review

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ARTICLE INFO

Keywords:
Expansive soil
Subgrade stabilisation
Engineering properties
California bearing ratio
Unconfined compressive strength

ABSTRACT

Expansive soils are problematic soils which pose a risk to the safety of civil engineering structures. These soils can be treated by compaction or by adding additives to the soil. Where the strength and properties of expansive soil cannot be improved via mechanical stabilisation (Compaction), a desirable strength can be achieved through the use of chemical admixture techniques. The swelling and shrinkage of expansive soils cause movement in the soil mass resulting in a deferential settlement in engineering structures such as roads and building leading to cracks and subsequent failure leading to high cost of maintenance. Calcium based additives such as cement and lime have been used in expansive subgrade stabilisation to enhance the strength, reduce swell and subsequent differential settlement. However, the growing concerns on carbon dioxide (CO_2) emission and climate change have reignited the need for a more sustainable soil stabilisation techniques using waste materials. In this study, non-traditional expansive subgrade treatment techniques using sustainable waste materials with respect to their efficiency in improving the geotechnical engineering properties of the subgrade materials have been investigated and reviewed. This study also discusses the engineering problems associated with expansive soils, proposing an effective, efficient, cheaper and sustainable application of non-traditional stabilisers in expansive soil stabilisation. The study concludes that, the addition of non-traditional stabilisers in expansive subgrade stabilisation using chemical stabilisation techniques can improve the engineering properties of expansive subgrade materials.

1. Introduction

An expansive soil is any soil that has the potential to swell when wet and shrink when dry. Clay mineral smectites found in expansive soils usually exhibits evident volume change with changes in moisture content, causing major structural and geotechnical challenges worldwide. Structures built on expansive soils develop defects due to swell and shrink activities causing fissures in the structure (Abbey et al., 2019). Each year the damage caused by expansive soil in buildings and infrastructural systems are more than the damage caused by floods, hurricanes, tornadoes and earthquakes combined (Wu et al., 2019). Over the past 10 years, effects from expansive soils have cost the UK economy an estimated amount of £3 billion making it the most damaging geohazard in Britain (Jones et al., 2019). Subgrade materials refer to the ground or soil underneath a road pavement. Oftentimes, these materials do not have sufficient capacity to support the weight of the road pavement and the traffic loads and will require some sort of modification and re-engineering to enhance its capacity to support the load. Expansive soils can lead to early distress causing the premature failure of the road pavement structure. Chemical soil stabilisation techniques have been reportedly used in addressing the problems associated with expansive subgrades (Jalal et al., 2020). Chemical stabilisation involves adding different types of admixtures such as lime, cement lignin, lignosulfonate, xanthan gum among others as additives to improve the strength of expansive road subgrade (Rivera et al., 2020). Lignin, a by-product of paper and timber industry exhibited high mechanical performance when used as highway subgrade course material and road embankment in civil engineering infrastructure (Abbey et al., 2018). The mechanical responds, strength and durability of stabilised soil and natural silt were improved with the addition of Lignin (Zhang et al., 2020). Cement is popularly used to improve the engineering properties of expansive subgrade materials (Lucena et al., 2014). Stabilising road pavement subgrade has proved to be very costly and unsustainable due to the amount of carbon dioxide (CO_2) emitted during cement production (Abbey et al., 2017). However, the use of non-traditional stabilisers in road subgrade stabilisation will enhance the engineering properties of expansive subgrade materials whiles reducing environmental effects and overall construction cost (Kassa et al., 2020). Non-traditional stabilisers

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https://doi.org/10.1016/j.clet.2021.100159
Received 20 August 2020; Received in revised form 15 May 2021; Accepted 4 June 2021

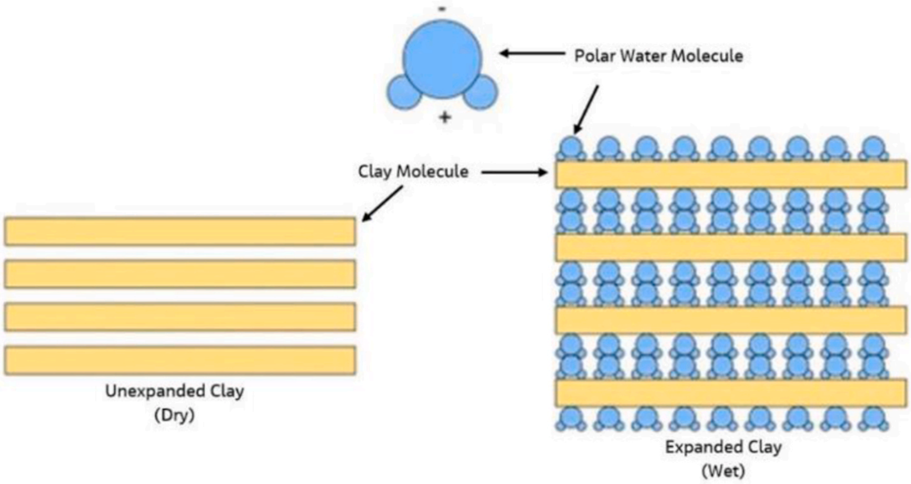

Fig. 1. Shrinking and Swelling of soils (Reda et al., 2016).

Table 1
Swelling potential of soils based on liquid limit (Dakshanamurthy et al., 1973).

Liquid limit	Classification
0–20	Non-Swelling
20–35	Low-Swelling
35–50	Medium-Swelling
50–70	High-Swelling
70–90	Very High-Swelling
>90 Extra	High-Swelling

Table 2
Classification of shrink potentials based on plasticity index (Jones and Jefferson, 2012).

I_p' (%)	Clay Fraction(<0.002 mm)	Shrinkage potential
>35	>95	Very High
22–48	60–95	High
12–32	30–60	Medium
<18	<30	Low

Where I_p' = Plasticity Index.

Table 3
Relation of Soil index Properties and Probably Volume Change for Highly Plastic Soils (ACPA Concrete Pavement Technology Series).

Data from Index Tests[1]			Estimation of probable expansion[2], percent total volume change (dry to saturated condition)	Degree of expansion
Colloid Content (percent minus 0.00004 in. (0.001 mm)) (ASTM D422)	Plasticity Index (ASTM D4318)	Shrinkage Limit Percent (ASTM D427)		
>28	>35	>11	>30	Very High
20–31	24–41	7–12	20–30	High
13–23	15–28	10–16	10–20	Medium
<15	<8	<15	<10	Low

such as rice husk ash (RHA), ground granulated blast-furnace slag (GGBS), plastic waste, synthetic fibres, sugarcane bagasse ash (SCBA), cow dung ash (CDA), fly ash, bituminous, thermal, electrical, silica fume, geo-textile and fabrics, among others can be used in soil stabilisation (Rivera et al., 2020). The result obtained in subgrade stabilisation using waste materials are suitable for application (Christopher et al., 2019). The current study presents a review on the use of non-traditional soil stabilisers and sustainable treatment of expansive subgrade materials.

2. Scope of the study

This current study presents an in-depth review into the characteristics and behaviour of expansive soils. The study focusses on expansive road pavement subgrade stabilisation providing information on geotechnical solutions based on current and non-traditional treatment of expansive subgrade stabilisation techniques. The main objective of this study was to review the engineering properties such as Unconfined Compressive Strength (UCS), California Bearing Ratio (CBR), Tensile Strength, Shrink-Swell and microstructural properties of expansive subgrade stabilised with non-traditional sustainable waste materials. This study will contribute to the existing knowledge on sustainable stabilisation of expansive subgrade using chemical stabilisation techniques.

