Performance of Expansive Soil blended with Waste Marble Dust and Natural Pozzolana for Road Subgrade

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Received: 9 December 2024 | Revised: 6 January 2025 and 26 January 2025 | Accepted: 31 January 2025

 DOI: https://doi.org/10.48084/etasr.9891

ABSTRACT

This research examined the effects of Natural Pozzolana (NP) on expansive soil blended with Waste Marble Dust (WMD), focusing on improving its engineering properties. The NP was sourced from Kanzenze, Rubavu, Rwanda, oven-dried, ground into powder, and sieved to 0.452 mm. WMD was added to the soil in 5% increments (5%-30%), with the optimal dosage found at 25%. The California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) tests showed that untreated soil had a CBR of 1.1%, UCS of 93.213 kN/m², a Plasticity Index (PI) of 39.5%, and linear shrinkage of 15.21%. Adding 25% WMD increased the CBR to 4.82% and UCS to 163 kN/m² after 7 days of curing, reaching 190 kN/m² and 219.5 kN/m² after 14 and 28 days, respectively. PI decreased to 25.38%, and linear shrinkage reduced to 13.93%. However, these values were below the standards of Kenya's Pavement Guidelines. Incorporating 20% NP also enhanced soil properties, with CBR increasing to 10.4%, UCS reaching 184.76 kN/m² after 7 days, 223.38 kN/m² after 14 days, and 371.819 kN/m² after 28 days. PI decreased to 13.93%, and linear shrinkage dropped to 11.5%. These results met the requirements of 15% PI and 5% CBR. The study results suggest that the combined use of WMD and NP significantly enhances the strength of expansive soils.

Keywords-waste marble dust; natural pozzolana; expansive soil; consistency limits; compaction; strength

I. INTRODUCTION

Soil is an essential component in different civil works. It is serving as both foundation and primary material [1]. It is very problematic when natural soil is unable to fulfill its intended function due to its strength limitations [2, 3]. Roads are generally made of several layers, including the sub-grade, sub-base, base, and surface layers [4]. The sub-grade consists of natural, undisturbed soil or imported fill material [5]. The natural soil must be sufficiently strong to support traffic loads without damaging the road [6]. It is very problematic when the subgrade layer of pavement is constructed under expansive soil [1]. Expansive soils present significant challenges for civil engineers, as they can be a natural hazard that causes severe damage to structures if not properly managed [7-9]. Their tendency to swell in wet conditions and shrink in dry conditions complicates construction projects [10-12]. In fact, expansive soils are responsible for more structural damage than any other natural hazard, including earthquakes and floods, if untreated [9, 13, 14] and the effects of expansive soil sum up to billions of dollars [15-17].

The process of stabilizing expansive soils started a long time ago [18, 19]. Cement and lime are widely used as stabilization agents for treating expansive soil [20, 21]. The use of cement in construction increases project costs [22-24] and poses environmental concerns [25, 26]. Assessing the environmental effects of cement production has become crucial for economic development [27-29]. Nevertheless, cement manufacturing is energy-intensive and leads to pollution, contributing to global warming by representing 5% of total carbon dioxide emissions [30-33]. This percentage encompasses both direct emissions from burning fossil fuels and indirect emissions from the production process [34, 35]. The utilization of various materials has been suggested to reduce cement production. Waste Marble Dust (WMD), a byproduct of cutting and polishing marble stone rich in calcium oxide (CaO), also known as quicklime [16, 36, 37], has been proposed as an alternative to reduce cement usage. Million tons of WMD are produced annually in many countries [11, 38, 39]. Marble dust is important in the construction industry, particularly for stabilizing expansive soil by reducing swelling, Plasticity Index (PI), and Optimum Moisture Content (OMC), while enhancing Unconfined Compressive Strength (UCS), California Bearing Ratio (CBR) and Maximum Dry Density (MDD) [40-42]. However, when WMD is used alone to stabilize clayey soil, it fails to meet the required standards for CBR, swell potential, and PI [40].

Pozzolanic materials have also been proposed to be used to improve soil properties. These materials are divided into two categories, namely natural and artificial. Materials such as volcanic ash, volcanic tuff, and pumice are classified as Natural Pozzolana (NP) while silica fume, fly ash, and blast furnace slag are artificial [3, 43]. ASTM C 125 (2003) defines pozzolana as a material made up of silica, or a mix of silica and alumina that when finely powdered and in the presence of moisture, it chemically reacts with calcium hydroxide at normal temperatures to produce cementitious properties [24, 44, 45]. NP (rock) and volcanic ash have been added on lime stabilized clayey soil and the results show considerable improvement in terms of reducing PI and swelling index and increasing durability and strength. After treating lime with additives, the results obtained from the combined materials are superior than that acquired with lime itself while being cost effective [24, 46, 47]. It is necessary to incorporate NP into clayey soil stabilized with the optimal amount of WMD, as the independent utilization of these materials may either weaken the strength or fail to provide significant improvements [40, 46]. To the best of the authors' knowledge, no research has been published on the combined use of NP and WMD. Recently, researchers have conducted studies on combining NP and lime, and the results show considerable high improvement in comparison with the obtained results when using NP or lime alone [19, 24]. This paper investigates the combined effects of NP and WMD on the engineering properties of expansive soils. The findings encourage the sustainable utilization of local material and mining waste in road construction, thereby fostering environmentally friendly building practices.

II. MATERIALS AND METHODS

A. *Materials*

Expansive soil, WMD, and NP (rock) were used in this study. The soil was collected from the site in Kiambu, Kenya. The soil sample was collected from a test pit to a depth of 2 m beneath the ground surface. WMD was collected from the industrial area in Nairobi, Kenya while NP was collected from Prime Cement Ltd located in Musanze district, Rwanda. X-Ray Fluorescence (XRF) was performed on all the materials to determine their chemical compositions. Figure 1 shows the materials used to conduct this research.

Fig. 1. (a) Expansive soil, (b) WMD, (c) oven dried NP, (d) crushed product of NP.

