scientific reports

OPEN

Comparative analysis of volume change behavior of expansive road subgrades stabilized with waste paper sludge

Muhammed TANYILDIZI[1,2]✉, İslam GÖKALP[3], Abdülhakim ZEYBEK[4] & Volkan Emre UZ[5]

Expansive soils have a high tendency for volume change in case of fluctuations in moisture content, potentially causing significant damage to light structures, particularly road pavements. This paper investigates the influence of waste paper sludge (WPS) as an alternative sustainable stabilizer on the volume change behavior of expansive road subgrade soils of different origins. For this purpose, WPS was added to the expansive soils at ratios of 3%, 6%, 9%, 12%, and 15% by dry weight of the soils. A series of Atterberg's limit, swelling, shrinkage, compaction, and consolidation tests were performed on pure soils and soil specimens with WPS to attain a comprehensive understanding of the role that WPS plays in the volume change behavior of expansive soils. The experimental test results showed that the addition of WPS led to a considerable decrease in the plasticity and swell-shrink potentials of subgrade soils. The consolidation settlement of expansive road subgrades was also reduced to some extent with WPS. Moreover, the statistical analysis of the test data indicated a significant relationship among different swelling-shrinkage parameters. The experimental results presented here suggest that the WPS may be a cost-effective, environmentally friendly, and sustainable stabilizer to reduce the volume change sensitivity of expansive road subgrade soils.

Keywords Expansive soil, Stabilization, Subgrade, Swelling-shrinkage, Waste paper sludge

List of symbols

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
BS	British standard
C_c	Coefficient of compression
C_s	Swelling index
e	Void ratio
e_0	Initial void ratio
CH	High plasticity clay
CL	Low plasticity clay
FSI	Free swell index
G_s	Specific gravity
IS	Indian standard
LL	Liquid limit
LS	Linear shrinkage
MDD	Maximum dry density
m_V	Coefficient of volume compressibility
ML	Low plasticity silt
OMC	Optimum moisture content
PI	Plasticity index
PL	Plastic limit

[1]Research Assistant, Faculty of Engineering and Architecture, Bitlis Eren University, Bitlis, Turkey. [2]Civil Engineering Department of Science, Graduate Education Institute, Batman University, Batman 72100, Batman, Turkey. [3]Faculty of Engineering and Architecture, Batman University, Batman, Turkey. [4]Faculty of Engineering and Architecture, Muş Alparslan University, Muş, Turkey. [5]Faculty of Engineering, Izmir Institute of Technology, İzmir, Turkey. ✉email: mtanyildizi@beu.edu.tr

SEM	Scanning electron microscope
USCS	Unified soil classification system
VS	Volumetric shrinkage
WPS	Waste paper sludge
XRD	X-ray diffraction
XRF	X-ray fluorescence

Expansive soils are one of the most problematic soil types in many engineering applications due to their high tendency for volume change during fluctuations in moisture content[1,2]. These soils may show excessive volume changes depending mostly on their interaction with water. They tend to swell as moisture content increases and shrink as moisture content decreases[3]. The undesirable volumetric instability of expansive soils causes great stress and serious damage to the loaded structures, especially road pavements constructed over expansive subgrade soils, and the annual costs required for the maintenance of such structures exceed billions of dollars all around the world[4,5]. Hence, the stabilization of expansive soils is of great importance to minimize volume change-induced damage[6].

In the state of practice, there are many techniques proposed to restrain the volume change behavior of expansive soils, including controlled compaction, reinforcement, replacement, pre-wetting, electrokinetic treatment, biological, confining moisture changes, chemical treatments, and innovative foundation structures[7,8]. Among these techniques, chemical stabilization, in which the composition of soil is altered chemically, has attracted great attention and has become one of the most widely used techniques due to its effectiveness, adaptability, and affordability[9,10]. Cement, lime, and their blends are the most familiar and preferred conventional stabilizers for expansive subgrade soil stabilization[11,12]. However, considering the adverse effects of these traditional stabilizers on the ecosystem, triggering global warming and leading to excessive depletion of natural resources, there is an urgent need to provide cost-effective and environmentally friendly alternative materials[13,14]. Over the years, a significant research effort has been put into the investigation of waste materials from industrial, agricultural, or domestic use as a greener way to reduce the volume change potential of expansive subgrade soils[15–17].

Waste paper sludge (WPS) is a by-product of recycling waste paper and continues to be disposed of in landfills. Hence, a beneficial application of such material would be advantageous in many ways such as reducing waste disposal costs, minimizing the adverse environmental effect due to waste storage, providing a sustainable stabilizer for the construction of green highways, and so on[18]. The quality of cellulose fiber from recycled paper continues to decline after each recycling process, leading to unusable paper sludge after 7–8 cycles, which is then disposed of in landfills[19]. An estimated 6 million tonnes of paper sludge are reportedly produced annually in Europe[20] and approximately 40,000 tonnes per annum in Türkiye. Recent studies have predominantly focused on the utilization of WPS for the production of concrete and cementitious mixtures[21–25]. An extensive review of the published literature indicates that studies regarding the use of WPS for the stabilization of expansive soils are quite rare[26,27]. The majority of the few studies on soil stabilization with WPS have focused solely on evaluating the effect of WPS on the strength properties of expansive soils[28–32]. However, there is a gap in the literature in terms of studies that comprehensively examine the effect of WPS on the volume change behavior (plasticity, swelling, shrinkage, consolidation) of expansive subgrade soils. In a such study, Surya et al.[33] reported that LL increased and PI decreased as WPS content when an highly swelling soil was stabilized with WPS. Patel et al.[32] investigated the effect of WPS content on the free swell potential of swelling soil and reported that an increase in the WPS content resulted in a systematic decrease in the swelling potential. Further studies are required to gain a comprehensive understanding of the effects of WPS on the volume change behavior of expansive soils. Only in that case, it can be reliably used in engineering projects. In particular, the impact that WPS has on the volume change behavior of the expansive subgrade soils needs to be clarified, and laboratory-based research studies will be quite useful to achieve this goal.

The study presented hereby investigated the effect of WPS on the volume change behavior of expansive subgrade soils of different origins. A series of laboratory experiments were conducted to examine the plasticity, swell-shrink characteristics, compaction, and consolidation parameters of expansive soils with and without WPS. Moreover, the relationship between different swelling-shrinkage parameters was examined to assess whether there is any meaningful correlation between each other. The test results are expected to provide useful insights into the effective use of WPS in improving the volume change behavior of expansive subgrade soils. The study is believed to be a step towards exploring new beneficial applications of WPS to produce possible sustainable subgrade for road pavements.

Materials and methods
Materials
The test materials used during the experimental work were expansive subgrade soils and waste paper sludge (WPS). Three different types of expansive subgrade soil, labeled Soil-A, Soil-B, and Soil-C, were utilized. The Soil-A and Soil-B were collected from two different road cuts located in Muş province, Türkiye. These two local soils were obtained from a depth of 1.5–2 m after removing organic residues. Soil-A and Soil-B can be classified as high plasticity clay (CH) and low plasticity clay (CL), respectively. The Soil-C is a commercially available soil purchased from a kaolin company in Eskişehir province, Türkiye. It is specified as kaolinite clay that can be classified as CL. The geotechnical and engineering properties of expansive subgrade soils are presented in Table 1.

The WPS was obtained from Varaka Paper Mill, Balıkesir province, Türkiye. It has a specific gravity (G_s) of 1.57 and was utilized as a non-traditional additive in this study. The WPS was received from the factory in wet form. It was dried in the oven until it reached a constant weight and then ground to the desired size in a blade mill. The particle size distributions of soils and WPS are given in Fig. 1. The chemical composition of soils and

Property	Soil-A	Soil-B	Soil-C
Sand (%)	19.99	17.24	4.00
Silt (%)	39.81	35.76	67.50
Clay (%)	40.20	47.00	28.50
Specific gravity	2.59	2.72	2.54
Liquid limit (%)	50.55	42.75	41.13
Plastic limit (%)	25.10	23.23	21.73
Plasticity index (%)	25.45	19.52	19.40
Linear shrinkage (%)	13.22	11.07	7.43
Free swell Index (%)	42.00	28.71	11.63
One-dimensional swell (%)	6.49	5.51	3.75
Swelling potential (%)	3.91	2.63	2.10
USCS classification	CH	CL	CL
AAHSTO classification	A-7-6 (16)	A-7-6 (13)	A-7-6 (12)
MDD (kN/m^3)	14.61	17.75	15.61
OMC (%)	17.62	15.70	19.37

Table 1. Geotechnical and engineering properties of expansive soil.

WPS were analyzed through X-ray Fluorescence (XRF), which is given in Fig. 2. Based on the explanations given in ASTM 4318 and literature, such as the inability to open a groove and the material piece continuing to slide within the container in the liquid limit test, it has been stated that WPS can be classified as non-cohesive and non-plastic material[34,35].

Mix proportion and experimental methods

A series of laboratory tests were conducted on pure soils and soil specimens with 3%, 6%, 9%, 12%, and 15% WPS by dry weight of soils to reveal the effect of WPS on the volume change behavior of expansive subgrade soils. The selection of the WPS ratio range (0–15%, with 3% increments) used in the study was based on preliminary experiments and literature findings[29–31]. In general, the procedures and methods described in $ASTM$ standards were followed during the tests. The soil and WPS grains were first air dried for 7 days, and then the specimens were exposed to oven drying at 105 $^\circ$C until completely dry conditions were accomplished. WPS grains were ground to the desired size. Before each test, the required amount of oven-dried soil, WPS , and clean water were weighed and mixed until a uniform mixture was achieved. The Atterberg's limits of each soil and soil-WPS mixtures were determined following the $ASTM$ D4318 standard[34]. Different test methods were employed to evaluate the effect of WPS addition on the swelling potential of soils. Free swell index (FSI), one-dimensional swell and swelling potential of each soil and soil-WPS specimens were determined as per IS 2720[36], $ASTM$ D4546[37] and $ASTM$ D1883[38] standards, respectively. The linear and volumetric shrinkage of pure soils and soils with WPS were measured according to the BS 1377 standard[39]. Modified proctor tests were conducted to calculate the maximum dry density (MDD) and optimum moisture content (OMC) of each soil and soil-WPS specimen following the $ASTM$ D698 standard[40]. The one-dimensional consolidation test was applied to the soils and soil-WPS specimens prepared at their each respective MDD and OMC in accordance with the $ASTM$ D2435 standard[41]. The binary correlations among swelling/shrinkage parameters of pure soils and soil specimens with WPS were assessed. Experimental tests used in this study are summarized graphically in Fig. 3.

Results and discussion

Atterberg's limits

A high liquid limit (LL) combined with a high plasticity index (PI) value may indicate the swelling, in other words, volume change potential[42]. The plasticity index ($PI = LL - PL$) of each respective specimen was determined, and the changes in LL, PL, and PI of each soil and soil- WPS mixtures are presented in Fig. 4.