3. Mechanisms of expansive soils

A soil is considered expansive when it has a high percentage of clay minerals such as montmorillonite expandable illite and vermiculite, or if the liquid limit of a soil exceeds 50% and the plasticity index exceeds 30% (Elarabi et al., 2010). The swelling ability of expansive soil is dependant on the total internal and external areas of its mineral particles. A small amount of swell can occur as a result of the enlargement of the capillary films in clay minerals when water is absorbed through their outer surface (Al-Rawas and Goosen, 2006). Water molecules in expansive soils are pulled into the gaps between the clay plates when the soil is introduced to water, causing the soil to absorb more water as the moisture content increase, forcing the plates further apart (Zaid, 2017). A study conducted by Reda, (2016) reviles that, expansive soils contain smectite clay materials which at the microscopic level looks like layered sheets due to their moisture-retaining abilities. The diffused double layer influences the engineering properties of clayey soil especially the hydraulic conductivity (Besq, 2003). Fig. 1 illustrates the mechanism of expansive soils. Table 1shows swelling potential of soils based on liquid limit, classification of shrink potentials based on plasticity index are shown in Table 2, and relation of soil index properties and probably volume change for highly plastic soils are shown in Table 3.

Table 4
Estimated cost of damage due to expansive soils in some countries.

Country	Amount (US$)	Reference
UK	>3.7 billion	Jones et al. (2019)
China	>1 billion	Jalal et al. (2020)
France	>3.3 billion	Toll et al. (2012)
India	Several millions	Gobena et al. (2019)
Saudi Arabia	>300 million	Adem et al. (2015)
Sudan	>6 million	Zumrawi et al. (2017)
USA	>15 billion annually	Jones et al. (2019)
Victoria, Australia	150 million	Adem et al. (2015)

Fig. 2. Road pavement defect (U.S. Department of Transport).

Fig. 3. Typical longitudinal crack developed on pavements over expansive clays (Zornberg and Gupta, 2015).

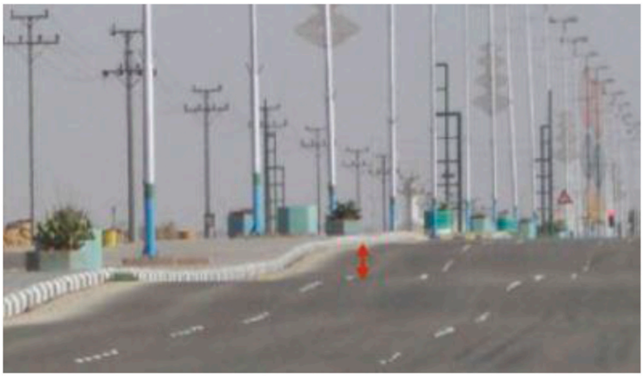

Fig. 4. Uplifting of flexible pavement due to expansive soil(Jalal et al., 2020).

Fig. 5. Slope failure of embankment caused by expansive soil(Jalal et al., 2020).

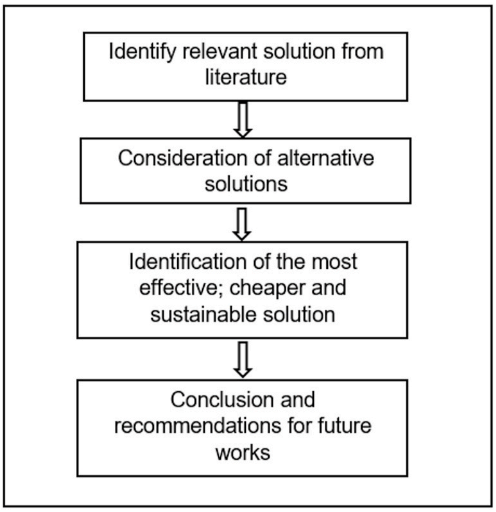

Fig. 6. Methodology for selecting literature.

4. Expansive pavement subgrade

Shrink swell behaviours of expansive subgrades are the major causes of pavement defects causing movement and differential settlement in pavement subgrade. The shrink-swell behaviour of weak subgrade materials when in contact with water can cause rutting, cracking, ravelling, formation of potholes and damage to pavements and light loaded civil engineering structures (Little et al., 2019). The economic effects caused by expansive subgrade in some countries are shown in Table 4, whiles Figs. 2–5 shows an overview of damage to road and embankments across different countries due to expansive subgrade (Mehmood et al., 2011).

5. Method for selecting literature

This section outlines how literature was selected for this current study and the method used to identify the most effective and sustainable solution for subgrade stabilisation using non-traditional stabilisers. Several works of literature on subgrade and soil stabilisation were investigated and alternative solutions considered to identify the cheaper and sustainable solution in expansive subgrade stabilisation. Fig. 6 visualises the methodology used.

6. Geotechnical solutions for expansive subgrade

Geotechnical solutions such as soil treatment and modification have been adopted to help overcome the problems of expansive subgrade

Table 5
Some methods and procedure of mechanical soil stabilisation (The Civil engineer, 2012).

Method	Procedure
Soil reinforcement	In this method, Geo-textiles and engineered plastic mechanical are used to help control soil moisture conditions and trap the soil. See Fig. 9.
Compaction	Pressure is exerted on soil material from above using heavyweight equipment to increase the density of the soil. See Fig. 10.
Mechanical remediation	In this method, expansive soil is removed and backfilled with more stable soil. See Fig. 11
Addition of graded aggregate materials	The engineering properties of expansive soil are improved by adding aggregates to the soil. See Fig. 12.

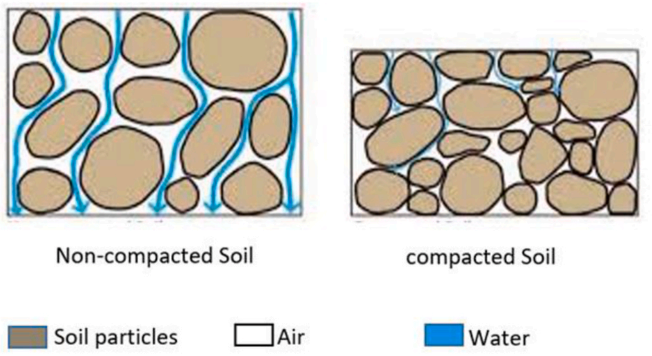

Fig. 7. Compacted and non-compacted soil(Tennessee stormwater Training).

Fig. 8. Different types of compactions (a) Pad-foot or tamping-foot roller (b) Smooth-drum vibratory roller (c) Walk-behind vibratory compactor and (d) Jumping-jack tamper (Meehan et al., 2009).

materials. Soil stabilisation techniques via mechanical, chemical and polymer techniques have been used in addressing the problems associated with expansive subgrade materials (Ikeagwuani et al., 2018).

6.1. Mechanical subgrade stabilisation

Subgrade compaction or densification using mechanical force is referred to as mechanical subgrade stabilisation (Afrin et al., 2017). Mechanical subgrade stabilisation involves the use of vibration, rammers, rollers and blasting to expulsion air voids within a soil mass and it is considered expansive compared to other forms of subgrade stabilisation (Nabil et al., 2020). Some methods and procedure of mechanical

Fig. 9. Soil reinforced with Geogrids(Kiganda, 2016).

Fig. 10. Compaction process(Compact Equipment).

Fig. 11. Soil removed and ready for backfill (Capital geotechnical services PLLC).

Fig. 12. Graded aggregate material(Longworth BRE Associate).

Fig. 13. Cement stabilisation process in road construction (Pleasants Construction, Inc).

Fig. 14. Lime stabilisation process in road construction (Saranya et al., 2017).

subgrade stabilisation, before and after compaction and different types of compaction equipment are shown in Table 5, Figs. 7 and 8.

Fig. 15. Fly ash stabilisation process in road construction (Beeghly et al., 2003).

Fig. 16. Construction and demolition waste, Geogrid and textile used in road construction(ABG Geosynthetics).

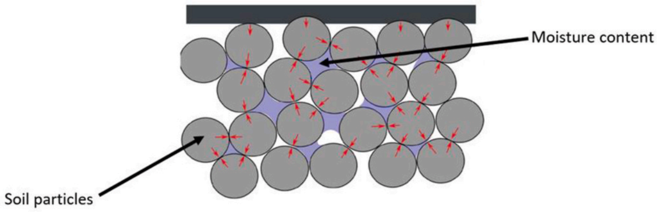

Fig. 17. Moisture content distribution inside an unpaved road (Cabezas et al., 2019).