B. *Methods*

NP was collected from a quarry located in Rubavu District, Rwanda. The material was transported in Prime Cement Ltd located in Musanze, Rwanda for processing. To remove the water from the pores, the material was oven dried for 24 h, then a vibratory mill was used to crush the rock into fine particles which passed through a 0.425 mm sieve. Figure 2 illustrates the full process to obtain fine particles.

Fig. 2. Treatment and preparation of NP: (a) Collection, (b) oven drying, (c) crushing in vibratory mill, (d) powder.

To determine the optimum amount of the two different required materials, WMD was first mixed with the soil in proportions of 5, 10, 15, 20, 25, and 30% by the dry weight of the soil [36-38, 47]. Standard compaction, CBR, and UCS tests were carried out to determine the optimum amount required to stabilize the expansive soil. After that, NP in proportions of 5, 10, 15, 20, 25, and 30% of the dry soil was added on the optimum WMD dosage sample. The particle size distribution analysis was determined per [49, 50]. Atterberg limits (Liquid

Limit (LL), Plastic Limit (PL), and PI) of the neat and treated samples were carried out per BS 1377-2:1990 [51]. Compaction test (MDD and OMC) and CBR tests for all combinations were determined under BS 1377-4:1990 [40, 52]. UCS after 7, 14, and 28 days of curing was tested under BS 1377- 7: 1990 [52].

III. RESULTS AND DISCUSSION

A. Expansive Soil, WMD, and NP Characterization

1) Particle Size Distribution

Results from sieve and hydrometer analysis showed that the test soil consisted of 70.1% clay, 25.0% silt, 1.9% sand, and 3.1% gravel. The LL and PL were 61.6% and 22.1%, respectively. The soil was classified as high plastic clay (CH) according to the Unified Soil Classification System. The Untreated CBR value was 1.1%. Figure 3 shows the particle size distribution curve while Table I summarizes the physical properties of the test soil. This soil is very weak to be used as subgrade material, and its stabilization is highly recommended.

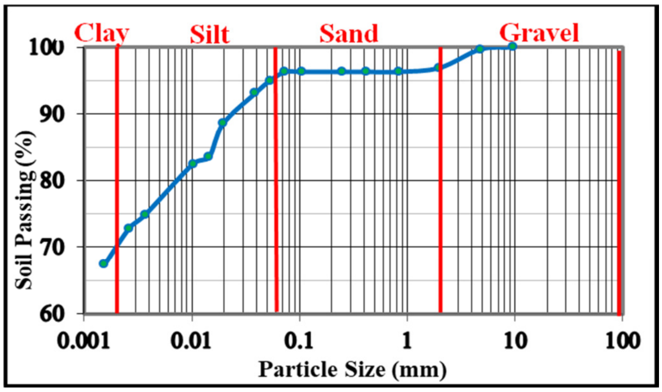

Fig. 3. Particle size distribution curve.

TABLE I. EXPANSIVE SOIL PROPERTIES

Property	Value
Specific gravity, %	2.25
Moisture content, %	7.08
Gravel, %	3.1
Sand content, %	1.9
Silt content, %	25.0
Clay content, %	70.1
LL, %	61.6
PL, %	22.1
PI, %	39.5
FSI, %	83
OMC, %	26.6
MDD, g/cm^3	1.386
UCS, kN/m^2	93.2
CBR (%)	1.1

2) Material Chemical Composition

Table II shows the main chemicals found in all the materials used in this research. The chemical compositions of the materials were determined with the use of the XRF apparatus. The main constituents for the clay were silicon oxide (SiO_2) at 74.609%, aluminum oxide (Al_2O_3) at 7.023%, and ferrous oxide (Fe_2O_3) at 11.509%. WMD is a calcium oxide (CaO) based material (87.190%), with 1.585% SiO_2, 2.280% Al_2O_3, 0.487% Fe_2O_3, and 6.096% Magnesium Oxide (MgO). NP was discovered to have 20.870% CaO, 12.725% Fe_2O_3, and 46.270% SiO_2.

TABLE II. CHEMICAL COMPOSITION OF MATERIALS

Constituent (%)	Clay	WMD	NP
CaO	2.086	87.190	20.870
SiO_2	74.609	1.585	46.270
Al_2O_3	7.023	2.280	8.398
Fe_2O_3	11.509	0.487	12.725
MgO	-	6.096	-
P_2O_5	-	1.192	0.654
LOI	14.36	25	1.29

B. Influence of WMD Content on Atterberg Limits

Various percentages of WMD, ranging from 5% to 30% in 5% intervals, were mixed with the soil. As the amount of WMD increased, the LL and PI decreased, while the PL increased as can be seen in Figure 4.

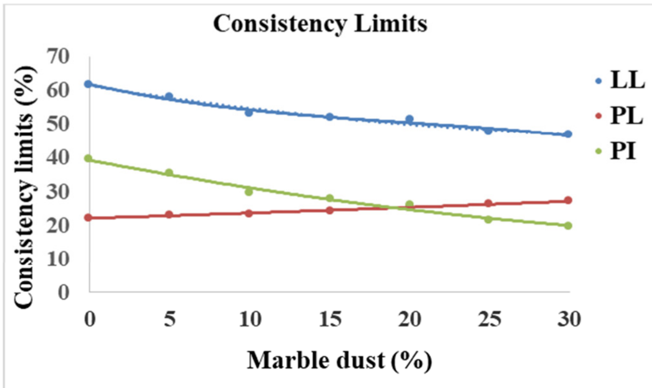

Fig. 4. Consistency limits.