It can be observed from the test results that when the WPS content increased from 0 to 15%, the LL of each soil specimen decreased while the PL increased, resulting in a consistent decrease in the PI of soil specimens. Considering the specimens with 15% WPS content, the reduction in LL and PI was by 7.09% and 64.6% for Soil-A, 8.75% and 65.57% for Soil-B, and 8.51% and 38.87% for Soil-C. The reduction rate in LL and PI appeared to be relatively higher for Soil-B. The decreasing trend observed in PI of soil specimens with the addition of WPS can be attributed to the increased flocculation and agglomeration caused by cation exchange between the soil and WPS grains. This situation is also likely to be observed in the stabilization of clayey soils with calcium-rich stabilizers[43,44]. During the cation exchange process, the Ca^{+2} ions in the calcium from the stabilizer replace Na^+, K^+ and other cations resulting in a flocculated structure causing a decrease in the surface activity of clay particles and reducing plasticity[45,46]. This results in the formation of coarser-sized particles and therefore a reduction in plasticity. The non-cohesive and non-plastic characteristics of WPS also significantly contributed to the decrease in the plasticity of soil specimens. In a study, the reduction in PI of expansive soils stabilized construction and demolition waste was associated with the non-cohesive and non-

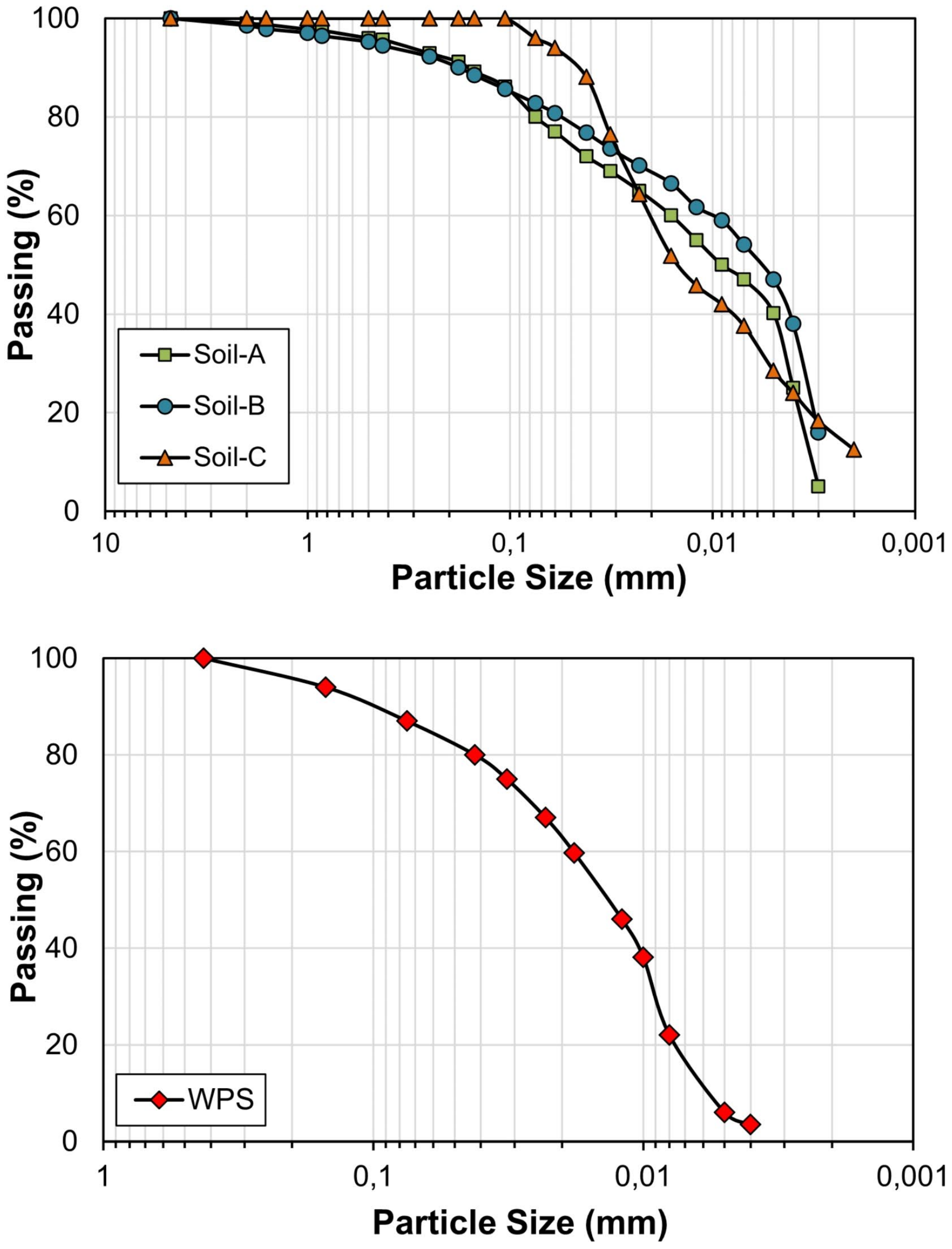

Fig. 1. Particle size distribution of soils and WPS.

plastic characteristics of waste[47]. A study by Singh and Bisen[48] reported similar results regarding the increase in LL and decrease in PI of an expansive soil stabilized with WPS.

The position of the expansive soils having different percentages of WPS is plotted on Casagrande's plasticity chart in Fig. 5. It is seen that Soil-A can be classified as high plasticity clay (CH), while Soil-B and Soil-C are classified as low plasticity clay (CL). The position of each soil specimen gradually shifted towards the low plasticity silt (ML) with increasing WPS content. This also proves that flocculation and agglomeration occur

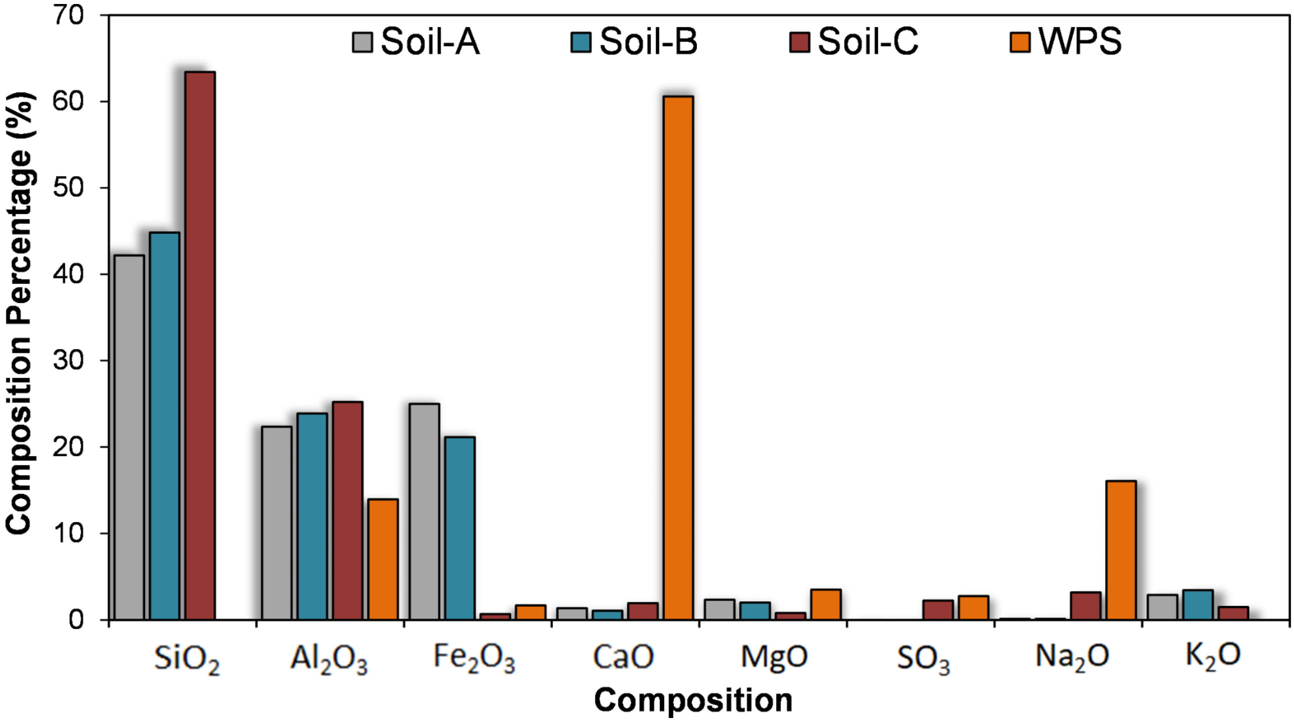

Fig. 2. Chemical composition of soils and WPS.

through stabilization due to the presence of calcium in WPS, resulting in a much coarser size of the soil mixture.

Swelling properties

Figure 6 shows the variation of the free swell index (FSI) with WPS content. It is seen that the stabilization of each soil with WPS caused a decrease in the free swell index. The FSI (%) value of pure Soil-A, Soil-B, and Soil-C specimens were 42.00%, 28.71%, and 11.63%, respectively. The FSI of Soil-A, Soil-B and Soil-C decreased to 7.97%, 4.86%, and 7.02% with the 15% WPS addition, respectively. These results indicate that the addition of WPS to soil specimens is effective in controlling and minimizing the swelling potential. Similar results were reported in a study by Surya et al.[33], where it was observed that the FSI of highly expansive soil decreased with increasing WPS content.

Figure 7 depicts the change in the one-dimensional swell of soil specimens with the WPS content. Apparently, the addition of WPS significantly altered the one-dimensional swell potential of soil specimens. The one-dimensional swell (%) of each pure soil specimen decreased consistently with increasing WPS content. In the case of soil specimens with 15% WPS content, the reduction in the one-dimensional swell (%) was approximately 35%, 41%, and 50% for Soil-A, Soil-B, and Soil-C, respectively.

Analogous results were observed during the swelling potential tests. Figure 8 shows the decreasing trend in the swelling potential of soils with increasing WPS content. The swelling potentials of pure soils were 3.91%, 2.63%, and 2.10% for Soil-A, Soil-B, and Soil-C, respectively. These values were reduced to 2.78%, 1.25%, and 1.09% with 15% WPS addition for Soil-A, Soil-B, and Soil-C, respectively.

The decreasing swelling tendency of soil specimens with increasing WPS content can be explained by the non-plastic and non-expansive properties of WPS. Cation exchange occurring between the soil and WPS grains is also expected to reduce the swelling potential of soils. The cation exchange process, replacing the Ca^{+2} ions with Na^{+}, K^{+} and other ions, resulted in a decrease in the diffuse double layer thickness of clay particles and reduced swelling potential[49,50]. Moreover, the formation of coarse particles with the flocculation and agglomeration, associated with calcium content in WPS, is another factor that resulted in a decrease the surface activity caused the swelling potential of soil specimens.

Shrinkage properties

Figure 9 presents the change in the linear shrinkage (LS) and volumetric shrinkage (VS) potentials of soils with WPS content. It is evident that the shrinkage potentials of soils consistently reduced with increasing WPS ratio. The LS and VS values were recorded to be 13.22% and 22.56% for Soil-A, 11.07% and 18.04% for Soil-B, and 7.43% and 10.12% for Soil-C. These values decreased to 10.58% and 14.23% for Soil-A, 11.07% and 18.24% for Soil-B, and 7.43% and 10.12% for Soil-C as WPS content was increased from 0 to 15%. The reduction rate in the shrinkage potentials of soils was relatively higher for Soil-C.

The decrease in the shrinkage potential of soils can be attributed to the non-shrinkage and non-plastic characteristics of WPS. Moreover, the pozzolanic reactions taking place between calcium in WPS and

Fig. 3. Experimental tests employed in the study.

silica in soil are more likely to cause the formation of calcium silicate hydrate (CSH) and calcium aluminate hydrates (CAH) cementitious compounds[48], improving the compactness of the soil-WPS mix and reducing the shrinkage potential of the samples.

