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Compressive and Shear Strengths of Coir Fibre Reinforced Activated Carbon Stabilised Lateritic Soil

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Abstract: Constructing structures on lateritic soil is challenging in geotechnical engineering due to the various physical and geotechnical characteristics. Many studies investigated different stabiliser materials to strengthen the geotechnical parameters of lateritic soil. This study used activated carbon and coir fibre (ACF) to stabilise lateritic soils as an environmentally friendly binder. Experiments including the unconfined compressive strength (UCS) test and the direct shear test (DST) are performed to investigate the mechanical properties of ACF-stabilised soil for different percentages of activated carbon (AC). Before and after ACF stabilisation, microstructural characterisations of soil samples were performed using field emission scanning electron microscopy (FESEM) and surface-area analysis (BET). The experimental results demonstrate that 3% ACF can considerably enhance the compressive strength, while 2% ACF significantly improves the shear strength, of lateritic soil. Accordant to the UCS results, using fibre in AC-stabilised soil improves post-peak behaviour and residual strength. Moreover, 2% ACF can significantly improve shear strength by creating an interlocking matrix among AC, soil particles, and fibre. The microstructural characterisation based on the findings obtained by FESEM and BET analysis confirms that AC particles fill soil voids. AC restrains the soil movement when exposed to external stresses. In addition, the formation of gel in the stabilised soil matrix binds the soil particles, increasing the strength of the ACF-stabilised soil in comparison with untreated soil.

Keywords: lateritic soil; activated carbon; direct shear test; geotechnical properties; microstructure

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1. Introduction

The behaviour and properties of soil significantly influence the economy, safety, and success of many civil engineering projects. Soil stabilisation and soil reinforcement are extensively used in many engineering structures to enhance geotechnical properties, such as the plasticity, durability, shear strength, density, and permeability of natural soils [1–3]. It is essential to consider all aspects of environmental control, including water pollution control, water resources, containment and waste disposal, and the mitigation of natural disasters effects such as earthquakes and landslides on structures. Therefore, stabilising underlaid soil is essential to have a stable system [4].

Although various additive materials are used as soil stabilisers, cement and lime are widely used as binders [5]. They have been employed in soft-soil improvement for decades because they improve soil strength, limit shrinkage and swelling, and decrease settlement [6]. Although these binders are efficient in enhancing the geotechnical characteristics of soil, they have some limitations, including environmental impacts and costs. For example, a tonne of cement requires 1.5 tonnes of raw materials and 5.6 GJ/tonne of energy [7] and releases about 0.95 tonnes of CO_2 [8], whereas production of a tonne of lime releases 0.86 tonnes of CO_2 [9]. Furthermore, around 7% of overall greenhouse-gas emissions in the atmosphere belong to cement-manufacturing processes [10,11]. Given these issues, using environmentally friendly and cost-effective stabilisers is significant for stabilising soils.

Many waste products in agriculture include coconut shells, straw, discarded apple pulp, coir pith, apricot stone shells, sawdust, sugarcane bagasse, olive stones, and peanut husk. As a result, these waste products will be abundant, and their disposal will be burdensome financially and environmentally. One environmentally responsible option is making activated carbon from them [12] and stabilising problematic soils such as lateritic soil. This is more inexpensive, cost-effective, and environmentally friendly than chemical additions. Moreover, many fibres that have been used as reinforcement in soil are also waste products. Generally, fibres are categorised into two groups, synthetic (polypropylene (PP), polyethene, glass, polyester, steel, carbon) and natural (palm, coir, sisal, jute, wheat, bagasse). Synthetic fibres are more durable and are highly resilient when exposed to environmental changes. Recently, researchers have focused on using some synthetic fibres, particularly recycled and waste fibres, for soil stabilisation [13], although synthetic fibres are mostly non-biodegradable and, thus, would persist in the environment for centuries without decomposition [14].

Furthermore, some synthetic fibres can leach dangerous chemicals into the soil, permeating groundwater or other nearby water sources and ecosystem [15]. In contrast, natural fibres are cheaper and more tolerable than synthetic fibres [16]. Some natural fibres such as coir fibres have a low cellulose content but a high lignin content, making them extremely durable, strong, and resilient as well as strongly resistant to abrasion, fungal and bacterial decay, and pilling. Besides, coir fibres can resist months of soaking without destruction; they have an extensive range of erosion-control applications [17].

Fibre-reinforced soils have become more popular due to their superior flexibility and strength to natural soils. They improve railway substructure and slope stability and reduce pavement thickness [18]. Some advantages of fibre as reinforcement compared to geosynthetic layers in soil are fewer catastrophic failures, more utility in complicated geometries and constrained places, higher flexibility and deformability, a lower chance of developing weak planes, and cost-effectiveness [19]. Besides, fibre also improves the flexural behaviour of cement-stabilised soil [20]. In addition, the SEM images of fibre-reinforced soil exposed to freezing–thawing cycles revealed that fibre is undamaged by the repeated freeze–thaw cycles [21], resulting in higher durability. The resilient modulus, permanent strain, and damping ratio improve when waste-tire textile fibres are used to reinforce sandy soil [22]. In sandy soil, the aspect ratio and fibre content reduced the critical confining stress and enhanced the shear strength [23]. Fibre also improved the strength, slope stability, and safety factors in embankments filled with fibre-reinforced soil [24]. Carbon fibres have a natural resistance to degradation, and randomly dispersed short carbon fibre could efficiently strengthen non-cohesive soil [25]. The authors of [26] also showed that adding carbon fibre to clay soil enhances its shear strength considerably. However, the authors of [27] demonstrated that adding low carbon to clay soil raises the interparticle forces. Moreover, the pores are filled with cementitious products. Many previous soil-improvement studies have concentrated on traditional calcium-based stabilisers such as lime and cement rather than non-traditional stabilisers. Hence, alternative eco-friendly additions to conventional stabilisers based on calcium have become widely popular to reduce the environmental effect of traditional stabilisers. Activated carbon is a material that finds wide application in many areas, especially in environmental protection [28]. According to a few studies, AC can absorb CO_2 due to the large surface area of the unit volume, and contaminants can be adsorbed in the submicroscopic pores. In addition, activated carbon is stable in basic and acidic environments [29,30]. Moreover, the compression strength and CBR value of soil are increased by adding AC contents [31].

This research investigates the influence of AC and coir fibre on the geotechnical properties of lateritic soil. A set of DST and UCS testing was performed to find the effect of AC (1, 2, 3 wt%) and 0.5% coir fibre on the strength properties of stabilised-soil specimens. The peak compressive strength, stress and strain behaviour, elastic modulus, initial friction angles, and cohesion were examined and discussed. Finally, FESEM and BET tests were carried out to reveal the microstructure of treated and untreated soil to understand the AC- and ACF-stabilising mechanisms.

