The Effect of Waste Marble Dust and Corncob Ash on the Engineering and Micro-Structural Properties of Expansive Soil for Use in Road Subgrades

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ABSTRACT

This research investigated the effect of Waste Marble Dust (WMD) and Corncob Ash (CCA) on expansive soil's engineering and microstructural properties. Various laboratory experiments were performed on the natural soil to ascertain its characteristics. The corncobs underwent pre-water treatment for fourteen days to remove excess potassium and increase their silica content, resulting in a rise in the silica level from 0% to 50%. At first, only WMD was added to the soil in increments of 5% to 30% using compaction and California bearing tests. The optimum dosage of 15% WMD addition yielded the best result. CCA was then incorporated by the weight of the soil from 2% to 10% in increments of 2% to the first optimum (15% WMD) to obtain the overall optimum for the study (15% WMD and 8% CCA). Stabilization of the natural soil using both materials led to the modification and solidification of the soil mass, evident by the rise in California bearing ratio values from 1.68% to 15.53% and unconfined compressive strength from 41.33 kN/m^2 to 174.68 kN/m^2. There was also a decrease in the soil's free swell from 120% to 15% as well as reductions in the liquid limits from 56.23% to 36.01% and in the plasticity index from 29.74% to 8.72%, respectively. The microstructural images showed the formation of cementitious compounds in the form of calcium silicate hydrate and calcium aluminate hydrate gels. The findings indicate that using WMD and CCA as a unit has great potential in enhancing engineering properties, like strength parameters and the swell potential of expansive soils.

Keywords-corncob ash; expansive soil; free swell index; microstructure; waste marble dust

I. INTRODUCTION

Maintaining and replacing existing pavement hugely increases the budget of transportation agencies [1]. The subsoil-supporting road infrastructure must have a sufficient load-bearing capacity to withstand vehicular traffic [2]. Expansive soils, which exhibit features of shrinking and swelling, are the major causative agents for structural and geotechnical damage to infrastructure worldwide [2, 3]. The structures built on these soils develop defects due to their swell and shrink activities [4-6]. The majority of pavement failures are due to poor subgrade conditions in expansive soils. As a result, the subgrade of road pavements would require some kind of alteration and redesigning to strengthen their ability to support the load [7]. There are huge economic losses due to construction on expansive soils in Africa, Europe, America, and Asia [3, 7-9]. As a way of mitigating these challenges, engineers have adopted various soil improvement techniques. Removing expansive soils and replacing them with coarser soil has become a common practice. However, this process, described as a cost-effective and environmentally friendly solution [10], is expensive and time-consuming, causing unnecessary delays in the project schedule. Thus, it may not always be economical [11, 12]. This is because there are increasing costs associated with the construction and transfer of appropriate soil from distant locations [13], affecting the investment cost of road projects [14].

Geotechnical engineers and transportation engineering professionals have made efforts to develop solutions for expansive soil, with a renewed focus on ecologically friendly mitigation methods, leading to the enhancement of soil properties either through stabilization and modification, or through both [15]. Lime and cement are two frequently used stabilizers for modifying the characteristics of soils. However, environmental pollution is greatly increased by the continuous emissions of carbon dioxide during the manufacture of cement [16]. Additionally, the production of cement requires the massive acquisition of non-renewable raw materials, like limestone, and the activities leading to the acquisition of these resources from the natural surroundings affect the environment. Furthermore, the processing of these raw materials, particularly in factories, releases pollutants into the environment [17]. Stabilizing the subgrade of expansive soils using cement has proved to be expensive and unsustainable [18]. Industrial and agricultural wastes like fly ash and rice husk ash have been utilized to stabilize expansive soils just as efficiently as cement and lime [19, 21]. Waste Marble Dust (WMD), a by-product produced in large amounts during the cutting and processing of marble stones, has been utilized in soil stabilization [20]. It is a mechanical stabilizer, often referred to as stone dust, which primarily works by enhancing gradation, plasticity, and compaction of the soil [11]. This material has an abundance of calcium oxide (CaO) or quicklime [22, 25], a primary ingredient of Portland cement. Its use as a stabilizer for weak soil leads to cation exchange, flocculation, and pozzolanic reactions [14]. Corncob Ash (CCA), an agricultural by-product obtained from the production of corn or maize, on the other hand, has been extensively employed in soil stabilization. It is similar to bagasse ash and rice husk ash with high silica, alumina, and iron oxide content. It can be used as a Supplementary Cementitious Material (SCM) in cement and concrete [12, 21-27].