Compaction parameters

Figure 10 gives the relationships between dry unit weights and moisture content of each soil specimen having different WPS content. The changes in the maximum dry density (MDD) and optimum moisture content (OMC) at different WPS ratios are also depicted in Fig. 11. For Soil-A, the MDD appeared to decrease in a consistent manner as OMC increased, as seen in Fig. 11a. In the case of the Soil-A specimen with 15% WPS content, MDD decreased from 14.61 to 13.86 kN/m^3, while OMC increased from 20.79 to 28.64%. Similarly, an increase in the WPS content resulted in a consistent decrease in the MDD values. Figure 11(b, c) show the experimental results for Soil-B and Soil-C, respectively. For soil specimens with 15% WPS content, the MDD decreased from 17.75 to 16.29 kN/m^3 for Soil-B and decreased from 15.61 to 14.48 kN/m^3 for Soil-C. As different from Soil-A, the OMC values of Soil-B and Soil-C initially showed a decreasing trend up to 6% WPS content and then an increasing trend with the further addition of WPS. The OMC of Soil-B seemed to decrease from 15.70 to 14.76% as WPS content increased from 0 to 3%. It then increased gradually and reached 19.69% with a

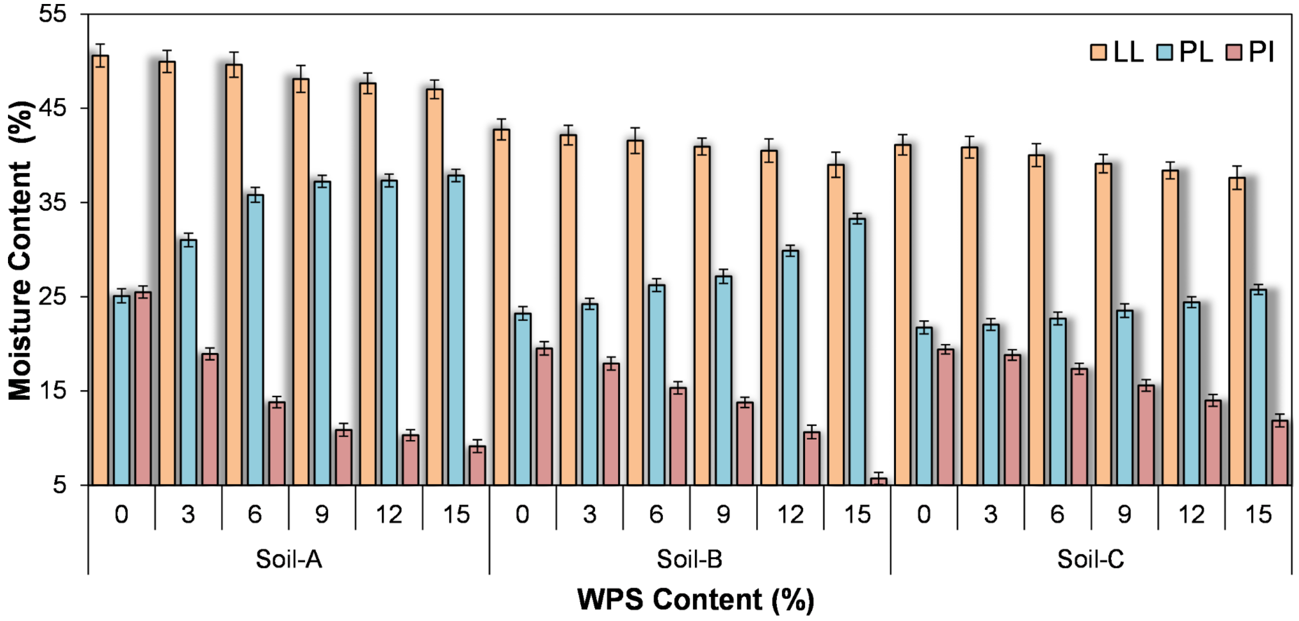

Fig. 4. Change in Atterberg's limits of soils with WPS content.

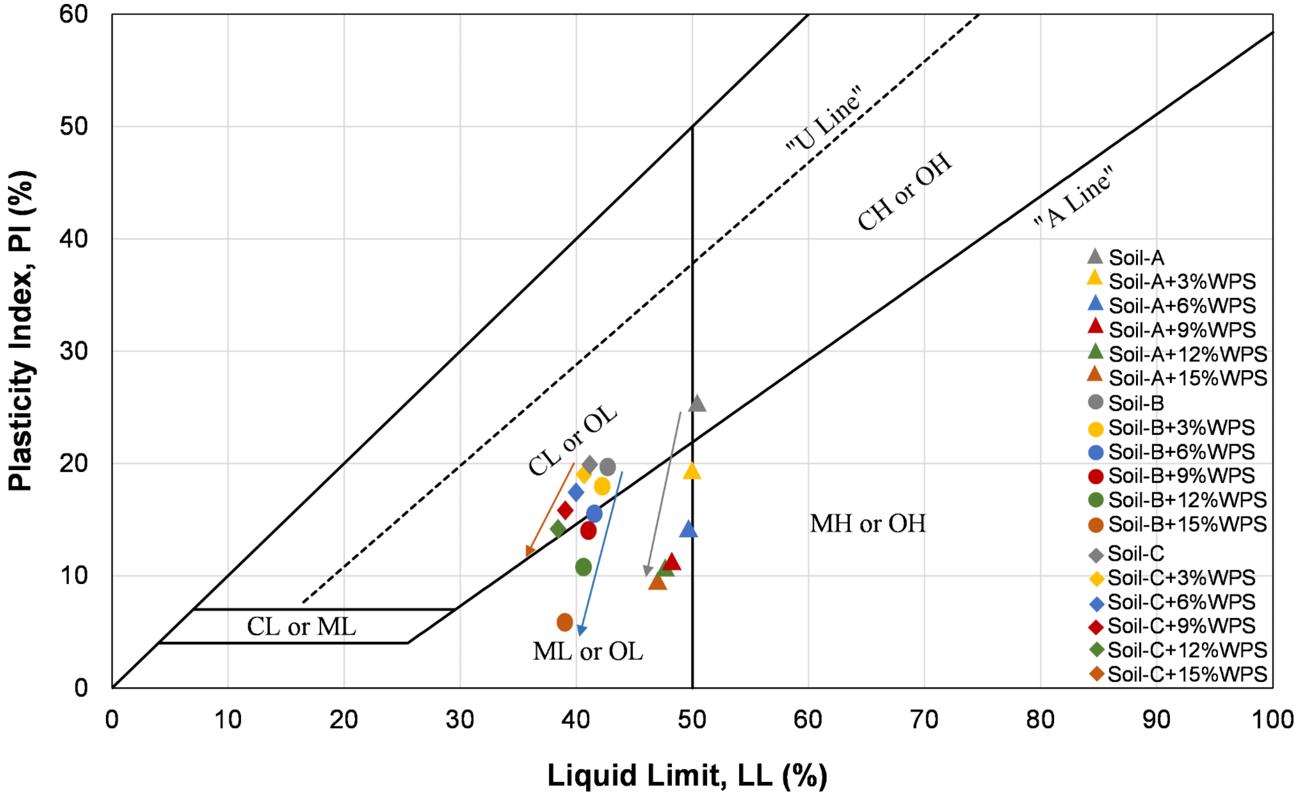

Fig. 5. Position of soil mixtures on the Casagrande's plasticity chart.

15% WPS addition. Similarly, the OMC of Soil-C decreased from 19.37 to 18.01% as WPS content increased from 0 to 3%, then increased evenly and reached 22.14% with 15% WPS addition.

The reduction in MDD of soil specimens with increasing WPS content may be attributed to the lower G_s of WPS particles compared to each soil. The increase in OMC of soil specimens with WPS content may be associated with the higher water attractiveness of WPS compared to soil particles. In general, the higher WPS content causes an increased water attractiveness due to the high water affinity of WPS, leading to an increase

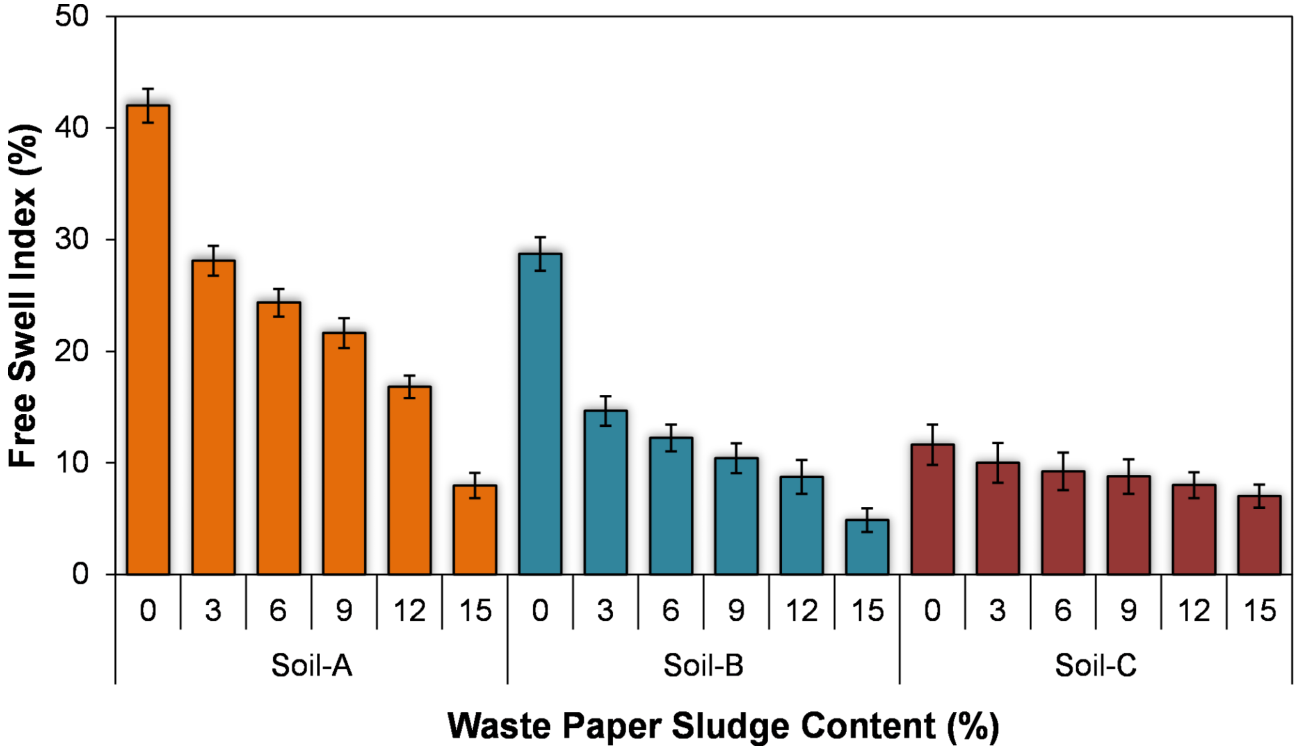

Fig. 6. Change in the free swell index (%) with WPS content.

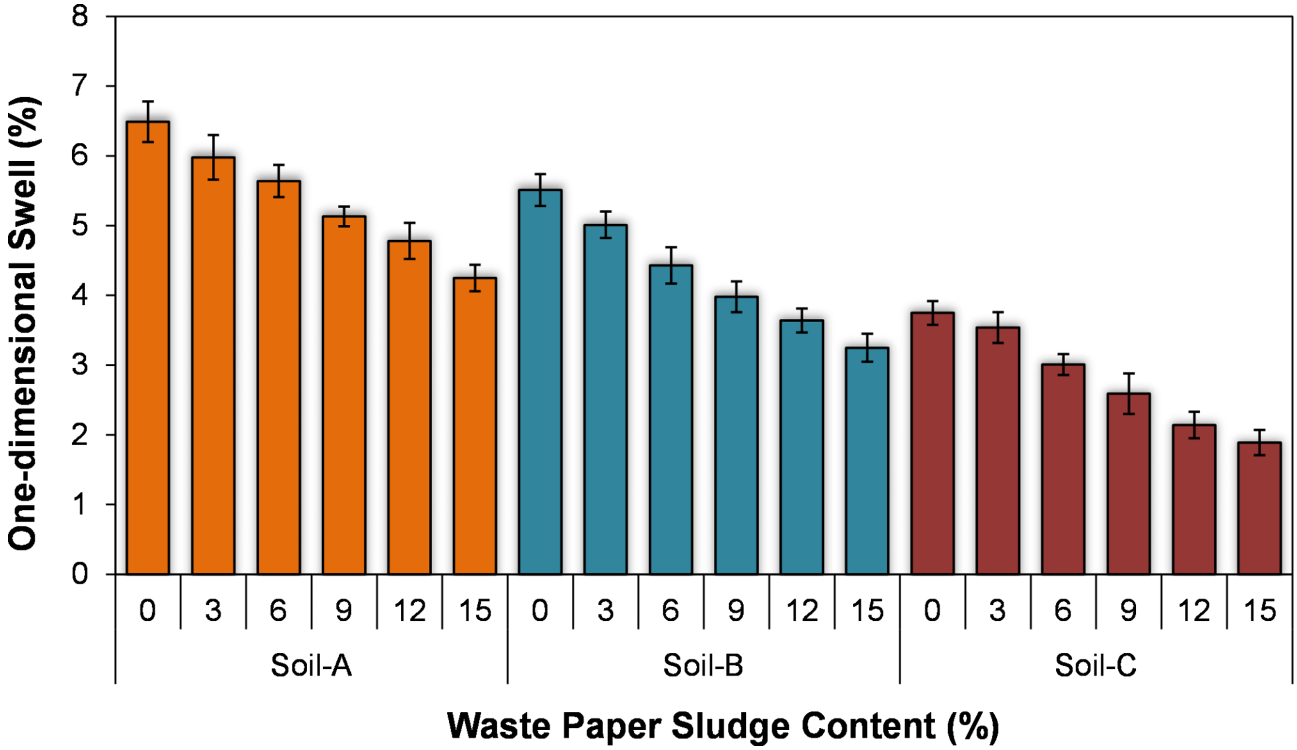

Fig. 7. Change in the one-dimensional swell (%) with WPS content.

