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IMPROVEMENT OF GEOTECHNICAL PROPERTIES OF A COIR REINFORCED LATERITE

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ABSTRACT

Laterites used mostly for construction in the tropics can sometimes be problematic due to insufficient geotechnical properties. This explores the potential benefits of incorporating coir reinforcement into laterite. Coir, derived from coconut husk fibers is a sustainable, renewable and abundant resource that has high tensile strength, low density, and good resistance to decay. Geotechnical properties such as Liquid limit (LL), Plastic limit, Plasticity index, Maximum dry density, Optimum moisture content (OMC) and California bearing ratio (CBR) of the laterite were determined before reinforcement. The coir was cut into different lengths (3 to 5 cm) and added to the laterite at different percentages (0.25 to 1.5% at 0.25% increment). The geotechnical properties of the reinforced soil were determined and the results were analyzed using analysis of variance and fuzzy logic. The CBR of the reinforced soil was predicted using fiber content, OMC, and LL The precision of the fuzzy logic model was obtained by comparing the model results with the actual experimental results. Addition of fiber at 0.25% was found to be the optimum as it increased the CBR of the soil by 27.24% and reduced the Liquid limit by 15.47%. The fuzzy logic prediction has a RMSE of 1.18, MAPE of 4.68% and R-squared of 0.98 which shows that the fuzzy logic model is satisfactory. The study concluded that coir is a potential reinforcement for improving the geotechnical properties of laterite and that Fuzzy Logic can be used to predict the CBR of coir reinforced laterite.

Keywords: Fuzzy Logic, Soil Stabilization, Soil Reinforcement, California Bearing Ratio, Coir

INTRODUCTION

Lateritic soils and laterites which are common in hot humid tropical and subtropical climates, are as a result of weathering of rock on site (Kehinde et al., 2020). They have abundant iron and aluminum oxides, they, however, have low silicates (Gidigasu, 1972). Lateritic soils are red in color due to the presence of iron oxides (Amu et al., 2011). Laterite can possess very low bearing capacity and strength due to high fines content in them (Ayodele & Falade, 2016; Nnochiri & Aderinlewo, 2016). Lateritic soil with a high clay concentration cannot be guaranteed to remain strong and stable under stress, especially in the presence of moisture (Alhassan, 2008). Thus, there is usually a need to improve the properties of laterite and lateritic soils before they can be suitable as construction materials.

One of the ways of improving the property of laterite is the addition of tensile materials such as geotextiles and geogrids to it (Das et al., 2021). This will result in mechanically stabilized laterite by reinforcement. Different fibers such as glass fibers were found to improve the California Bearing Ratio (CBR) and density of a laterite by Kehinde et al. (2020) and a cohesive soil by Patel & Singh (2019). They also found that glass fibers increases the cohesion between soil particles and the angle of internal friction. Majid & Baba, (2023) also found that the use of plant fibers can reduce the tendency of an expansive soil to swelling, while Raj et al. (2020) found that fiber extracted from water hyacinth can be used to alter the properties of a clayey soil beneficially. Researchers such as Danso (2017), Kaushik & Singh (2021), Shukla et al. (2022) and Stuti et al. (2015) showed that the use of coir fiber at certain quantities can improve the properties of soil for building and road construction. These researches have shown that fibers can improve soil deformation properties This is achieved by slowing down cracking and its rate of propagation within the soil (Majid & Baba, 2023). It has also been shown that reinforcement of subgrade soils with fibers is one of the successful potential applications in the construction of flexible pavements (Kehinde et al., 2020). The reinforcement of soil with fibers are advantageous in various ways. They are inexpensive, lightweight and capable of preserving strength isotropy across the soil mass (Al Adili et al., 2012). The weather has minimal effect on how it is utilized in structures (Patel & Singh, 2016).

Coir is a byproduct of coconut processing that is becoming widely recognized as an efficient soil stabilization material (Al Adili et al., 2012). Coir has important properties that increase strength, improves drainage and offers great resistance to biodegradation. Their use in reinforcing pavement material can lead to reduction in pavement thickness, and lower construction costs (Kaushik & Singh, 2021; Shukla et al., 2022). Due to its high lignin concentration, coir fiber is one of the toughest natural fibers accessible (Stuti et al., 2015). Coir is significantly more favourable in numerous applications for erosion control, strengthening, and soil stabilisation, and is chosen above any other natural fiber (R. R. Singh & Mittal, 2014) .