The results presented in Figure 4 showed that the LL decreased from 61.6% to 47.8% at the optimal WMD. This change was attributed to the formation of calcium ions (Ca^{2+}) that replaced sodium ions (Na^+) in the clay's double-layer structure, leading to the formation of cementitious compounds, specifically Calcium Silicate Hydrate (C-S-H) and Calcium Aluminate Hydrate (C-A-H). The formation of these compounds reduced the water-retaining capacity of the expansive soil. The PL increased from 22.1% to 22.42% due to the introduction of WMD, which formed cementitious compounds that enhanced interparticle bonding, making the soil stiffer and less malleable at higher moisture contents. Stabilizing expansive soil with WMD lowered the PI from 39.5% to 25.38%. This reduction was attributed to the combined effects of the decrease in the LL and the increase in the PL. Incorporating WMD into the expansive soil reduced the cohesion between particles, and the cementitious compounds formed after the addition of WMD lowered the soil's plasticity. Linear shrinkage dropped from 15.21% to 13.93%. However, these improvements are below the standards recommended by Pavement Guidelines for Low-Volume Sealed Roads in Kenya, which specifically requires maximum 15% PI.

C. Influence on Atterberg Limits of Optimum WMD combined with NP

Various percentages of NP, ranging from 5% to 30% in 5% increments, were blended with clayey soil stabilized by the optimum amount of WMD. Figure 5 illustrates the changes in consistency limits for all the mixtures. The results showed significant improvement when varying amounts of NP were added to the optimal WMD mix. At the optimum combination of WMD and NP, the LL decreased from 47.8% to 40.9%. Incorporating NP into the optimal WMD led to the formation of strong cementitious compounds, specifically Calcium Silicate Hydrate (C-S-H) and Calcium Aluminate Hydrate (C-A-H). The combination of these materials effectively reduced the water-retaining capacity of the expansive soil. The PL increased with increasing NP dosage 22.42% - 26.69%. As more cementitious compounds formed, stronger interparticle bonds were created, making the soil stiffer and less malleable at higher moisture contents. The PL, which is calculated as the difference between the LL and the PL, was significantly reduced when incorporating optimal NP into clayey soil stabilized with optimal WMD dosage. This combination greatly improved the soil by lowering the PI from 25.38% to 13.93%, indicating enhanced soil properties. Furthermore, linear shrinkage decreased to 11.5%. The result meets the requirement recommended by the Pavement Guidelines for Low-Volume Sealed Roads in Kenya.

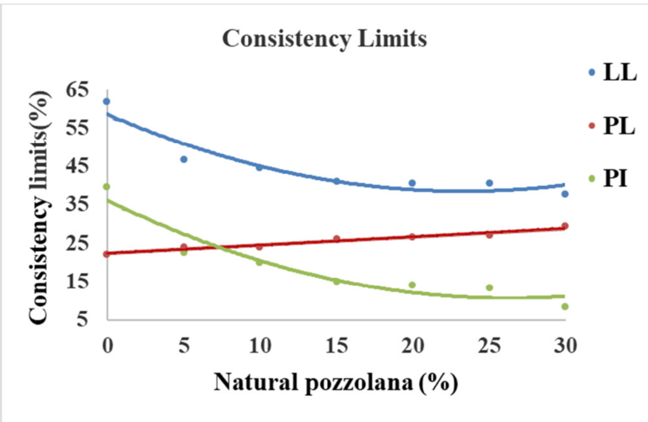

Fig. 5. Consistency limits.

D. Influence of WMD and NP on Compaction Parameters

As the WMD content increased, increase of MDD and reduction of OMC were noticed. At the optimal WMD content of 25%, the MDD increased from 1386 kg/m³ to 1514 kg/m³, and the OMC decreased from 26.6% to 21.8%. The specific gravity of waste marble dust was higher than that of expansive soil (GsWMD = 2.63 > GsBCS = 2.25). Figure 6 illustrates the change in specific gravity after mixing with WMD. The increase in specific gravity resulted in a higher MDD and a lower OMC. Figure 7 shows the relationship between dry density and moisture content

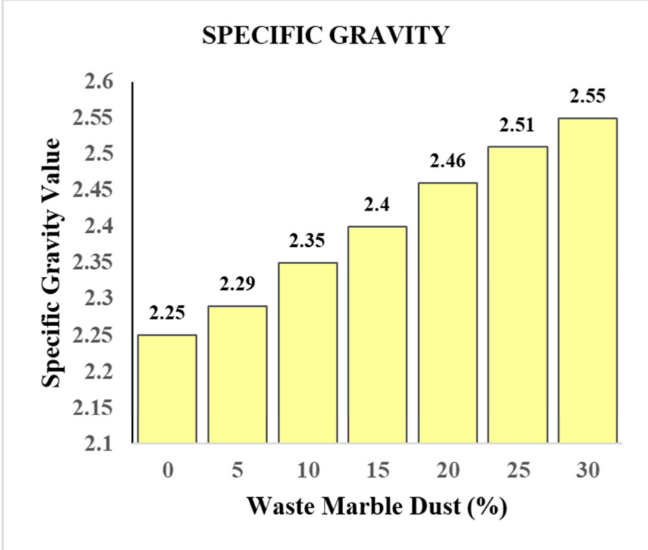

Fig. 6. Change of specific gravity of the expansive soil after mixed with WMD.

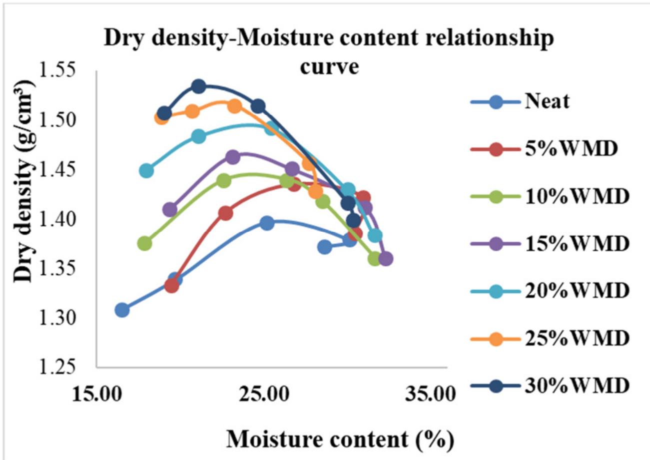

Fig. 7. Dry density-moisture relationship with WMD.