6.2. Chemical subgrade stabilisation

The process of adding chemicals to improve the engineering properties of expansive subgrade material is termed chemical subgrade stabilisation (Afrin et al., 2017) (seeFig. 15). The addition of these chemicals changes the gradation and physico-synthetics within and around the soil particles promoting cation exchange which leads to flocculation and agglomeration of the expansive soil particles (Jawad et al., 2014). Cement, fly ash, bituminous, rice husk ash, lime, construction and demolition waste, electrical and thermal waste, geotextile fabrics and recycled waste can be used as admixtures in this process as shown in Figs 13, 14, 15 and 16 (Rivera et al., 2020). The addition of this materials as admixtures can alter the geotechnical properties of expansive soil such as strength, bearing capacity, hydraulic conductivity, compressibility, workability, durability and swelling potentials (Cabezas et al., 2019). Chemical subgrade stabilisation is an effective technique to improve expansive subgrade (Phanikumar et al., 2020). An investigation into the application of stabilisation of wastewater sludge proves that cement, lime and bitumen can be used as subgrade materials (Lucena et a., 2014). During chemical road subgrade stabilisation, the shear strength of expansive subgrade is improved when stabilisers react with water within the soil leading to an increase in stiffness of the soil (Phanikumar et al., 2020) Fig. 17 shwons moisture content distribution inside an unpaved road.

Fig. 18. Application of liquid polymer in road construction (Soil stabilisation Innovations).

Fig. 19. Soil stabilised with polymer for road construction (K31 Roads, 2018).

6.3. *Polymer stabilisation*

Polymers are large molecules composed of many repeated subunits. Polymer subgrade stabilisation involves the addition of polymer to expansive or unstable subgrade material to make it suitable for construction (AggreBind, 2020). Adding polymers as an admixture in subgrade stabilisation prevents the penetration of water that can cause failure in road pavement. The addition of polymer increases the density and load-bearing capacity of pavement subgrade after proper compaction (Midwest, 2020). Studies have shown that the application of polymer in subgrade stabilisation has favourable and improved engineering properties. Proportions of polymer (1%, 2%, 3% and 4%) and cement (10%, 20% 30% and 40%) were mixed with expansive soil to improve its engineering properties (Iyengar et al., 2012). The application of polymer in road construction and soil stabilised with polymer are shown in Figs. 18 and 19. A summary of some advantages and disadvantages of mechanical, chemical and polymer subgrade stabilisation techniques are shown in Table 6.

7. Sustainable stabilisation of expansive subgrades

Sustainable stabilisation of expansive subgrade in this study refers to the use of sustainable non-biodegradable waste materials as additives to stabilise expansive subgrade materials. This emerging trend in subgrade stabilisation focuses on the used of locally available industrial waste to improve the engineering properties of soil (Bhardwaj, 2020). Waste and secondary materials such as silica fume, volcanic ash, rice husk, bitumen, kiln dust, natural fibre, Ground Granulated Blast-furnace Slag (GGBS) among others can be used as a partial substitute in conventional subgrade stabilisation (Ijaz et al., 2020). These wastes can improve the workability and durability of expansive subgrade while getting economic benefits (Ijaz et al., 2020). Crushed waste and quarry dust was used in soil treatment in a study to improve the engineering properties of soil (Onyelowe et al., 2018). Other studies have shown an increase in the pH of sludge above 10 with the addition of 34% of cement kiln dust in expansive subgrade stabilisation (Singh et al., 2015). Bagasse ash, industrial waste sand and ground shell reinforced fibre has been successfully used to stabilise expansive subgrade material (Joe et al., 2015). Literature has shown that lime can be used in civil engineering to

Table 6
Summary of advantages and disadvantages of mechanical, chemical and polymer subgrade stabilisation techniques(Christopher et al., 2019).

Technique	Advantages	Disadvantages
Mechanical	• Easy to apply and does not require skilled personnel. • No additives needed hence less time-consuming. • Environmentally friendly no potentially harmful materials involved. • It is an effective waste management alternative when waste materials are used. • Application is quicker when the engineering properties of soil are not critical.	• It can be time-consuming when prolonged physical activities are involved. • Unexpected outcome can be achieved in cases of pre-wetting or drying cycles. • It is not efficient when soil condition is critical. • The method sometimes requires the support of chemical stabilisation.
Chemical	• Laboratory test process is involved to determine the results. • Quantity of binders required is usually small making it cost-effective. • It is less time consuming because chemical reaction occurs spontaneously. • The use of waste in the process promotes waste management. • It is effective in improving the engineering properties of soil.	• In-situ application in this method may be inept if field conditions vary. • The process is mostly associated with the release of toxic components that can affect the environment. • Can be ineffective when the cost or amount of additives cannot be achieved. • Unfortunate conditions can lead to achieving adverse results.
Polymer	• Easy to apply and does not require highly skilled personnel. • They are environmentally friendly and energy-efficient to produce compared to traditional chemical additive. • It is effective irrespective of the engineering properties of the soil. • Gives maximum weather ability	• They are not a permanent solution. • Ideal results are difficult to obtain in this process when the soil has a high percentage of clay. • In-situ application may be pragmatically inept in varying field condition. • Unsuitable when the cost or amount of additives needed cannot be achieved

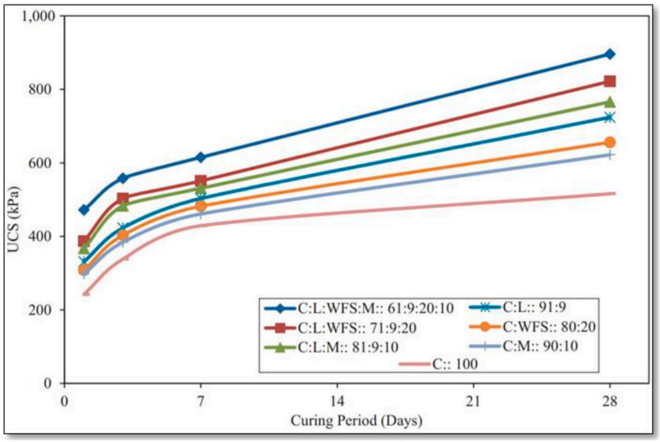

Fig. 20. UCS of clayey soil with different mixes (Bhardwaj et al., 2020).

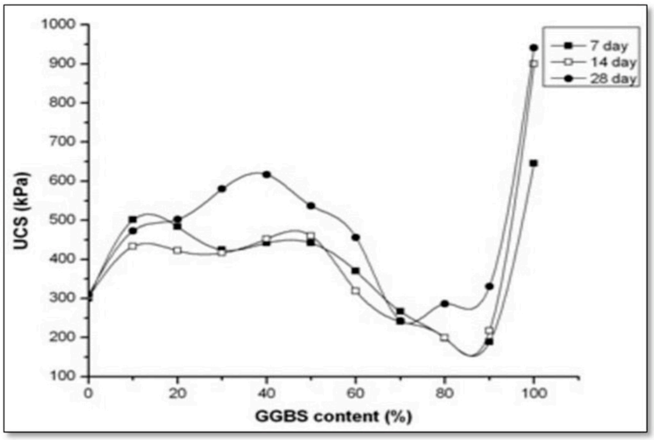

Fig. 21. Variation of UCS of black cotton soil with GGBS (Sharma et al., 2011).

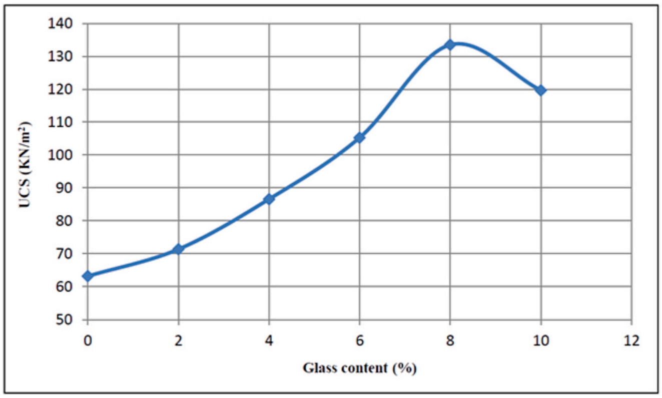

Fig. 22. Variation of UCS values for different glass powder content (Javed et al., 2020).

