Clay Stabilisation using Modified Anionic Bitumen Emulsion and Waste Glass

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Abstract

Clay (black cotton soil) is among the most difficult soils to stabilise against land movement. This study explores the possibility of mixing binders with the soil to increase its internal properties and stabilise clay from landslide prone areas. A modified anionic bitumen emulsion was mixed with the soil at different percentages and tested for angle of friction and cohesion. It was found that an optimum modified anionic bitumen emulsion content (OBC) of 4% mixed with the clay at optimum moisture content (OMC) and at maximum dry density (MDD) resulted in a reduction of cohesion by 310% and an improvement of 96% in terms of angle of friction. The OBC was further mixed with waste glass particles of different sizes and tested for improvement. While adding 9% of 0.4mm glass, there was an additional improvement of 94% in terms of Cohesion as compared to only OBC-stabilised soil. However, the soil was found to be less stable in terms of angle of friction for all glass size additives as compared to OBC only. Thus, clay stabilised with OBC only has been retained as the best choice for soil stabilisation. OBC-stabilised soil is 14.3 times less polluting at production than traditional cement-stabilised soil.

Keywords: Soil stabilisation, Waste management, Bituminous binder, Laboratory, Sustainability.

List of Abbreviations:

MDD – Maximum dry density

OBC – Optimum modified anionic bitumen emulsion content

OMC – Optimum moisture content

Introduction

Soil instability has been a recurrent problem recently due to excessive human activity and climate change-induced precipitation (Shukla *et al.*, 2019; Tan, Zahran and Tan, 2020); It is the root cause of geotechnical disasters such-as landslides, rockfall, debris flow and slope failure among others, which may cause loss of life, damage to property and displacement of people from their homes (Crozier, 2010). One solution to mitigate such geotechnical disasters is soil stabilisation. Soil stabilisation may be classified into three types, namely mechanical stabilisation where the soil and its surroundings are physically altered to change the soil properties such-as lowering the water table, piling, anchoring, and mixing non-reactive additives to the soil among others (Yamashita, Hamada and Yamada, 2011; Olufowobi et al., 2014). The second type of stabilisation is chemical stabilisation which involves mixing reagents to the soil to chemically alter the soil and its properties to achieve stabilisation (Prasad, 2016; Ikeagwuani and Nwonu, 2019). Another form of stabilisation is biological stabilisation where plants are used to stabilise the soil through their roots holding the soil together (Hou et al., 2016; Punetha et al., 2019).

Most of the above mentioned stabilisation methods have their own disadvantages. For example, the biological method of stabilisation has a shallow reach due to the depth to which the plant’s roots can extend, which is in the range of two to three metres depth (Punetha, Samanta and Sarkar, 2019). Chemical stabilisation usually involves reagents containing high contents of calcium compounds such as cement and lime. However, the compound formed from those reagents tend to be brittle and thus breaking easily at some point of stress (Geng *et al.*, 2023). Traditional forms of stabilisation, such-as piling, anchoring and water table-lowering wells and drains are usually applicable in most cases, but the most costly and labour intensive methods which make them less sustainable. Thus, a more modern method of mechanical soil stabilisation has been selected for this study, which involves the mixing of non-reactive additives to the soil to alter its internal properties to stabilise the soil (Afrin, 2017). Bitumen was the first choice for investigation in this paper due to its flexibility, but it was soon rejected due to its extremely high viscosity at room temperature and low workability for mixing in small amounts when hot (Diab *et al.*, 2023). The next option was bitumen emulsion where charged particles of bitumen and water are mixed to prevent the bitumen particles from binding to each other, thus making it very workable (Batra and Arora, 2016).

Bitumen emulsion may contain 30% to 70% water depending on per-calculated manufacturing processes (Batra and Arora, 2016). The emulsion is manufactured by dispersing hot bitumen in water with the help of emulsifiers (Al-Mohammedawi and Mollenhauer, 2022). The type of emulsifier chemical used will determine the charge on the bitumen particles, whether anionic (negatively charged) or cationic (positively charged) (Abdullin and Emelyanycheva, 2020). The anionic bitumen emulsions will typically be alkaline, while the cationic bitumen emulsions are acidic. Anionic and cationic bitumen emulsions cannot be mixed together since the negatively charged particles will react with the positively charged particles and neutralise the emulsion, making it unworkable (Abdullin and Emelyanycheva, 2020). It is to be noted that anionic bitumen emulsions, being mostly neutral or slightly alkaline just like clays will not react with the soil, but only fill in the gaps in between the soil particles and act as a glue (Momeni, Bayat and Ajalloeian, 2022). Batra and Arora (2016) have tested clays with cationic bitumen emulsions and found that a 6% cationic bitumen emulsion mixed with 94% clay gave an optimal stabilization, increasing the angle of friction from 20.0° to 67.3° and reducing the cohesion from 0.1964 N/mm^2 (196.4 kPa) to 0.1638 N/mm^2 (163.8 kPa).