Reinforcing laterite with coir fibers can improve some essential properties such as tensile strength, ductility and toughness needed for construction (Aguwa, 2013; Krishnendu & Bhasi, 2021; Shankar et al., 2021).

There is currently a higher awareness of the need to conserve the environment. This study relates to the United Nations (UN) Sustainable Development Goals (SDG). The initiative is relevant to SDGs 9 and 11, which aim to make cities and human settlements inclusive, safe, resilient, and sustainable. SDG 9 aims to construct robust infrastructure, encourage inclusive and sustainable industrialization, and support innovation. Using natural fibers which would have been wastes will solve issues related to sustainability (Danso, 2017). Furthermore, reinforcement of laterite with coir has potential impact on sustainability by providing eco-friendly organic material (Lal et al., 2017), reduce cost and potential global warming potential (Ravikumar et al., 2023) while improving road pavement (Subgrade and subbase) strength and compressive strength of laterized bricks for building construction.

Fuzzy logic is a high-level computation that allows the turning of language strategy into control actions (Sivanandam et al., 2007). It is also a mathematical tool for dealing with ambiguity. In the field of civil engineering, fuzzy logic has proven to be extremely useful. There are usually output and input parameters. The output parameter are the geotechnical soil properties that are relatively intensive to determine such as California bearing ration and shear strength parameters while the input parameters are those geotechnical soil properties such as liquid limit, plastic limit, plasticity index, particle size distribution, optimum moisture content and maximum dry density (that are relatively easy to perform). Singh et al. (2020) employed a fuzzy logic-based modelling approach for geogrid-reinforced subgrade soil of unpaved roads and found fuzzy logic to be satisfactory in predicting the CBR when depth of reinforcement and reinforced/unreinforced sections were included as the input parameter. Zorluer & Cavus (2021) did a fuzzy logic assessment of engineering properties of granular soil with wastes for environment protection and road base use. Marble dust and fly ash were used as the input parameter while the California bearing ratio was used as the output parameter, The study revealed that the CBR can be predicted with a high rate of confidence using the developed model.

The main objectives of this research are to determine the effect of reinforcement on the geotechnical properties of the selected soil and develop a fuzzy logic model to predict the California bearing ratio of the reinforced laterite from the percentage of fiber, liquid limit and optimum moisture content. Fuzzy logic is explored in this research because it has been shown to give more accurate predictive models than conventional methods such as linear regression etc. (Dewidar et al., 2019).

MATERIALS AND METHODS

Materials

Laterite and coir were used in this study. Laterite was obtained from a GPS location of 7°30'53.0" N 4°33'10.4" E in South West Nigeria. Coir was obtained from coconut husk. The coconut husks were soaked in water for four days under ambient condition to make the fibers swell and soften. The fibers were manually separated from the softened husks and cut into lengths of 3 to 5 cm which is withing the range used by Kaushik & Singh (2021).

Determination of geotechnical properties of laterite

For classification of laterite as well as assess its suitability as a subgrade material, its index properties including gradation, specific gravity, and Atterberg's limits (i.e liquid limit, LL; plastic limit, PL and plasticity index, PI) were determined in accordance with ASTM D 422, ASTM D 854 and ASTM D 4318, respectively. West African method of compaction was also used to estimate the maximum dry density (MDD) and optimum moisture content (OMC) of the laterite. The laterite was compacted in five layers using 27 blows from a 4.5 kg rammer dropping at 450 mm height into a mold of size 0.002305 m^3. The OMC was used to compact the laterite to establish its CBR. The west Africa method of compaction was chosen as specified by Nigerian Road manual (Federal Ministry of works and Housing, 2013) due to the relevance local condition.

Determination of geotechnical properties of the reinforced laterite

The soil was mixed with coir fiber manually in different proportions. The percentage of coir used were 0.25, 05, 0.75, 1, 1.25 and 1.5% by dry weight of laterite. For example, when 0.25% coir is to be used, 12.5 g of coir will be mixed with 5 kg of dry laterite. The LL, PL, PI, OMC, MDD and CBR of reinforced laterite were established. The LL, PL, PI and CBR of reinforced laterite were determined because they are indices that are used to establish the effectiveness of soil as material for road construction. The OMC and MDD were determined and used for reconstituting compacted laterite used for CBR determination.

