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Effect of Sugarcane Molasses on the Physical Properties of Metakaolin Based Geopolymer Stabilized Laterite Soil

Ismaël Dabakuyo[1], Raphael N. Mutuku[2], Richard O. Onchiri[2]

[1]*Department of Civil and Construction Engineering, Pan African University Institute for Basic Sciences, Technology and Innovation Hosted at Jomo Kenyatta University of Agriculture and Technology, Kenya*

[2]*Department of Building and Civil Engineering, School of Engineering and Technology, Technical University of Mombasa, Kenya*

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Abstract — *The study focused on the effect of sugarcane molasses (SM) on the physical properties of metakaolin-based geopolymer stabilized laterite soil. The laterite soil, acquired from the farm of Jomo Kenyatta University of Agriculture and Technology, and classified as an A-2-7 on AASHTO classification, was stabilized according to two scenarios. In scenario 1, the optimum metakaolin based geopolymer (MKG) percentage was partially replaced by SM (8% MKG + 2% SM, 6% MKG + 4% SM, 4% MKG + 6% SM and 2% MKG + 8% SM); in scenario 2, the percentage of the MKG used as stabilizer, was fixed while SM was added at various percentage (5% MKG + 2% SM, 5% MKG + 4% SM, 5% MKG + 6% SM, 5% MKG + 8% SM). The effects of SM on the physical properties of metakaolin-based geopolymer stabilized soil was studied in terms of Atterberg Limits, Linear Shrinkage, and Compaction. The use of SM decreases the Liquid Limit, Plastic Limit, Plastic Index, Linear Shrinkage, and Optimum Moisture Content of metakaolin-based geopolymer stabilized laterite soil while the Maximum Dry Density raises. In general, sugarcane molasses has been found to improve the physical properties of metakaolin-based geopolymer stabilized soil.*

Keywords — *Metakaolin-based geopolymer, Sugarcane Molasses, Atterberg Limits, Maximum Dry Density, Optimum Moisture Content.*

I. INTRODUCTION

From time immemorial, laterite soil has been used as the main building material by humans due to its abundance and maneuverability. Pavements, embankments, low-cost houses, and other uses for such soils have emerged over time. However, in its raw state, this material does not often display good characteristics for being used in construction projects. As a result, there is a need to improve the qualities of the currently accessible materials. Such improvement is carried out through stabilization. Soil stabilization is the method of adding additional materials to the natural soil in order to enhance its strength and/or other properties for the purpose of construction [1]. These admixtures are, among others, cement, lime, pozzolans, bituminous products, and various organic and inorganic materials. Nevertheless, the efficiency of soil cement stabilization has made cement the most used binding agent since the invention of soil stabilization technology in the 20th century. Indeed, cement has been found to improve the engineering properties of available soil, such as strength, compressibility, permeability, swelling potential, frost susceptibility, and sensitivity to changes in moisture content [2]. Despite all these advantages of soil cement stabilization, the production of cement is one of the highest contributors to worldwide greenhouse gas emissions because of its energy-intensive manufacturing processes. Hence, there is a pressing need for a sustainable alternative. It is in this perspective that the craze for geopolymers as an alternative to cement was born.

Geopolymers are aluminosilicate materials belonging to the family of alkali-activated materials, which, unlike cementitious materials, require alkalis to harden [3]. The synthesis of geopolymers is obtained by polycondensation and can be made from materials rich in both silica and amorphous alumina. These materials are either natural (kaolin, micas, andalusite, spinel, volcanic slag) or synthetic (metakaolin). Metakaolin remains the most used for making geopolymer because it provides a purer, more readily characterized starting material for polymerization [4]. In recent years, some studies have shown that geopolymer synthesized by using metakaolin is as suitable as cement in soil stabilization [5,6,7]. Due to its efficiency and ecological perspective, metakaolin-based geopolymer is seen as one of the best alternatives to cement in soil stabilization. However, one of the main concerns is that a higher dosage of metakaolin is required for stabilizing soils, which makes this stabilization method expensive [6,8,9].

Increasingly, the new trend in soil stabilization is to take into consideration the reuse of industrial waste products to address the expensive cost of standard stabilizers. Sugarcane molasses, a by-product of the sugar refinery, is one of the industrial waste products which has been found to improve the properties of natural soil [2,10,11,12] slightly. Sugarcane molasses looks like a very thick and viscous black liquid, obtained after cooking sugarcane after the sugar crystals have been removed. It shows the presence of lime and sulfur dioxide, among others. Those elements, plus others imbibed from the soil by the sugarcane as nutrients to support growth, are the ones, which probably interact with expansive soil to change its characteristics during stabilization [13]. Additionally, the use of sugarcane molasses allows to solve waste management (since molasses is sugar refinery waste) and reduce pollution [13]. Indeed, sugarcane molasses could lead to environmental pollution through aesthetic degradation if spills are not properly cleaned up. It can lead to water pollution if large spills or factory effluents enter waterways too.

Therefore, substituting proportions of metakaolin-based geopolymer with an industrial waste product like sugarcane molasses will address the cost-effective issue and some environmental concerns.

II. EXPERIMENTAL METHODS

A. Materials

a) Laterite Soil

The laterite soil used in this study was collected from the farm of Jomo Kenyatta University of Agriculture and Technology. The particle size distribution in Figure 1 illustrates that the soil was composed of 75% gravel, 18% sand, and 7% silt. Therefore, the laterite soil studied was described as Silty Sandy GRAVEL. The chemical composition of the studied laterite soil, as well as its overall geotechnical properties, are illustrated respectively in Table 1 and Table 2.

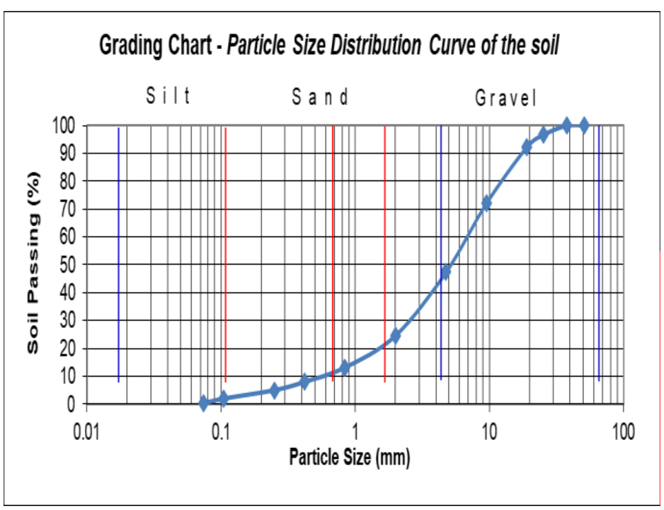


Fig 1: Particle Size Distribution Curve of the laterite soil

Table 1: Chemical composition of the laterite soil

Element Name	Percentage (%)
Al_2O_3	17.260
SiO_2	56.770
Cl	0.041
K_2O	1.217
CaO	0.781
Mn	2.288
Fe_2O_3	19.693

Table 2: Geotechnical properties of the laterite soil

Colour	Greyishbrown
Natural Moisture Content (%)	14.93
SpecificGravity	2.65
Uniformity Coefficient Uc	14.00
Curvature Coefficient Cc	1.79
Gravel (%)	75.00
Sand (%)	18.00
Silt (%)	7.00
Clay (%)	0.00
LiquidLimit (%)	42.6
Plastic Limit (%)	16.75
Plastic Index (%)	25.85
Linearshrinkage (%)	12.71
Maximum Dry Density (g/cm³)	1.729
Optimum Moisture Content (%)	19.00
AASHTO Classification	A-2-7

b) Geopolymer Binder (MKG)

The geopolymer binder used in this study was synthesized using metakaolin (MK) as an alumina-silicate source and sodium hydroxide as an activating solution. To get the metakaolin, local kaolin was milled and sieved at 75 µm. Then, kaolin powder was calcined at 650°C for 1h 30min to get the final material. The transformation process of the kaolin in the metakaolin is shown in Figure 2. The chemical composition of the metakaolin used is shown in Table 3.