To the authors' best knowledge, no study has been published regarding the usage of both WMD and CCA on the engineering and microstructural properties of expansive soils. It should be noted that the independent utilization of WMD and CCA did not lead to significant increase in the bearing capacity and reduction in the swell potential of the soils. The extent of chemical bonding between soil particles after stabilizing with these materials through microstructural analysis has yet to be studied. Hence, the current paper focuses on the effect of the combined employment of these materials on the engineering and microstructural properties of expansive soils. The results from this study can ensure the proper utilization of locally available agricultural and mining wastes in road construction, thus contributing to eco-friendly construction.

II. MATERIALS AND METHODS

A. Materials

Expansive soil, WMD, and CCA were the materials employed to conduct this study. Materials from various places across Kenya were sourced. The expansive soil was collected from the Jomo Kenyatta University of Agriculture and Technology (JKUAT) campus in Kiambu County, Kenya. The soil sample was obtained by excavating at a depth of 2 m below the ground surface. The marble dust was collected from the industrial area in Nairobi, Kenya, and was taken to the Ministry of Mining and Petroleum for X-Ray Fluorescence (XRF) to determine its chemical composition. The corn cobs were gathered from local marketers in Juja and Eldoret and transported to the Structural Engineering Laboratory of Jomo Kenyatta University of Agriculture and Technology for pre-water treatment and incineration. The materials are displayed in Figure 1.

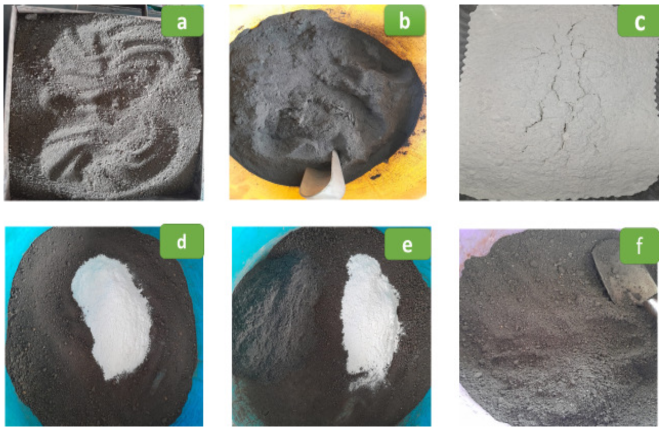

Fig. 1. (a) Expansive soil, (b) CCA, (c) WMD, (d) soil mixed with WMD, (e) soil mixed with CCA, (f) Soil mixed with WMD and CCA.

B. Methods

To remove the excess potassium content in the corn cobs and increase the silica content, which was initially low, the cobs were subjected to water treatment. Figure 2 illustrates the pre-water treatment process for the corn cobs. Water was placed into the tanks containing the corn cobs and was renewed three times a week to facilitate the elimination of the excess potassium. After being removed from the tanks, the cobs were left to dry in the sun for several days in preparation for incineration. The material was subsequently incinerated in open air [28] and filtered through a 0.42 mm sieve [16, 29].

To determine the optimum dosage of the two materials, waste marble dust was initially added to the soil at 5, 10, 15, 20, 25, and 30% by weight of dry soil [24, 30]. Several researchers have adopted this approach to stabilize expansive soils [31, 32]. Two separate tests, compaction and CBR tests [33], were carried out to obtain the optimum WMD content. Thereafter, CCA at 2% intervals, up to the maximum of 10% by weight of the dry soil was added to the soil with the optimum (15%) WMD dosage. The optimum dosage obtained (15% WMD and 8% CCA) from the two materials was used on various experiments, based on prescribed guidelines. The soil particle size analysis was conducted as per [34] procedures. The Atterberg limits (liquid limit, plasticity index, and plastic limit) of the parent materials and their combinations were done as per BS 1377-2:1990 [35, 36]. The specific gravity and free swell index of the samples were determined as per BS 1377-2:1990 [35] and IS 2720 (Part 3) 1980 [37], respectively. Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) values of all the samples were determined based on BS1377- 4:1990 [38].

Fig. 2. Treatment and preparation of CCA: (a) Soaking of cobs, (b) drying of cobs, (c) incineration, (d) sieving, (e) ash.