Analysis of results with ANOVA

The results of the geotechnical properties tests were analyzed with one-way Analysis of Variance (ANOVA) to establish the statistical significance of percentage of coir (which is the independent variable) on the LL, PL, PI, OMC, MDD and CBR (which are the dependent variables) of the reinforced soil. ANOVA is essential in geotechnical analysis as it can help identify significant differences between groups of data and determine whether the differences are due to chance or not. The P value is usually used to determine the statistical significance. If P is less than 5%, the varied factor (e.g. percentage of the coir) is said to have significant effect on the property tested, if P is greater than 5%, the less the factor is statistically significant.

Fuzzy logic

Fuzzy inference method was used for the prediction of CBR of reinforced laterite. Fuzzy logic toolbox from MATLAB software was used as a tool for achieving the prediction. The model consists of 3 input variables which are LL, OMC and the percentage of fiber (F) while the CBR is the output variable. The structure of the model is shown in Figure 1. Seven membership functions were defined for the variables used for modelling as presented in Figure 2. The input variables were defined using linguistic terms: F1 to F7 for percentage of fiber, LL1 to LL7 for liquid limit and OMC1 to OMC7 for optimum moisture content. The linguistic term used for the output variable are CBR1 to CBR7. Triangular membership functions were used to train the fuzzy model for both the input and output parameters (Figure 2). The choice of the number of membership functions and their initial values was based on knowledge of the system and experimental conditions.

The rules created for the model are in the form:

If (fiber = F1) and (OMC = OMC2) and (MDD = MDD4), then (CBR = CBR1) (1)

In this study, 103 rules were created for implementing the model. The fuzzy rules were created based on the results of the laboratory geotechnical analysis. Some studies (Alaneme et al., 2021; M. Singh et al., 2020) have shown the relevance of fuzzy logic in prediction geotechnical properties of soil.