Adding varying percentages of NP to the optimal amount of WMD increased MDD from 1386 kg/m³ to 1519 kg/m³ while the OMC decreased from 26.6% to 22.1%. These changes occurred due to the variation in specific gravity. The rise in MDD is due to the higher specific gravity of NP (Gs NP = 2.73) compared to that of WMD and expansive soil. Figure 8 illustrates the change of specific gravity after NP was mixed with optimum WMD and soil. The combination of two different materials changed further MDD and OMC in accordance with the findings in [46]. Figure 9 shows the dry density-moisture relationship.

E. Influence of WMD and NP on CBR

The addition of WMD increased the CBR of the expansive soil, with the highest value of 4.82% observed at 25% WMD from 1.1% of the neat material. However, this value remained below the minimum recommended CBR of 5% for subgrade, as outlined in the Pavement Guidelines for Low-Volume Sealed Roads in Kenya. Figure 10 shows the CBR results. The incorporation of varying percentages of NP with the optimal WMD significantly improved the strength of the expansive soil. The optimal NP content was found to be 20%, in accordance with the findings in [24]. This led to an increase in CBR from 4.82% to 10.4%, meeting the standard. Figure 11 illustrates the change in CBR with the increasing amount of NP.

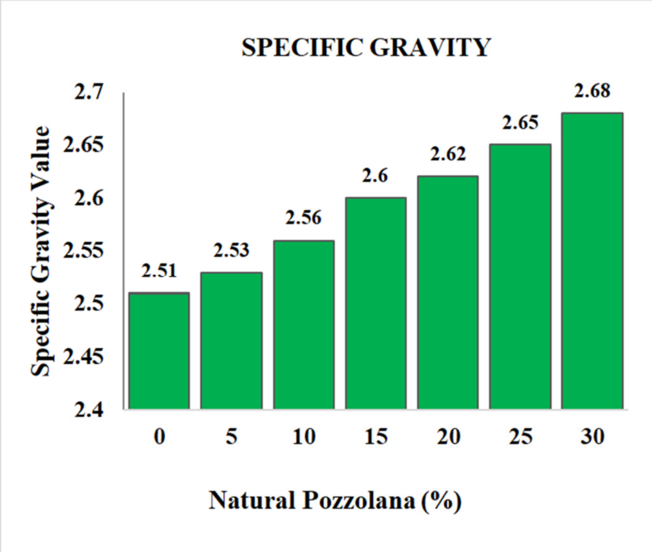

Fig. 8. Change of specific gravity of the expansive soil after mixing with optimum WMD and NP.

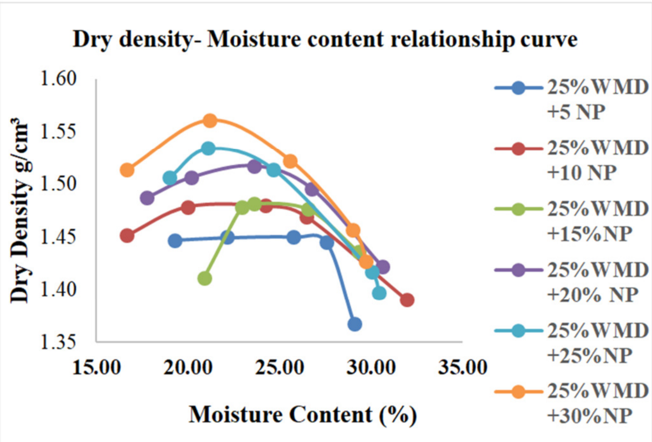

Fig. 9. Dry density-moisture relationship with optimum WMD and varying NP.

F. Influence of WMD and NP on UCS

The UCS was determined for soil untreated and treated with WMD and a combination of optimized WMD and NP. The study examined changes in UCS after 7, 14, and 28 days of curing. The untreated soil exhibited a UCS value of 93.213 kN/m². When treated with optimum WMD, the UCS increased to 163 kN/m² after 7 days of curing. The values continued to rise with curing days, reaching 190 kN/m² at 14 days and 219.5 kN/m² at 28 days. The UCS increase is due to the formation of cementious compounds specifically Calcium Silicate Hydrate (C-S-H) and Calcium Aluminate Hydrate (C-A-H) which developed after stabilizing the clayey soil with WMD. Figure 12 presents the UCS results of expansive soil stabilized with optimum WMD.

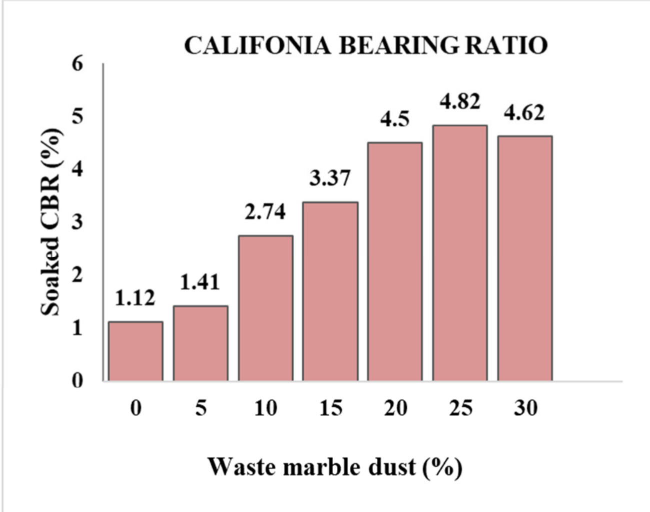

Fig. 10. Soaked CBR of expansive soil treated with WMD.