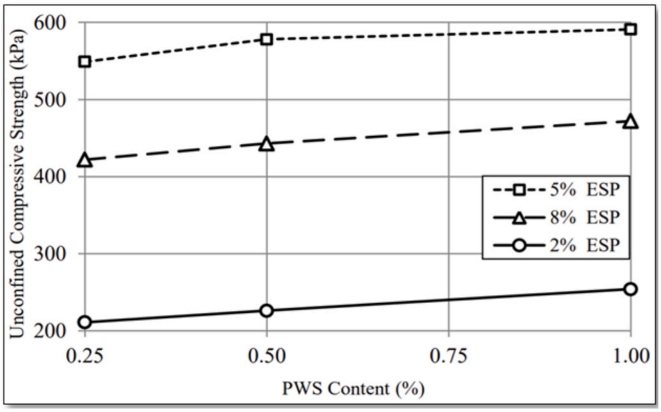

Fig. 23. UCS of ESP-PWS stabilised soil samples after 28 days of curing (Alzaidy et al., 2019).

stabilise subgrade, roadbeds, embankment, plies and foundations (Cai et al., 2006). In other studies, varying proportion of sawdust (4%, 8%, 12%, 16% and 20%) were added to black cotton soil to make it suitable for use as subgrade material (Ikeagwuani et al., 2018).

Peter et al. (2014) used palm oil fuel ash (POFA) to stabilise Sarawak peat composite for used as road subbase material and Foner et al. (1998) used fly ash in the construction of road embankment in Israel. Industrial waste such as copper slag was recommended for subgrade, subbase, bitumen mixes (Chandrshekhar et al., 2015). Crushed glass, recycled concrete aggregate plus 0.5% fine rubber and 0.5% coarse rubber was used to stabilised road subgrade (Saberian et al., 2020). The mechanical characteristics and resistance factor of subbase and subgrade material in flexible pavement improved with the addition of steel slag, crushed limestone mixture and fly fiery debris (Andavan et al., 2019). Research conducted by Saltan et al. (2007) proves that pumice waste can be used as subbase material of highway and stabilisation material when building roads.

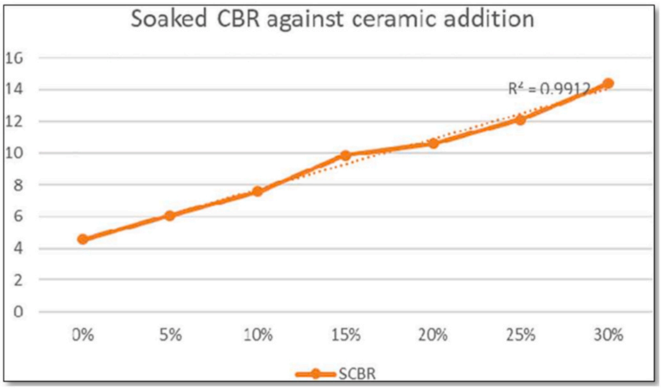

Fig. 24. Soaked CBR with ceramic dust addition(Onakunle et al., 2019).

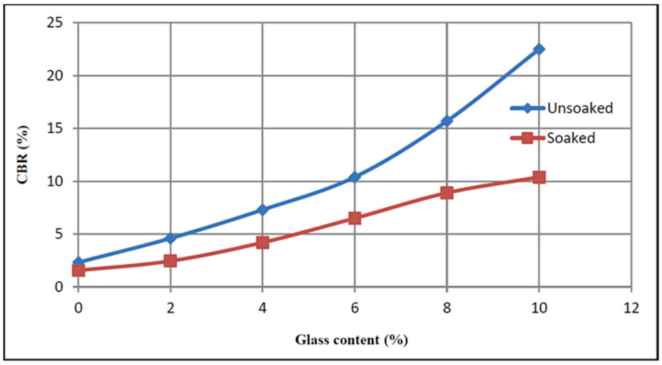

Fig. 25. Variation in CBR values for different glass powder content(Javed et al., 2020).

Construction and demolition waste (CDW) and various sizes of tyre derived aggregate (TDA) blended with crushed rocks (CR) at 1%, 2% and 3% by weight was used in pavement subbase application (Tavia et al., 2019). Crushed rubber and recycled concrete aggregate were used in pavement base/subbase application (Li et al., 2018). Reports have shown the use of by-product of acetylene gas and municipal incinerated bottom ash (MIBA) in highway subgrade and road pavement construction (Du et al., 2016). Recycling waste such as concrete aggregate was classified as excellent highway pavement and embankment material due to their gradation and Atterberg limits (Yap et al., 2019). Recycling screening waste mixed with recycled aggregate from construction and demolition waste were used in the construction of paved bike lanes (Yap et al., 2019). Using recycled waste as a substitute for expansive subgrade will improve the structural capacity and reduce ratting damage (Zhang et al., 2019). Studies have shown the use of coal wash (CW) and fly ash (FA) as base and subbase material in road construction (Wang et al., 2019). The engineering properties of subgrade material was improved when clay soil was mixed with oil palm shell at 10%, 20% and 30% after 7, 10 and 14 days of curing (Gungat et al., 2013).

Geotechnical properties of expansive subgrade with high plasticity was improved when quarry dust at proportions 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40% and 50% was mixed with the soil (Duc et al.,

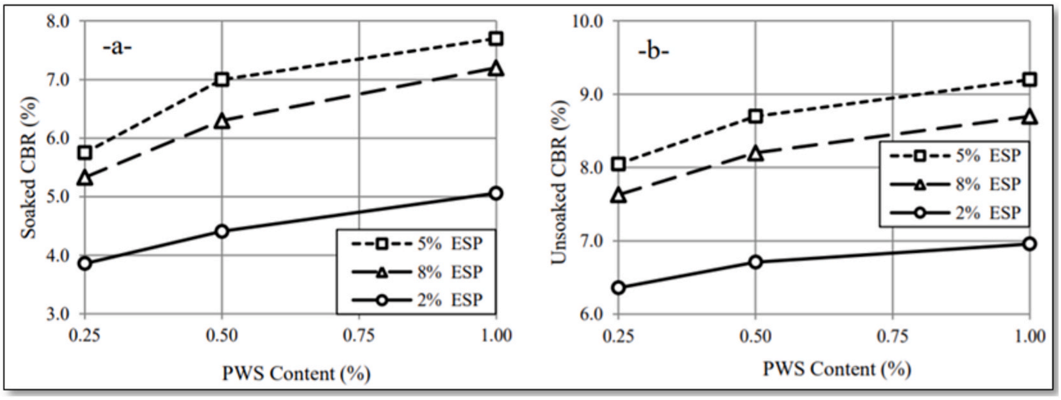

Fig. 26. CBR values for ESP-PWS stabilised soil samples, a -soaked, b- Unsoaked(Alzaidy et al., 2019).

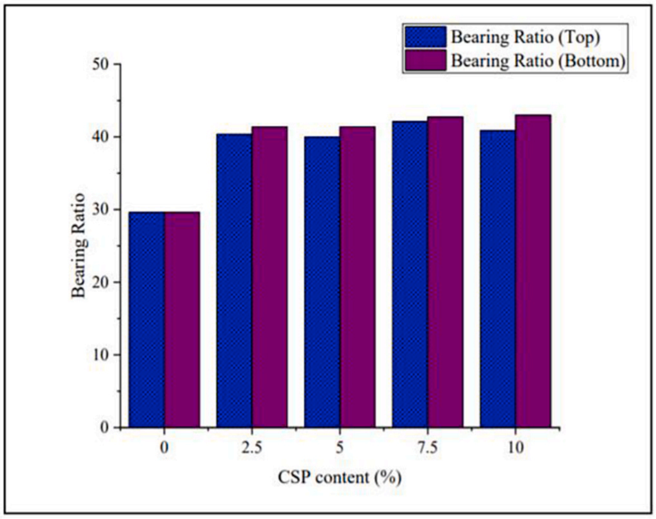

Fig. 27. CBR of stabilised marine clay with varying CSP content(Nujid et al., 2020).