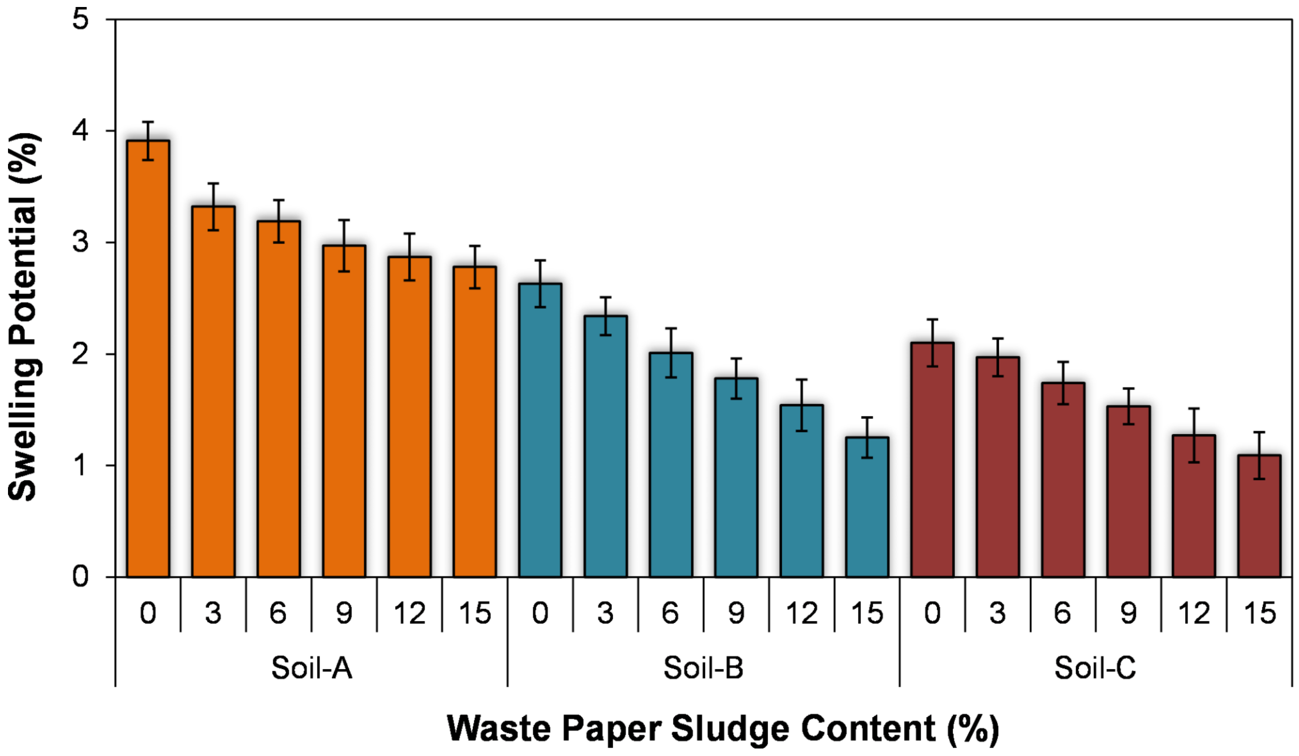

Fig. 8. Change in the swelling potential (%) with WPS content.

in the OMC of the soil specimens. Additionally, the increase in OMC can be attributed to the need for more water for hydration of the calcium-based stabilizer[51,52]. For Soil-B and Soil-C samples, relatively lower OMC values were observed with 3% and 6% WPS. This can be attributed to the rearrangement of soil particles at the corresponding WPS ratios, leading to a compact structure with fewer voids. In a study, conducted by Elias[53], focusing on the stabilization of clayey soil with WPS, it was reported that MDD decreased and OMC increased with further addition of WPS, and this decrease in MDD was attributed to the lower specific gravity of WPS compared to soil. Kumar and Gupta[54] also reported in their study that as WPS increases, MDD and OMC follow a decreasing and increasing trend, respectively. Similar results were reported in their studies performed by Singh and Bisen[48] and Akshatha et al.[31].

Consolidation test

The consolidation tests were performed to reveal the time-dependent settlement behavior of pure soil and soil-WPS specimens. In each test, the specimens were prepared at the relevant MDD and OMC values in a consolidation ring with a diameter of 50 mm and a height of 20 mm. The effective stresses during the consolidation test were selected as 25 kPa, 50 kPa, 100 kPa, 200 kPa, 400 kPa, and 800 kPa, and each load was applied to the samples for 24 h. The consolidation parameters including void ratio (e), compression index (C_c), coefficient of volume compressibility (m_v), swelling index (C_s) and settlement (mm) were determined for each soil and soil-WPS specimen.

Figure 12 presents the change in the initial void ratio (e_0) of soil specimens with WPS content. The e_0 values of Soil-A, Soil-B, and Soil-C were 0.825, 0.845, and 0,894, respectively. For Soil-A, the e_0 value was observed to increase to 1.001 as WPS content increased from 0 to 15%. This increase can be due to the increasing water content of the soil mix. On the other hand, the e_0 of Soil B and Soil C decreased up to a threshold value (3% WPS content). It started to increase with a further addition of WPS, eventually exceeding the e_0 of the pure soil.

The e_0 values for Soil-B and Soil-C specimens with 15% WPS content were 0.958 and 1.016, respectively. The reduction observed in the e_0 of specimens having 3% and/or 6% WPS compared to the pure soils content may be due to the rearrangement of soil particles that probably resulted in a compact soil mix with lesser void. On the other hand, e_0 increased with a much higher *WPS* content (above 6%) compared to the pure soils, causing higher water attraction to increase the void ratio.

Figure 13 gives the change in the void ratio (e) of specimens with increasing effective stress obtained during the consolidation tests. Figure 14 presents the change in the compression index (C_c) of soils and soils- WPS samples measured from the slope of e versus $log\sigma'$ under different effective stress. As expected, the e of each soil and soil- WPS specimens reduced with increasing effective stress (Fig. 13). The compression index (C_c) of Soil-A specimens increased with increasing WPS content, which indicated the increase in the consolidation settlement of soil. This behavior can be associated with the increase in the void ratio with WPS content, resulting in the increase of compressibility under applied pressure (Fig. 14).

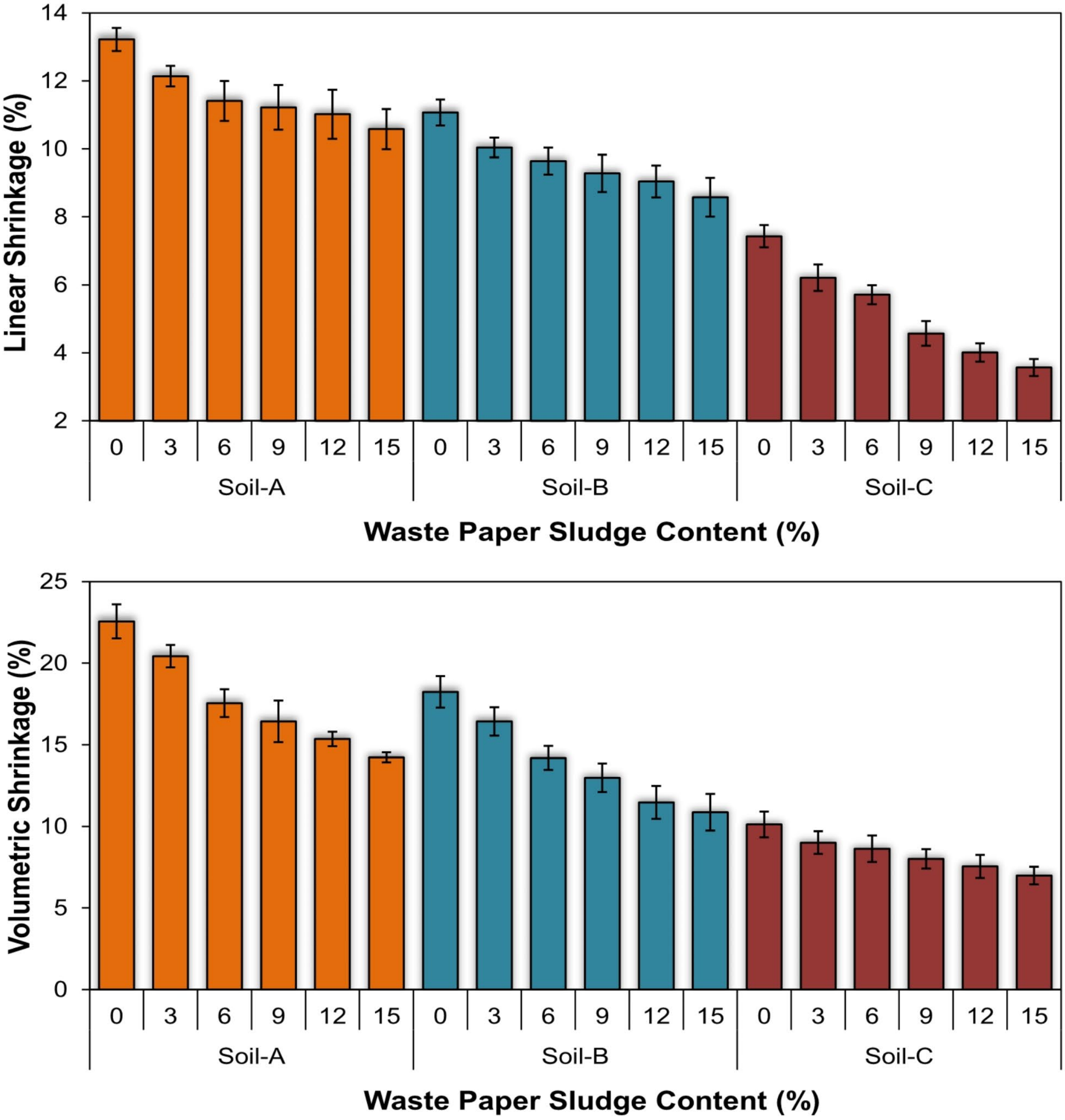

Fig. 9. Change in the linear and volumetric shrinkage potential with WPS content.

Similar trends were observed for Soil-B and Soil-C specimens with 3% and 6% WPS content. For both Soil-B and Soil-C, the C_c decreased up to 6% WPS content compared to the pure soils, corresponding to a decrease in the consolidation settlement of soil specimens. Further addition of WPS, on the other hand, increased the C_c of Soil-B and Soil-C (Fig. 14). Comparable results obtained in a study performed by Akbulut[55] that C_c of expansive soil increased with increased calcium rich sewage sludge content.