2. Materials and Methods

This research investigates the soil collected from location 1°33′32.9′′ N, 103°38′39.4′′ E coordinates in Universiti Teknologi Malaysia, Johor campus. Table 1 shows the physical and engineering characteristics of lateritic soil used in this research. Lateritic soils are usually too poor and unsuitable for infrastructure facilities construction such as railways and highways. In addition, Figure 1 depicts the particle-size analysis of soil and AC. Regarding Table 1, the particle-sizes analysis of lateritic soil is within the ranges found in other studies [32]. The soil particles less than 75 microns and AC were measured using laser-diffraction equipment, model 2000 E Ver. 5.52 (ISO:13320, 2009), to be more effective and reliable [33]. Then, the sieving results are used to analyse soil particles greater than 75 microns. This study combines laser diffraction with conventional techniques due to time savings and high accuracy [34]. Moreover, the soil used in this research mainly consists of clay minerals, as illustrated in the X-ray-diffraction analysis results in Figure 2.

Table 1. Geotechnical properties of soil.

Properties	Value	Method Standard
Liquid limit (LL)	70.3%	BS 1377
Plasticity index (PI)	28.3%	
Gravel	12.79%	
Sand	17.54%	
Silt	61.26%	
Clay	8.41%	
Specific gravity	2.74	
Maximum dry density (kg/m^3)	1390	
Optimum moisture content	28%	
pH	4.05	

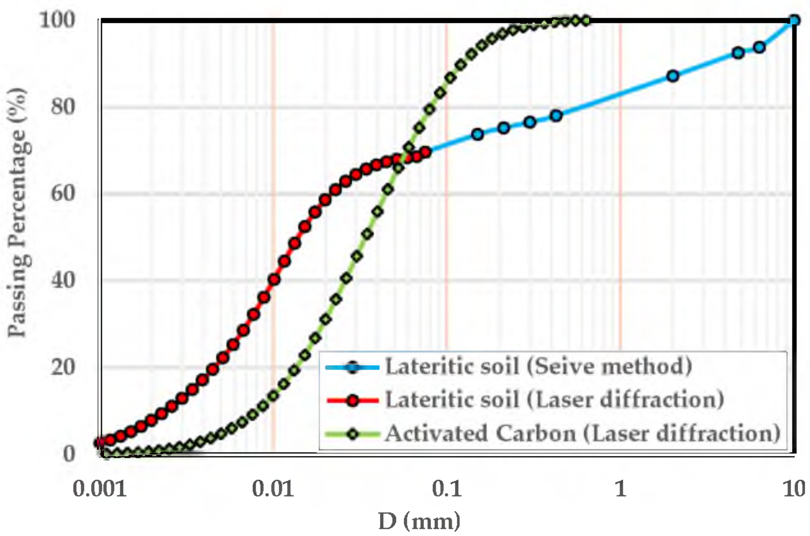


Figure 1. Particle-size analysis of soil and AC.

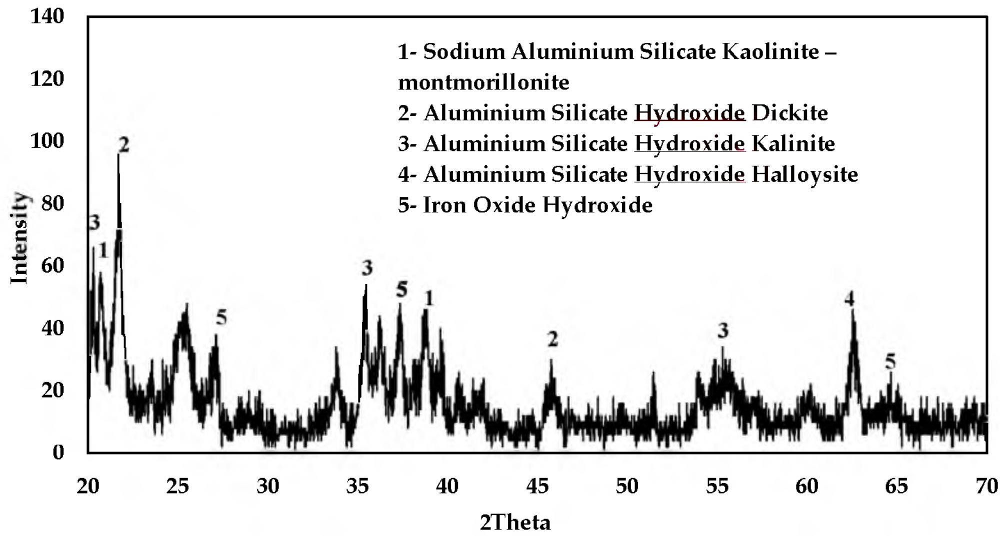


Figure 2. X-ray-diffraction pattern of lateritic soil.

The additive used in this study is AC coconut derivative that was obtained from Evachem company in Selangor, Malaysia. Table 2 summarises the significant oxides of AC achieved by XRF testing (equipment model EDX 720, Shimadzu, Japan). AC is a kind of carbon that is often used to filter organic pollutants from air and water and for various other applications [28]. AC contains minor, low-volume porosity that enhances the surface area available for chemical reactions [35]. The surface area of one gram of AC is over 3000 m^2 due to its high degree of microporosity [36]. The increased surface area alone can provide an activation level suitable for practical applications [37]. Activated carbons usually have been derived from waste products such as coconut shells, straw, discarded apple pulp, coir pith, apricot stone shells, sawdust, sugarcane bagasse, olive stones, and peanut husk [12].

Table 2. Chemical composition of AC.

Composition	(%) by Weight
CaO	39.77
K_2O	17.68
P_2O_5	16.62
Fe_2O_3	11.27
SO_3	7.83
ZnO	3.47
MnO	2.57
CuO	0.62
SrO	0.18

Coir fibre is also employed in this study as a reinforcement material besides AC. It comes from the husk of a coconut and is a fibrous material, thus known as being environmentally friendly. Figure 3 shows an image of lateritic soil, activated carbon, and coir fibre. Coir fibre has higher tensile strength, is lighter, contains more hemicellulose, cellulose, and lignin, and has a slower degradation rate than other natural fibres. The coir fibre utilised in the current research has an average diameter of 0.3 mm, unit weight of 1430 kg/m^3, and average tensile strength of 125 MPa.

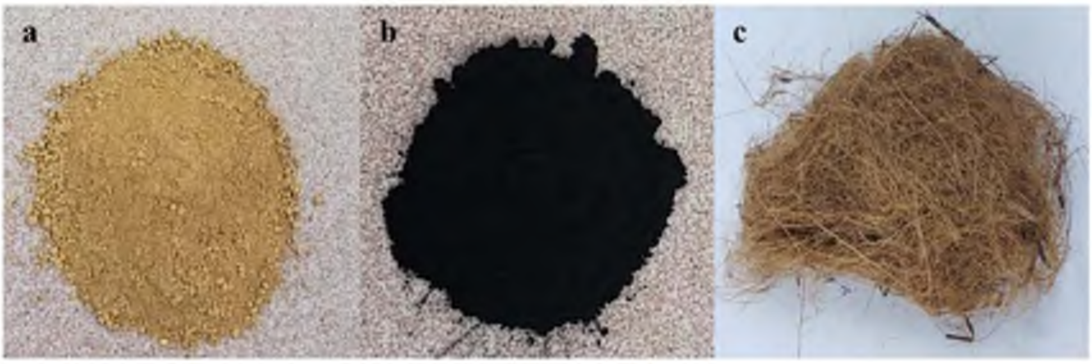


Figure 3. Image of (**a**) lateritic soil, (**b**) activated carbon, and (**c**) coir fibre.