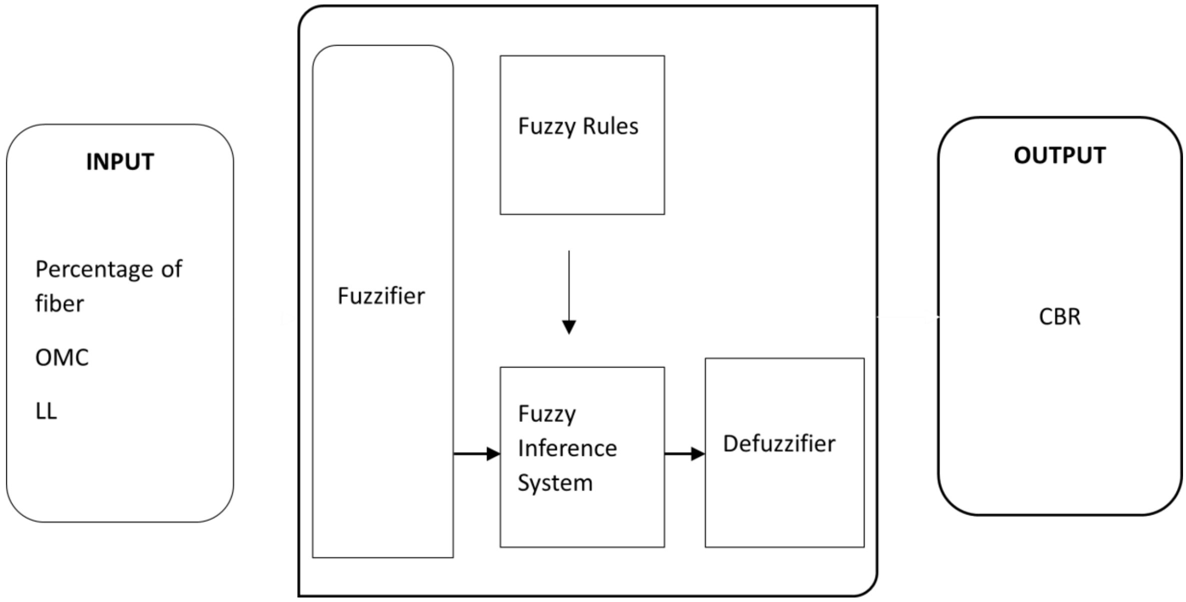

Figure 1: Structure of the fuzzy logic model

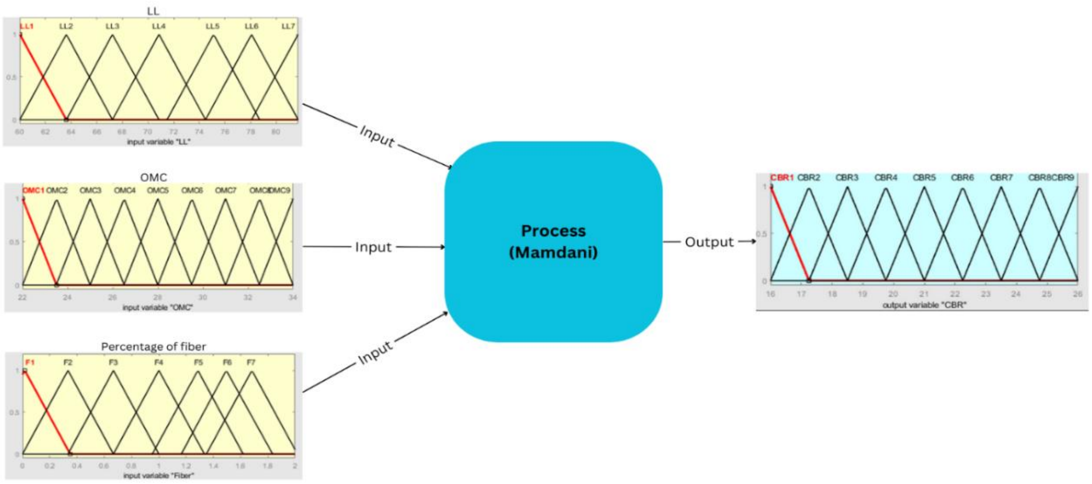

Figure 2: Input and output membership functions

RESULTS AND DISCUSSION

Geotechnical properties of unreinforced laterite

The specific gravity of the laterite was 2.65, this fell between 2.55 and 4.6 which according to Gidigasu (1972) indicates lateritic soil. The laterite is a silty clay material based on a P_{200} (percent passing sieve No. 200) of 76.98%, LL of 71.69% and a PI of 37.87% and classifies as A-7-5 using the AASHTO classification. According to the USCS classification, the soil classifies as CH (high plasticity clay) (Das, 2006). High plasticity clay is usually unstable when used for roads or foundation of building as they are prone to volume change causing differential settlement which can ultimately lead to the failure of the structure constructed on it. The MDD and OMC of unreinforced laterite are 1485.45 g/m^3 and 23.95%, respectively. These results show that the soil will have to be stabilized for it to be utilized as road construction material. The specification for a suitable road material by (Federal Ministry of works and Housing, 2013) is a LL of less than 30% and a PI of less than 12%, since the values obtained for the laterite is greater than these specifications, the laterite must be stabilized before it can be utilized as a road construction material.

Atterberg's limits of reinforced laterite

The addition of coir to the laterite caused changes in it's liquid and plastic limits as shown in Figure 3. There was an initial decrease of about 15% in LL on mixing the soil with 0.25% of coir, the LL increased afterwards with values higher than the initial LL. The initial decrease in LL can be as a result of coir fibers absorbing water and reducing the amount of free water available in the soil. This probably led to increase in soil stiffness and a decrease LL as also observed by (Naresh et al., 2022). The subsequent increase in LL when the percent of coir increased can be attributed to increase pore water pressure due to the agglomeration of coir fibers.

The PL, however, increased with about 39% when the soil was mixed with 0.25% coir can be attributed to coir fiber increasing the soil cohesion and reducing brittleness (Naresh et al., 2022). This led to about 64% decrease in the PI of the soil. The PI of the reinforced laterite was also consistently smaller than that of the unreinforced soil. These changes align with the requirements for subbase material in road construction.