The solution used to activate the metakaolin was 12 M sodium hydroxide. This solution was made by dissolving the caustic soda flakes in distilled water. The caustic soda flakes used were of 99% purity.

Fig 2: Transformation process of Kaolin in Metakaolin

Table 3: Chemical composition of metakaolin

Element Name	Percentage (%)
Al_2O_3	14.883
SiO_2	73.303
P_2O_5	0.113
Cl	0.011
K_2O	4.697
CaO	0.509
Fe_2O_3	5.515

c) Sugarcane Molasses (SM)

The sugarcane molasses used in this study (Figure 3) was obtained from a supplier in Kenya. Some chemical and physical properties of these molasses are summarized in Table 4.

Fig 3: Sugarcane molasses

Table 4: Characteristics of sugarcane molasses

Element Name	Percentage (%)
Magnesium	11.0
Potassium	5.8
Calcium	3.4
Manganese	12.8
Copper	11.6
Iron	70.0
Dry Matter	23.1
Glucose	12.2
Fructose	12.8
Crude Protein	5.6
Sucrose	18.2
Magnesium Oxide	1.88
Calcium Oxide	0.75
Potassium Oxide	36.0
Sodium Oxide	6.3

d) Cement (C)

In this study, 6% of cement was also used to stabilize the laterite soil. The cement used for this purpose was savannah cement 32.5R (CEM IV/32.5R). It is a pozzolanic cement produced locally in Kenya and conforming to Kenya Standards KS EAS 18-1:2001. Its specific gravity is 2.89. The chemical composition of the cement used is shown in Table 5.

Table 5: Chemical composition of cement

Element Name	Percentage (%)
Al_2O_3	9.327
SiO_2	51.094
P_2O_5	0.171
S	1.144
Cl	0.025
K_2O	2.859
CaO	30.168
Fe_2O_3	4.458

B. Methods

The stabilization process adopted consisted of three stages. Firstly, the geopolymer slurry was prepared by mixing the metakaolin with a 12 M sodium hydroxide solution in a mass ratio (sodium hydroxide solution/metakaolin) of 0.8. Then, the geopolymer slurry was added to the laterite soil, and the soil-geopolymer matrix was well mixed. After that, sugarcane molasses was combined with the mixture of soil and geopolymer, and additional water was added.

In this study, the laterite soil was stabilized according to two scenarios. In scenario 1, the optimum metakaolin based geopolymer percentage was partially replaced by sugarcane molasses (8% MKG + 2% SM, 6% MKG + 4% SM, 4% MKG + 6% SM and 2% MKG + 8% SM). On the other hand, in scenario 2, the percentage of the metakaolin based geopolymer used as stabilizer, was fixed while sugarcane molasses was added at various percentages (5% MKG + 2% SM, 5% MKG + 4% SM, 5% MKG + 6% SM, 5% MKG + 8% SM). The control samples were natural laterite soil, the laterite soil stabilized with 6% cement, and the laterite soil stabilized with 10% MKG, where 6% cement and 10% MKG are respectively the optimum cement and metakaolin-based geopolymer percentages for stabilizing the laterite soil.

The standard tests used for the determination of the physical properties of the laterite soil stabilized with metakaolin-based geopolymer and sugarcane molasses were the Atterberg Limits, the Linear Shrinkage, and the Compaction test. The liquid limit was determined using the cone penetrometer method, and the normal proctor was used for the compaction test. The Atterberg Limits and linear shrinkage were performed according to the requirements of BS 1377, part 2, 1990 [14], and the compaction test was performed according to BS 1377, part 4, 1990 [15].

III. RESULTS AND DISCUSSIONS

A. Effect of sugarcane molasses on the Atterberg Limits of metakaolin based geopolymer stabilized soil

a) Liquid Limit (LL)

The LL of the natural and stabilized laterite soil was determined according to BS 1377, part 2, 1990 [14]. Table 6 shows a summary of the findings. It can be noted that the LL of the neat laterite soil treated with 6% cement and 10% MKG (control samples) increased, respectively, from 42.6% to 44.80% and 42.6% to 48.70%. The slight increase of the LL of stabilized soil with 6% cement can be explained by the notion of water trapped with intra-aggregate pores [16]; while the increase of the LL of the stabilized soil with 10% MKG may be due to the formation of a new compound that is Sodium Aluminosilicate Hydrate (NASH). This new compound has a high absorption capacity hence a higher liquid limit because of its large specific surface area derived from its fineness. This new compound has a high absorption capacity, hence a higher liquid limit, because of its large specific surface area derived from its fineness [17].

In scenario 1 of the stabilization, sugarcane molasses was used as the partial replacement of the optimum metakaolin-based geopolymer. The effect of sugarcane molasses on the stabilized soil with metakaolin-based geopolymer is illustrated in Figure 4. It should be noted that the LL decreased with the decrease of the metakaolin-based geopolymer and the increase of sugarcane molasses percentage. Indeed, the LL of the stabilized laterite soil with 10% MKG decreased from 48.70% to 45.10% when 20% of the MKG was replaced by sugarcane molasses (i.e., when the soil is stabilized with 8% MKG + 2 SM). As the percentage of replacement of the metakaolin-based geopolymer by sugarcane molasses increases, LL decreases. Thus, the LL decreases from 48.70% to 40.60%, 39.40% and 35.80% when the soil is stabilized with 6% MKG + 4% SM, 4% MKG + 6% SM and 2% MKG + 8% SM, respectively.