Glass waste is another major concern worldwide due to the scarcity of landfills and increasing human activity (Jani and Hogland, 2014; Ichinose, 2023). Glass waste is generated from various sources such as bottles, jars, construction window glass, lamps, monitors and other glass containers (Sobolev, 2003). Glass is a fully recyclable high-cost material that is very in demand worldwide (Kazmi, Williams and Serati, 2020). 130 million tonnes are produced and disposed every year, however only 27 million tonnes is recycled globally, representing only 21% of the volume, while 79% goes to the landfill every year (Ferdous *et al.*, 2021). Glass is not an easily degradable material that can take thousands of years to degrade (Tamanna *et al.*, 2013). Thus there is a real need to find new methods to recycle glass instead of disposing it in landfills. Glass has been used in the construction field as additives to concrete among others as an attempt to tackle this issue (Lu and Poon, 2019; Kazmi, Williams and Serati, 2020; Małek *et al.*, 2020). Re-utilisation of waste glass in the geotechnical field is relatively under-researched (REFs). Glass could potentially be used as backfilling material in pavements, embankments, roads, beach filling and soil stabilisation as well (Kazmi, Williams and Serati, 2020). The properties of glass mixed with soil and/or cement have been analysed in terms of friction angle and compressive strength as well as reduction of swelling of clays by various research (Kazmi, Williams and Serati, 2020).

The aim of this study is to explore the possibility of using glass mixed with bitumen emulsion in clay stabilisation to recycle waste glass. To achieve this, the soil mixture will be tested using small shearbox apparatus as per clause 25.2 of BS1377-2: 2022. Results will be critically compared, and assessment of cohesion intercept and angle of friction will be made and will be framed in the context of land stabilisation.

Methods

Clay, being among the most problematic soil types, was selected as the model medium for this study. Black cotton soil clay was collected from a landslide-prone area in Mauritius (Black Riviere Noire) and tested in laboratory according to the BS1377-2:2022 norms. Table 1 below shows the parameters of the soil being investigated.

Table 1: Properties of clay being investigated

Properties of Clay	**Value**
Onsite moisture content	42.5 ± 0.6 %
Onsite dry density	1.288 ± 0.004 Mg/m^3
Liquid limit	58.1 ± 0.2 %,
Plastic limit	25.2 ± 0.8 %
Plasticity index	32.9
Liquidity index	0.526
Linear shrinkage	15.0 ± 0.4 %,
Particle density	2.78 ± 0.00 Mg/m^3
Gravel content	4.3 ± 0.1 %
Sand content	16.3 ± 0.2 %
Silt content	65.2 ± 0.1 %
Clay content	14.3 ± 0.1 %
Maximum dry density (MDD)	1.584 ± 0.002 Mg/m^3
Optimum moisture content (OMC)	25.2 ± 0.2 %
California Bearing Ratio	3.23 ± 0.03 %
Swell pressure	0 kPa
Hydraulic conductivity	K < 10^{-5} m/s
Angle of friction (Site conditions)	17.2 ± 0.4 °
Cohesion (Site conditions)	18.3 ± 1.5 kPa

As mentioned earlier, anionic bitumen emulsion does not react with soil and act as a mechanical stabilisation method instead of chemical stabilisation method. Modified anionic bitumen emulsion containing 9% synthetic resin (typically used in waterproofing) was used as binder for this study and tested for angle of friction and cohesion through unsaturated shearbox test (British Standards, 2022; clause 25.2 of BS1377-2: 2022). The binding agent used for this study has the following properties as shown in table 2 below.