2018). Better performance was observed in red mud soil used as subgrade material when dome fine, ground granulated blast furnace slag (GGBS), cement kiln dust, fly ash and recycled asphalt (RAP) was used as an additive (Mukiza et al., 2018). According toZhang et al. (2020), recycled aggregate from construction and demolition waste was used as alternative filling materials for highway subgrade. Reclaimed asphalt pavement (RAP) and crushed stone aggregate (CSA) were stabilised with varying percentages of cement (Saha et al., 2017). Waste fly ash, oil shale ash and a by-product of paper and timber industry (Lignin) were used to modify silty clay as a subgrade material (Wei et al., 2018). Improved strength was achieved when recycled PET fibre and fly ash wash mixed with expansive subgrade material at proportions 1.2% and 15% by weight of the soil (Mishra et al., 2018). Studies have shown satisfactory results in subgrade and embankment material when pond ash, rice husk ash and cement was used to stabilise expansive subgrade material at 30%–45% and 5%–20% proportion (Gupta et al., 2016). Industrial waste and lime sludge were used to stabilise expansive subgrade leading to a reduction in the lifecycle cost and overall road pavement thickness (Phanikumar et al., 2020). Although there are enough proof from the authors that waste materials can be used in subgrade stabilisation, concerns have been raised on the availability of these waste materials in large quantities to meet current demand. The manufacturing of processed waste however, has some environmental effects which need to be investigated.

8. Properties of waste materials stabilised expansive subgrade

8.1. Unconfined compressive strength (UCS)

Unconfined compressive strength (UCS) test are conducted to determine the stress-strain characteristics and strength of the subgrade material in accordance with relevant standards. Several studies have shown that the use of waste material dumped as landfill such as colliery spoil, waste steel slag among others used as additives yielded high UCS results in subgrade layer (Morales et al., 2019). It has been proven in a study that the addition of kiln dust is enough to achieve a significant increase in UCS values (Michael et al., 2016). The addition of rice husk ash, sugarcane bagasse ash and cow dung as an additive to stabilise subgrade material at 0%, 2.5%, 5%, 7.5%, 10% and 12.5% resulted in high UCS (Yadav et al., 2016). Weak soil was improved using deep mixing techniques by adding waste material such as pulverised fly ash (PFA) and GGBS at varying proportions of 5%, 10%, 15% and 20% (Abbey et al., 2017). An improvement in UCS and other mechanical properties of the subgrade material after 7, 14, 28 and 56 days of curing (Abbey et al., 2017). A study carried out by Bassani et al. (2019) shows an increase in UCS after 3, 7 and 28 days of curing. An investigation conducted on find-grained by Abbey et al. (2018) shows improvement in UCS with the addition of pulverised fly ash (PFA) and GGBS.

Krishana et al., (2016) recorded an increase in UCS from 55 kN/m^2 to 98 kN/m^2 when ceramic dust content was increased from 3% to 30%. Zinc-coated steel milling waste significantly increases UCS vales to 298 kPa, 334 kPa and 390 kPa in road subgrade stabilisation (Cabalar et al., 2020). The Road and maritime Services Specification 3051 states that the unconfined compressive test of subgrade materials are required to be less than 1000 kPa to prevent highly brittle behaviour. The addition of plastic bottle strips at 0.5%, 1% and 2% in subgrade stabilisation recorded improved UCS values (Kassa et al., 2020). Unconfined compressive strength increases with the addition of 5% lime to fly ash stabilised expansive during subgrade whiles UCS increase up to 236 kN/m^2 in a similar study (Tan et al., 2020). An increase in UCS value in Fig. 20 was recorded after waste foundry sands (WFS) and Molasses along with Lime was added to improve the strength characteristics of clayey soil (Bhardwaj et al., 2020). Fig. 21 shown an increase in UCS values when 40% GGBS was used to stabilise black cotton soil after 7, 14 and 28 days (Sharma et al., 2011). Significant increase in UCS from 63.2 kN/m^2 to 133.5 kN/m^2 was recorded in Fig. 22 when glass powder content was increased to 8% (Javed et al., 2020). Results in Fig. 23 shows an increase in UCS when varying proportions of eggshell powder (2%, 5% and 8%) and plastic waste strips (0.25%, 0.5% and 1%) were used to stabilise expansive subgrade material (Alzaidy et al., 2019). A significant increase in UCS was achieved in most of the findings in this section, this shows the that waste materials can be used to improve the engineering properties of subgrade materials. Even though some UCS

Table 7
Summary of findings on UCS and CBR achieved in waste material used in expansive soil stabilisation.

Waste source	Waste Type	Curing Time (days)	Content (%/Ratio)	Information Source	Findings
Industrial	GGBS	7–28	5–15	Estabragh et al. (2020)	UCS strength increased with 5% and 10% GGBS content
	Silica fume	28	2.5–10	Saygilli et al., (2019)	Increased UCS and promote the formation of CSH gel
	Rice husk ash	–	0–12.5	Yadav et al. (2017)	Maximum CBR value of 7.68% and UCS was 2.16 kg/cm^2
	Industrial waste sand	–	5–30	Joe et al. (2015)	Maximum UCS of 197 kN/m^2 and CBR of 25% was achieved
	Copper slag	–	25–75	Mohanraj et al. (2017)	Maximum UCS achieved at 50% copper slag
	Cement kiln dust	7–28	7.5–15	Adeyanju et al. (2019)	CBR increased from 1.49% to 28.6%
	Brick dust	–	10–20	Rank et al. (2020)	UCS increased as Brick dust increase
	Polyvinyl waste	–	–	Michael et al. (2016)	UCS had 60% increment and CBR had about 50% increment
	Ceramic dust waste	–	–	Onakunle et al. (2019)	CBR increased from 6.82% to 21.97% with addition of 5% CDW
	Lignin	7–15	8–12	Zhang et al. (2016)	CBR values increased from 50.6% to 124% for 12% lignin
	Pumice waste	–	10–35	Saltan et al. (2007)	CBR increased by 93%, the best performing mixture is 30% pumice
	Plastic waste	–	0.5–2	Kassa et al. (2020)	UCS reduced at a high percentage of strip content
	Gypsum waste	–	0–15	Al-Adili et al. (2019)	UCS increased by adding up to 5% recycled gypsum
	Coal waste	14–60	0–20	Afrakoti et al. (2019)	UCS increased with the addition of CW at 28 and 60 days
	Sawdust	–	4–12	Ikeagwuani et al. (2018)	Optimum increase in CBR achieved at 16% sawdust content
	Milling waste spiral	–	5–25	Cabalar et al. (2020)	CBR of 11.22% and UCS of 390 kPa was achieved
	Fly ash	–	–	Andavan et al. (2019)	CBR and UCS values can be improved with RHA
	Limed leather waste	4–28	2–10	Parihar et al. (2020)	UCS increased at 10% additive concentration
Construction	Recycled demolition waste	–	–	Zhang et al. (2020)	Gravel particles have sufficient CBR value
	Crushed bricks	–	3–5	Perera et al. (2019)	CBR was higher than the minimum required doe subgrade
	Unselected demolition waste	3–28	–	Bassani et al. (2019)	An increase in strength was achieved without thermal treatment
Electrical	E-waste	–	5–12	Kumar et al. (2019)	UCS increased by 56% and 60% in direct shear value
Others	Waste paper sludge ash	7–28	1:1	Mavroulidou et al. (2018)	High UCS was achieved with the addition of WPSA
	Calcium carbide residue	–	1–4	Varaprasad et al. (2020)	USC and CBR increased
	Burned sewage sludge	7–28	0–15	Amminudin et al. (2020)	UCS increased to 16.72N/mm^2, can be used in road construction
	Locust bean waste	–	0–12	Aliyu et al. (2019)	UCS increased up to 236 kN/m^2 and CBR from 21% to 46%
	Bagasse ash	–	0–30	Maheshwar et al. (2020)	Compressive strength increases with increase in ash content
	Crumb rubber	–	5–15	Kumar et al. (2017)	UCS increased with the addition of crumb rubber
	Coir waste	–	0–3	Peter at al. (2014)	CBR values increased by 192% and 335%
	Bassanite	1–28	1:1	Ahmed et al. (2013)	Increase in CBR and UCS with increase in time was recorded
	Palm fuel ash	7–28	1–6	Abdeldjouad et al. (2019)	UCS strength increased largely after 28days curing
	Fuel ash desulphurisation	7–28	–	Salih et al. (2020)	UCS increased with increase in age with same red mud content
	Wood & sunflower waste	0–13	24hr	Wang et al. (2019)	UCS increased with the addition of 7% fly ash
	Waste glass powder	–	2–10	Javed et al. (2020)	CBR increased to 22.5% with increase in UCS of 133.5 kN/m^2