The mechanical characteristics of the AC- and ACF-stabilised specimens are investigated using unconfined compression tests (Instron 3366 universal testing machine, US). The UCS testing is conducted based on BS1377: Part 7:1990, with a 1 mm/min rate, to determine the stabilised soil's compressive strength (q_u). The specimens are compacted in three layers, similar to the compaction test. Figure 4 shows the machine utilised in this investigation for UCS testing.

(**a**) (**b**)

Figure 4. UCS test (**a**) before compressing and (**b**) after compressing.

To examine the impact of AC on shear strength properties of lateritic soil, according to BS1377: Part 7:1990, a small direct shear test (direct/residual shear apparatus, model TKA-DSS-10, Quilin Town, Jiangsu, China) is performed at a 1.5 mm/min strain rate under normal stress of 100, 200, and 300 kPa. For preparing the specimens, the soil is dried in an oven and then wetted to the optimum water content. After that, it is compacted in three layers to the target unit weight within the shear box. Figure 5 shows an ACF specimen before and after the direct shear test.

Figure 5. ACF specimen (**a**) before shearing and (**b**) after shearing.

To explore the chemical composition and microstructural changes of the AC-stabilised soil, FESEM analysis (model Nova Nano SEM, FEI, Holland) has been conducted on both natural soil and stabilised soil, following the procedure in the previous study [38]. Specimens for microstructural testing are obtained from UCS samples. In addition, this research has used the BET test to evaluate changes in surface area and pore-size distribution of natural and treated specimens. This analysis is an essential factor in exploring how the soil interacts with its surroundings physically and chemically due to most chemical reactions in soils occurring at the surface of particles [39]. BET technique is among the most widely used methods for measuring the quantified external surface area and pore size distribution [40]. This method gathers inert gas adsorption isotherm data and modelling the data according to the BET isotherm equation [41].

$$\left(\frac{v}{v_m}\right) = \frac{c\left(\frac{P}{P_0}\right)}{\left(1-\frac{P}{P_0}\right)\left[1+(c-1)\frac{P}{P_0}\right]}, \quad (1)$$

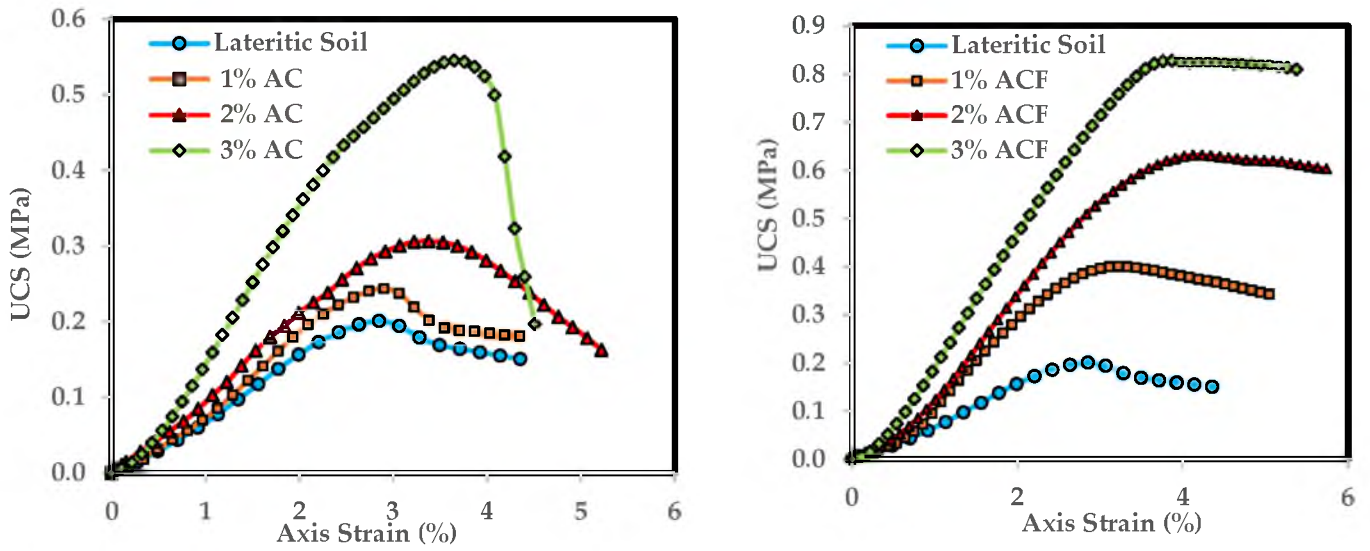
where v is adsorbed gas quantity, v_m is monolayer-coverage adsorbed gas, P is the equilibrium pressure of adsorbates, P_0 is the saturation pressure of adsorbates, and c is the BET constant.

3. Tests Results

3.1. Unconfined Compression-Strength Test

The stress–strain curves are illustrated in Figure 6 for natural soil, the AC-stabilised soil, and the ACF-stabilised soil. First, the soil was examined for 1%, 2%, and 3% AC content. Then, the soil was tested for 1%, 2%, 3% AC, and 0.5% coir fibre, due to adding coir fibre with more than a 5% decrease in the compacted density consequently decreases the soil strength [42]. As illustrated in Figure 6a, the strength of the soil raised with the rising AC content, similar to the previous study. For instance, the untreated UCS value of 200.87 kPa increased to 243.65 kPa, 306.31 kPa, and 545.40 kPa for 1%, 2%, and 3% AC, respectively, as shown in Figure 6a. The combination of 0.5% coir fibre further increased the UCS of the AC-stabilised soil, as depicted in Figure 6b. Similarly, Crane et al. [43] also found that adding activated carbon enhanced the UCS value of soil.

The high strength of AC depends on soil-porosity reduction. The cementation bonds and denser fabric are the main causes of UCS values and shear-strength improvement [44,45]. Figure 6b shows that the additive fibre in the AC-stabilised soil changes the brittleness behaviour of the AC-stabilised soil to flexible behaviour, along with improving the compression strength. The stress–strain curves of AC specimens show a fast hardness up to the peak, then softening afterwards. However, the reinforced specimens illustrate a ductile behaviour, by adding 0.5% coir fibre to AC specimens. Fibre additions in the AC specimens enhance the soil strength by tightly enclosing the particles around the fibres as a bridge surface [46].



(**a**) (**b**)

Figure 6. UCS results for (**a**) AC specimens and (**b**) ACF specimens.