Table 2: Properties of modified anionic bitumen emulsion

Properties	**Value**
Brand name	Pekay T570
Anionic bitumen emulsion	85%
Synthetic resin emulsion	9%
Content of solids	60 ± 2 %
Water content	40%
Specific gravity	1.0 kg/L
Appearance	Thick brown buttery
Solubility in water	Freely soluble
Toxicity	None
Ecological information	Harmless

The soil was first compacted at maximum dry density (MDD) and optimum moisture content (OMC), then tested in an unsaturated condition in a small shearbox to serve as a control experiment. The modified anionic bitumen emulsion was then mixed with the soil in different percentages (3%, 6%, 9%, 12% and 15% by mass to plot a 5 point curve while staying in the reasonable material replacement range, similar to the methods used by Arabani et al. 2012; Canakci et al. 2016; Khan et al. 2018; and Attom 2018) while maintaining MDD and OMC, and tested under normal pressures of 50kPa, 100kPa, 200kPa to represent loading of buildings on the lands prone to landslide. It is to be noted that the bitumen emulsion already contains 40% of water. This was taken into account while preparing the sample from sun-dried clay to maintain the exact OMC. No curing period was required since the bitumen does not react with the soil. Three trials of unsaturated shearbox test were carried out for each normal pressure and a graph of max shear stress vs normal applied stress was created to find the average cohesion intercept and the average angle of friction at a specific percentage mix which, together, determined the shear strength of the soil.

The optimum modified anionic bitumen emulsion (OBC) percentage mix was then determined through a graph plot, thus comparing the different results of each mix. The point showing maximum reduction in cohesion intercept and greatest increase in angle of friction was recorded as optimum since an increase in angle of friction increases the soil’s ability to resist shearing and reduced cohesion means a better drainage, thus better stability (Mesri and Abdel-Ghaffar, 1993; Arvanitidis, Steiakakis and Agioutantis, 2019). Once the OBC was determined, the clay was further tested for any possible strength improvement using waste glass in an attempt to reduce landfill waste. Crushed waste glass was collected from a glass crushing facility and 30 kg of sub-milimetre glass particles were collected. The same was separated by size to test for the effect of size particle on the stabilisation. The glass was thus sieved mechanically for 30 minutes through 0.6mm, 0.4mm, 0.2mm and 0.1mm sieves. Each size of glass particle was mixed in percentages of 3%, 6%, 9% and 12% with the OBC and clay. The whole was tested for angle of friction and cohesion through unsaturated shearbox test (British Standards, 2022; clause 25.2 of BS1377-2: 2022). The results of cohesion intercept and angle of friction were all compiled and compared through a detailed bar chart. All tests were repeated in 3 trials and an average result was determined with a standard error. The results were statistically compared using an unpaired T-test to compare site conditions and OMC & MDD compacted soil results. A one-way ANOVA test was used to compare the stabilisation using modified anionic bitumen emulsion and a separate one-way ANOVA test was used to compare glass particle additives. In all cases, the OMC & MDD compacted soil was used as a control and all stabilisers were subsequently compared to it. A significance level of 0.05 was retained for all statistical analysis.

Results and Discussion

The black cotton soil compacted at MDD and OMC without any additives has an average cohesion intercept of 28.7 ± 2.4 kPa and an average angle of friction of 23.0 ± 0.1 °. When 3% of modified anionic bitumen emulsion was added to the soil, the soil obtained an average cohesion intercept of 9.0 ± 3.5 kPa and an average angle of friction of 42.8 ± 0.9 °. At 6% modified bitumen emulsion mix, the clay had an average cohesion intercept of 12.3 ± 0.9 kPa and an average angle of friction of 42.2 ± 0.3 °. 9% modified anionic emulsion gave the clay an average cohesion intercept of 29.0 ± 3.2 kPa and an average angle of friction of 35.9 ± 1.2 °. At a mix of 12% of modified anionic bitumen emulsion changed the soil properties to an average cohesion intercept of 44.7 ± 3.2 kPa and an average angle of friction of 27.7 ± 1.2 °. Mixing15% of modified bitumen emulsion with clay resulted in an average cohesion intercept of 50 ± 1.7 kPa and an average angle of friction of 30.1 ± 1.1 °. Table 3 shows a summary of the results used for plotting the cohesion intercept and angle of friction graphs to determine an OBC.

Table 3: Test results for modified bitumen emulsion with clay

Description	Percentage (%)	Cohesion Intercept (kPa)	Angle of Friction (°)
Site Conditions	N/A	18.3 ± 1.5	17.2 ± 0.4
MDD, OMC Compacted	N/A	28.7 ± 2.4	23.0 ± 0.1
Modified Bitumen Emulsion	3	9.0 ± 3.5	42.8 ± 0.9
	6	12.3 ± 0.9	42.2 ± 0.3
	9	29.0 ± 3.2	35.9 ± 1.2
	12	44.7 ± 3.2	27.7 ± 1.2
	15	50.0 ± 1.7	30.1 ± 1.1