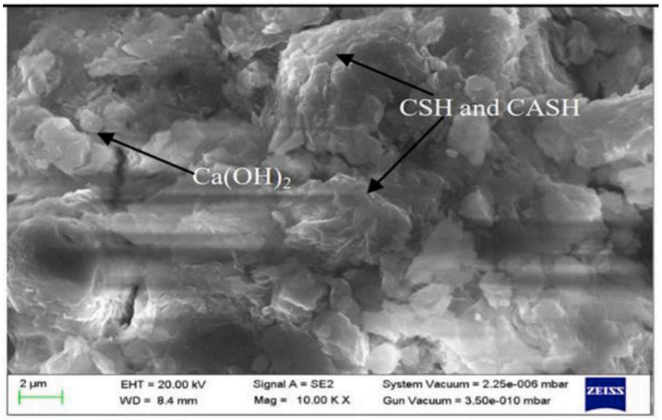

Fig. 28. SEM results of soil +6% LLWA cured(Parihar et al., 2020).

values were low, they are still useable in road construction.

8.2. *California bearing ratio (CBR)*

California bearing ratio is a penetration test to evaluate the strength of the stabilised subgrade materials to ascertain the bearing capacity of road subgrade in accordance with the relevant standards. Studies have shown that CBR has been improved when waste materials were used to stabilise expansive subgrade. In recent study, CBR values were greater than 30% translating into an improved foundation during subgrade stabilisation using recycled concrete aggregate as an additive (Pooni et al., 2019). Amadi et al. (2014) in a study stated that CBR values increased to 13 when cement kiln dust content was increased to 4% and a significant increase in CBR of up to 48 was achieved at 16% cement kiln dust required for subgrade in a flexible pavement system. Its been proven in several studies that the addition of about 0%–25% cement kiln dust is enough to achieve a significant increase in CBR values (Michael et al., 2016). Results from a study show an increase in CBR value from 31 to 42 fold rated as good material for road subgrade construction (Mahmood et al., 2019). CBR values increased by 93% after the stabilisation process of subgrade material when pumice was added (Saltan et al., 2007). CBR value increased by 192% and 335% when 2% of coir pith, 0.6% of short coir fibre waste and adjusted and activated steel slag (ASS) was used as stabilising materials (Peter et al., 2014). High CBR was achieved when six polyethylene terephthalate (PET) plastic waste blend used as construction materials were higher than the minimum CBR required for use as subgrade material (Perera et al., 2019).

Using up to 40% reclaimed asphalt pavement (RAP) and basic oxygen furnace (BOF) aggregate in subgrade stabilisation satisfies the requirement for CBR and a maximum fly ash content of up to 13% can achieve high CBR in subgrade stabilisation (Chen et al., 2017). Mixing crushed stones aggregate and reclaimed asphalt pavement (RAP) from 20% to 100% is makes it suitable for subgrade in flexible pavement

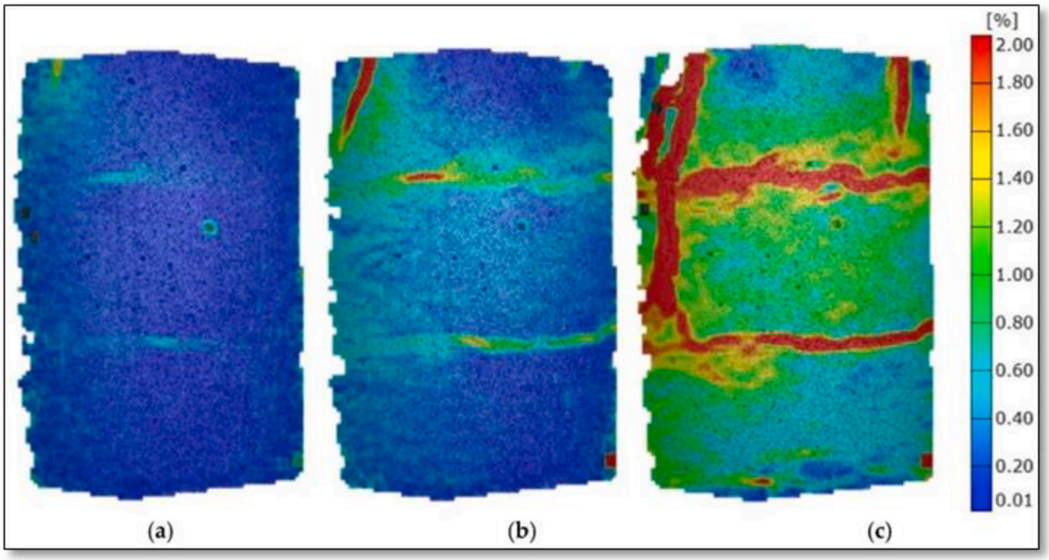

Fig. 29. Mises strain at various load stages with wheat fly ash. (a) 0.3 Fmax, (b) 0.6 Fmax, (C) 1.0 Fmax (Barišić et al., 2019).

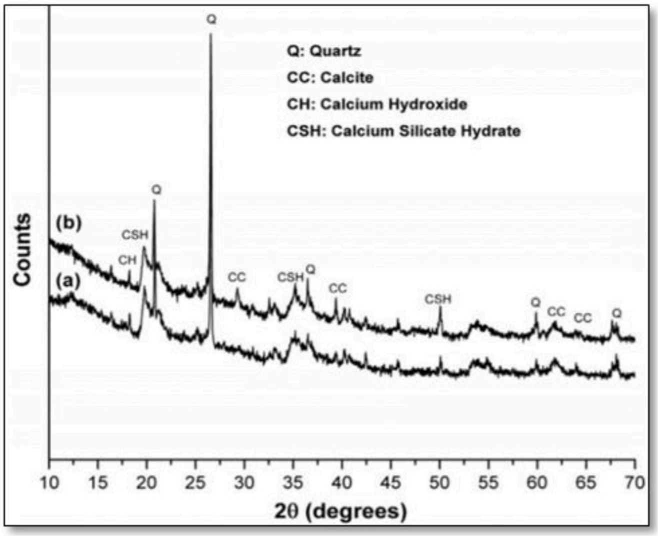

Fig. 30. X-ray diffraction patterns of the soil stabilised with 20% binder cured for 28 days (a) no lime (b) 1% lime(Sharma et al., 2015).

(Saha et al., 2017). According to Yap et al., (2019), CBR value of subgrade materials can be improved using recycled concrete aggregate (RCA). Crushed stone aggregate used as additives improved soaked CBR values substantially while municipal incinerated bottom ash (MIBA) achieved good CBR value of up to 90% in subgrade stabilisation (Saha et al., 2017). During expansive subgrade stabilisation, CBR values increased from both double and single layer of lime treated Cori geotextile by 399% and 435% respectively (Tiwari et al., 2019). CBR values of pavement subgrade increase with intensities of 1, 5, 10, 20 and 30 million standard axles leading to a reduction in pavement thickness above the subgrade material (Selvi et al., 2014). The addition of waste fly ash and oil shale ash at ratio 40:20:40 for oil shale ash (OSA), fly ash (FA and silty clay (SC) exhibited a higher CBR value and improved physical properties of silty clay (Wei et al., 2018). CBR value for treated and untreated soil increased from 3.4% to 48% when 20% cement kiln dust was added to poor subgrade material and cured for 14 days (Mosa et al., 2017).