In scenario 2, the percentage of the metakaolin-based geopolymer used as a stabilizer was fixed to 5% MKG while sugarcane molasses was added at various percentages. The results showed that when the natural soil was stabilized with only 5% MKG, the LL increased from 42.6 % to 51.40%. It was also noted that the addition of sugarcane molasses to the stabilized soil with 5% MKG decreased the LL. As the amount of sugarcane molasses increased, the LL decreased. Indeed, the LL dropped from 51.40% (for 5% MKG) to 38.80%, 35.80%, 35.20%, and 34.10% for 5% MKG + 2% SM, 5% MKG + 4% SM, 5% MKG + 6% SM, and 5% MKG + 8% SM, respectively. It can subsequently be inferred that sugarcane molasses improved the plasticity of the stabilized soil with the metakaolin-based geopolymer by decreasing its LL. The improvement of the LL, induced by the stabilization of the natural soil with both sugarcane molasses and metakaolin based geopolymer, is better than for cement-soil stabilization (6% cement) and then for the geopolymer-soil stabilization (soil stabilized by the optimum metakaolin based geopolymer content, i.e., 10% MKG). This decrease of the LL can be explained by the adhesivity properties of sugarcane molasses. When metakaolin based geopolymer is partially replaced by sugarcane molasses in stabilizing soil, molasses holds a part of clay soil particles together, forming larger particles than clay size grains, resulting in a drop in clay content and, as a result, a lower liquid limit due to a lower specific surface [18]. The Hydrogen bonding ascribed to the Hydroxyl group found in sucrose of molasses is responsible for the molasses' adhesivity properties. In addition, the cation exchange due to the addition of sugarcane molasses causes flocculation and decreases the quantity of absorbed water in the soil, resulting in the decrease of the LL [18].

Table 6: Liquid Limit of Natural Soil and Stabilized Soil

Specimen	Liquid Limit LL (%)
Soil	42.6
Soil+ 6% C	44.80
Soil + 10% MKG	48.70
Soil + 8% MKG + 2% SM	45.10
Soil + 6% MKG + 4% SM	40.60
Soil + 4% MKG + 6% SM	39.40
Soil + 2% MKG + 8% SM	35.80
Soil + 5% MKG	51.40
Soil + 5% MKG + 2% SM	38.80
Soil + 5% MKG + 4% SM	35.80
Soil + 5% MKG + 6% SM	35.20
Soil + 5% MKG + 8% SM	34.10

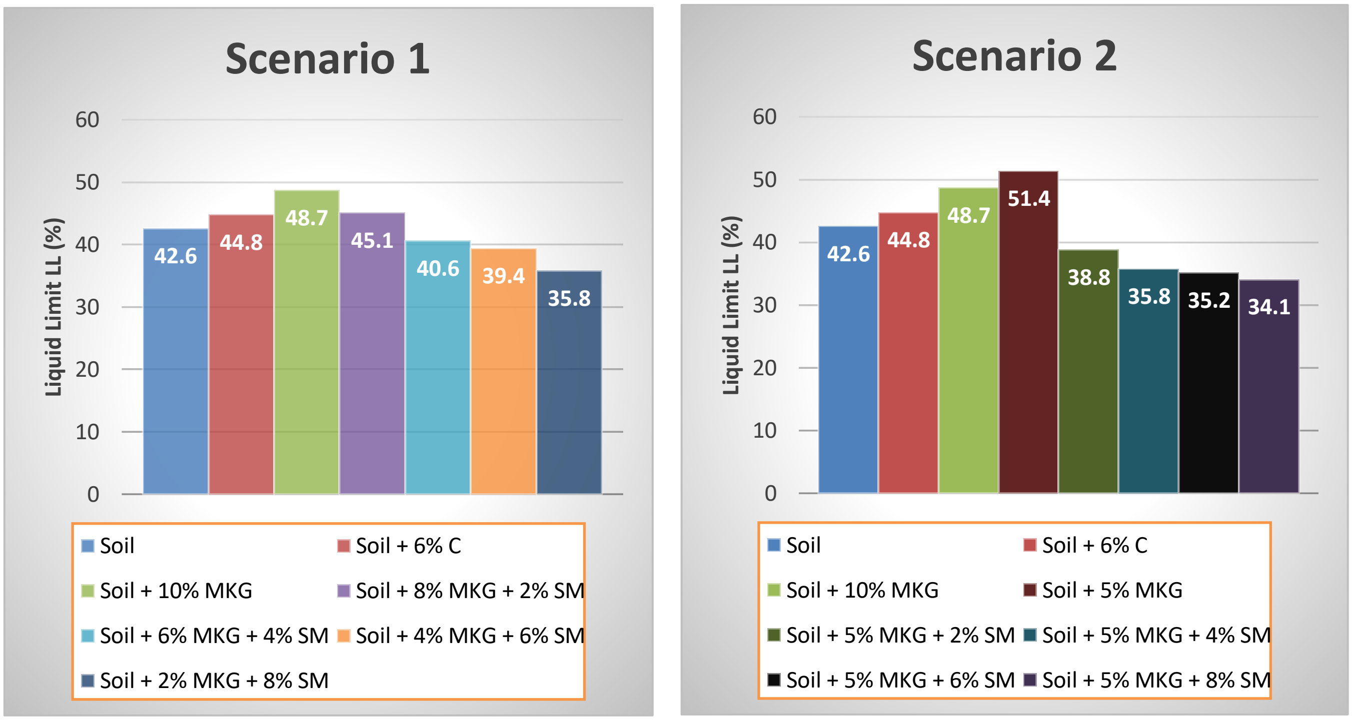


Fig 4: Effect of sugarcane molasses and metakaolin based geopolymer on the Liquid Limit of laterite soil

b) Plastic Limit (PL)

The PL of the natural and stabilized laterite soil was determined according to BS 1377, Part 2, 1990 [14]. Table 7 shows a summary of the results. It can be noted that the PL of the stabilized soil with 6% cement and 10% MKG (control samples) is higher than for the natural soil. The PL increased from 16.75% to 30.00% and from 16.75% to 26.42%, respectively, for stabilized soil with 6% cement and 10% MKG. The increase of the PL of soil stabilized with 6% cement is consistent with the study of Bayat et al. (2013) [19]and. This may be explained by the aggregation and cementation of particles into larger size clusters [20]. As for the increase of the PL of stabilized soil with 10% MKG, it is in agreement with the study of Samuel (2019) [8]. In this case, the increase of PL may be explained by the cation exchange reaction that takes place between the geopolymer and the soil particles. Indeed, the geopolymer binds soil particles together in micro-aggregates, which act like silt particles and increase PL.

The results of the stabilization scenarios are illustrated in table 7 and figure 5. In scenario 1, it should be noted that the PL slightly decreases with the decrease of the metakaolin-based geopolymer and the increase of sugarcane molasses percentage. Indeed, the PL of the stabilized laterite soil with 10% MKG decreased from 26.42% to 21.82%, 20.07%, 19.63% and 16.42% when the MKG is partially replaced by 8% MKG + 2% SM, 6% MKG + 4% SM, 4% MKG + 6% SM and 2% MKG + 8% SM, respectively. As for scenario 2, it has been noted that the addition of sugarcane molasses to the stabilized soil with 5% MKG decreases the PL, and it continues decreasing as the amount of sugarcane molasses increases. Indeed, the PL dropped from 27.78% (for 5% MKG) to 19.40%, 17.94%, 17.61%, and 16.91% for soil stabilized with 5% MKG + 2% SM, 5% MKG + 4% SM, 5% MKG + 6% SM, and 5% MKG + 8% SM, respectively.