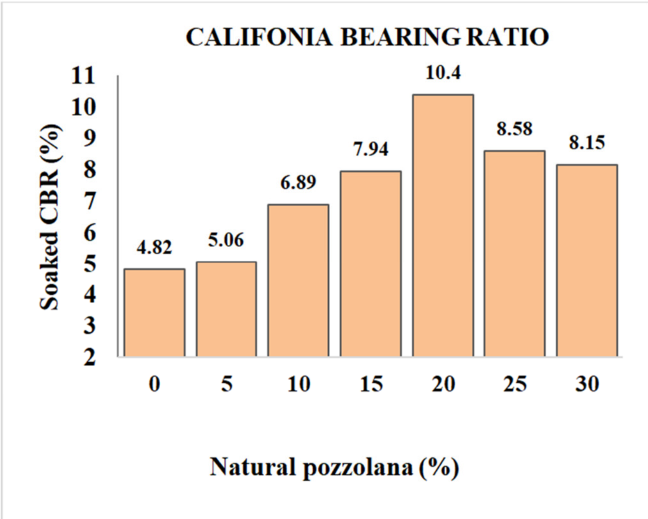

Fig. 11. Soaked CBR of expansive soil treated with optimum WMD and varying NP.

After finding the optimum WMD dosage, varying percentages of NP were added to expansive soil. Significant improvement was observed with increasing curing days. The optimum NP content was determined to be 20%. The UCS reached 184 kN/m² at 7 days, 223.38 kN/m² at 14 days, and 371.819 kN/m² at 28 days. As shown in Figure 13, a higher increase in UCS was achieved when the optimum NPcontent was used to stabilize the expansive soil blended with optimized WMD. Adding NP to WMD-stabilized clayey soil enhanced the cementitious reactions (C-S-H and C-A-H).

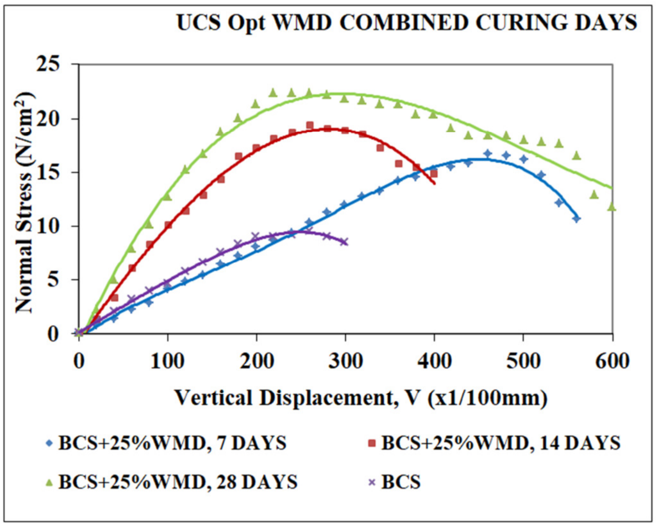

Fig. 12. UCS of expansive soil stabilized by optimum WMD.

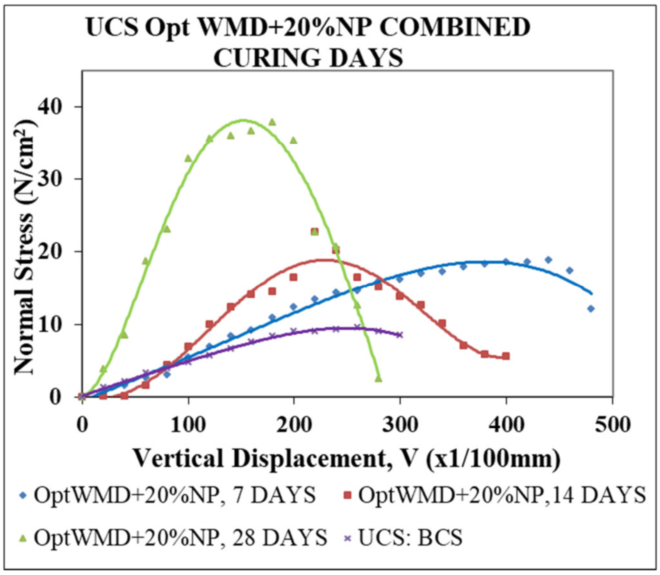

Fig. 13. UCS of expansive soil stabilized with optimum WMD and optimum NP.

The maximum UCS can be found from Figure 13. For stabilizing expansive soil, there it is preferable to combine both materials than using WMD alone. At 28 days, the UCS was highly raising compared to day 7 and 14. When the material reached its maximum stress, the failing behavior was similar to that of a brittle material. The same observation was found on shear mode for prepared samples of both soils stabilized with lime or a combination of NP and lime [46]. The addition of NP to the clayey soil stabilized with WMD reduced the plasticity to some extent, leading to the formation of cracks. Moreover, incorporating NP into clayey soil blended with WMD formed rigid and strong cementitious bonds (C-S-H and C-A-H) between the soil particles. Although these bonds increased the material's strength, they lost elasticity at maximum stress, causing the material to break as a brittle material.

IV. CONCLUSIONS

This study examined the combined use of Waste Marble Dust (WMD) and Natural Pozzolana (NP) to enhance the properties of expansive soil, which is unsuitable for road subgrades due to its high plasticity, significant swelling, low California Bearing Ratio (CBR), and low Unconfined Compressive Strength (UCS). The neat was found to have Plastic Index (PI) of 39. 5%, free swelling index of 83%, MDD of 1386 kg/m³, OMC of 26.6%, CBR of 1.1%, and UCS of 93.213 kN/m^2. Various researchers have proposed WMD as an eco-friendly construction material which can be used to stabilize expansive soil. There is considerable improvement on soil properties after stabilizing with WMD, however its performance alone fails to meet the road subgrade standards.

- Incorporation of 25% of WMD as optimum dosage shows improvement on PI. The PI was reduced from 39.5% to 25.38% and the linear shrinkage was reduced from 15.21% to 13.93%.
- MDD increased from 1386 kg/m³ to 1514 kg/m³ and OMC reduced from 26.6% to 21.8%. The increase of MDD is related to the change of the specific gravity of the material. It was found that WMD is denser than the neat black cotton soil (Gs WMD=2.63>Gs BCS=2.25).
- Incorporation of WMD on expansive soil shows significant effects on CBR and UCS. At 25% WMD, CBR was increased from 1.1% to 4.82% and the UCS was increased from 93.213 kN/m^2 to 219.5 kN/m^2 after 28 days of curing. However, the results did not meet the standard's requirements.