A two tailed t-test for independent samples showed that the difference in cohesion intercept between OMC & MDD compacted soil and soil at site conditions was statistically significant ($p= 0.021$, $n=3$), In terms of angle of friction also, the difference was statistically significant ($p < 0.001$, $n = 3$, variables = 6). A one -way ANOVA test without repeated measures for the different percentages of modified anionic bitumen emulsion were significantly different ($p < 0.001$, $n = 3$) for cohesion intercept and also for angle of friction ($p < 0.001$, $n = 3$). The results were compiled in the forms of two graphs; figure 1 compares the cohesion intercepts while figure 2 compares the angle of friction to determine an optimum percentage of modified anionic bitumen emulsion – clay mix. From the graphs, it can be determined that 4% modified bitumen emulsion may give the lowest cohesion intercept of 7kPa and also the highest angle of friction of 45°. This represents a 310% decrease in cohesion from 28.7 ± 2.4 kPa for plain compacted soil to 7kPa and an increase of 96% in angle of friction from 23.0 ± 0.1 ° from plain compacted soil to 45°.

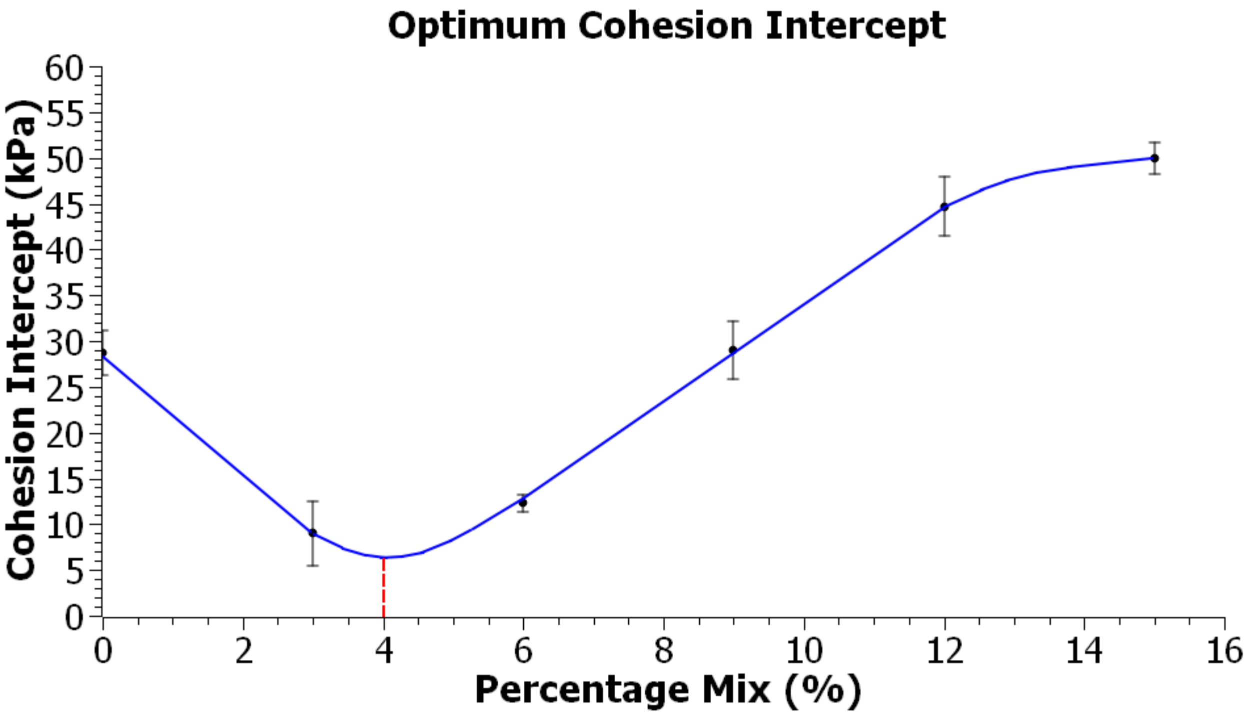

Figure 1: Average cohesion intercept of different percentage of modified bitumen emulsion-clay