Figure 15 displays the variation of consolidation settlements with WPS under different effective stresses. The settlement values measured during the consolidation tests, in fact, supported the aforementioned findings related to C_c measurements. It seems that consolidation settlement of Soil-A consistently increased with increasing WPS content. The increase in OMC of Soil-A mixtures containing WPS caused the void ratio of the soil mixture to increase and as a result, the compressibility and thus the consolidation settlement to increase. On the contrary, consolidation settlement of Soil-B and Soil-C initially decreased as WPS content was raised up to 6% compared to the pure soils and then increased with further addition of WPS. The decrease in the consolidation settlement of the Soil-B and Soil-C with up to 6% WPS content compared with the pure

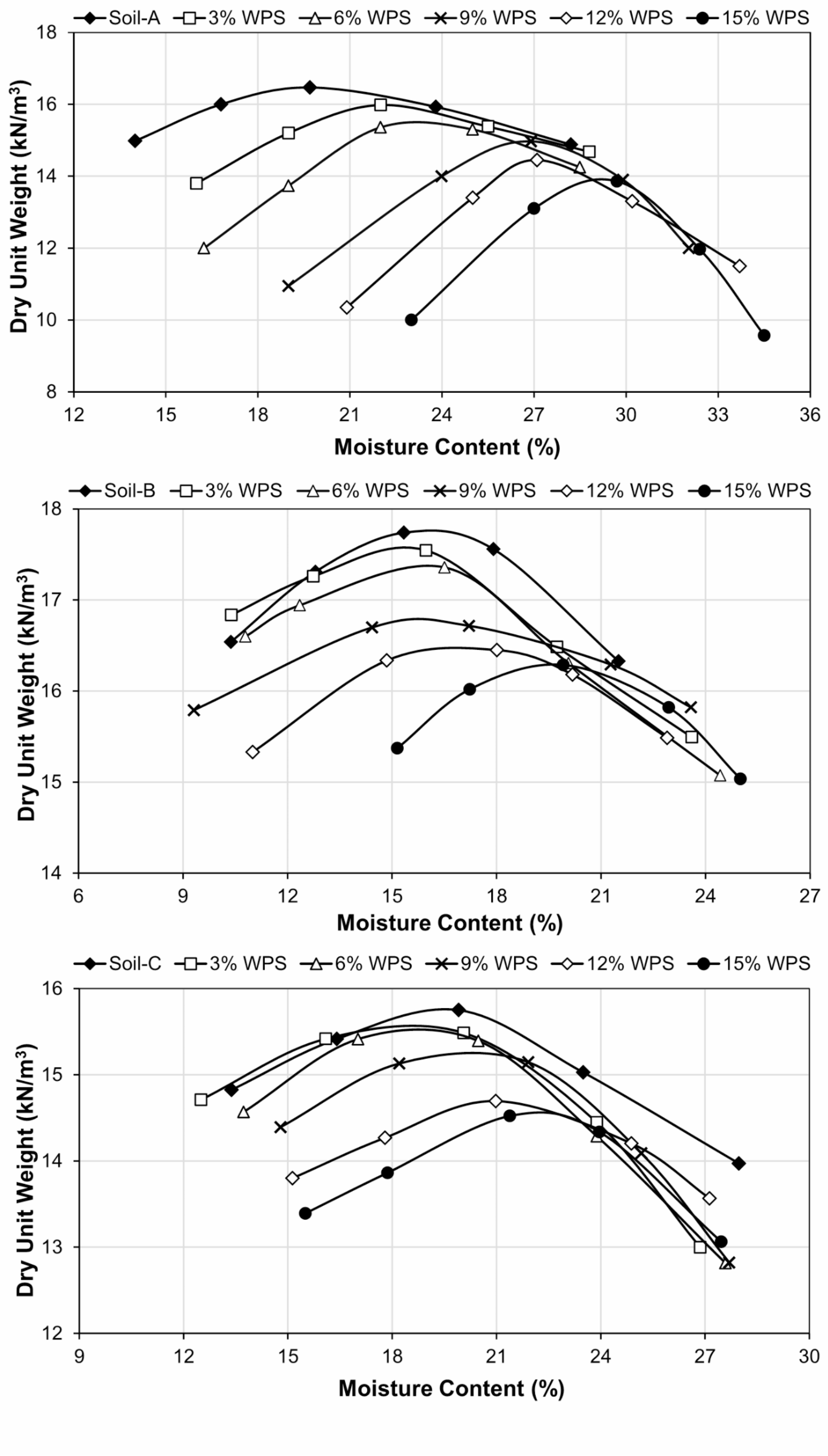

Fig. 10. Dry unit weight and moisture content relationships of soil mixtures.

soils can be attributed to the lower water affinity of soil mixture with the rearrangement of soil particles at the corresponding WPS ratios, leading to a compact structure with fewer voids.

Figure 16 presents the change in the coefficient of volume compressibility (m_v, m^2/kN) of soils with various WPS content under different effective stresses. It can be seen that for Soil-A, the m_v increased under each effective stress with increasing WPS content, which may be ascribed to the increase in the void ratio of the soil. For both Soil-B and Soil-C, the m_v showed a decreasing trend up to 3% WPS content and then increased with a further increase in the WPS ratio. The decrease in m_v at 3% and 6% WPS contents compared to the

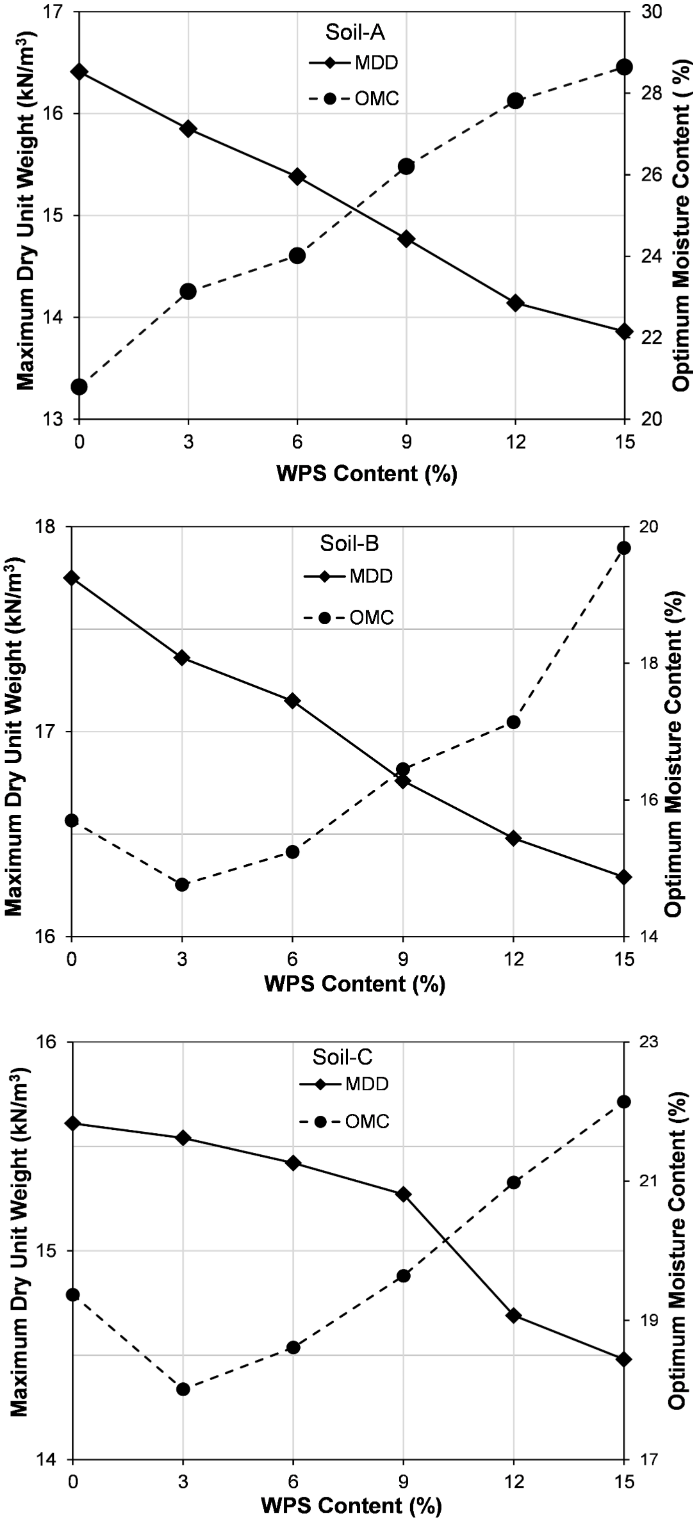

Fig. 11. Change in the MDD and OMC of soil specimens with WPS content.

pure soils may be explained by the reduction in the void ratio caused by the rearrangement of soil particles in their respective WPS contents. Nevertheless, further addition of WPS (above the threshold value of 3%) caused the void ratio to rise as a result of the increase in water affinity of the soil mixture and thus enhanced compressibility.

Figure 17 depicts the change in the swelling index (C_s) of soil specimens with various ratios of WPS under different effective stresses. It can be seen from the figure that the C_s values decreased for each soil specimen with increasing WPS content. The observed behavior can be linked to the non-swelling characteristics of WPS

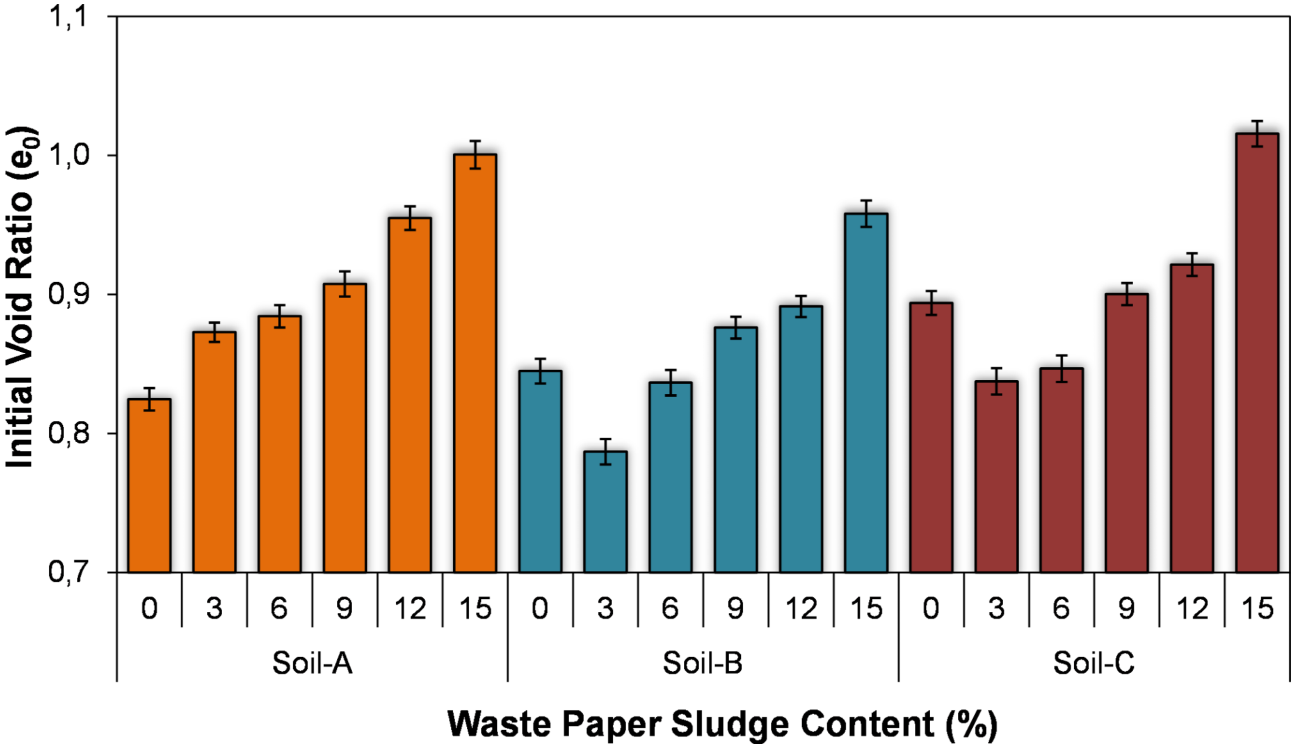

Fig. 12. Change in the initial void ratio with WPS content.

and cation change between soil and WPS particles, which probably causes a decrease in the swelling potentials of soil specimens. Similar findings were observed in a study performed by Okoro et al.[56] that the C_s of clayey soil decreased with increasing calcium based stabilizer content. Comparable results were observed by Chenarboni et al.[57] that the C_c increased while C_s decreased of cement stabilized expansive soil with zeolite content."

Relationship between swelling/shrinkage parameters

Figure 18 presents the relationships between the investigated swelling/shrinkage parameters of the pure soils and soils with WPS. It is seen that there was a strong linear relationship (with an R-square value over 0.90) between one-dimensional swell and linear shrinkage; swelling index (800 – 200 kPa) and one-dimensional swell. On the other hand, there were moderate to strong linear relationships (with relatively lower R-square values ranging from 0.73 to 0.86) between one-dimensional swell and swelling potential; swelling index (800 – 200 kPa) and swelling potential; swelling index (800 – 200 kPa) and linear shrinkage; swelling index (800 – 200 kPa) and free swell index; free swell index and swelling potential; free swell index and one-dimensional swell; and swelling potential and linear shrinkage. Besides, there was a relatively poor linear relationship (with an R-square value lower than 0.70) between free swell index and linear shrinkage. These findings indicate that the experimental results presented in this study were not obtained by chance, but obtained through a systematic experimental program.