Compared to untreated soil specimens, all specimens illustrate more strength and ductility at failure strain. The failure strain increased from 2.85% for untreated soil to 2.90%, 3.22%, and 3.65% for 1%, 2%, and 3% AC, respectively, showing the increased flexibility. Moreover, the brittleness of the ACF specimens further decreased, resulting in plastic deformation and a significant increase in failure strain for about 3.22%, 4.13%, and 3.87% for 1%, 2%, and 3% ACF, respectively. It indicates that adding fibre to AC soils improves soil strength dramatically, due to coir fibre combining with additives and promoting interlocking between soil particles [3]. Anggraini et al. [47] observed similar results by adding coir fibres and lime into the marian clay soil. They presented improvements in mechanical properties such as UCS values, shear-strength parameters, and flexibility. Previous research found that coir fibre improves the stiffness, strength [48], and bearing capacity of clay soil [49].

3.2. Direct Shear Test

Figure 7a demonstrates the shear strength versus shear strain for the AC specimens. Peak shear strength raised with rising normal stress, particularly 300 kPa normal stress. In addition, peak shear strength increased with increasing AC content. Figure 7b presents the stress–strain curves of the AC-stabilised soil upon adding 0.5% coir fibre. By comparing Figure 7a,b, it is perceived that the influence of the AC-stabilised soil further enhances upon adding coir fibre. It is also apparent from the stress–strain curves that adding coir fibre improves both peak shear strength and post-peak residual strength. Comparable findings for kenaf-fibre-reinforced soil were presented by Ghadakpour et al. [50]. While Dutta et al. showed that carbon tetrachloride and sodium hydroxide treated coir fibres improved the post-peak strength slightly in clay soil [51]. Although the AC-stabilised specimens also demonstrate fast hardening up to the peak, post-peak residual strength is considerably lower than for the ACF samples, as seen in Figure 7. Given this issue, it is concluded that the strength-softening behaviour of the AC-stabilised soil decreases upon the inclusion of coir fibre. In addition, the ductility of the AC-stabilised soil increased when 0.5% coir fibre was added. It is similar to previous studies that showed ductility rose when discrete plastic [52] and waste-tire textile [53] fibres were added to stabilised soil.

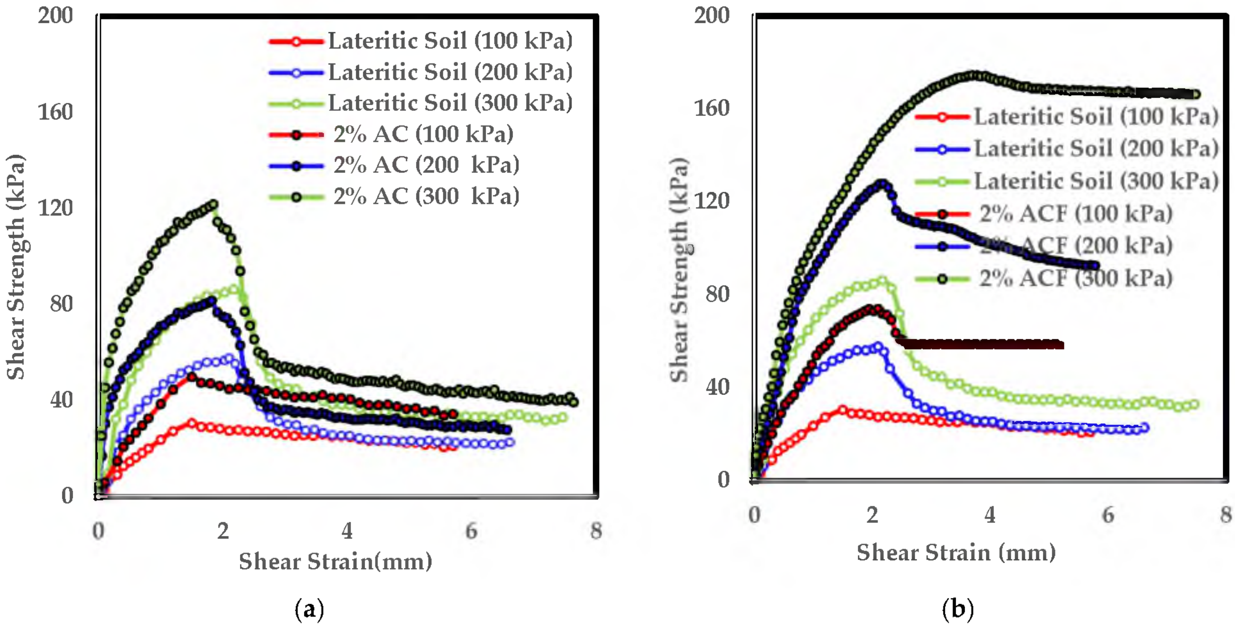


Figure 7. The shear stress–shear strain of untreated and treated lateritic soil for (**a**) 2% AC and (**b**) 2% ACF under different normal pressures.

Moreover, adding AC increases peak shear strength, and the enhancement rate increases with increasing normal stress, as shown in Figure 8. Similarly, the inclusion of 0.5% coir fibre further enhanced the peak shear strength of the AC-stabilised soil, as illustrated in Figure 9. Although adding AC in natural lateritic soil increases the peak strength, the increasing rate is not significant for more than 2% AC. For instance, the peak strengths of the AC-stabilised soils are 121.8 kPa and 123.72 kPa for 2% and 3% AC, respectively. Overall, similar to the findings of this study, Kamaruddin et al. [54] found that using coir fibre in lime-stabilised soil further increases tensile strength and compressive strength. Sivakumar and Vasudevan also observed that the inclusion of coir fibre raised both shear parameters in expansive soils [55].

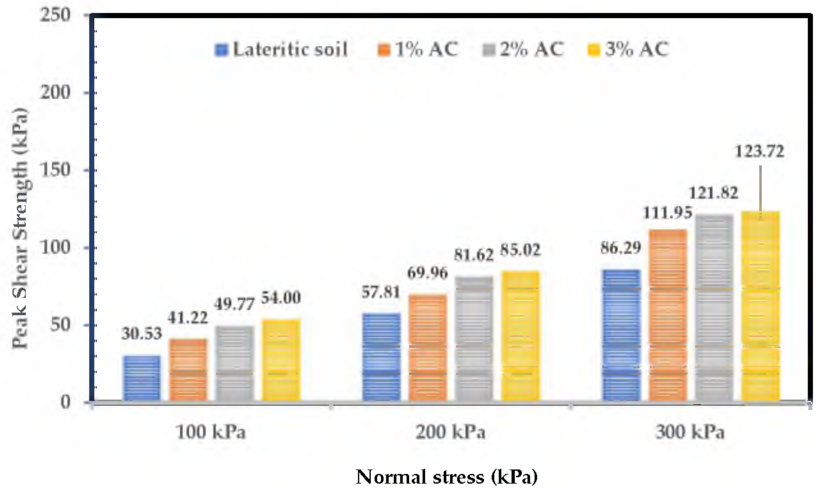


Figure 8. Effect of various percentages of AC on shear strength at different normal stress.