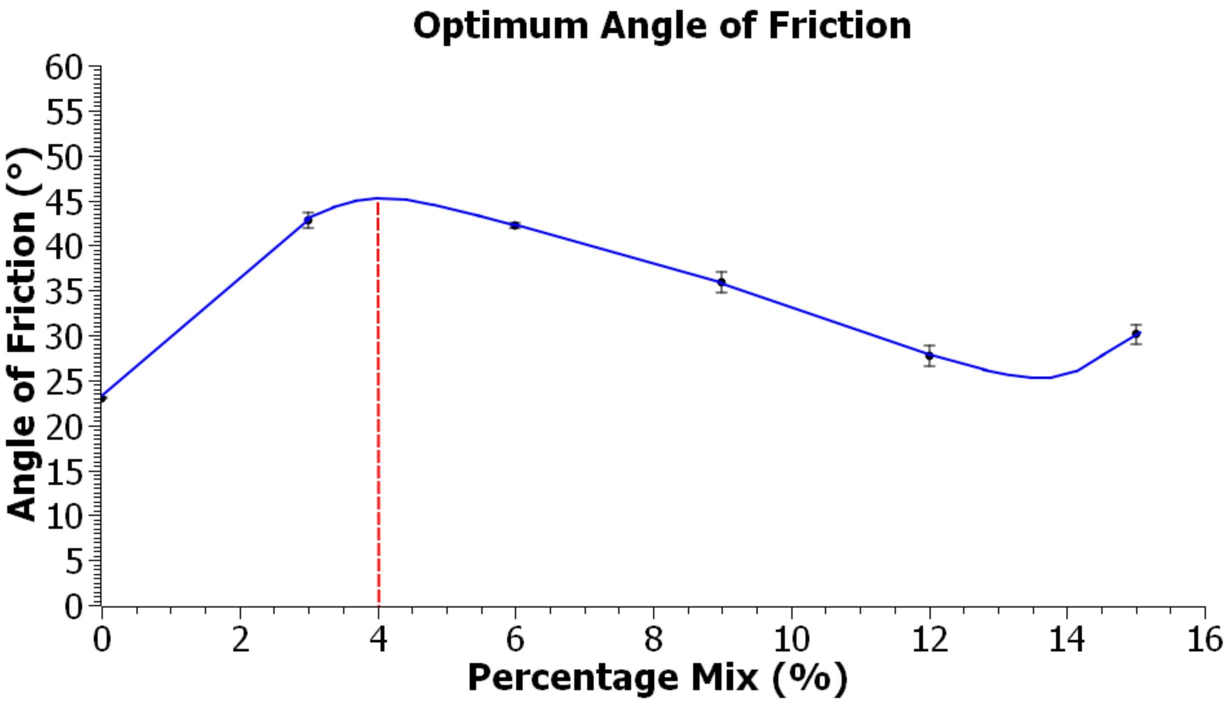

Figure 2: Average angle of friction of different percentage of modified bitumen emulsion-clay mix

Once the OBC of 4% was established, waste glass particles were tested. 0.1mm glass particles at 3% with OBC and compacted soil gave 27.7 ± 2.6 kPa cohesion and an angle of friction of 23.0 ± 1.1°. At 6% it gave a cohesion intercept of 19.7 ± 2.3 kPa and an angle of friction of 27.3 ± 0.5°, while at 9% modified bitumen emulsion it gave a cohesion intercept of 23.7 ± 1.4 kPa and an angle of friction of 26.7 ± 0.7°. At 12%, the cohesion intercept was 19.0 ± 2.0 kPa and the angle of friction was 27.8 ± 0.7°. Glass particles of size 0.2mm at 3% concentration gave 32.7 ± 1.8 kPa cohesion intercept and 24.0 ± 0.2° angle of friction on average. At 6% glass, a cohesion intercept of 34.7 ± 3.4 kPa and angle of friction of 19.9 ± 1.2°. The cohesion intercept was 18.3 ± 1.5 kPa and angle of friction was 17.4 ± 0.6° at 9% glass additive, while the cohesion intercept for 12% glass was 19.3 ± 0.9 kPa with an angle of friction of 25.5 ± 0.7°. 0.4mm glass additives at 3% gave a cohesion intercept of 23.0 ± 2.1 kPa with an angle of friction of 37.5 ± 0.7° and at 6% concentration gave a cohesion intercept of 35.0 ± 1.2 kPa with an angle of friction of 30.5 ± 0.3°. At 9% concentration, the stabilised mix showed a cohesion intercept of 5.7 ± 1.8 kPa and an angle of friction of 38.9 ± 1.0° while at 12% glass additive, the cohesion intercept was 42.3 ± 0.9 kPa and the angle of friction was 23.8 ± 0.9°. Lastly, the soil was tested with glass additives of 0.6mm size. At 3%, the cohesion intercept was 19.3 ± 1.5 kPa and the angle of friction was 28.0 ± 0.4° on average. At 6%, the cohesion intercept was found to be 23.0 ± 1.5 kPa and the angle of friction was 26.3 ± 0.8, while at 9%, the cohesion intercept was 24.0 ± 0.6 kPa and the angle of friction was 23.5 ± 0.9°. At 12% additive, the stabilised mix gave a cohesion intercept of 22.7 ± 0.3 kPa and an angle of friction of 23.7 ± 0.4°.