Conclusions

The increase in waste generation with rapid industrialization and urbanization has urged societies to develop a sustainable approach to waste management. Waste materials from industrial and agricultural activities have become a good alternative to traditional stabilizers for the stabilization of expansive subgrade soils. Waste paper sludge (WPS) is one of the alternative stabilizers originating from paper mill plants. The study presented hereby focused on investigating the effect of waste paper sludge on the volume change behavior of different sourced, locally and commercially available, expansive subgrade soils. The Atterberg's limits, swelling-shrinkage properties, and consolidation parameters of pure soils and soil specimens with 3%, 6%, 9%, 12%, and 15% WPS contents were evaluated. Based on a detailed examination of the experimental data, the following conclusions were drawn:

- Atterberg limits test results revealed that the PI of expansive soil specimens decreased with an increase in WPS content. It was observed that with the addition of 15% WPS, PI decreased by approximately 65%, 71%, and 39% for Soil-A, Soil-B, and Soil-C, respectively.
- The swelling potential of soil specimens, examined with different test methods, was shown to decrease remarkably with increasing WPS content. In the case of soil specimens having 15% WPS content, free swell index (FSI) decreased by 81.02%, 83.07%, and 7.02%; one-dimensional swell (%) decreased by 34.51%,

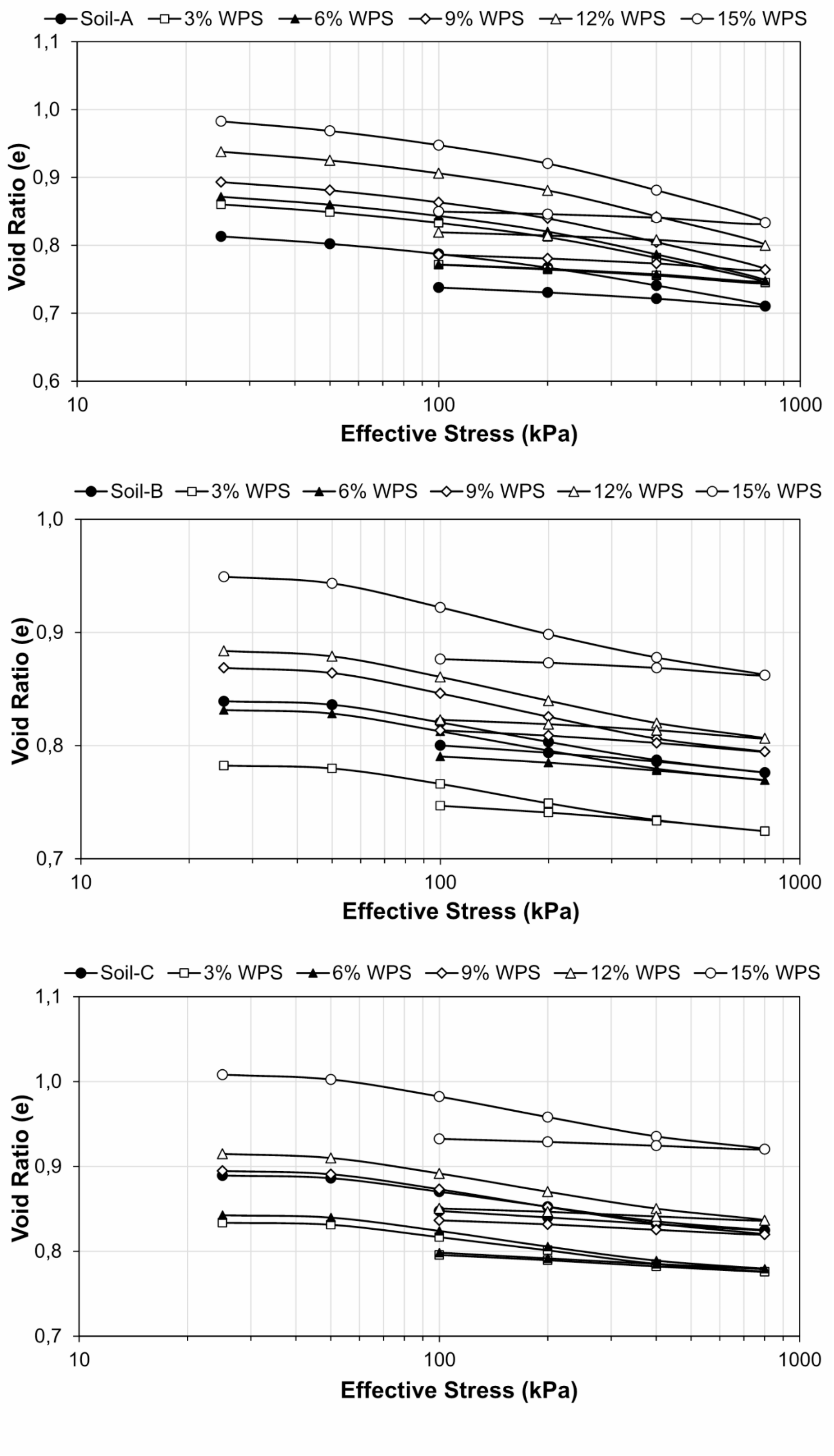

Fig. 13. Change in the void ratio with WPS content under different effective stresses.

41.02%, and 49.60%; and swelling potential (%) decreased by 28.90%, 52.47% and 48.10% for Soil-A, Soil-B, and Soil-C, respectively.

- The shrinkage potential of soil specimens was considerably affected by WPS content. Linear shrinkage (LS) potential of Soil-A, Soil-B, and Soil-C decreased by about 20%, 23%, and 52% with the addition of 15% WPS, respectively. Volumetric shrinkage (VS) potential reduced from 22.56 to 14.23% for Soil-A; 18.24–10.87% for Soil-B; 10.12–6.99% for Soil-C when 15% WPS was added to the soil specimens.

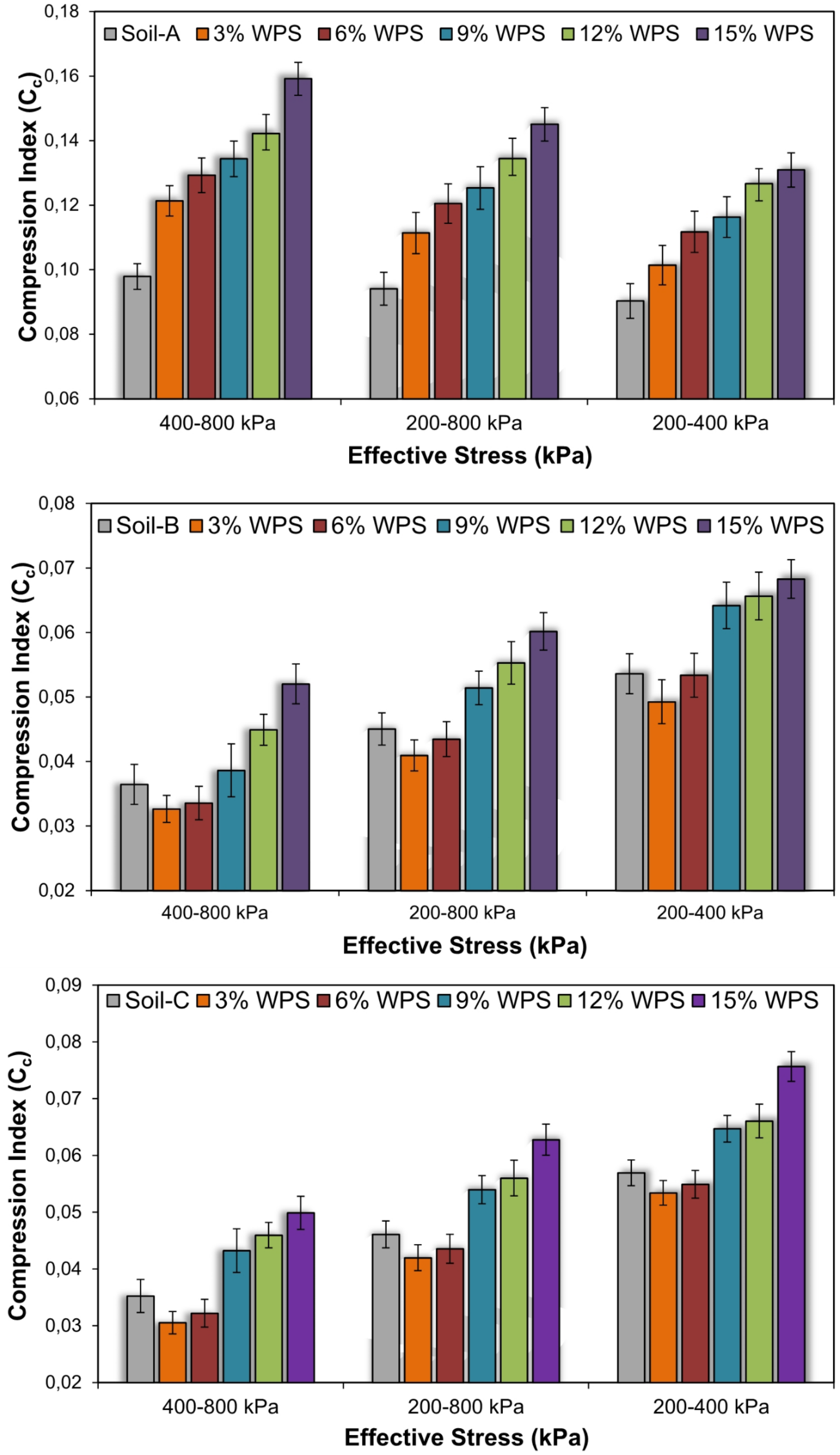

Fig. 14. Change in the compression index with WPS content under different effective stresses.

- Compaction parameters showed different trends depending on the type of soil. For soil-A, the MDD decreased and OMC increased consistently with increasing WPS content. For Soil-B and Soil-C, the MDD decreased steadily with increasing WPS content. On the other hand, the OMC of soil specimens initially decreased until 6% WPS content was reached, and then started to increase and eventually exceeded the OMC of the pure soil specimen with further addition of WPS.
- Consolidation test parameters indicated that the time-dependent settlement increased with increasing WPS content for Soil-A. However, for Soil-B and Soil-C, the settlement of soil specimens containing 3% and 6%

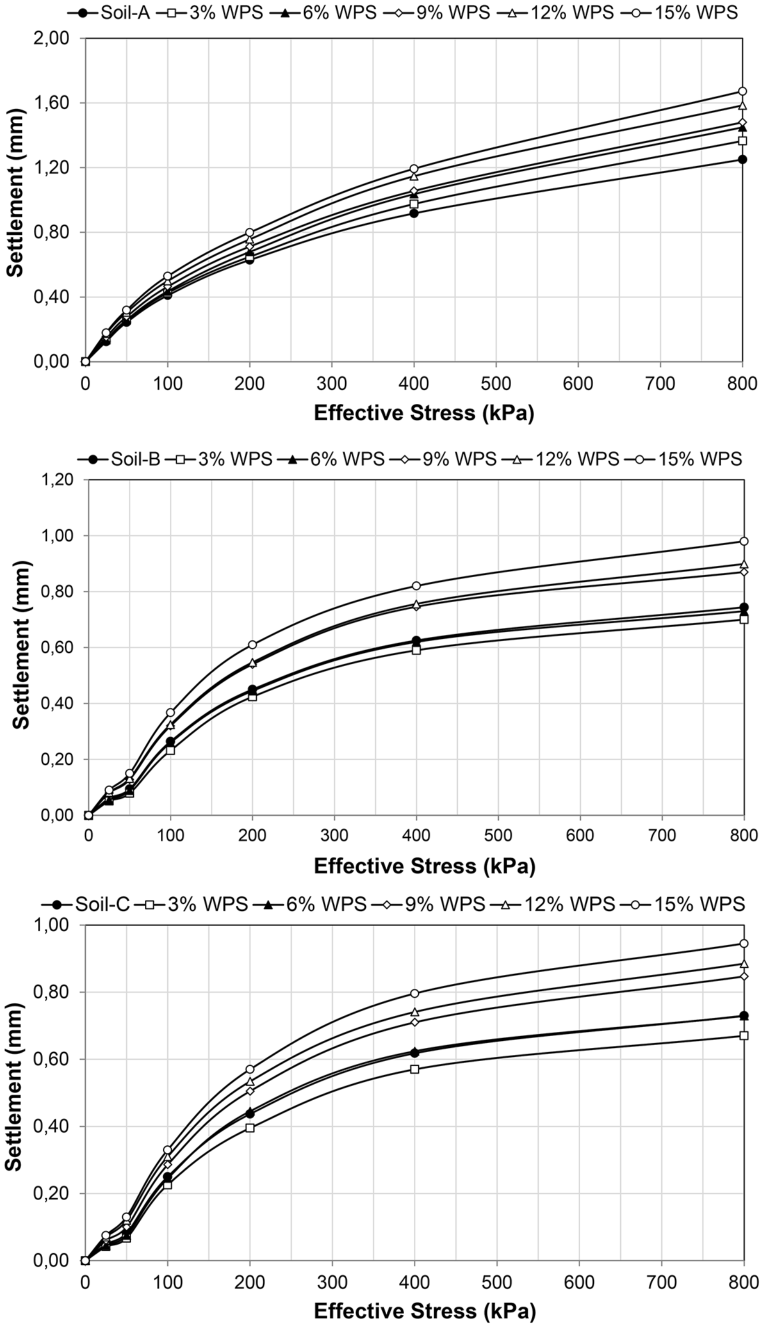

Fig. 15. Variation of consolidation settlements with WPS content under different effective.