3.3. Microstructural Analysis

FESEM and BET tests have been used to assess the influence of AC and fibre on lateritic soil at the micro level. Figure 10 presents the FESEM results of untreated and ACF soil. Untreated lateritic soil contains minerals in platy shapes, leading to large holes, as seen in Figure 10a by the dark patches, similar to prior research findings [56,57]. Clayey particles float and separate when they contact water, forming enormous pores [58]. The FESEM results of ACF and AC are shown in Figure 10b,c, respectively. Regarding Figure 10b, small amounts of calcium aluminate (CA) and calcium silicate (CS) are formed due to the available calcium in AC. Hence, pores and gaps are filled by them and the AC particles.

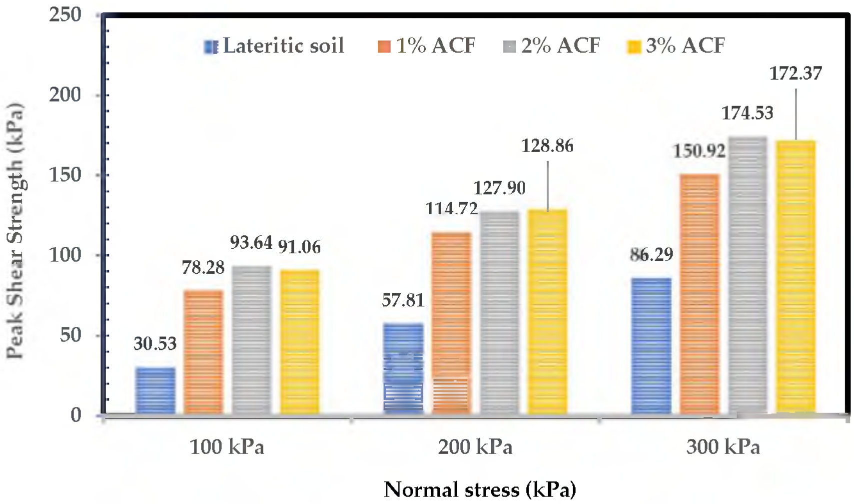
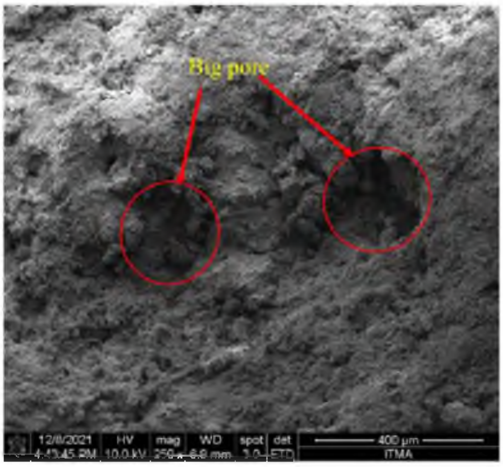
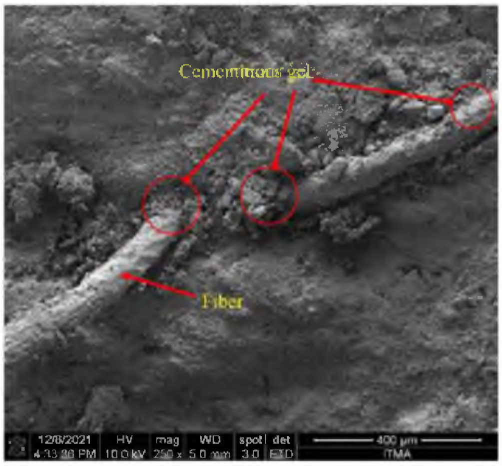


Figure 9. Effect of inclusion fibre in AC-stabilised soil on shear strength at different normal stress.



(**a**)



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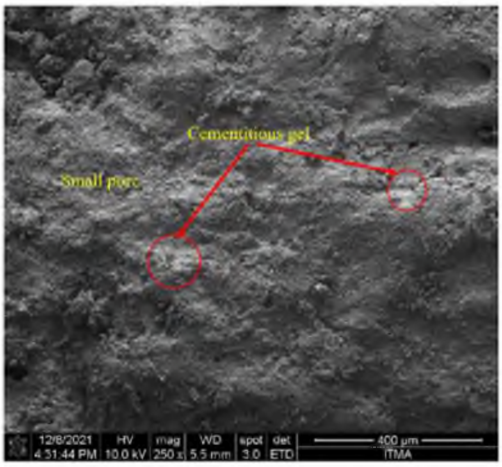


(**c**)

Figure 10. FESEM results for (**a**) lateritic soil, (**b**) ACF, and (**c**) AC.

The microstructure of untreated soil is altered by the inclusion of AC. As present in Figure 2, lateritic soil is mainly composed of alumina (Al_2O_3) and silica (SiO_2), whereas AC is primarily composed of calcium ions. The most significant values in terms of chemical components belong to calcium in AC (Table 2) and silicon and aluminium in the soil. The stabilising procedure with the inclusion of AC in the soil occurs in physical and chemical stages: initially, AC fills the tiny pores and gaps (short term), and then pozzolanic reactions and calcium hydration (long time) happen in the soil. Lime and cement, as calcium-based stabilisers, are being used to strengthen the soil during the hydration and pozzolanic processes [59]. However, in the AC-stabilised soil, the physical stage is considerable rather than in lime and cement because the particle size of the activated carbons is smaller. In addition, coir fibre fills pores and connects soil particles that create an integration structure as a bridge. The surface of coir fibre is rough as well, and under shear load, soil particles are imbanded into the pores and grooves of the fibre. Consequently, the soil's efficient contact area and the interlinkage between the fibre and the soil are enhanced. In contrast, polypropylene fibre drew out the soil because of weaker superficial adhesion on the soil–fibre interaction surface, resulting in a gap between thesoil and the fibre [60].

3.4. *Surface Area Analysis (BET)*

The changes in the micropores and surface area of natural soil and 2% ACF-treated soil have been evaluated using the BET surface-area technique. The impact of AC on the lateritic soil's pore volume, surface area, and pore size is presented in Figure 11. The BET values of the untreated lateritic soil and 2% ACF increase from 25.57 m^2/g to 45.57 m^2/g, respectively, while the pore size and pore volume decrease from 3.05×10^{-7}dm and $3.89 \times 10^{-4}dm^3/g$ to 1.51×10^{-7}dm and $3.51 \times 10^{-4}dm^3/g$, respectively. The BET results confirmed that micropores and porous structures are filled with AC particles during stabilisation. Therefore, activated carbon changes the lateritic soil structure into a completely interlocking system with fewer tiny pores because it has a high surface area [36].