These results contradict that of Naresh et al. (2022) who found that the LL and PL consistently reduced while PI increased with increasing fiber content. Reduced PI in the present study is, however, more desirable for the laterite to be used as a subbase material (Oluremi et al., 2017)

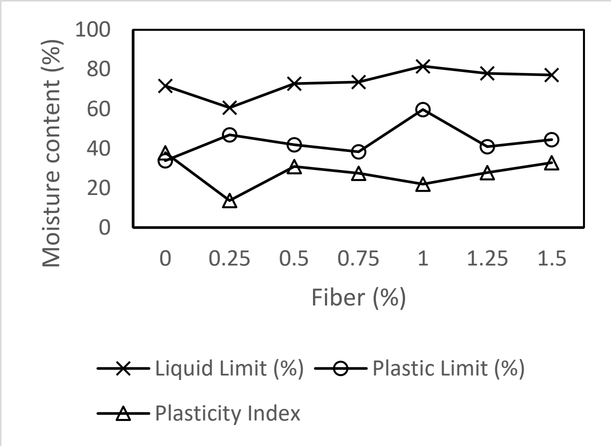

Figure 3: LL, PL and PI of laterite with varying coir content

Compaction properties of reinforced soil

The effect of coir on compaction parameters (MDD and OMC) of the laterite is presented in Figure 4. MDD decreased while coir content increased, this was with a corresponding increase in OMC of reinforced laterite. The decrease in MDD with increasing coir content is most likely due to the fiber possessing smaller specific weight when compared to that of laterite particles according to (Raj et al., 2020). The coir occupying more space by replacing soil grains would lead to reduced density (MDD) of the soil-coir composite. The added absorbed water by the coir can also lead to reduced MDD of the soil-coir composite (Jairaj et al., 2018). Higher OMC was probably due to the absorption of moisture by the increased coir as postulated by Naresh et al. (2022).

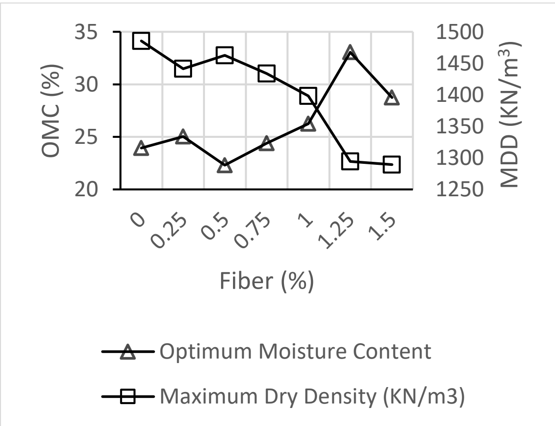

Figure 4: Compaction properties with varying coir content

California Bearing Ratio of Reinforced Soil

The California Bearing Ratio (CBR) of the reinforced laterite is presented in Figure 5. There is an initial increase in the CBR of the laterite up to 0.75% coir content after which the CBR decreased below that of the unreinforced soil. The increased CBR can be due to the reinforcing effect of the added coir which improves the load-deformation characteristics of the laterite (Peter et al., 2016). This result is in agrees with the findings of (Kumar & Batra, 2019; Naresh et al., 2022; Peter et al., 2016; Raj et al., 2020). Increased CBR of the reinforced soil was despite the increased OMC and decreased MDD, which furthers shows the reinforcing effect of the coir.

Optimum percent of coir for the reinforced soil based on the CBR is 0.25%. Researchers such as Ayininuola (2016), Babu & Vasudevan (2008), Kumar & Batra (2019) and Naresh et al. (2022) obtained a range of 1 to 1.5% as optimum coir content. This variation might be due to the type of soil and fiber used. Sujatha et al. (2018) also obtained an optimum percent of 1.25 for a lime stabilized soil.