Table 4 shows the results for the 4 different glass particle sizes at the 4 different percentages. The results were plotted as a graph for cohesion intercept as shown in figure 3 and angle of friction as shown in figure 4.

Table 4: Test results for glass particle size mixing

Description	Percentage (%)	Cohesion Intercept (kPa)	Angle of Friction (°)
Optimum Bitumen Emulsion	4	7	44
0.1mm Sieved Glass + OBC	3	27.7 ± 2.6	23.0 ± 1.1
	6	19.7 ± 2.3	27.3 ± 0.5
	9	23.7 ± 1.4	26.7 ± 0.7
	12	19.0 ± 2.0	27.8 ± 0.7
0.2mm Sieved Glass + OBC	3	32.7 ± 1.8	24.0 ± 0.2
	6	34.7 ± 3.4	19.9 ± 1.2
	9	18.3 ± 1.5	17.4 ± 0.6
	12	19.3 ± 0.9	25.5 ± 0.7
0.4mm Sieved Glass + OBC	3	23.0 ± 2.1	37.5 ± 0.7
	6	35.0 ± 1.2	30.5 ± 0.3
	9	5.7 ± 1.8	38.9 ± 1.0
	12	42.3 ± 0.9	23.8 ± 0.9
0.6mm Sieved Glass + OBC	3	19.3 ± 1.5	28.0 ± 0.4
	6	23.0 ± 1.5	26.3 ± 0.8
	9	24.0 ± 0.6	23.5 ± 0.9
	12	22.7 ± 0.3	23.7 ± 0.4

A one-way ANOVA analysis without repeated measures showed that the difference in cohesion intercept between all the glass particle sizes and percentages were statistically significant ($p < 0.001$, $n = 3$, variables = 17). Same significant difference was observed for angle of friction ($p < 0.001$, $n = 3$, variables = 17).