California Bearing Ratio test was carried out as per BS1377-4:1990 [38]. Each Unconfined Compressive Strength (UCS) test was performed on all combinations [39]. For this test, the samples were prepared by being statically compacted at their respective MDD and OMC, and tested after seven days of curing. The microstructural characteristics were determined with the help of Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD). The samples for the test were prepared at their moisture contents of the optimum mix of 15% WMD and 8% CCA using the UCS test. Initially, SEM and XRD analyses of the untreated samples were determined after seven (7) days of curing. Then, the analysis of the soil samples blended with the optimum percentage of WMD and CCA, was determined after 7, 28, 56, and 90 days of curing. The samples for SEM analysis were mounted onto aluminum SEM stubs using carbon tape and were then coated with carbon to make them conductive. The images were taken on the Tescan MIRA SEM. The operating conditions are observed in the data bar at the bottom of the images.

III. RESULTS AND DISCUSSION

A. *Characterization of Expansive Soil, WMD, and CCA*

1) *Particle Size Distribution*

As indicated in Figure 3 and Table I, the soil was found to have 62% clay, 28% silt, 8% and 2% gravel. This finding describes the soil as gravelly sandy and silty clay. The soil was classified as A-7-6 according to the AASTHO classification system [40], being placed under the category of clay soil. The abundance of clay in the soil suggests that the latter was weak and poor to be utilized as a subgrade material, and it was therefore necessary for it to be stabilized to become befitting for use as a road subgrade material [41].

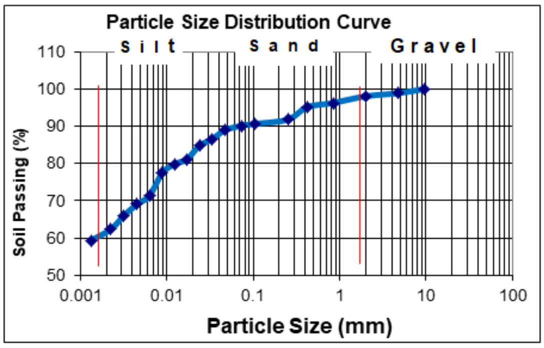

Fig. 3. Particle size distribution curve.

TABLE I. PHYSICO-MECHANICAL PROPERTIES OF EXPANSIVE SOIL

Property	Value
Specific gravity, %	2.47
Moisture content, %	6.41
Gravel, %	2
Silt content, %	28
Sand content, %	8
Clay content, %	62
Liquid limits, %	56.23
Plastic limit, %	26.50
Plasticity index, %	29.74
FSI, %	120
OMC, %	32.7
MDD, g/cm^3	1.33
UCS, kN/m^2	41.33
AASHTO classification	A-7-6
CBR (%)	1.68

2) *Chemical Composition of Materials*

As shown in Table II, the chemical compositions of the research materials were determined using the XRF apparatus. The most abundant oxides in the expansive soil were silicon oxide (SiO_2) at 76.136%, aluminum oxide (Al_2O_3) at 11.1833%, and ferrous oxide (Fe_2O_3) at 8.887%. Calcium oxide (CaO) was discovered to be the most abundant oxide in WMD, accounting for 51.65%. These results indicate that WMD has a sufficient amount of CaO, similar to cement. The main oxides detected in CCA were silica oxide (SiO_2) (50.009%) magnesium oxides (MgO) (12.599%), ferrous oxide (Fe_2O_3) at 4.639%, and aluminum oxide (Al_2O_3) at 4.530%. The cementitious properties of a CaO content greater than 20% or the pozzolanic and cementitious properties of a CaO content between 10% and 20%, as discussed by [43-44] were satisfied. The ratio of (CaO + MgO)/SiO_2 to exceed 1 for cementitious materials [44] was not satisfied. However, a conclusion that CCA could possess pozzolanic properties was reached since the BSI's requirement of a SiO_2 content of at least 25% was satisfied. The obtained results indicate that the CCA contains a SiO_2 content of 50.009%, which exceeds the recommended minimum requirement of 25% according to BS EN 197-1 (2011) [44] and 39.90% according to ASTM C618 [45]. The total SiO_2+Fe_2O_3+Al_2O_3 content is 59.178% and falls short of the minimum requirement of 70% of ASTM C618 for classification as Class N and Class F pozzolana. However, it meets the minimum requirement of 50% as per ASTM C618 and can be consequently classified as a class C pozzolana.