Whether in scenarios 1 or 2, the PL of the stabilized soil with metakaolin-based geopolymer decreased in the presence of sugarcane molasses. The drop in the PL becomes increasingly substantial as the percentage of sugarcane molasses increases.

Table 7: Plastic Limit of Natural Soil and Stabilized Soil

Specimen	Plastic Limit PL (%)
Soil	16.75
Soil+ 6% C	30.00
Soil + 10% MKG	26.42
Soil + 8% MKG + 2% SM	21.82
Soil + 6% MKG + 4% SM	20.07
Soil + 4% MKG + 6% SM	19.63
Soil + 2% MKG + 8% SM	16.42
Soil + 5% MKG	27.78
Soil + 5% MKG + 2% SM	19.40
Soil + 5% MKG + 4% SM	17.94
Soil + 5% MKG + 6% SM	17.61
Soil + 5% MKG + 8% SM	16.91

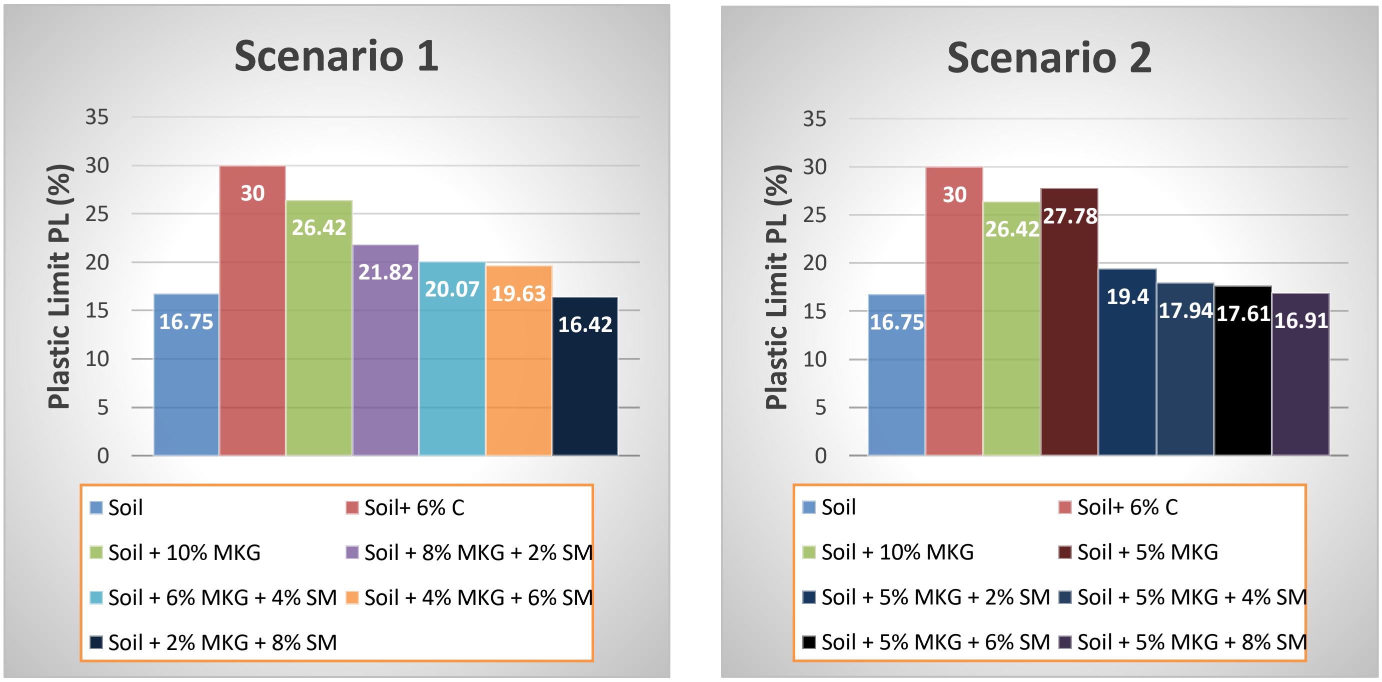


Fig 5: Effect of sugarcane molasses and metakaolin based geopolymer on the Plastic Limit of laterite soil

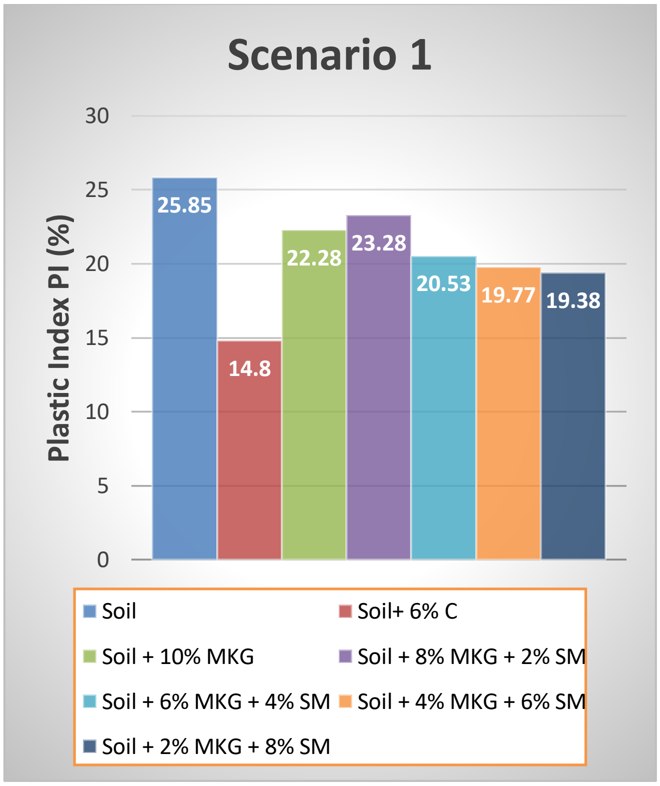
c) Plastic Index (PI)

The results of the PI are summarized in table 8. It can be noted that the PI of the neat soil decreases when the soil is stabilized with 6% cement and 10% MKG (control samples). The PI of the neat soil decreased from 25.85% to 14.80% and from 25.85% to 22.28% when the soil was stabilized with 6% cement and 10% MKG, respectively. The reduction in the PI of the laterite soil stabilized with 6% cement is consistent with the studies of Dabou et al. (2021) and Ghasabkolaei et al. (2016) [21, 22], whereas the reduction in the PI of the stabilized soil with 10% MKG is consistent with the study of Ahmed (2021) [23]. These decreases of the PI are due to the slight increase of the LL and the huge increase of PL, as discussed above.