The Pavement Guidelines for Low-Volume Sealed Roads in Kenya require a PI of 15% and a CBR of 5% for road subgrade and incorporating only WMD into expansive soil failed to meet these requirements. So, clayey soil stabilized with optimal WMD was enhanced to ensure that its engineering properties meet the standards. Many researchers have conducted studies on combining NP and lime, and the results show considerable high improvements when these materials are combined. The findings highlight the importance of incorporating NP into expansive soil mixed with an optimal amount of WMD. The combined materials performed significantly better than WMD alone.

- NP was added on clayey soil stabilized by optimum WMD. The best results were found at 20% NP. The PI reduced from 25.38% to 13.93% and the shrinkage limit reduced to 11.5% from 13.93%.
- The MDD increased from 1368 kg/m³ to 1519 kg/m³, while the OMC decreased from 26.6% to 22.1%. This improvement occurred due to the higher specific gravity of the NP. The CBR increased up to 10.4% and the UCS of combined material was superior than that of WMD alone. At 28 days of curing, UCS increased up to 371.819 kN/m^2 from 219.5 kN/m^2.

This study investigated the combined use of WMD and NP to enhance soil strength. The optimal mix of 25% WMD and 20% NP significantly enhanced soil properties, meeting

Kenya's Pavement Guidelines for low-volume roads, addressing the challenges posed by high plasticity and shrinkage. The study offers an eco-friendly solution to the problem by utilizing waste materials for soil stabilization in road subgrade applications.

FUNDING STATEMENT

The authors extend their gratitude to the African Union Commission for providing the financial support for this research and its publication.

ACKNOWLEDGEMENT

The authors sincerely thank the Pan African University Institute for Basic Sciences, Technology and Innovation (PAUSTI) and Jomo Kenyatta University of Agriculture and Technology (JKUAT) for providing access to the laboratories while conducting this research.

REFERENCES

[1] G. Archibong, E. Sunday, J. Akudike, O. Okeke, and C. Amadi, "A review of the principles and methods of soil stabilization," *International Journal of Advanced Academic Research | Sciences, Technology and Engineering*, vol. 6, no. 3, pp. 2488–9849, Mar. 2020.

[2] M. Ashraf, S. M. S. Rahman, Md. O. Faruk, and Md. A. Bashar, "Determination of Optimum Cement Content for Stabilization of Soft Soil and Durability Analysis of Soil Stabilized with Cement," *American Journal of Civil Engineering*, vol. 6, no. 1, pp. 39–43, Jan. 2018, https://doi.org/10.11648/j.ajce.20180601.17.

[3] A. Al-Kalili, A. S. Ali, and A. J. Al-Taie, "A Review on Expansive Soils Stabilized with Different Pozzolanic Materials," *Journal of Engineering*, vol. 28, no. 1, pp. 1–18, Jan. 2022, https://doi.org/10.31026/j.eng.2022.01.01.

[4] A. Adebayo and M. Oloruntola, "Evaluation of Sub Base / Subgrade Soils Along Ikorodu-Shagamu Road," in *First International Conference of the Nigerian Association of Engineering Geology and the Environment*, Lagos, Nigeria, Sep. 2016, pp. 1–9.

[5] T. K. Roy, "Influence of Sand on Strength Characteristics of Cohesive Soil for Using as Subgrade of Road," *Procedia - Social and Behavioral Sciences*, vol. 104, pp. 218–224, Dec. 2013, https://doi.org/10.1016/j.sbspro.2013.11.114.

[6] M. K. Soni and S. Singh, "Statistical Interpretation of Marble Dust and Alccofine for Soil Stabilization," *International Journal of Innovative Technology and Exploring Engineering*, vol. 8, no. 7, pp. 1609–1613, Dec. 2019.

[7] S. Z. Syed Zuber, H. Kamarudin, A. Mustafa, M. M. A. B. Abdullah, M. Binhussain, and M. Salwa, "Review on Soil Stabilization Techniques," *Australian Journal of Basic and Applied Sciences*, vol. 7, pp. 258–265, Jan. 2013.

[8] L. D. Jones and I. Jefferson, "Expansive soils," in *ICE Manual of Geotechnical Engineering*, Second edition., Leeds, England: Emerald Publishing Limited, 2023, pp. 447–478.

[9] M. Mahedi, B. Cetin, and D. J. White, "Cement, Lime, and Fly Ashes in Stabilizing Expansive Soils: Performance Evaluation and Comparison," *Journal of Materials in Civil Engineering*, vol. 32, no. 7, Jul. 2020, Art. no. 04020177, https://doi.org/10.1061/(ASCE)MT.1943-5533.0003260.

[10] A. A. Kassa and A. O. Abdulkadr, "Expansive Soil Stabilization by Waste Marble Dust and Volcanic Ash: Experimental Approach in the Case of Lachi Area, Mekelle, Ethiopia," *Journal of Civil & Environmental Engineering*, vol. 12, May 2022, Art. no. 4, https://doi.org/10.37421/2165-784X.22.12.445.

[11] H. A. M. Abdelkader, M. M. A. Hussein, and H. Ye, "Influence of Waste Marble Dust on the Improvement of Expansive Clay Soils," *Advances in Civil Engineering*, vol. 2021, no. 1, 2021, Art. no. 3192122, https://doi.org/10.1155/2021/3192122.

[12] S. Amena and W. F. Kabeta, "Mechanical Behavior of Plastic Strips-Reinforced Expansive Soils Stabilized with Waste Marble Dust," *Advances in Civil Engineering*, vol. 2022, no. 1, 2022, Art. no. 9807449, https://doi.org/10.1155/2022/9807449.