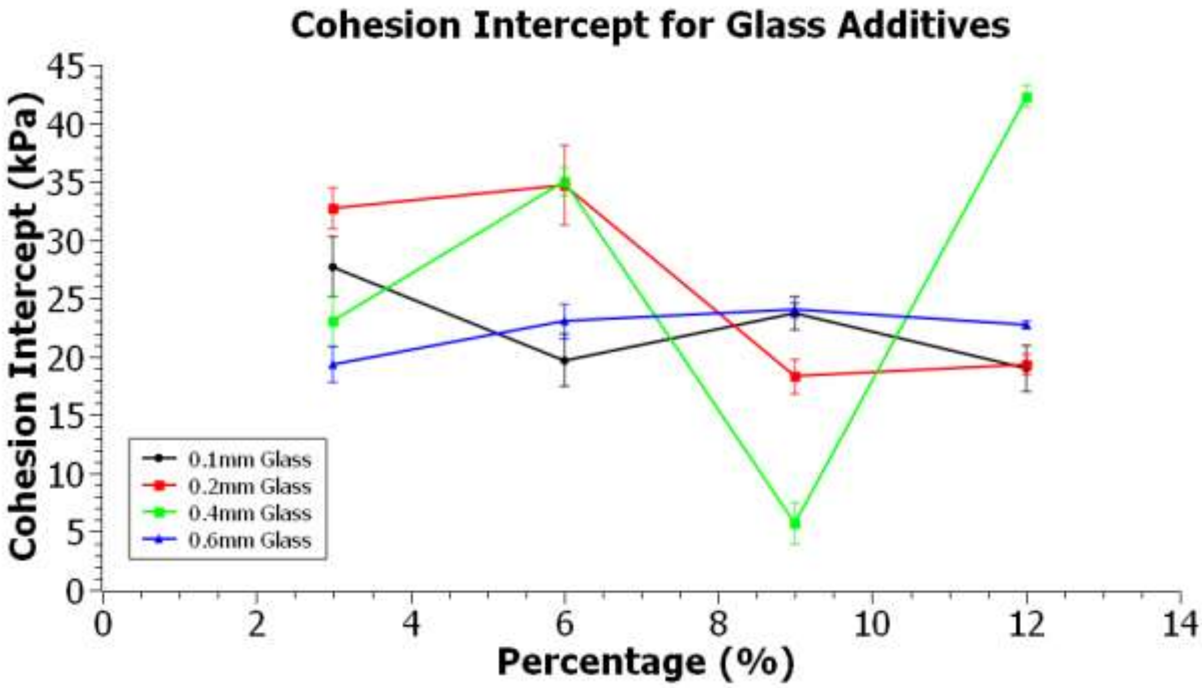

Figure 3: Cohesion intercept for glass additives

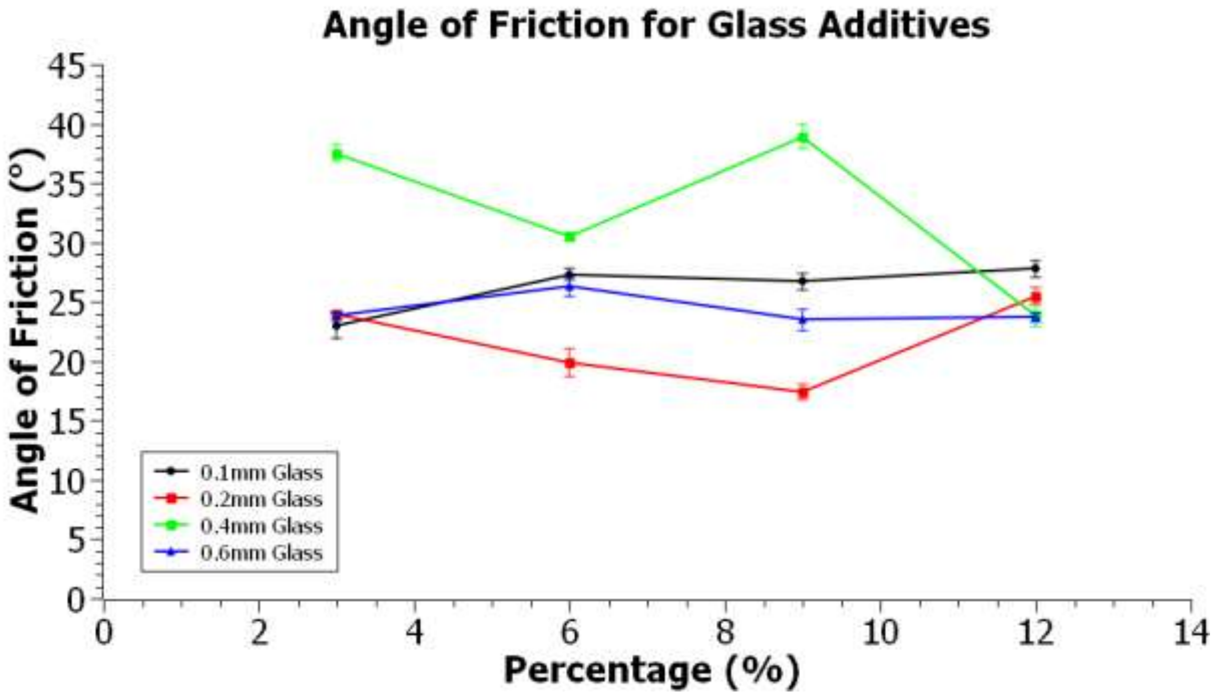

Figure 4: Angle of friction for glass additives

A double-peak pattern was noticed in almost all the graphs of particle size additives when tested at different percentages. The data was compared to the original OBC and plain compacted soils. It was found that only the mix of 0.4mm glass particles at 9% gave an improvement in cohesion by 404% as compared to plain compacted soil at MDD & OMC (from 28.7 ± 2.4 kPa to 5.7 ± 1.8 kPa), which represents an increase of 94% as compared to OBC-stabilised soil (from 7 kPa to 5.7 ± 1.8 kPa). While many glass size particles gave an improvement compared to plain compacted soil, none of them matched the optimum angle of friction given by OBC stabilised clay. This implies that the glass additive of 0.4mm size at 9% concentration could be used in a situation where high water drainage is necessary through the soil, but not necessarily needing a high increase of angle of friction, for example where the soil is already contained by a retaining wall, but requires evacuation of pore pressure. However for most efficient and cost-effective soil stabilisation, OBC remains the most optimal solution.