The effect of sugarcane molasses on the stabilized soil with metakaolin-based geopolymer is depicted in figure 6. In scenario 1, it can be noted that the PI of the stabilized soil with the optimum geopolymer content (10% MKG) increases when the MKG is partially replaced with 2% SM. The PI increased from 22.28% for soil stabilized with 10% MKG to 23.28% for stabilized soil with 8% MKG + 2% SM. Nevertheless, the PI of the stabilized soil with the optimum geopolymer content (10% MKG) decreases gradually as the percentage of MKG decreases and one of sugarcane molasses increases. Thus the PI of stabilized soil with 10% MKG decreased from 22.28% to 20.53%, 19.77% and 19.38% when the soil is stabilized with 6% MKG + 4% SM, 4% MKG + 6% SM and 2% MKG + 8% SM, respectively. In scenario 2, it should be noted that the addition of sugarcane molasses to 5% MKG decreases its PI. The PI of the stabilized soil with 5% MKG decreased from 23.62% to 19.40%, 17.86%, 17.59% and 17.19% with the addition of 2% SM, 4% SM, 6% SM, and 8% SM, respectively. These decreases of the PI in scenarios 1 and 2 are related to the variation of LL and PL discussed before. It can be concluded, with respect to the results, that the stabilization of the natural soil with both sugarcane molasses and the metakaolin based geopolymer is more effective, in decreasing the PI of the natural soil, than the stabilization of the soil with only the metakaolin based geopolymer (10% MKG which is the optimum metakaolin based geopolymer for soil stabilization). However, 6% cement (optimum cement content for stabilizing soil) has been found to be more effective in reducing the PI of the neat soil than the combinations of sugarcane molasses and metakaolin-based geopolymer used in this study.

Table 8: Plastic Index of Natural Soil and Stabilized Soil

Specimen	Plastic Index (%)
Soil	25.85
Soil+ 6% C	14.80
Soil + 10% MKG	22.28
Soil + 8% MKG + 2% SM	23.28
Soil + 6% MKG + 4% SM	20.53
Soil + 4% MKG + 6% SM	19.77
Soil + 2% MKG + 8% SM	19.38
Soil + 5% MKG	23.62
Soil + 5% MKG + 2% SM	19.40
Soil + 5% MKG + 4% SM	17.86
Soil + 5% MKG + 6% SM	17.59
Soil + 5% MKG + 8% SM	17.19



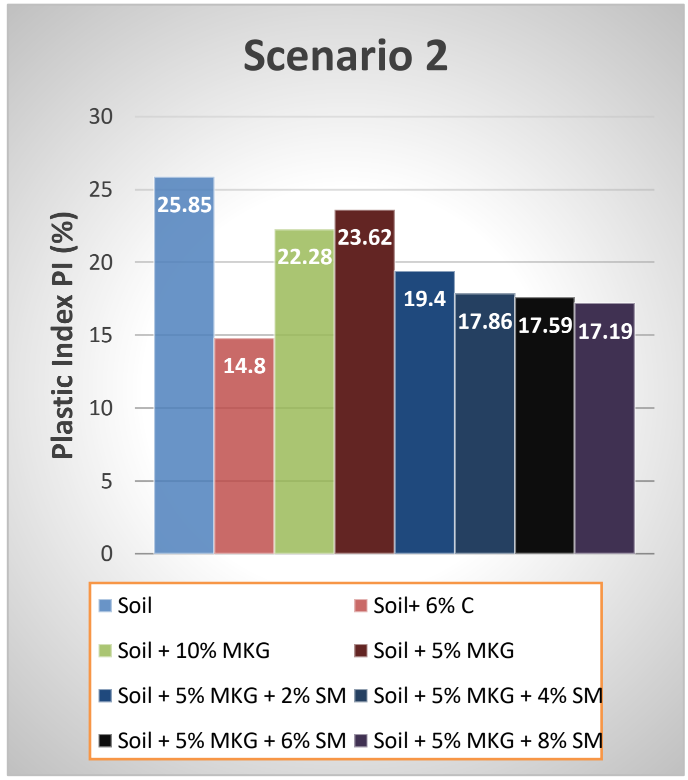


Fig 6: Effect of sugarcane molasses and metakaolin based geopolymer on the Plastic Index of laterite soil

B. Effect of sugarcane molasses on the Linear Shrinkage (LS) of metakaolin based geopolymer stabilized soil

The Linear Shrinkage (LS) of the natural and stabilized laterite soil has been determined according to BS 1377, part 2, 1990 [14]. When a soil sample is oven-dried, linear shrinkage occurs, starting with a moisture content of the sample at the liquid limit. Table 9 shows a summary of the results. It can be noted that the LS of the neat soil is lower than that of the stabilized soil with 6% cement and 10% MKG (control samples). Indeed, the LS decreased from 12.71% to 12.07% and from 12.71% to 11.71%, respectively, for stabilized soil with 6% cement and 10% MKG. The decrease of the LS of stabilized soil with 6% cement and 10% MKG is, respectively, in agreement with the study of Sabry et al. (2017) [24] and Ahmed (2021) [23]. The decrease of the LS in the cement stabilized soil may be explained by the strong bond of soil particles due to the matrix formed in the soil by the hydration reaction between cement and water; while the decrease in the LS of stabilized soil with 10% MKG is due to the bond in soil particles created by the geopolymer.

The effect of sugarcane molasses on the LS of the stabilized soil with MKG is depicted in figure 7. In scenario 1, the LS decreases when the percentage of MKG decreases while the percentage of sugarcane molasses increases. The LS of the stabilized soil with the optimum geopolymer content (10% MKG) is higher than for soil stabilized with a partial replacement of MKG by SM. The LS dropped from 11.71% (for 10% MKG) to 11.57%, 11.25%, 10.86% and 9.00% when the MKG is partially replaced by 8% MKG + 2% SM, 6% MKG + 4% SM, 4% MKG + 6% SM and 2% MKG + 8% SM, respectively. In scenario 2, it can also be noted that the LS of the stabilized soil with 5% MKG decreases with the addition of SM. The LS continues decreasing gradually when the amount of sugarcane molasses increases. The LS of the stabilized soil with 5% MKG decreased from 12.43% to 9.93%, 8.86%, 8.29% and 7.36% with the addition of 2% SM, 4% SM, 6% SM and 8% SM, respectively. All in all, it can be resumed that the soil stabilization with both sugarcane molasses and the metakaolin-based geopolymer is effective in reducing the linear shrinkage of the soil. It is more effective in decreasing the LS than the optimum cement and metakaolin-based geopolymer. These decreases of the LS in scenarios 1 and 2 may be explained by the adhesive properties of sugarcane molasses and the cation exchange between the soil particles and sugarcane molasses.