[13] R. Shumbusho, G. S. Ghataora, M. P. N. Burrow, and D. R. Rwabuhungu, "The Use of Geogrids in Mitigating Pavement Defects on Roads Built over Expansive Soils," *Rwanda Journal of Engineering, Science, Technology and Environment*, vol. 4, no. 1, pp. 1–25, Jul. 2021, https://doi.org/10.4314/rjeste.v4i1.4.

[14] D. Barman and S. K. Dash, "Stabilization of expansive soils using chemical additives: A review," *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 14, no. 4, pp. 1319–1342, Aug. 2022, https://doi.org/10.1016/j.jrmge.2022.02.011.

[15] A. A. Firoozi, C. Guney Olgun, A. A. Firoozi, and M. S. Baghini, "Fundamentals of soil stabilization," *International Journal of Geo-Engineering*, vol. 8, no. 1, Dec. 2017, Art. no. 26, https://doi.org/10.1186/s40703-017-0064-9.

[16] U. Zada *et al.*, "Recent advances in expansive soil stabilization using admixtures: current challenges and opportunities," *Case Studies in Construction Materials*, vol. 18, Jul. 2023, Art. no. e01985, https://doi.org/10.1016/j.cscm.2023.e01985.

[17] P. Akula and D. N. Little, "Analytical tests to evaluate pozzolanic reaction in lime stabilized soils," *MethodsX*, vol. 7, Jan. 2020, Art. no. 100928, https://doi.org/10.1016/j.mex.2020.100928.

[18] A. L. Elson, A. Singh, E. Joy, L. M. John, and T. Mathew, "Soil Stabilization of Cochin Marine Soil Using Locally Available Materials," *International Journal of Innovative Science, Engineering & Technology*, vol. 4, no. 5, pp. 57–61, 2017.

[19] K. Harichane, M. Ghrici, and S. Kenai, "Effect of the combination of lime and natural pozzolana on the compaction and strength of soft clayey soils: a preliminary study," *Environmental Earth Sciences*, vol. 66, no. 8, pp. 2197–2205, Aug. 2012, https://doi.org/10.1007/s12665-011-1441-x.

[20] V. O. Okonkwo and V. M. Nwokike, "Soil-Cement Stabilization For Road Pavement Using Soils Obtained From AguAwka In Anambra State," *Journal of Multidisciplinary Engineering Science and Technology*, vol. 2, no. 10, pp. 2668–2670, 2015.

[21] A. A. Bello, J. T. Olayiwola, and O. S. Awogboro, "Assessment of Flexible Pavement on Some Selected Roads in Ola Oluwa Local Government, South Western Nigeria," *Civil and Environmental Research*, vol. 7, no. 10, pp. 20-24, 2015.

[22] I. Shooshpasha and R. Alijani Shirvani, "Effect of cement stabilization on geotechnical properties of sandy soils," *Geomechanics and Engineering*, vol. 8, no. 1, pp. 17–31, Jan. 2015, https://doi.org/10.12989/gae.2015.8.1.017.

[23] G. S. Kumaran, S. Nsesheye, N. Msinjili, W. Schmidt, M. Florea, and P. Nibasumba, "A study on sustainable energy for cement industries in Rwanda," in *Advances in Cement and Concrete Technology in Africa*, Johannesburg, South Africa, Jan. 2013, pp. 1169–1175.

[24] A. Al-Swaidani, I. Hammoud, and A. Meziab, "Effect of adding natural pozzolana on geotechnical properties of lime-stabilized clayey soil," *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 8, no. 5, pp. 714–725, Oct. 2016, https://doi.org/10.1016/j.jrmge.2016.04.002.

[25] S. P. Dunuweera and R. M. G. Rajapakse, "Cement Types, Composition, Uses and Advantages of Nanocement, Environmental Impact on Cement Production, and Possible Solutions," *Advances in Materials Science and Engineering*, vol. 2018, no. 1, 2018, Art. no. 4158682, https://doi.org/10.1155/2018/4158682.

[26] R. I. Cruz Juarez and S. Finnegan, "The environmental impact of cement production in Europe: A holistic review of existing EPDs," *Cleaner Environmental Systems*, vol. 3, Dec. 2021, Art. no. 100053, https://doi.org/10.1016/j.cesys.2021.100053.

[27] O. Oguntola and S. Simske, "Continuous Assessment of the Environmental Impact and Economic Viability of Decarbonization Improvements in Cement Production," *Resources*, vol. 12, no. 8, Aug. 2023, Art. no. 95, https://doi.org/10.3390/resources12080095.

[28] O. E. Ige, O. A. Olanrewaju, K. J. Duffy, and O. C. Collins, "Environmental Impact Analysis of Portland Cement (CEM1) Using the

Midpoint Method," *Energies*, vol. 15, no. 7, Jan. 2022, Art. no. 2708, https://doi.org/10.3390/en15072708.

[29] O. E. Ige, K. J. Duffy, O. A. Olanrewaju, and O. C. Collins, "An Integrated System Dynamics Model and Life Cycle Assessment for Cement Production in South Africa," *Atmosphere*, vol. 13, no. 11, Nov. 2022, Art. no. 1788, https://doi.org/10.3390/atmos13111788.

[30] S. Adjei and S. Elkatatny, "A highlight on the application of industrial and agro wastes in cement-based materials," *Journal of Petroleum Science and Engineering*, vol. 195, Dec. 2020, Art. no. 107911, https://doi.org/10.1016/j.petrol.2020.107911.

[31] D. Song, J. Yang, B. Chen, T. Hayat, and A. Alsaedi, "Life-cycle environmental impact analysis of a typical cement production chain," *Applied Energy*, vol. 164, pp. 916–923, Feb. 2016, https://doi.org/10.1016/j.apenergy.2015.09.003.

[32] M. Uwasu, K. Hara, and H. Yabar, "World cement production and environmental implications," *Environmental Development*, vol. 10, pp. 36–47, Apr. 2014, https://doi.org/10.1016/j.envdev.2014.02.005.