A high CBR value and resilient modulus were recorded when calcium

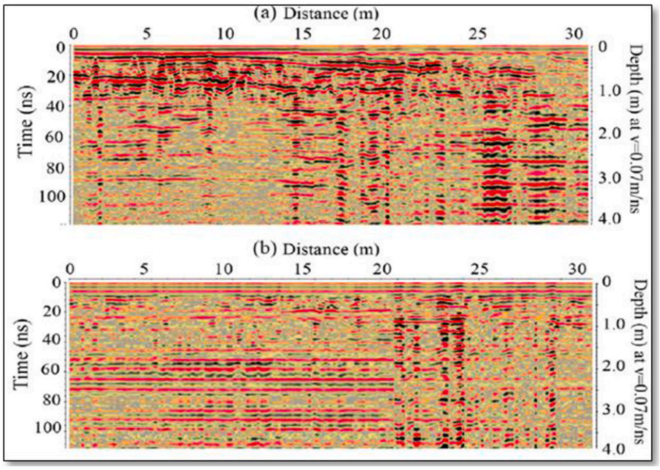

Fig. 31. Radar detection results of two subgrade section made of different materials: (a) CDW (b) Clay (Zhang et al., 2020).

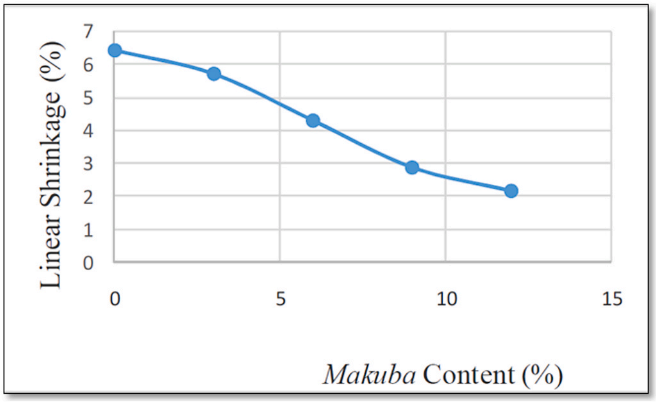

Fig. 32. Variation of linear shrinkage with Makuba content(Aliyu et al., 2019).

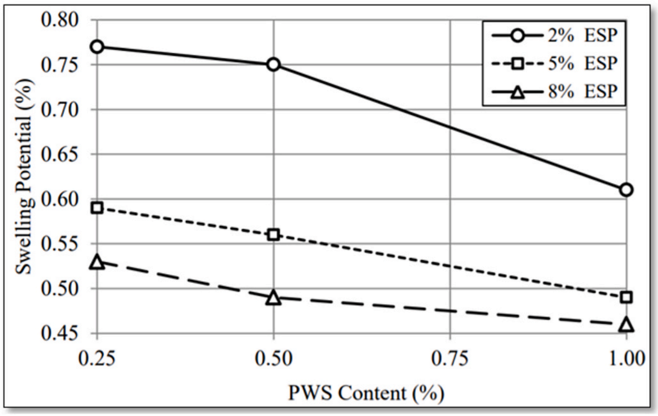

Fig. 33. Swell percent of ESP-PWS stabilised soil sample after 7 days (Alzaidy et al., 2019).

carbide residue was used to stabilise clayey soil concluded that, calcium carbide residue is a viable alternative binder for stabilising soft subgrade soil (Du et al., 2016). The highest CBR value was achieved in expansive subgrade material in pavement construction when 30% oil palm shell was used as an additive and cured for 20 days period (Gungat et al., 2013). The bottom zone layer of road pavement made up of 12% lignin stabilised silt exhibits high value of CBR when by-product of paper and timber industry (Lignin) was used an additive in a field trial (Zhang et al., 2016). Enhanced CBR values were achieved when recycled basanite produced from gypsum waste plasterboards was mixed with furnace slag cement at ratio 1:1 during weak road subgrade stabilisation (Ahmed et al., 2013). Polyethylene terephthalate (PET) and fly ash were mixed in proportions ranging from 0% to 20% by weight of the soil increased CBR value (Mishra et al., 2018). 19% increase in CBR reflected in a reduction in the overall thickness and life cycle cost of a road in Uganda were reduced in a study through the application of geogrids in pavement layers (Melling et al., 2017). Results from an investigation where pond ash (PA) and rice husk ash (RHA) was replaced at 30%–40% in expansive subgrade material shows high CBR values useable for road subgrade and embankment (Gupta et al., 2016). Other studies have shown increasing CBR values using waste plastic materials and industrial waste to stabilise expansive black cotton subgrade material with red mud used for subgrade pavement (Kassa et al., 2020). High CBR was achieved with the addition of sludge, a by-product of paper industry to stabilise and improve expansive soil characteristics (Phanikumar et al., 2020). Lateritic soil mixed with ceramic dust with ratio from 0% to 30% achieved an increase in CBR from 6.82% to 21.97% and 4.55%–14.39% respectively as shown in Fig. 24 (Onakunle et al., 2019). CBR values increased at 2.32% and 1.56% when 10% glass powder was used as an additive to stabilise expansive subgrade at ratios 2%, 4%, 6%, 8% and 10% as shown in Fig. 25 (Javed et al., 2020). Results in Fig. 26 shows an increase in CBR value when eggshell powder (ESP) (2%, 5% and 8% and plastic waste strips (PWS) (0.25%, 0.5% and 1%) were used to stabilise expansive subgrade material (Alzaidy et al., 2019). CBR values increased with varying content of cockle shell powder (CSP) at 0%, 2%, 5.5%, 7.5% and 10% at 5.0 mm penetration as shown in Fig. 27 (Nujid et al., 2020). Table 7 shows a summary of findings on UCS and CBR achieved in waste material used in expansive subgrade stabilisation. CBR in road constructing is crucial, this is because, subbase thickness are selected based on the CBR values achieved after CBR test. CBR values achieved by the various findings when waste materials where used in this section are promising and can be used in road subgrade stabilisation.

8.3. *Microstructural properties*

Microstructural properties are the properties that influence the physical properties such as hardness, strength, high/low-temperature behaviour, toughness wear resistance etc. Microstructural properties of a material can be determined in the laboratory by conducting tests such as Scanning Electron Microscopy (SEM), X-ray, Radar detection, Mises strain test among others. A study conducted by Parihar et al. (2020) shows SEM analysis results after adding 6% of limited leather waste ash (LLWA) shows high CSH gel development resulting in high strength in Fig. 28. Wheat fly ash mixture from a 3D digital image correlation (DIC) measurement in Fig. 29 shows deformations transforming into a vertical and horizontal crack at maximum force (Fmax) (Barišić et al., 2019). The addition of 5% lime to fly ash in a study decreased the plasticity index of expansive soil by 64.9%, reducing the free-swelling ratio to about 10% whiles reducing the swell ratio to nearly 4% (Zhou et al., 2019). Fig. 30 shows XRY patterns of reaction products of soil stabilised with 20% binder after 28 day in a study where fly ash and GGBS was used to stabilise expansive soil (Sharma et al., 2015). The hydration products result in pozzolanic reaction primarily consist of C–S–H gel and calcium hydroxide (CH) as shown in Fig. 31 (Zhang et al., 2020).