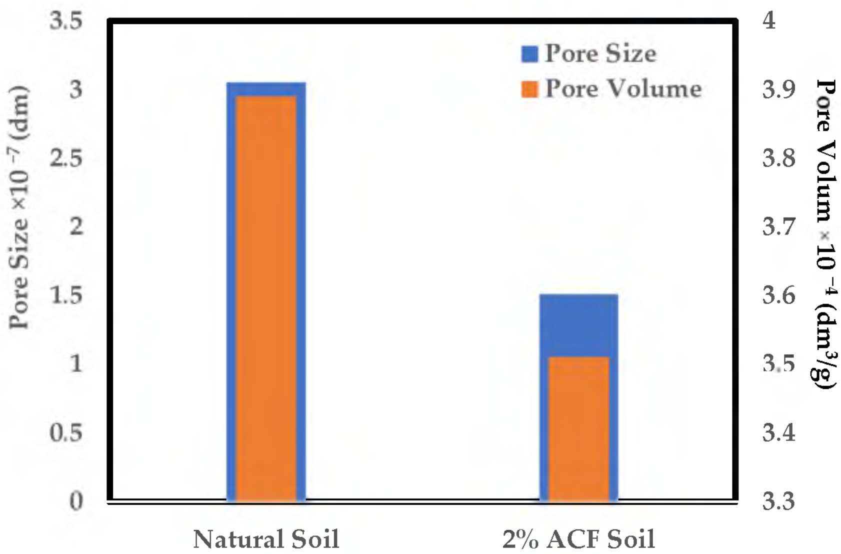


Figure 11. Pore volume, surface area, and pore size of lateritic soil and 2% ACF soil.

4. Discussion

The stability of the underlying soils has a considerable influence on the long-term performance of pavement systems. In situ subgrade soil is commonly unable to provide the necessary support for optimum efficiency under traffic loads and environmental conditions. Soil stabilisation and soil reinforcement are one alternative for improving the geotechnical properties of a poor subgrade [61]. This study addresses soil treatment with activated carbon and coir fibre, natural materials obtained from abundant local materials.

4.1. Unconfined Compressive Strength

Concerning Figure 12, the UCS values demonstrate that the 3% AC with 0.5% fibre is sufficient for improving the lateritic soil. In other words, adding 3% AC with 0.5% coir fibre to the natural lateritic soil used in this study is adequate to fulfill the minimum UCS value of 800 kPa requirement of the Malaysia Public Works Department (MPWD) specifications for medium- and low-volume road construction. The findings in the current study are similar to a previous research study [62], in which 6% cement was found to be enough to stabilise the lateritic soil. According to Sobhan [52], chemically stabilised soil is resistant to compression, but its contribution to tensile strength is negligible. It is a significant issue when tension cracks appear in the soil due to shrinkage; it is expected that the stabilisation will be able to resist it. As a result, it is essential to enhance the stabilised soil's hardness, flexibility, and tensile strength with fibre reinforcement. As presented in Figure 12, the compressive strength increases when using fibre in the AC-stabilised soil. The UCS values for 1%, 2%, and 3% AC-treated soil increased further to 64.32%, 106.24%, and 51.87%, respectively, upon the addition of 0.5% coir fiber. Given Figure 12, adding 2% AC and 0.5% fibre results in the highest increased compressive strength. This improvement might be due to the effective interlocking between the fibre, AC, and soil [26].

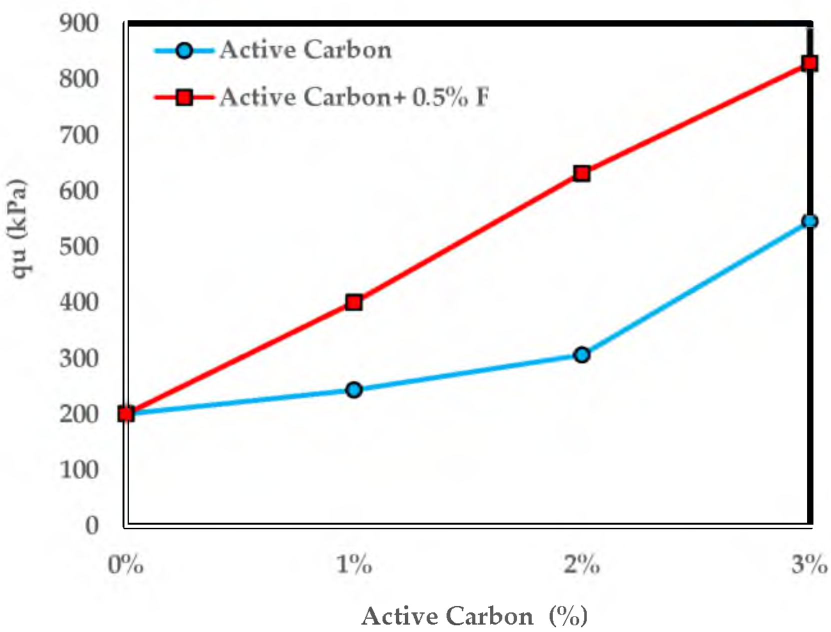
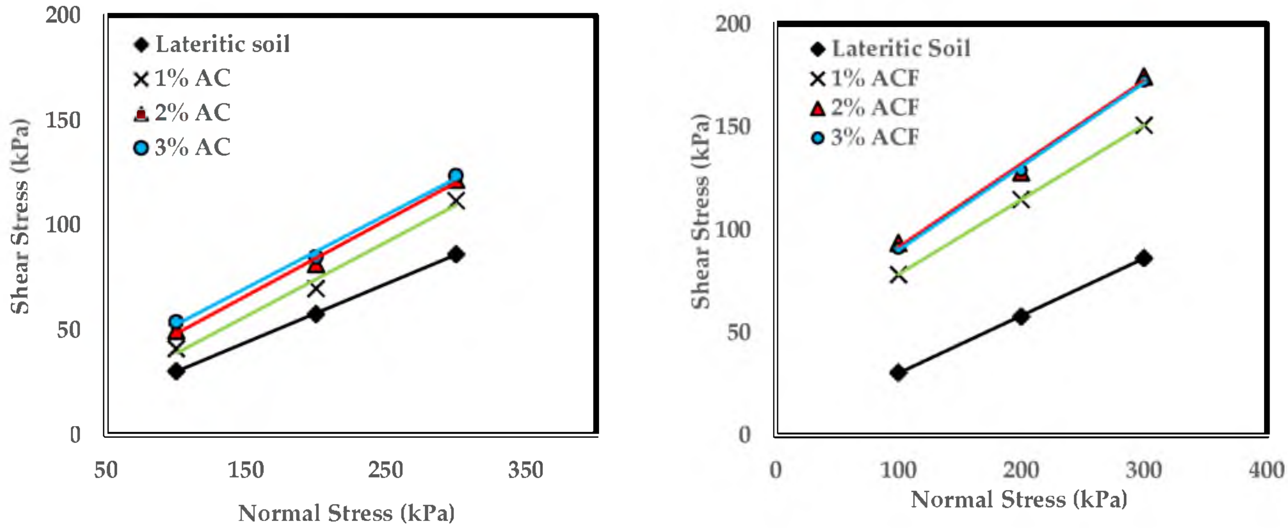


Figure 12. Compressive strength (UCS) for different AC contents.