TABLE II. CHEMICAL COMPOSITION OF MATERIALS

Analysis (%)	Expansive soil	WMD	CCA
CaO	1.478	51.65	13.89
SiO_2	76.14	3.42	50.01
Al_2O_3	11.18	2.05	4.530
Fe_2O_3	8.887	1.26	4.639
MgO	-	-	12.6
K_2O	0.511	0.01	5.784
SO_3	-	-	-
Na_2O	0.002	0.001	0.01
LOI	-	39.59	2.65

B. Influence of WMD and CCA Atterberg Limits

The combination of the two materials (15% WMD and 8% CCA) exhibited a reduction of the liquid limit from 56.23% to 36.01%, as shown in Figure 4. Based on the reduction in the liquid limit, the soil behaves as a highly expansive soil [46]. As demonstrated in Figure 5, the plastic limit which defines the moisture content at which the soil changes from semisolid to plastic increased with the addition of stabilizers. This could be due to the introduction of fine particles into the soil, which altered its mineralogy and cation exchange capacity.

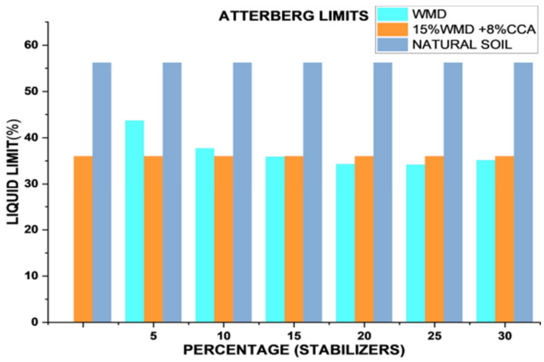

Fig. 4. Liquid limit.

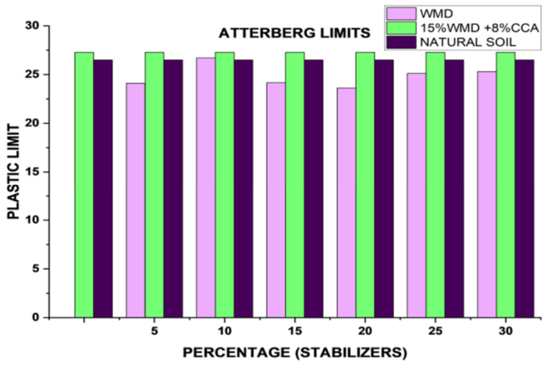

Fig. 5. Plastic limt.

Figure 6 presents the Plasticity Index (PI), which represents the difference between the liquid limit and the plastic limit. The combination of 15% WMD and 8% CCA resulted in a reduction in PI from 29.74% to 8.72%, which is a 70.6% decrease. This result satisfies the 15% minimum PI value, suggested by the Pavement Guidelines for Low-Volume Sealed Roads in Kenya [47]. The process of conducting the test is depicted in Figure 11.

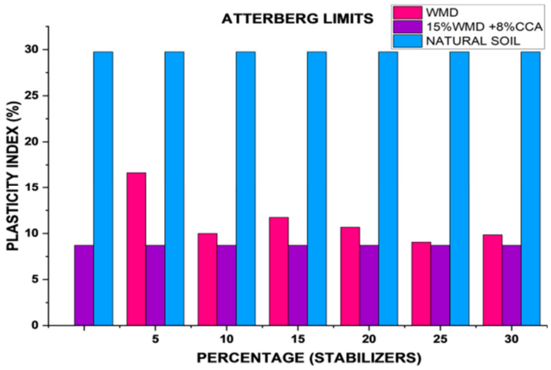

Fig. 6. Plasticity index.

C. Influence WMD and CCA Compaction Parameters

The combination of 15% WMD obtained through utilizing waste dust as a stand-alone material and varying percentages of CCA during compaction experienced a rise in MDD at only 2% addition of CCA. This could be due to the replacement of light soil particles by the larger WMD particles [25, 31]. Beyond 2%, the MDD kept decreasing, as spotted in Figure 7. This could be an outcome of the soil becoming lighter when the content of stabilizer increased. On the other hand, OMC kept reducing gradually with up to 6% CCA addition to 15% WMD.