In comparison, traditional stabilisers such as 15% cement addition to the soil the most stabilisation (Estabragh et al., 2020), while 6% cationic bitumen emulsion gave a 65% improvement in shear strength according to Batra and Arora (2016).Olufowobi et al. 2014 reported that 15% cement additive with 5% glass gave highest CBR and 15% cement with 10% glass passing sieve number 400 gave highest angle of friction. Yadav and Tiwari (2017) stated that 6% cement with 7.5% rubber fibres of 2-3 mm width and 15mm length gave best results both in terms of CBR and swelling. Bekhiti et al. (2019) on the other hand found that 10% cement with 2% rubber of 2-3mm lenth and 0.45mm diameter gave optimum stabilisation. Malikarjuna and Mani (2016) stated that 4% plastic additives resulted in optimum MDD, OMC and CBR while Gowtham et al.(2018) Found that 4-6 % glass and plastic powder mixed gave an optimised stabilised soil. Further investigation into the different materials such as plastic, glass and rubber and their combinations along with cement and/or bitumen emulsion, while considering for particle sizing and percentage mix, needs to be done to fully grasp the potential of an even more stabilised mix which would solve both problems of land stabilisation and landfill scarcity.

Conclusion

Through this study, it was determined that mixing modified anionic bitumen emulsion in proportions of 4% to the clay, an optimal stabilisation was achieve with an improvement in cohesion reduction by 310% and an increase in angle of friction by 96%. When adding powdered glass of different sizes to the mix, it was found that mixing 9% of 0.4mm glass to the soil with 4% OBC, a further 94% reduction of cohesion was achieved as compared to plain OBC with soil. However, no improvement in angle of friction was noticed for any size of glass added to the mix. 9% glass additive along with OBC could potentially be used in an application where high water drainage is required through the soil to relieve pore pressure, but not necessarily requiring a lot of angle of friction enhancement. It was thus determined that OBC stabilised clay without any glass additives is the best option for soil stabilisation. OBC stabilisation of clay implies that a cheaper solution to the issue of landslides can be achieved, which would be a great relief for developing and under-developed countries in the world as compared to expensive traditional methods of land stabilisation such as piling, anchoring and reduction of water table through wells and drainage systems. This method is however limited to a 4m depth stabilisation through shallow soil mixing method with excavators, or up to 20m through dry soil mixing (DSM) in high water content soils such as clay where the mixture is injected using drills (Olufowobi *et al.*, 2014; Egorova *et al.*, 2017).

The bitumen emulsion used is an inert product which is harmless to the environment as mentioned in Table 2 for the specifications of the modified anionic bitumen emulsion used. The production of bitumen is a by-product of fossil fuel fractional distillation. This by-product is relatively cheap in itself, however, the process of making it into an emulsion by adding emulsifiers and hot water to make anionic bitumen emulsion and further adding 9% of synthetic resin to it has an additional cost. However, as compared to the 15% cement typically used in soil-cement chemical stabilisation (soilcrete) is still more expensive and polluting than 4% modified anionic bitumen emulsion (Tingle and Santoni, 2003: Marsala et al., 2019; Zahri and Zainorabidin, 2019; Abdullin and Emelyanycheva, 2020). Moreover, soilcrete is known to be brittle; bitumen emulsion has more flexibility, thus reduces this issue of brittleness of the stabilised soil (Olufowibi et al.,2014). Soilcrete has a curing period of 28 days as compared to OBC which does not require any curing time (Kalipcilar et al., 2018; Estabragh et al., 2020). In terms of carbon foot print, 1 kg of cement releases 0.9 kg of CO2 in the atmosphere (Fayomi et al., 2019; Rajesh et al., 2023) while 1kg of bitumen emulsion releases 0.221 kg of CO2 into the atmosphere (Chehovits and Galehouse, 2010). This implies that 1 ton of cement-stabilised soil at 15% cement concentration would release 135 kg CO_2 emission during its production while 1 ton of OBC stabilised soil at 4% bitumen emulsion concentration would release only 8.84 kg CO_2 emission during its production. This represents a reduction of carbon emission by 14.3 times, thus making it the most sustainable option environmentally.

Further testing of combinations of different waste materials such as glass, rubber and plastic along with binding agents such as cement and bitumen emulsion, under same conditions and parameters is a must to further the possibility of an even more optimised solution to the problem of soil stabilisation and reduction of landfill scarcity. The up-scaling of this method of soil stabilisation could greatly help achieve the Sustainable Development Goals of the United Nations: SDG9 in terms of sustainable innovation in the geotechnical field, SDG 11 in terms of making cities safe and resilient by stabilising the land and SDG 13 in terms of helping mitigate effects of climate change induced landslides (UNDESA, 2015).

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