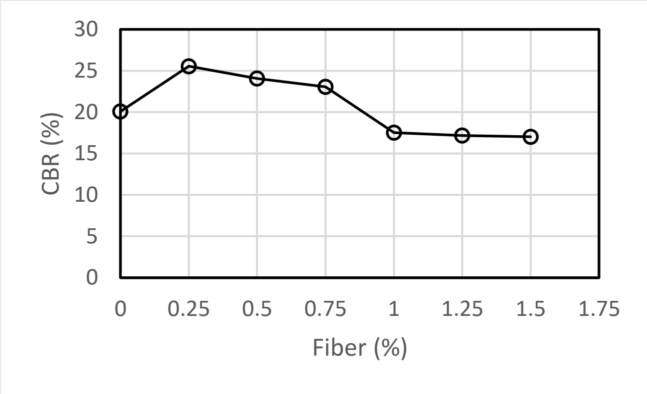

Figure 5: CBR variation for the different percentages of fiber

Statistical Analysis of Results Using ANOVA

Statistical Analysis using Analysis of Variance (ANOVA) showed that the amount of coir has significant effect (at 5% confidence level) on LL, PI and PL of the soil with p values of 8.25×10^{-12}, 4.05×10^{-9} and 3.02×10^{-6}, respectively.

ANOVA also showed the percent of coir has significant effect on OMC and MDD with p values of 3.48×10^{-10} and 5.84×10^{-15}, respectively. The percent of coir also has a significant effect on the CBR with p value of 5.47×10^{-9}.

Prediction of the CBR of the reinforced laterite

Attempts were made to predict CBR of reinforced laterite from the OMC, LL and coir content. CBR is the output while the OMC, LL and percent coir are the input in the model used. Seven membership functions were defined for the input and output parameters in order to ensure sufficiently accurate prediction of the CBR of the soil. Figure 6 presents the correlations between the observed and predicted CBR. The accuracy of the prediction was evaluated with statistical metrics which are Mean Absolute Percentage Error (MAPE) and Root Mean Squared Error (RMSE). The prediction has a MAPE of 4.68% and the RMSE is 1.18, RMSE and MAPE close to 0, this shows that the prediction is satisfactory according to Alaneme et al. (2021). The MAPE value signifies that the predictions are off by only 4.68%. The R-squared value of the regression line is 0.9759 as presented in Figure 6. According to Alaneme et al. (2021), R-squared greater than 0.8 shows that the actual values are well correlated with the predicted values. This suggest a well correlated experimental and predicted CBR of reinforced laterite (Singh et al., 2020). This results also show that fuzzy logic can be used to estimate the strength of coir reinforced laterite. Control surfaces of the fuzzy logic models are presented in Figure 7. The control surfaces in Figure 7 show how the output (CBR) changes in response to the different inputs (coir content, LL and OMC). Smooth transitions show gradual changes while sharp transitions show abrupt changes. As the fiber content and LL increased, the CBR decreased as indicated by the sharp transitions in Figure 7a.