4.2. Shear Strength

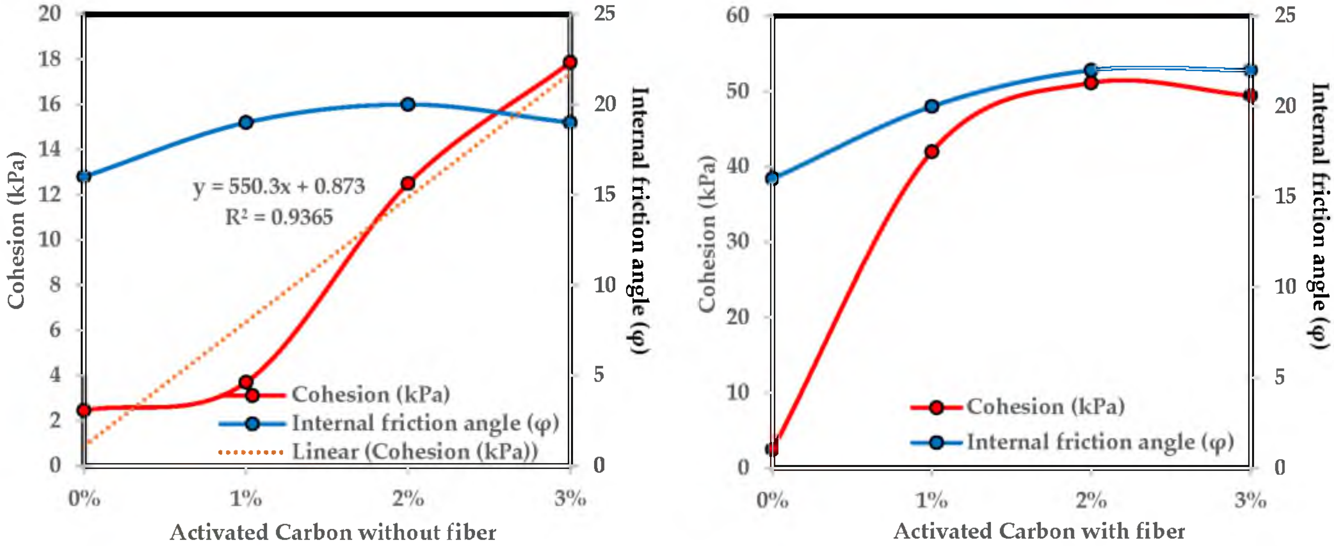
Figure 13 demonstrates the relationship between the shear stress and normal stress of the AC, ACF, and untreated specimens. The shear strength improves with rising AC and ACF contents. However, the difference in shear strength for the 3% AC and 3% ACF samples is not considerable compared to the 2% AC and 2% ACF samples, respectively. Hence, 2% AC and 2% ACF effectively improve the strength of lateritic soil.

In addition, Figure 14 has shown the effect of adding AC and ACF on improving internal-friction angle and cohesion. The adhesion of AC-treated samples increases linearly with increasing AC content, reaching 17.9 kPa for 3% AC, which is 616% greater than the untreated soil.



(**a**) (**b**)

Figure 13. The relationship between peak shear strength and normal stress lateritic soil treated with (**a**). various AC content and (**b**) various ACF content.



(**a**) (**b**)

Figure 14. Internal-friction angle and cohesion of treated specimens with (**a**) AC and (**b**) ACF.

Nonetheless, the influences of AC on the internal-friction angle are not considerable, with just a 25% improvement ratio observed in the 2% AC specimen compared to untreated soil. Considering Figure 14, it is perceived that the coupled effects of AC and coir fibre are more significant than the influence of AC. Figure 14b indicates that adding fibre in the AC specimens improves the internal-friction angle and cohesion. The shear parameters of the ACF-stabilised soil illustrate an increasing trend with increasing AC up to 2%, beyond which the shear parameters decrease. Therefore, 2% ACF can be considered optimum due to the highest shear-strength parameters, as seen in Figure 14b. The internal-friction angle and cohesion with 2% ACF are 51.1 kPa and 22°, respectively, showing 20.44% and 37.5% higher strength parameters than the untreated specimen. The results show that adding coir fibre improves the strength of lateritic soil. Coir fibre can increase soil cohesion by contributing reciprocal friction between the soil and the complex structure [48]. Indeed, coir fibre can fill part of the gaps and provide interlocking effects when dispersed equally in soil. Hence, shear strength can improve significantly by increasing the frictional angle and internal cohesion. The finding obtained in the current study is comparable to previous results, in which carbon fibre as a non-traditional additive in clay soil developed cohesiveness [26]. Moreover, Tang et al. [63] also reported that adding palm fibre limited soil-creep rate and deformation, while long-term strength increased.

4.3. Elastic Modulus (E_{50})

The influence of ACF on the stiffness and flexibility of soil is evaluated with the secant modulus. As in previous studies, the secant modulus is considered half of the maximum UCS and DST values [64,65]. The impact of ACF on the elastic modulus of soil obtained from the UCS values and direct shear values is presented in Figure 15. This figure shows the relation between the secant moduli (E_{50}) and peak shear strength (q_{DST}) and the UCS values (q_{UCS}) of soil treated with 1%, 2%, and 3% AC, and 1%, 2%, and 3% AC with 0.5% fibre. The equation of $E_{50} = 31.283\ q_{UCS}$ is derived from the UCS values that cover $q_{UCS} > 200$ kPa, while the equation of $E_{50} = 79.95\ q_{DST}$ from the DST test results is appropriate for q_{DST} between 50 to 200 kPa. According to the UCS results, the elastic modulus shows an increasing trend from 8767.81 kPa for 1% AC-treated soil to 23,730.22 kPa for 3% ACF-treated soil. In the direct shear test, the elastic modulus rises with rising normal pressure. The minimum and maximum elastic-modulus values are 3696.90 and 13,549.12 kPa for 1% AC (100 kPa) and 3% ACF (300 kPa) specimens, respectively. AC and coir fibre additive improves the secant modulus. The findings of this research are in line with previous research conducted by [66], which added coir fibres and fly ash in high-plasticity clay.