WPS initially showed a decreasing trend, then started to increase with further addition of WPS. This pointed out that the Soil-B and Soil-C specimens with lower WPS content ($\leq\ 6\%$) exhibit lower compressibility than the pure soil specimens.

- The statistical analysis of the test data obtained in this study suggested that a moderate to strong linear relationship existed between investigated swelling/shrinkage parameters.
- The overall test results showed that stabilization, particularly reducing the volume change potential, of soils through WPS appears to be more effective and feasible for the low-plasticity clay soils than the high-plasticity clay soils. In this study, except for consolidation settlements, WPS with content up to 15% can be used to minimize volume change flocculations for CH soil. For CL soil types used here, WPS with content up to 6% can be effective in controlling consolidation-induced settlements and however, it can perform well in reducing volume change behavior with WPS content up to 15%.
- The experimental results presented in this paper indicated that WPS possesses a high potential to significantly reduce the volume change potential of subgrade soils, especially for soils classified as CL. The data presented in this study covers only a limited range of WPS content (0–15%) due to its complex structure

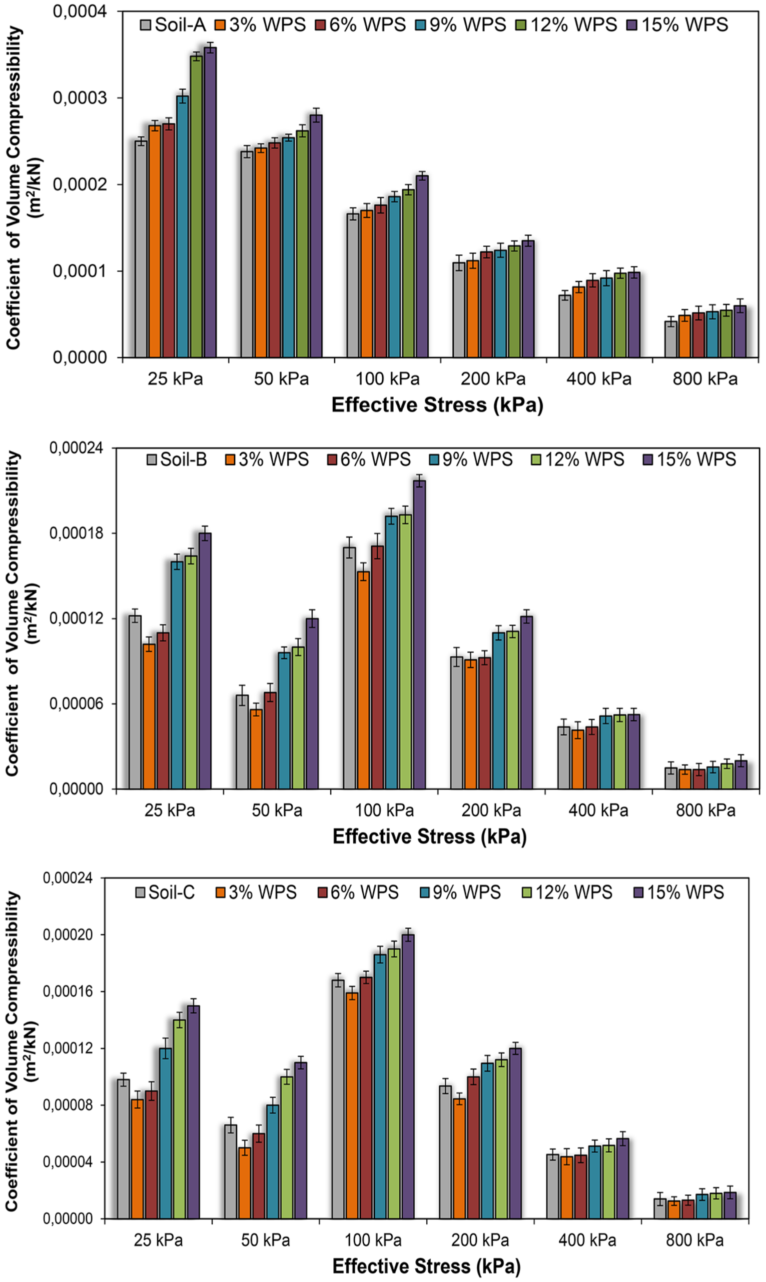

Fig. 16. Variation of coefficient of volume compressibility with WPS content.

and further experimental studies at much higher rates may be useful to fully explain the volume change behavior of such soils. There is also a research avenue to investigate long-term volume change fluctuations of soils stabilized using WPS. Comprehensive experimental studies on the strength properties of such soils, which are underway, may be useful in fully clarifying the usability of WPS for the stabilization of expansive subgrade soils.

- In engineering applications, the volumetric instability of expansive soils is generally treated by traditionally used chemical stabilizers such as cement and lime throughout the world. However, due to the environmental concers arised the greenhouse gases during the production of these traditional stabilizers and financial considerations, researchers and sector representatives look for waste materials that can be alternatively used in the stabilization of expansive soils. Replacing these types of conventional stabilizers with WPS, which has the potential to be a cost-effective, environmentally friendly and sustainable material, would be a good approach at this point.

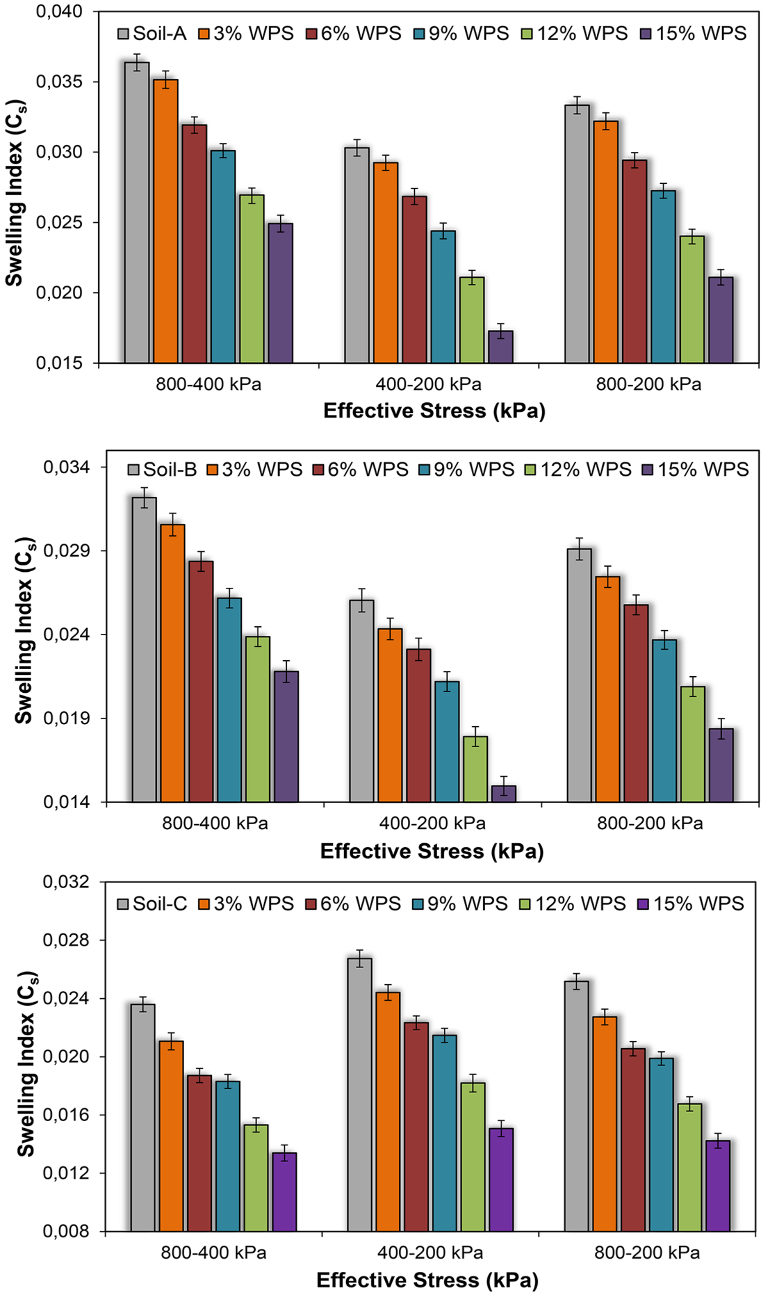

Fig. 17. Change in the swelling index with WPS content under different effective stresses.

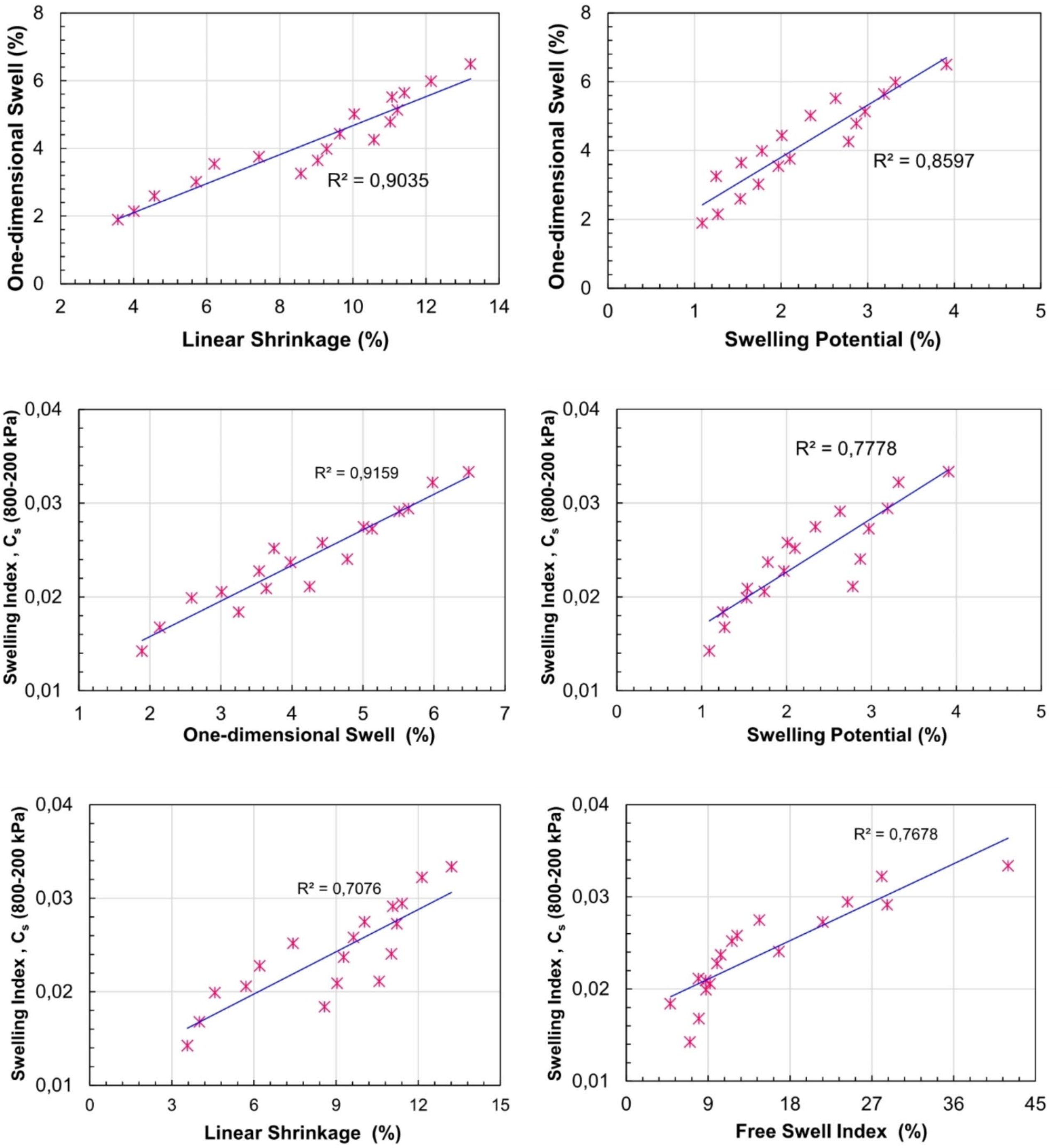

Fig. 18. Relationships between investigated swelling/shrinkage parameters.