Volume 8 Issue 12, 1-12, Dec 2021

Table 9: Linear Shrinkage of Natural Soil and Stabilized Soil

Specimen	Linear Shrinkage (%)
Soil	12.71
Soil+ 6% C	12.07
Soil + 10% MKG	11.71
Soil + 8% MKG + 2% SM	11.57
Soil + 6% MKG + 4% SM	11.25
Soil + 4% MKG + 6% SM	10.86
Soil + 2% MKG + 8% SM	9.00
Soil + 5% MKG	12.43
Soil + 5% MKG + 2% SM	9.93
Soil + 5% MKG + 4% SM	8.86
Soil + 5% MKG + 6% SM	8.29
Soil + 5% MKG + 8% SM	7.36

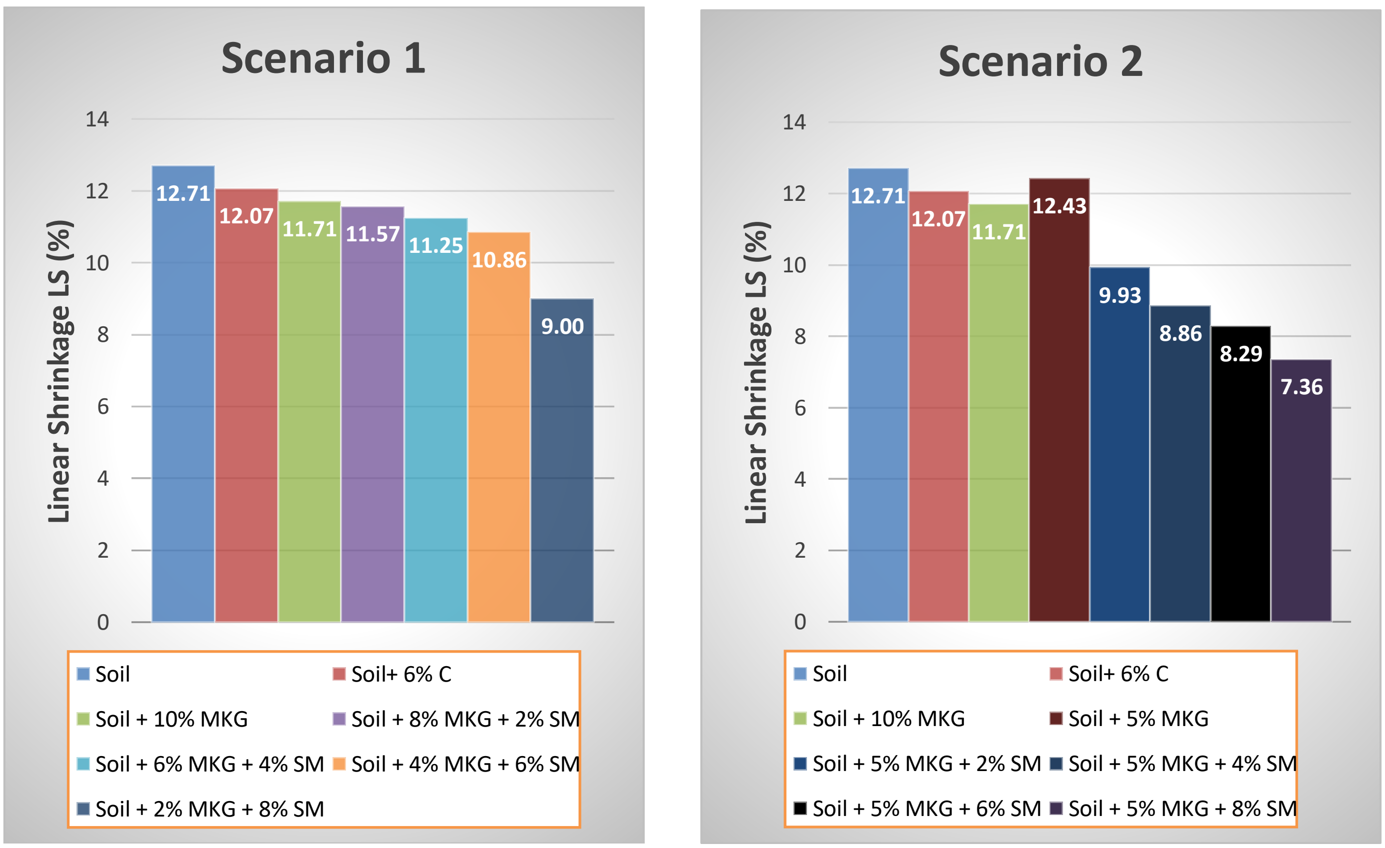


Fig 7: Effect of sugarcane molasses and metakaolin based geopolymer on the Linear Shrinkage of laterite soil

C. Effect of sugarcane molasses on the Maximum Dry Density and Optimum Moisture Content of metakaolin based geopolymer stabilized soil

The Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of the natural and stabilized soil have been determined through the Standard Proctor test according to the requirements of BS 1377, part 4, 1990 [15]. The results of the MDD and the OMC of the natural and stabilized soil are summarized in table 10. It can be noted that the control samples stabilized with 6% cement and 10% MKG have an MDD and an OMC different from those of the natural soil. Indeed, 6% of cement increased the MDD from 1.729 g/cm^3 to 1.730 g/cm^3 while the OMC decreased from 19.00% to 18.40%. This increase of MDD and the decrease of OMC is due to the formation of interparticle bonding caused by the cement's pozzolanic activity [25]. As a result of the pozzolanic activity response, the amount of inter-particle spaces is reduced, resulting in a denser material. Therefore, the amount of water required to achieve the MDD is lesser than for the natural soil. On the other hand, the stabilization of soil with 10% MKG decreased the MDD from 1.729 g/cm^3 to 1.728 g/cm^3 and the OMC from 19.00% to 18.70%. In this case, the decrease of the MDD may be due to the agglomeration and flocculation of soil particles generated by the geopolymer's interaction with the soil.

The different effects of sugarcane molasses on the MDD and the OMC of the metakaolin-based geopolymer stabilized soil are depicted in figure 8, figure 9, and figure 10. In scenario 1 of stabilization, it can be noted that the MDD of the stabilized soil with a small amount of sugarcane molasses as a partial replacement of metakaolin-based geopolymer is lower than the one of the soil stabilized with only the optimum geopolymer content (10% MKG). However, as the percentage of sugarcane molasses increases and one of the metakaolin-based geopolymer decreases, the MDD increases gradually. Thus, the MDD has been found to increase from 1.602 g/cm^3 for the stabilized soil with 8% MKG + 2% SM to 1.634 g/cm^3, 1.653 g/cm^3, and 1.710 g/cm^3 for stabilized soil with 6% MKG + 4% SM, 4% MKG + 6% SM, and 2% MKG + 8% SM, respectively. Notwithstanding these increases of the MDD of the stabilized soil with SM as a partial replacement of MKG, these values remain lower than the MDD of the stabilized soil with only the optimum geopolymer content (10% MKG), which is 1.728 g/cm^3. The opposite trend is observed with the OMC. It increased from 19.00%, for soil stabilized with the optimum geopolymer content (10% MKG), to 19.50% for stabilized soil with 8% MKG + 2% SM. Then, the OMC decreased as the percentage of SM increased, and the one of MKG decreased. The OMC dropped from 19.50%, for stabilized soil with 8% MKG + 2% SM, to 19.30% for stabilized soil with 6% MKG + 4% SM. From 4% MKG + 6% SM, the OMC displayed a lower value compared to the stabilized soil with the optimum geopolymer content. It continues decreasing from 18.20%, for stabilized soil with 4% MKG + 6% SM, to 16.40% for stabilized soil with 2% MKG + 8% SM.