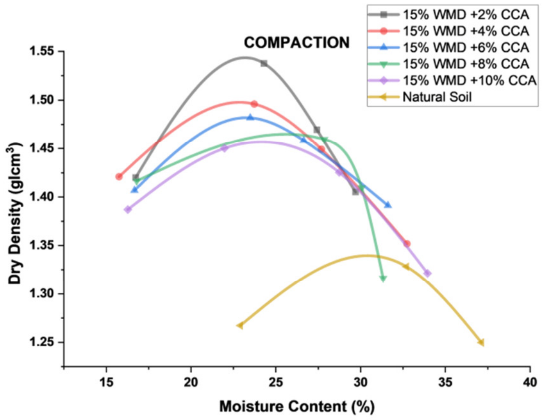

Fig. 7. Compaction with the optimum mix.

D. Influence of WMD and CCA on CBR Expansive Soil

The CBR test, an essential parameter for examining the strength of the subgrade of roads, was determined. Before testing, samples for the natural and blended soils were prepared at their optimum moisture contents and were soaked for four days [30, 48]. Adding different percentages of WMD increased the CBR from 1.68% for the natural soil to 4.50%, with the highest CBR value achieved with 15% of the material. Using the optimum of 15% WMD with varying proportions of CCA, the CBR increased from 4.50% to 15.53% for 8% CCA addition. The 15% WMD and 8% CCA were thus used as the optimum addition percentage for all the other experiments. The rise in CBR is attributed to the pozzolanic activities emanating from the reaction between CaO and SiO_2 in WMD and CCA, respectively. Equation (1) highlights the combined reaction. The process of CBR testing is indicated in Figure 11.

$$CaO + SiO_2 \rightarrow CaOSiO_3 \quad (1)$$

The formation of cementitious compounds like Calcium Silicate Hydrate (CSH) could also occur, leading to an augmentation in the bearing capacity. Equation (2) highlights the process of the CSH reaction. The result of the CBR test is outlined in Figure 8.

$$Ca^{2+} + 2OH^{-} \rightarrow 3CaO.2SiO.3H_2O \text{ or } CSH \quad (2)$$

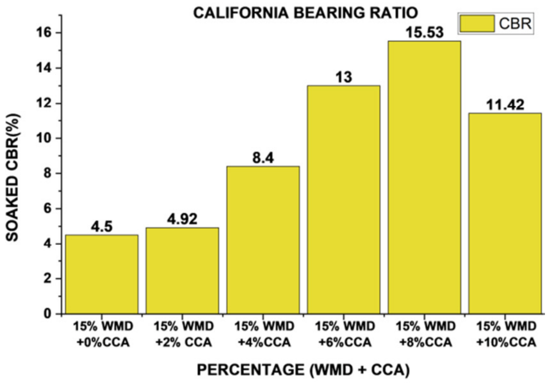

Fig. 8. CBR with the optimum mix.

E. *Influence of WMD and CCA on Unconfined Compressive Strength*

There was an increase in the Unconfined Compressive Strength (UCS) value from 41.33 kN/m^2 for the natural soil to 174.68 kN/m^2, using the optimum mixture with 15% WMD and 8% CCA. The results were obtained after 7 days of curing of the samples. There were further increments in the UCS value after 14, 28, and 56 days of curing. These increments in the UCS values could be caused by the pozzolanic reaction [51,53] from the use of the two stabilizers with curing time. These results were higher than the ones acquired when the stabilizers were separately utilized. The findings from the UCS test are displayed in Figure 9.

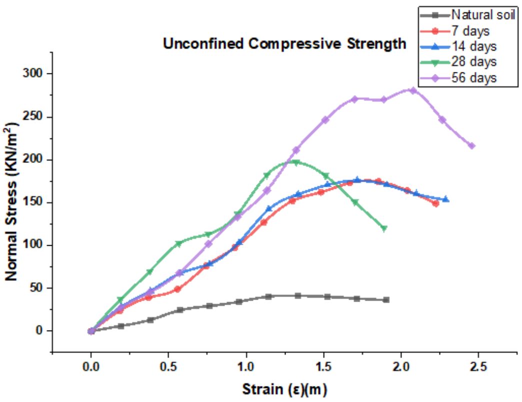

Fig. 9. Unconfined compressive strength.