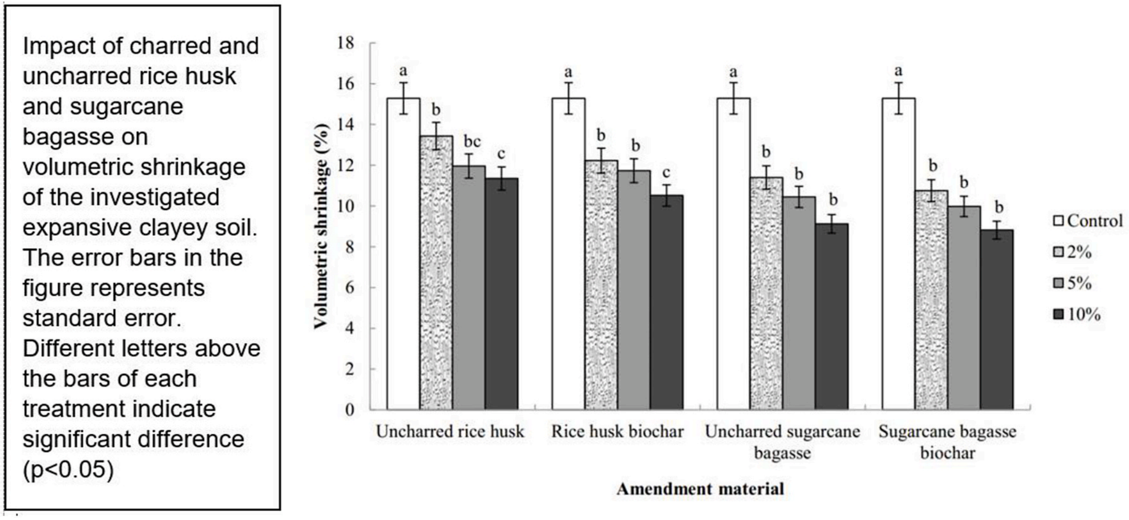
Impact of charred and uncharred rice husk and sugarcane bagasse on volumetric shrinkage of the investigated expansive clayey soil. The error bars in the figure represents standard error. Different letters above the bars of each treatment indicate significant difference ($p<0.05$)

Fig. 34. Volumetric shrinkage against amendment material (Malongweni et al., 2019).

Table 8
Summary of findings on microstructural and tensile properties and shrink-swell of waste used in expansive subgrade stabilisation.

Waste source	Waste Type	Curing Time (days)	Content (%/Ratio)	Information Source	Findings
Industrial	GGBS	7–28	5–15	Estabragh et al. (2020)	Sem shows high strength between soil particles and stabilising agents.
	Silica fume	28	2.5–10	Saygilli et al., (2019)	SEM shows silica fume/lime addition promoted the creation of CSH gel.
	Cement kiln dust	7–28	7.5–15	Adeyanju et al. (2019)	Swell test shows a rise in geotechnical properties of stabilised soils
	Brick dust	–	10–20	Rank et al. (2020)	Swelling potential reduced with lower content
	Polyvinyl waste	–	–	Michael et al. (2016)	X-ray diffraction shows high montmorillonite content in the soil
	Ceramic dust waste	–	0–30	Onakunle et al. (2019)	Maximum dry density increased CWD
	Plastic waste	–	0.5–2	Kassa et al. (2020)	Swell behaviour of soil reduced
	Gypsum waste	–	0–15	Al-Adilli et al. (2019)	5% rise in swelling index decreased with increase in gypsum
	Coal waste	14–60	0–20	Afrakoti et al. (2019)	Tensile strength increased at short curing periods of 14 days
	Sawdust	–	4–12	Ikeagwuani et al. (2018)	X-ray diffraction test shows the occurrence of pozzolanic reactions
	Milling waste spiral	–	5–25	Cabalar et al. (2020)	Values decrease in swell index (Cs) and compression index (Cc)
	Limed leather waste	4–28	2–10	Parihar et al. (2020)	SEM results confirm formation of CSH gel increases with curing time.
Construction	Recycled demolition waste	–	–	Zhang et al. (2020)	Radar detection of subgrade section made of CDW and clay
	Unselected demolition waste	3–28	–	Bassani et al. (2019)	FESEM demonstrate the feasibility of using unselected CDW
Others	Waste paper sludge ash	7–28	1:1	Mavroulidou et al., (2018)	SEM shows developed reaction hydration coatings after 28days curing
	Burned sewage sludge	7–28	0–15	Amminudin et al. (2020)	XRF test shows DSS has good potential to replace cement in concrete.
	Bassanite	1–28	1:1	Abdeldjouad et al. (2019)	SEM-EDS shows strengthening in the mechanism of alkaline activation
	Palm fuel ash	7–28	1–6	Salih et al. (2020)	Highest tensile strength of 0.078 MPa was observed

8.4. *Tensile and shrink-swell properties*

Tensile strength in this study refers to the measure of the stress responses of stabilised subgrade material by applying a tensile or pulling force to the specimen and shrink-swell is the extent to which expansive subgrade will expand when wet and shrink when dry. Research has shown that indirect tensile strength values mixture satisfies the minimum requirements for granular mixture for subbase layer of road pavements when unselected construction and demolition waste (UCDW) was used as an additive (Bassani et al., 2019). Tensile strength and shrink-swell properties of expansive subgrade material can be improved using waste materials as additives. In a similar experiment, tensile strength values increased by adding 5% lime to fly ash was added to expansive subgrade material (Zhou et al., 2019). 52.19% cori geotextile mat in single layer and 81.89% in double-layer reduce road pavement thickness after expansive subgrade stabilisation (Zhou et al., 2019). Other studies have shown a reduction in shrink-swell potentials from 6.43% to 2.14% with an increase in powered locust bean pod in Fig. 32 (Aliyu et al., 2019). Swell potential was reduced when eggshell powder (ESP) 2%, 5% and 8% and Plastic waste strip PWS) was used to stabilise expansive subgrade material shown in Fig. 33 (Alzaidy et al., 2019). Tensile strength increased by 4.5 times when mud masonry blocks were stabilised using waste plastic fibres (Subramaniaprasad et al., 2014). High tensile strength was recorded in a study when waste fibres were used as an additive in clay soil stabilisation (Muntohar et al., 2012). Swell potentials of expansive subgrade were suppressed with an improvement in strength when waste steel slag was used to stabilise subgrade material for road construction (Wu et al., 2019). Other studies have also shown an improvement in the physcio-mechanical properties related to swelling potentials of expansive subgrade when charred and uncharred rice husk and sugarcane bagasse were used as additives as shown in Fig. 34 (Malongweni et al., 2019). The application of lime has been reported to have strong bonds between soil particles resulting in reduced shrink-swell potentials (Kamaruddin et al., 2020). Swell ratio was increased from 3.4% for untreated soil to 48% for treated soil when 20% cement kiln dust was added to poor subgrade material after 14 days of curing (Mosa et al., 2017). Recycled basanite produced from gypsum waste plasterboards was used to enhance tensile splitting strength of weak subgrade clay soil used in road construction (Ahmed et al., 2013). Summary of findings on micro and tensile properties and shrink-swell of waste used in expansive subgrade stabilisation are shown in Table 8. The results achieved in this section indicates that soils are weak in tension but strong in compression. On the other hand, shrink-swelling potentials of expansive subgrade materials were reduced with the addition of waste.

8.5. *Limitations and future focus*

There are limitations associated with the use of waste materials as additives in expansive subgrade stabilisation. Some of these limitations in waste materials dumped as landfill include contamination through leaching of toxic into the waste. Using contaminated waste in soil stabilisation can affect the performance and engineering properties of the soil. The cost effects of decontamination of these waste materials is a limitation to the use of waste materials in subgrade stabilisation. The application of additives to expansive soils insitu can be stabilised only to a shallow depth which is not suitable for deep soil stabilisation. However, the easy accessibility and the low cost of waste materials used in subgrade stabilisation hold promising keys to a sustainable future. Using waste in subgrade stabilisation focus on providing a better understanding of the use of new technology and materials in subgrade stabilisation to exploit any improvement in the future.

9. Conclusion

Current expansive subgrade stabilisation techniques is focused on using chemical agents such as cement and lime in subgrade stabilisation. However, these chemical agents have limitations and prove to be non-environmentally friendly and expensive. This has called for the use of non-traditional stabilisers as additive in subgrade stabilisation. The addition of non-traditional stabilisers in subgrade stabilisation using chemical stabilisation techniques has proven to be more environmentally friendly, cheaper and effective in improving the engineering properties of expansive subgrade materials. Using non-traditional industrial waste materials in subgrade stabilisation will reduce overall project cost and greenhouse gas emission while saving landfill space. It is essential to carryout performance base testing to prove the effectiveness of non-traditional stabilising agents and focus on exploring other novel by-products that can be used in expansive subgrade stabilisation. It is crucial to carry out further research into the effects of climate change on stabilised expansive subgrade materials stabilised with non-traditional by-products and how they can improve.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sector.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors acknowledge the advice, comments and suggestions from anonymous reviewers which significantly improved the quality of this paper.

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