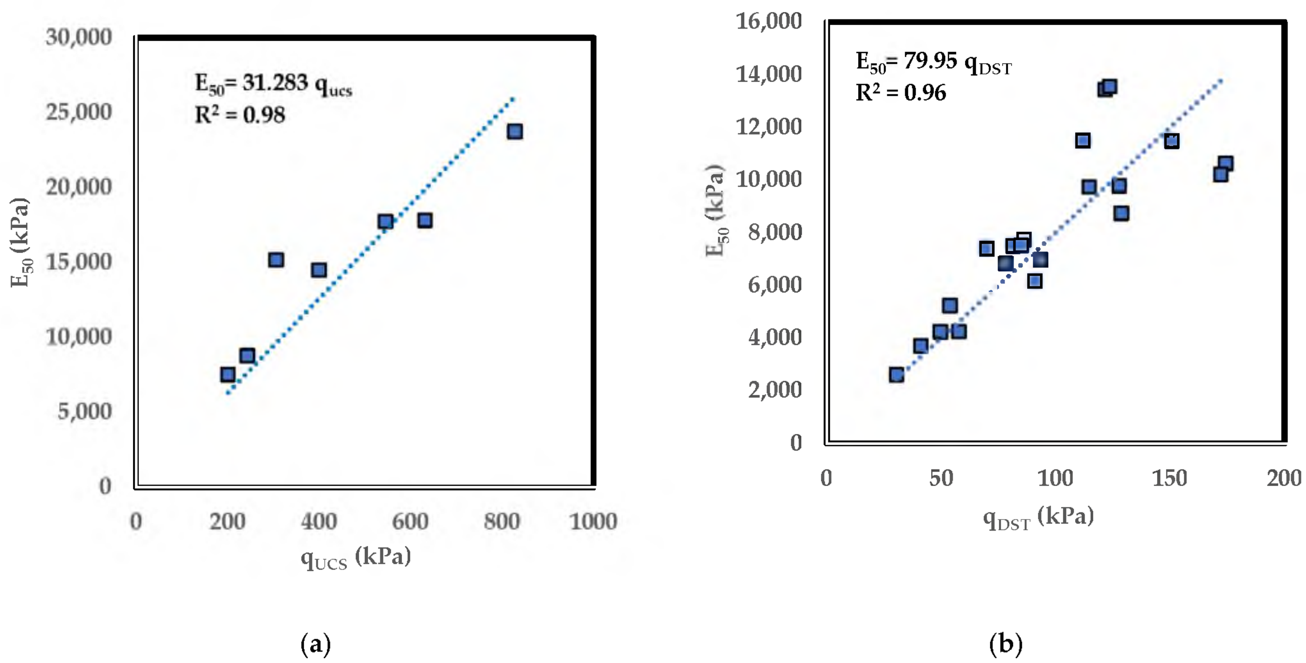


Figure 15. Relationship between elastic modulus (E_{50}) and (**a**). UCS values for $q_{ucs} > 200$ kPa and (**b**) DST values for q_{DST} between 50 to 200 kPa.

4.4. Deformability Index (I_D)

According to Equation (2), the deformability index is another factor utilised to explain the deformation behaviour of soils in this study [67].

$$I_D = \frac{\text{strain at the peak strength of stabilised soil}}{\text{strain at the peak strength for natural soil}}, \quad (2)$$

The deformability factor has shown the deformation behaviour of treated soil compared to untreated soil [68]. According to the UCS results in Table 3, the deformability of the AC-stabilised soil rises from 1.02 to 1.28 for 1% and 3% AC content, respectively.

Similarly, the deformability index increased to 1.13, 1.45, and 1.36 for 1%, 2%, and 3% ACF, respectively. Therefore, the maximum deformation index depends on 2% ACF-treated soil. This issue reveals that the bonding between AC, soil particles, and fibre results in more strains in ACF than just adding AC in lateritic soil. It confirms that using fibre in AC-treated soil improves soil behaviour from brittle to ductile [56].

Table 3. Result of deformability index, elastic modulus, and failure strain (UCS).

Mixture	E50 (kPa)	Failure Strain (%)	ID
Lateritic soil	7515.41	2.85	-
1% AC	8767.81	2.90	1.02
2% AC	14,045.07	3.22	1.13
3% AC	17,725.91	3.65	1.28
1% ACF	14,480.51	3.22	1.13
2% ACF	17,810.64	4.13	1.45
3% ACF	23,730.22	3.87	1.36

In this study, when AC is added to lateritic soil as a stabiliser, it improves compressive strength, shear strength, cohesion, and deformability and decreases pore size and pore volume in the soil. Adding coir fibre in the AC-stabilised specimens significantly improves the peak shear strength and post-peak residual strength and increased the elastic modulus, UCS value, deformability, internal-friction angle, and cohesion. Moreover, adding coir fibre to AC-treated soil improves the ductility in the soil. Figure 16 presents a scheme of influence AC and ACF on some parameters that are investigated in this research.

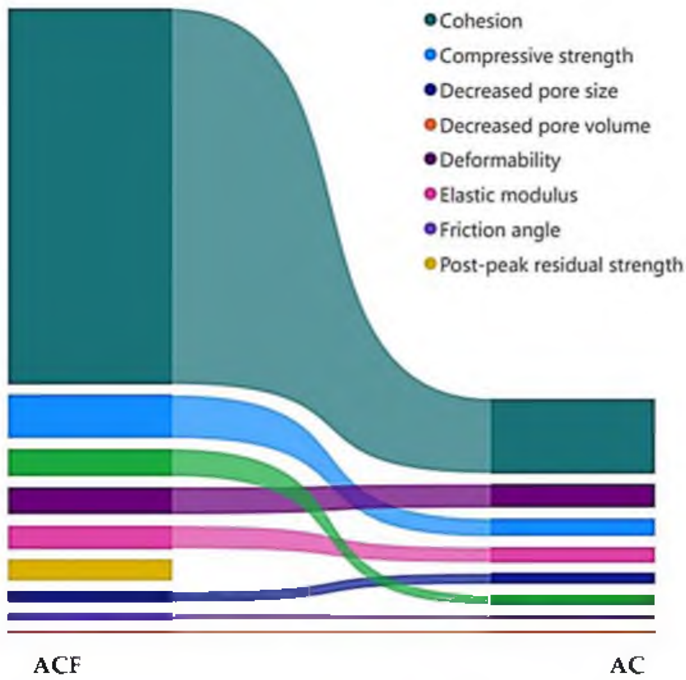


Figure 16. Scheme of effect-activated carbon and coir fiber on geotechnical parameters.

Optimum content was obtained at 2% ACF for treating lateritic soil because the UCS values for 2% AC-treated soil improved by 106.24% upon adding 0.5% coir fibre. Similarly, the direct shear-test result showed that 2% ACF is more suitable than other combinations. By the way, it is observed that 3% ACF can enable the lateritic soil to reach the minimum UCS value of the MPWD specifications and improve the shear strength and flexibility, which are applicable for road construction.

5. Conclusions

These days, green technology and ecologically friendly technique are critical components of all-over development. Following this, a technique for lateritic soil stabilisation was examined, including activated carbon and coir fibre. This study evaluates soils stabilised with activated carbon and coir fibres through a set of UCS, DST, FESEM, and BET tests. According to the MPWD specifications and test results, untreated lateritic soil could not be used as road pavement for low-volume roads unless stabilised with activated carbon and coir fibre. In general, the following conclusions are advanced based on the finding of this experiment work:

- The compressive strength of soil samples enhances significantly with rising AC content and adding coir fibre. This improvement is due to effective interlocking between fibre, AC, and soil.
- Adding coir fibre in AC soil improves mechanical parameters, such as peak shear strength, friction angle, cohesiveness, flexibility, and residual strength, which are key parameters in construction engineering.
- Cohesions of the ACF-modified specimens are higher than the untreated specimen. AC fills micropores and porous structures during the stabilisation process. Coir fibre can fill some gaps and provide interlocking effects when dispersed equally in soil. Hence, coir fibre and AC can considerably improve soil shear strength due to increased cohesiveness and frictional angle. Therefore, these materials create a complex mixture of soil, which sudden failure decreases on the ground due to overloading.
- The FESEM results of AC and ACF have presented which pores are filled with AC. Therefore, cohesiveness, compression, and shear strength have been improved, due to the materials, from the reaction between minerals and additives bonding the soil particles.
- The BET data also verify that the porous structures and micropores fill with AC particles during stabilisation. Consequently, pore size and pore volume decrease in AC lateritic soil.

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