As for scenario 2, it can be noted that the addition of sugarcane molasses in small amounts decreases the MDD of the stabilized soil with 5% MKG. The MDD of the stabilized soil with 5% MKG decreases from 1.715 g/cm^3 to 1.692 g/cm^3 with the addition of 2% SM. Nevertheless, MDD starts increasing with the increase of the amount of SM. Thus, it increased from 1.692 g/cm^3, for stabilized soil with 5% MKG + 2% SM, to 1.696 g/cm^3 for stabilized soil with 5% MKG + 4% SM. From, 5% MKG + 6% SM, the MDD is higher than for stabilized soil with 5% MKG, increasing from 1.715 g/cm^3 (for 5% MKG) to 1.722 g/cm^3. In parallel, the opposite phenomenon is observed with the OMC of the stabilized soil. It decreased gradually as the amount of SM increased. As noticed, the OMC of the stabilized soil with 5% MKG increased from 17.90% to 18.50% with the addition of 2% SM. Then, the OMC decreased as the amount of SM increased. It can be observed that the OMC decreases from 18.50%, for stabilized soil with 5% MKG + 2% SM, to 18.20%, 16.30% and 15.90% for stabilized soil with 5% MKG + 4% SM, 5% MKG + 6% SM and 5% MKG + 8% SM, respectively. The OMC of the stabilized soil with 5% MKG becomes lower from the addition of 6% SM and continues decreasing beyond this percentage of sugarcane molasses. By considering the overall results of every scenario, it can be concluded that the stabilization of the soil with both sugarcane molasses and the metakaolin-based geopolymer is effective in increasing the MDD of the soil and decreasing its OMC.

Table 10: Maximum Dry Density and Optimum Moisture Content of Natural Soil and Stabilized Soil

Specimen	Maximum Dry Density MDD (g/cm^3)	Optimum Moisture Content (%)
Soil	1.729	19.00
Soil+ 6% C	1.730	18.40
Soil + 10% MKG	1.728	18.70
Soil + 8% MKG + 2% SM	1.602	19.50
Soil + 6% MKG + 4% SM	1.634	19.30
Soil + 4% MKG + 6% SM	1.653	18.20
Soil + 2% MKG + 8% SM	1.710	16.40
Soil + 5% MKG	1.715	17.90
Soil + 5% MKG + 2% SM	1.692	18.50
Soil + 5% MKG + 4% SM	1.696	18.20
Soil + 5% MKG + 6% SM	1.722	16.30
Soil + 5% MKG + 8% SM	1.755	15.90