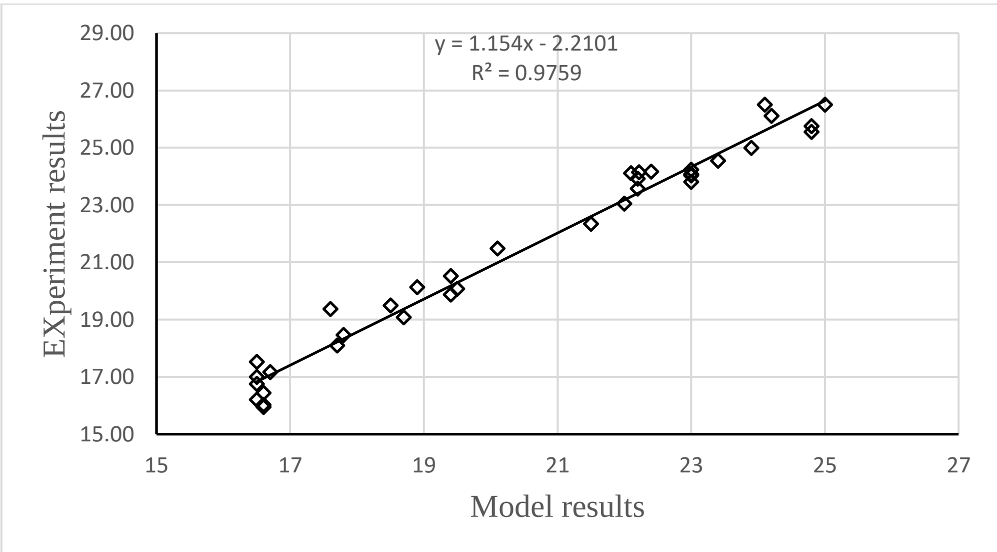

Figure 6: Actual and predicted CBR

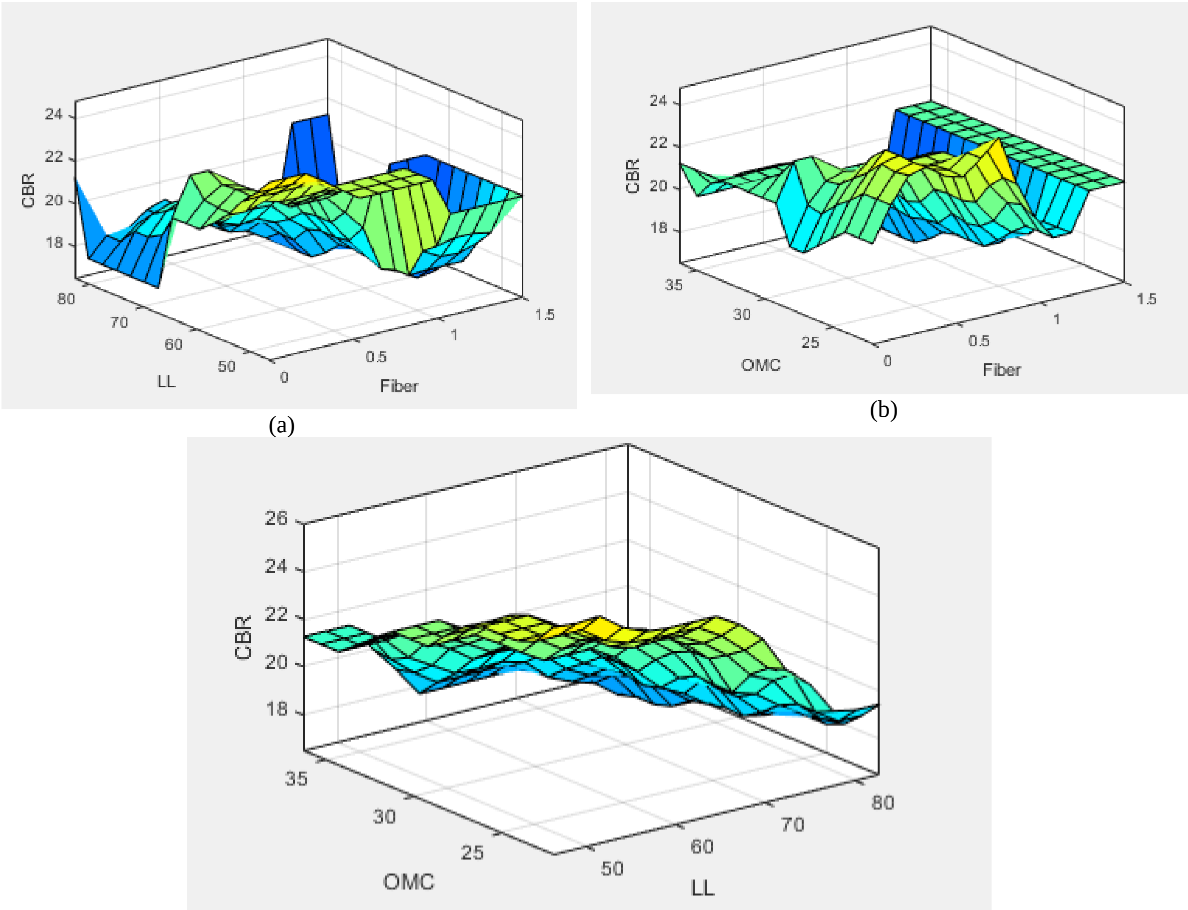

Figure 7: Control surfaces of fuzzy model (a) Fiber & LL, (b) fiber & OMC, (c) LL & OMC

CONCLUSION

In this work, the impact of the inclusion of coir on the strength characteristics of a laterite was explored using laboratory studies. Attempt was also made to predict the CBR from OMC, LL and percent of coir. Some of the conclusions from the results are:

i. inclusion of coir to laterite soil caused reduction in LL and PI with up to 15 and 64%, respectively;
ii. optimum amount of coir to the soil is 0.25% by weight of the soil as it showed the most promising increase in the CBR value; and
iii. fuzzy logic modeling provides an easy way to predict the CBR of coir-reinforced laterite in real-world applications.

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