[33] W. Chinkhuntha, A. Owayo, and N. Ambassah, "Performance Evaluation of Red Clay Soils stabilized with Bluegum Sawdust Ash and Sisal Fiber as Low-Volume Road Sub-base Materials," *Engineering, Technology & Applied Science Research*, vol. 14, no. 6, pp. 18105–18113, Dec. 2024, https://doi.org/10.48084/etasr.8772.

[34] T. Gao, L. Shen, M. Shen, F. Chen, L. Liu, and L. Gao, "Analysis on differences of carbon dioxide emission from cement production and their major determinants," *Journal of Cleaner Production*, vol. 103, pp. 160–170, Sep. 2015, https://doi.org/10.1016/j.jclepro.2014.11.026.

[35] J. Ke, M. McNeil, L. Price, N. Z. Khanna, and N. Zhou, "Estimation of CO2 emissions from China's cement production: Methodologies and uncertainties," *Energy Policy*, vol. 57, pp. 172–181, Jun. 2013, https://doi.org/10.1016/j.enpol.2013.01.028.

[36] C. Neeladharan, P. Sathish, A. Nandhini, R. Priya, I. Sadiqua Fathima, and J. Srimathi, "Stabilization of Soil by using Marble dust with Sodium silicate as binder," *International Journal of Advanced Research Trends in Engineering and Technology*, vol. 5, no. 5, pp. 45–49, Mar. 2018, https://doi.org/10.20247/IJARTET.2018.05S0503009.

[37] S. Aaqib Javed and S. Chakraborty, "Effect of Expansive Soil Stabilization using Rice Husk Ash & Marble Dust," *Journal of Earth Engineering*, vol. 4, no. 1, pp. 41–49, Mar. 2020.

[38] A. Saygili, "Use of Waste Marble Dust for Stabilization of Clayey Soil," *Materials Science*, vol. 21, no. 4, pp. 601–606, Nov. 2015, https://doi.org/10.5755/j01.ms.21.4.11966.

[39] A. Minhas and V. U. Devi, "Soil stabilization of alluvial soil by using marble powder," *International Journal of Civil Engineering and Technology*, vol. 7, no. 5, pp. 87–92, 2016.

[40] L. Z. Wongbae, C. Kabubo, and A. Owayo, "The Effect of Waste Marble Dust and Corncob Ash on the Engineering and Micro-Structural Properties of Expansive Soil for Use in Road Subgrades," *Engineering, Technology & Applied Science Research*, vol. 14, no. 2, pp. 13765–13772, Apr. 2024, https://doi.org/10.48084/etasr.7034.

[41] A. K. Jain, A. K. Jha, and Shivanshi, "Geotechnical behaviour and micro-analyses of expansive soil amended with marble dust," *Soils and Foundations*, vol. 60, no. 4, pp. 737–751, Aug. 2020, https://doi.org/10.1016/j.sandf.2020.02.013.

[42] I. H. Umar, H. Lin, and A. S. Ibrahim, "Laboratory Testing and Analysis of Clay Soil Stabilization Using Waste Marble Powder," *Applied Sciences*, vol. 13, no. 16, Jan. 2023, Art. no. 9274, https://doi.org/10.3390/app13169274.

[43] A.-A. Balog, N. Cobîrzan, C. Aciu, and D. A. Iluțiu-Varvara, "Valorification of Volcanic Tuff in Constructions and Materials Manufacturing Industry," *Procedia Technology*, vol. 12, pp. 323–328, Jan. 2014, https://doi.org/10.1016/j.protcy.2013.12.493.

[44] M. Salimi, A. Dordsheykhtorkamani, A. Afrasiabian, and A. Khajeh, "Incorporation of Volcanic Ash for Enhanced Treatment of a Cement-Stabilized Clayey Soil," *Journal of Materials in Civil Engineering*, vol. 33, no. 2, Feb. 2021, Art. no. 04020465, https://doi.org/10.1061/(ASCE)MT.1943-5533.0003571.

[45] M. M. Barbero-Barrera, N. Flores-Medina, and E. Moreno-Fernández, "Thermal, physical and mechanical characterization of volcanic tuff masonries for the restoration of historic buildings," *Materiales de Construcción*, vol. 69, no. 333, Mar. 2019, Art. no. e179, https://doi.org/10.3989/mc.2019.12917.

[46] K. Harichane, M. Ghrici, S. Kenai, and K. Grine, "Use of Natural Pozzolana and Lime for Stabilization of Cohesive Soils," *Geotechnical and Geological Engineering*, vol. 29, no. 5, pp. 759–769, Sep. 2011, https://doi.org/10.1007/s10706-011-9415-z.

[47] Y. Cheng, S. Wang, J. Li, X. Huang, C. Li, and J. Wu, "Engineering and mineralogical properties of stabilized expansive soil compositing lime and natural pozzolans," *Construction and Building Materials*, vol. 187, pp. 1031–1038, Oct. 2018, https://doi.org/10.1016/j.conbuildmat.2018.08.061.

[48] S. Firat, J. M. Khatib, G. Yilmaz, and A. Comert, "Effect of curing time on selected properties of soil stabilized with fly ash, marble dust and waste sand for road sub-base materials," *Waste Management & Research*, vol. 35, no. 7, pp. 747–756, Jul. 2017, https://doi.org/10.1177/0734242X17705726.

[49] *ISO 11277:2020 - Soil quality — Determination of particle size distribution in mineral soil material — Method by sieving and sedimentation*. ISO, 2020.

[50] *IS 2720 - Methods of Tests for Soil*. IS, 1991.

[51] *BS 1377-2 (2022), Methods of test for soils for civil engineering purposes. Classification tests and determination of geotechnical properties*. London, UK: British Standards Institution, 2022.

[52] W.-A. Chong, C.-M. Chan, P.-C. Cheong, S. Sani, and N. F. Yahya, "Strength Characteristics of Clay Soil Admixed with Sand and Ca-based Stabiliser for Reduced Carbon Emissions," *IOP Conference Series: Earth and Environmental Science*, vol. 1249, Oct. 2023, Art. no. 012043, https://doi.org/10.1088/1755-1315/1249/1/012043.