F. *Influence of WMD and CCA on Free Swell Index*

The findings obtained from the free swell index test are detected in Figure 10. The results show a reduction in swelling with increasing content of WMD. This pattern aligns with the findings of [31]. The presence of CaO could be responsible for this modification and reduction in swell, due to the cation ion exchange that emerges from the reaction of CaO or quicklime with water to form calcium hydroxide ($Ca(OH)_2$) or slaked lime. The reduction in the free swell could be an outcome of the decrease in the specific surface as well as the placement of the soil with materials that have non-swelling and pozzolanic characteristics [31]. As reported in [52], further dissolution of $Ca(OH)_2$ in water breaks into OH^- and Ca^{2+}, thus reducing the double diffused layer thickness of the soil particles. The reaction is indicated in (4) and (5).

$$CaO + H_2O \rightarrow Ca(OH)_2 + \text{Heat} \quad (3)$$

$$Ca(OH)_2 \rightarrow Ca^{2+} + 2OH^{-} \quad (4)$$

The optimum combination of WMD and CCA leads to a drop in the swell from 120% to 15%. This result changes the soil type from expansion to low expansion [47, 55], exhibiting a significant reduction in the swell potential.

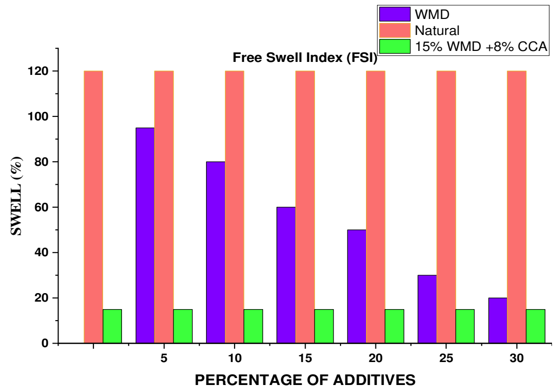

Fig. 10. Free swell index with the optimum mix.

Fig. 11. Tests conducted during the study.

G. *Microstructural Analysis of Expansive Soil Blended with WMD and CCA*

1) *Scanning Electron Microscopy*

From the microstructural analysis using SEM, large voids having honeycomb-like structures were observed in the natural soil. Figure 12 displays significant pores in the expansive soil, indicating shrinkage fractures caused by its interaction with moisture. Authors in [54] observed a similar pattern. The SEM image of the soil clearly showed the existence of several larger void spaces and a less cohesive soil structure. However, the introduction of the WMD-CCA mix resulted, after 7 days of curing, in the filling of the voids. The soil particles underwent flocculation, leading to the development of calcium silicate hydrate gel. After 7 days of curing, there was a creation of bigger particles and a reduction in the size of larger pores, as portrayed in Figure 12. As a result, the attraction forces between particles reduce the material's ability to change shape and ultimately increase its ability to withstand compression. Additionally, the soil matrix experienced enhancement after a 14-day curing period. The WMD-CCA mixture and the natural soil reaction with moisture caused an alteration in the distribution of pore sizes. This reaction led to an increase in cementing agents and the aggregation of particles [55]. There was an overall increment in the compressive strength of the soil matrix, after 56 days of curing [49], due to the presence of gritty and rough surfaces that were detected in the SEM images. At 90 days of curing, there was a full densification of the soil particles, leading to the formation of cementitious compounds.

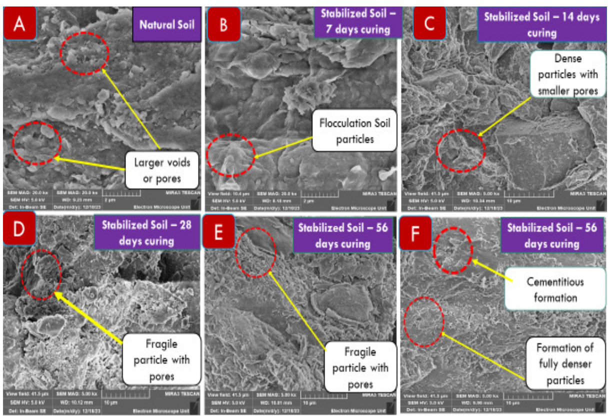

Fig. 12. SEM images for 7 - 90 days of curing.