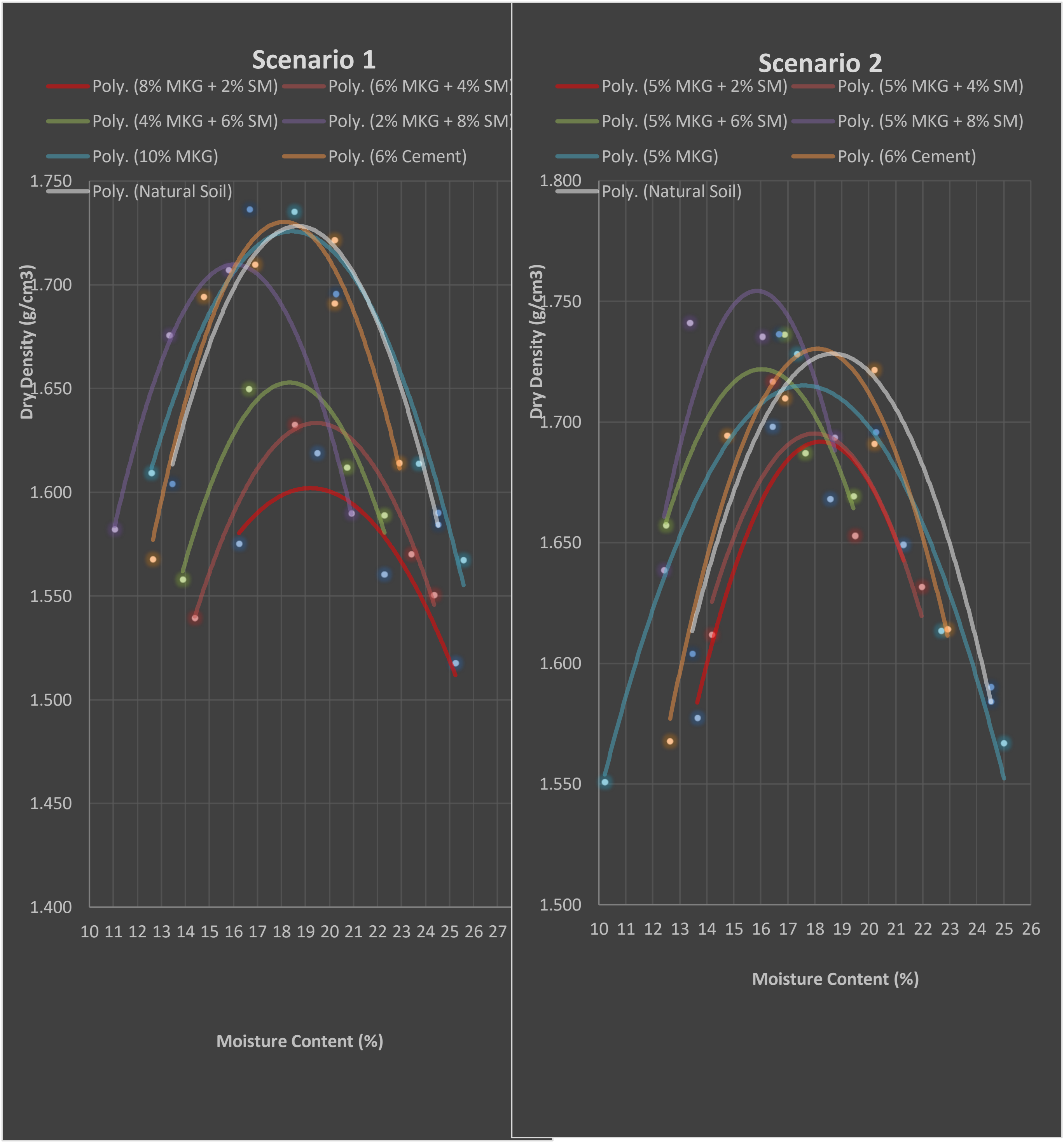


Fig 8: Moisture content-dry density relationships in the stabilization scenarios

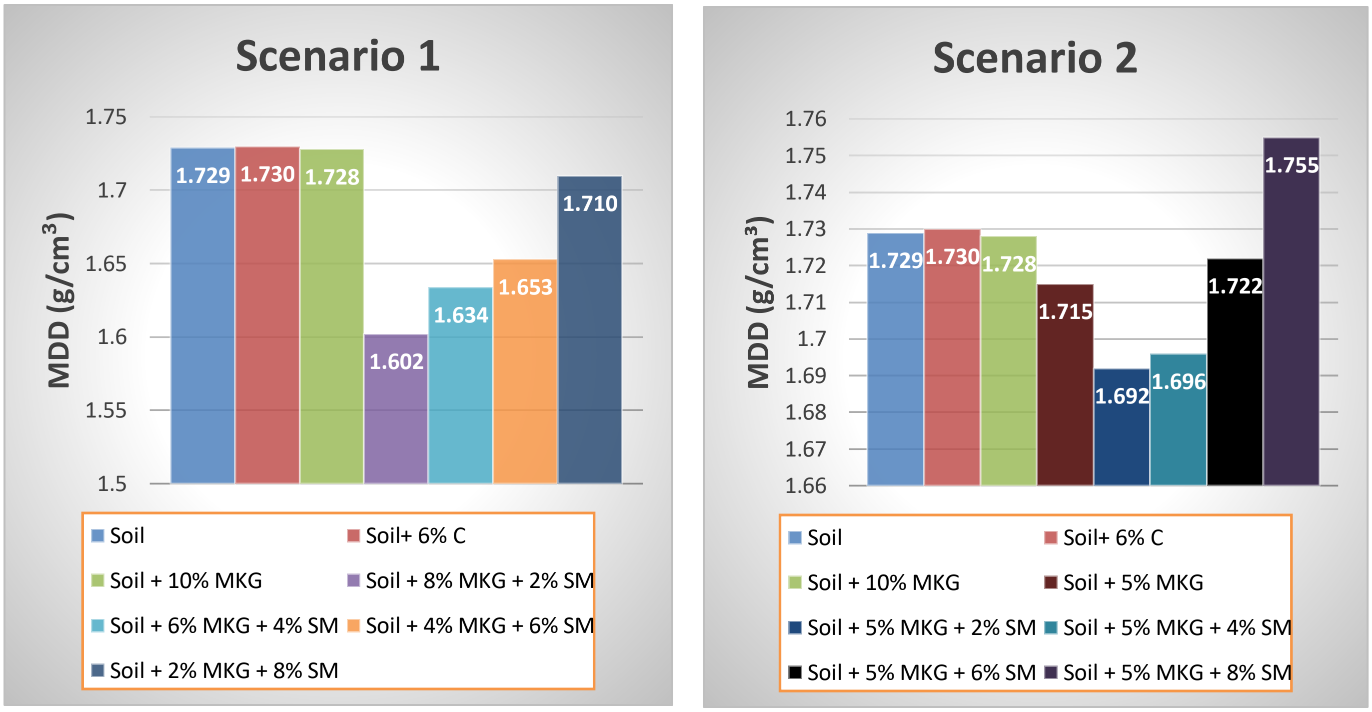


Fig 9: Effect of sugarcane molasses and metakaolin based geopolymer on the Maximum Dry Density of laterite soil

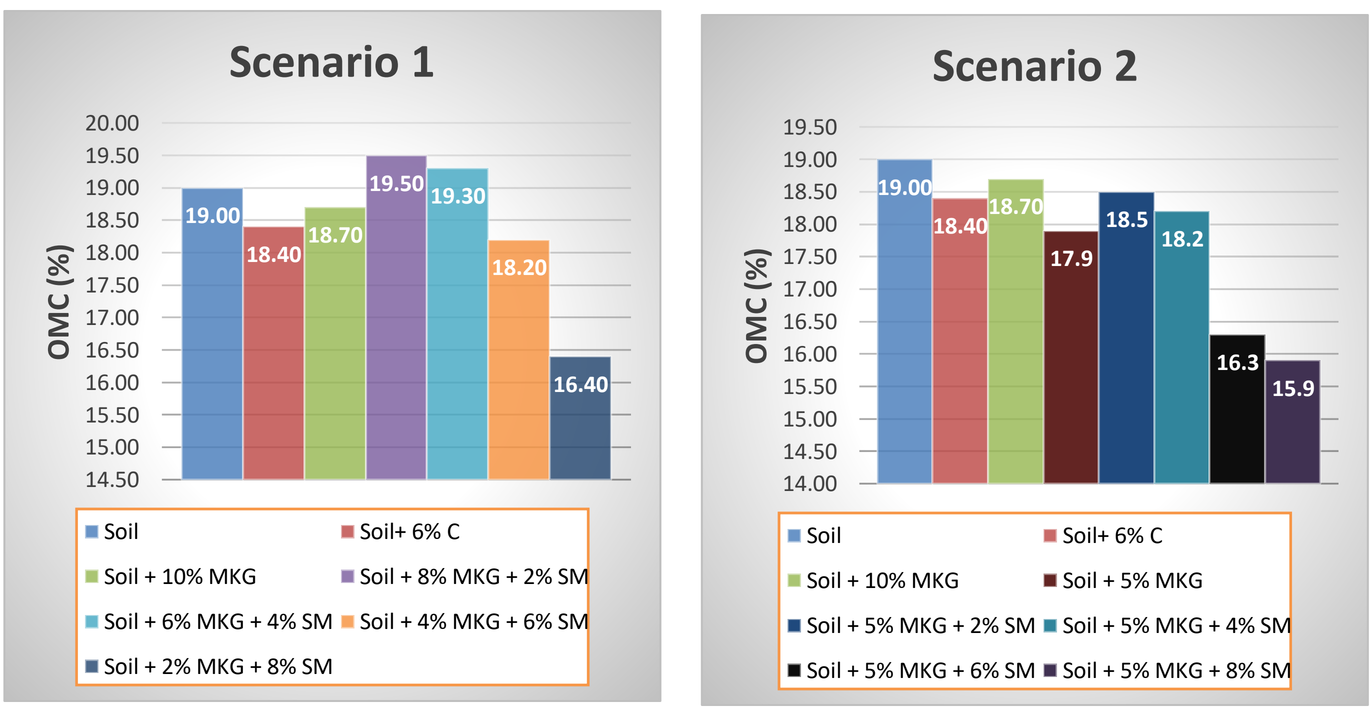


Fig 10: Effect of sugarcane molasses and metakaolin based geopolymer on the Optimum Moisture Content of laterite soil

VI. CONCLUSIONS

From the results of the above-mentioned experimental investigations, the following conclusions have been drawn:

(i) Sugarcane molasses decreases the LL of the stabilized soil with the metakaolin-based geopolymer.

(ii) The PL of the stabilized soil with the metakaolin-based geopolymer decreases as the percentage of sugarcane molasses added increases.

(iii) Sugarcane molasses decreases the PI of the stabilized soil with the metakaolin-based geopolymer. The stabilization of the natural soil with both sugarcane molasses and the metakaolin-based geopolymer is more effective in decreasing the PI of the natural soil than the stabilization of the soil with only the metakaolin-based geopolymer. However, 6% cement (optimum cement content for stabilizing soil) is more effective in reducing the PI of the neat soil than the combinations of sugarcane molasses and metakaolin-based geopolymer.

(iv) The LS of the stabilized soil with the metakaolin-based geopolymer decreases as the percentage of sugarcane molasses added increases. The soil stabilization with both sugarcane molasses and the metakaolin-based geopolymer is more effective in decreasing the LS than the optimum cement and metakaolin-based geopolymer.

(v) At a high percentage, sugarcane molasses increases the MDD of the stabilized soil with the metakaolin-based geopolymer and decreases its OMC.

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