2) *X-Ray Diffraction (XRD) Analysis*

XRD analysis determines the crystallographic arrangement of a substance. It is advantageous for determining the mineralogical composition of crystalline substances, such as minerals, rocks, soils, and other solid materials. Figures 13 and 14 present the XRD images of the untreated expansive soil and the soil with stabilizing materials (15% WMD and 8% CCA) after a 28-day curing period. These images provide an insight into the mineralogical modifications in the soil treated with stabilizers.

Dolomite, a kind of CaO and magnesium oxide (MgO) exhibited a greater peak in the soil-WMD-CCA combination. The presence of dolomite in WMD could be responsible for the production of a densely packed soil matrix, leading to an increase in the soil strength. Quartz and orthoclase were also identified as the dominant components in the soil and CCA. The presence of quartz in the soil and the CCA contributes to durability and aids the formation of calcium silicate hydrate and calcium aluminate hydrate gel in the presence of water [49]. These minerals contributed to the increase of the CBR and UCS of the soil. The mineralogical compositions of the materials can be pinpointed in Table III.

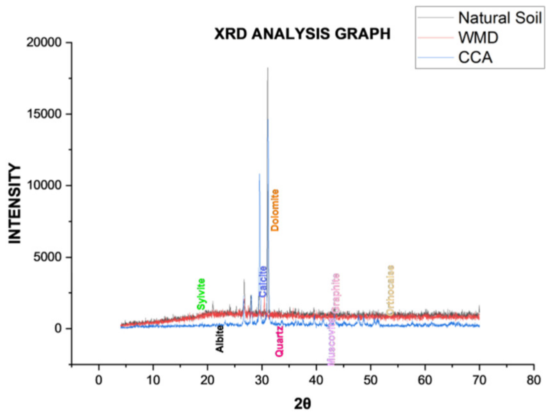

Fig. 13. XRD analysis of the materials.

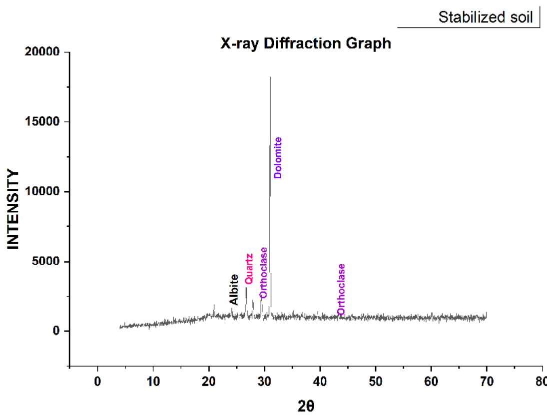

Fig. 14. XRD analysis of stabilized soil.

TABLE III. MINERALOGICAL COMPOSITION OF THE MATERIALS THROUGH XRD ANALYSIS

Materials	Phases identified from XRD
Natural soil	Quartz, Muscovite, Albite, Orthoclase
WMD	Dolomite, Calcite, Orthoclase, Quartz
CCA	Sylvite, Albite, Graphite, Orthoclase, Quartz
Stabilized Soil	Dolomite, Albite, Calcite, Orthoclase, Quartz

IV. CONCLUSION

In this study, the effects of the addition of Waste Marble Dust (WMD) and Corncob Ash (CCA) on the engineering and microstructural properties of the soil were assessed and the following conclusions were drawn:

- Integrating WMD and CCA led to enhancements in Atterberg limits, by specifically decreasing the Plasticity Index (PI) and the Liquid Limit (LL), and slightly increasing the Plastic Limit (PL), compared to the use of these materials separately. The improvement of the compaction parameters, witnessed through an increase in the Maximum Dry Density (MDD) and a decrease in Optimum Moisture Content (OMC), leads to higher soil stability and appropriateness for road subgrades.

- The optimum addition mixture was defined as 15% WMD and 8% CCA.
- The California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) values showed satisfactory improvements with the combined optimum mixture. The high strength gain indicates that WMD and CCA, when used as a unit have far greater potential to increase the load-bearing capacity and overall strength of expansive soils.
- The Scanning Electron Microscopy (SEM) analysis on the stabilized soil samples demonstrated noticeable alterations in the soil mass with increasing curing time. The denseness in the soil mass and the filling of large voids are traceable to the formation of CSH and CAH gel leading to the development of cementitious compounds and pozzolanic activities. The X-Ray Diffraction (XRD) examination on the stabilized soil matrix revealed the presence of newly created stable compounds, which correlates with the enhanced strength.

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