Data availability

The datasets generated and/or analysed during the current study are not publicly available but are available from the corresponding author on reasonable request.

Received: 20 July 2024; Accepted: 15 November 2024

References

1. Canakci, H., Aziz, A. & Celik, F. Soil stabilization of clay with lignin, rice husk powder and ash. *Geomech. Geoengin*. **8**, 67–79. https://doi.org/10.12989/gae.2015.8.1.067 (2015).
2. She, J., Lu, Z., Duan, Y., Yao, H. & Liu, L. Experimental study on the engineering properties of expansive soil treated with Al13. *Sci. Rep.* **10**, 13930. https://doi.org/10.1038/s41598-020-70947-6 (2020).
3. Sahoo, S. & Prasad Singh, S. Strength and durability properties of expansive soil treated with geopolymer and conventional stabilizers. *Constr. Build. Mater.* **328**, 127078. https://doi.org/10.1016/j.conbuildmat.2022.127078 (2022).
4. Al-Mukhtar, M., Khattab, S. & Alcover, J. F. Microstructure and geotechnical properties of lime-treated expansive clayey soil. *Eng. Geol.* **139**, 17–27. https://doi.org/10.1016/j.enggeo.2012.04.004 (2012).
5. Kianimehr, M., Shourijeh, P. T., Binesh, S. M., Mohammadinia, A. & Arulrajah, A. Utilization of recycled concrete aggregates for light-stabilization of clay soils. *Constr. Build. Mater.* **227**, 116792. https://doi.org/10.1016/j.conbuildmat.2019.116792 (2019).
6. Estabragh, A., Babaei, M. & Javadi, A. Effect of glycerol on the behaviour of an expansive soil during wetting and drying cycles. *Int. J. Pavement Eng.* **22**, 1284–1294. https://doi.org/10.1080/10298436.2019.1683176 (2021).
7. Cinar, M. Utilization of earthquake demolition wastes and Afşin–Elbistan fly Ash for Soil Improvement after the Kahramanmaraş Earthquake (6 February 2023). *Sustainability* **16** (538). https://doi.org/10.3390/su16020538 (2024).
8. Saltan, M., Kavlak, Y. & Ertem, F. S. Utilization of pumice waste for clayey subgrade of pavements. *J. Mater. Civ. Eng.* **23**, 1616–1623. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000336 (2011).
9. Cabalar, A. F., Awraheem, M. H. & Khalaf, M. M. Geotechnical properties of a low-plasticity clay with biopolymer. *J. Mater. Civ. Eng.* **30**, 04018170. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002380 (2018).
10. Liu, Y. et al. Stabilization of expansive soil using cementing material from rice husk ash and calcium carbide residue. *Constr. Build. Mater.* **221**, 1–11. https://doi.org/10.1016/j.conbuildmat.2019.05.157 (2019).
11. Ávila, F., Puertas, E. & Gallego, R. Characterization of the mechanical and physical properties of stabilized rammed earth: a review. *Constr. Build. Mater.* **325**, 126693. https://doi.org/10.1016/j.conbuildmat.2022.126693 (2022).
12. Li, M., Fang, C., Kawasaki, S. & Achal, V. Fly ash incorporated with biocement to improve strength of expansive soil. *Sci. Rep.* **8**, 2565. https://doi.org/10.1038/s41598-018-20921-0 (2018).
13. Nhuchhen, D. R., Sit, S. P. & Layzell, D. B. Decarbonization of cement production in a hydrogen economy. *Appl. Energy*. **317**, 119180. https://doi.org/10.1016/j.apenergy.2022.119180 (2022).
14. Zhang, Y. et al. Development of sustainable geopolymer with excavation soil powder as precursor: Cementitious properties and thermal-activated modification. *J. Build. Eng.* **91**, 109745. https://doi.org/10.1016/j.jobe.2024.109745 (2024).
15. Tanyıldızı, M., Uz, V. E. & Gökalp, İ. Utilization of waste materials in the stabilization of expansive pavement subgrade: an extensive review. *Constr. Build. Mater.* **398**, 132435. https://doi.org/10.1016/j.conbuildmat.2023.132435 (2023).
16. Amakye, S. Y., Abbey, S. J., Booth, C. A. & Mahamadu, A. M. Enhancing the Engineering Properties of Subgrade materials using processed Waste: a review. *Geotechnics* **1**, 307–329. https://doi.org/10.3390/geotechnics1020015 (2021).
17. Bilgen, G. & Altuntas, O. F. Sustainable re-use of waste glass, cement and lime treated dredged material as pavement material. *Case Stud. Constr. Mater.* **18**, e01815. https://doi.org/10.1016/j.cscm.2022.e01815 (2023).
18. Jeremiah, J. J., Abbey, S. J., Booth, C. A. & Eyo, E. U. Viability of calcinated wastepaper sludge ash geopolymer in the treatment of road pavement subgrade materials. *Transp. Geotech.* **44**, 101165. https://doi.org/10.1016/j.trgeo.2023.101165 (2024).
19. Ozola, Z. U., Vesere, R., Kalnins, S. N. & Blumberga, D. Paper waste recycling. Circular economy aspects. *Environ. Clim. Technol.* **23**, 260–273. https://doi.org/10.2478/rtuect-2019-0094 (2019).
20. Frías, M., Rodríguez, O., Vegas, I. & Vigil, R. Properties of calcined clay waste and its influence on blended cement behavior. *J. Am. Ceram. Soc.* **91**, 1226–1230. https://doi.org/10.1111/j.1551-2916.2008.02289.x (2008).
21. Wang, X., Yu, X., Li, Z., Han, Z. & Zou, W. -l. dynamic responses of a waste sludge modified by magnesium-cement-based multiphase cementitious material under influences of temperature and moisture cycles. *Constr. Build. Mater.* **402**, 133054. https://doi.org/10.1016/j.conbuildmat.2023.133054 (2023).
22. Frías, M., Rodríguez, O. & de Sánchez, M. I. Paper sludge, an environmentally sound alternative source of MK-based cementitious materials. A review. *Constr. Build. Mater.* **74**, 37–48. https://doi.org/10.1016/j.conbuildmat.2014.10.007 (2015).
23. Elbasri, O. M. M., Nser, S., Shubaili, M., Abdullah, G. M. S. & Zeyad, A. M. Performance of self-compacting concrete incorporating wastepaper sludge ash and pulverized fuel ash as partial substitutes. *Case Stud. Constr. Mater.* **17**, e01459. https://doi.org/10.1016/j.cscm.2022.e01459 (2022).
24. De Azevedo, A. R. G. et al. Technological and environmental comparative of the processing of primary sludge waste from paper industry for mortar. *J. Clean. Prod.* **249**, 119336. https://doi.org/10.1016/j.jclepro.2019.119336 (2020).
25. Bui, N. K., Satomi, T. & Takahashi, H. Influence of industrial by-products and waste paper sludge ash on properties of recycled aggregate concrete. *J. Clean. Prod.* **214**, 403–418. https://doi.org/10.1016/j.jclepro.2018.12.325 (2019).
26. Mavroulidou, M. Use of waste paper sludge ash as a calcium-based stabiliser for clay soils. *Waste Manag Res.* **36**, 1066–1072. https://doi.org/10.1177/0734242x18804043 (2018).
27. Khalid, N., Mukri, M., Kamarudin, F. & Arshad, M. F. Clay soil stabilized using waste paper sludge ash (WPSA) mixtures. *Electron. J. Geotech. Eng.* **17**, 1215–1225 (2012).
28. Prakash, M. & Raveendran, R. Comparison between paper sludge and rice husk ash as a stabilizing agent for soft soil. *IOSR J. Mech. Civ. Eng.*, e-ISSN: 2278-1684, 08–11 (2016).
29. Kumar, A. & Gupta, S. Strength development of soil using waste paper sludge (WPS). *Int. Res. J. Eng. Technol.* **3**, 2144–2147 (2016).
30. Bawa, A. & Bawa, N. Development of strength in soft soil stabilized with waste paper sludge. *Int. J. Eng. Sci. Inv Res. Dev.* **III**, 821–826 (2017).
31. BA, A., Jain, S. R. M. & HP, V. A. An experimental study of laterite soil stabilized with waste paper sludge. *Int. Res. J. Mod. Eng. Technol. Sci.* **4**, 260–268 (2022).
32. Patel, K. et al. Soil stabilization by using waste paper sludge. *Int. J. Innov. Res. Sci. Eng. Technol.* **9**, 3004–3007 (2020).
33. Teja, V. S., Sindhuja, K. & Krishna, G. S. Improvement of properties of highly swelling soil by using waste paper sludge. *Int. J. Eng. Dev. Res.* **4**, 417–419 (2016).
34. ASTM D4318, Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. (2018).
35. Orhan, M., Ozer, M. & Işık, N. S. Doğal zeminlerin likit limitinin belirlenmesinde Casagrande ve Koni batma yöntemlerinin karşilaştirilmasi. *Gazi Üniv. Mühendislik Mimarlık Fakültesi Dergisi* **21**, 711–720 (2006).
36. IS 2720 (Part–40)–1977, Determination of free swell index of soils. (2002).
37. ASTM D4546, Standard test methods for one-dimensional swell or collapse of soils. (2014).
38. ASTM D1883, Standard test method for CBR (California bearing ratio) of laboratory-compacted soils. (2007).
39. BSI, Methods of test for soils for civil engineering purposes. (1990).
40. ASTM D2166, Standard test method for unconfined compressive strength of cohesive soil. (2013).
41. ASTM D2435, Standard Test Method for One-Dimensional Consolidation Properties of Soils. (2020).
42. Netinger Grubeša, I., Barišić, I., Fucic, A. & Bansode, S. S. *In Characteristics and uses of Steel slag in Building Construction (eds IN Grubeša, I Barišić, A Fucic, SS Bansode)* Woodhead Publishing, 141–160. (2016).
43. Sefene, S. S. Determination of effective wood ash proportion for black cotton soil improvement. *Geotech. Geol. Eng.* **39**, 617–625. https://doi.org/10.1007/s10706-020-01508-x (2021).
44. Jalal, F. E., Xu, Y., Jamhiri, B. & Memon, S. A. On the recent trends in expansive soil stabilization using calcium-based stabilizer materials (CSMs): A Comprehensive review. *Adv. Mater. Sci. Eng.* https://doi.org/10.1155/2020/1510969 (2020).

45. Holtz, R. D., Kovacs, W. D. & Sheahan, T. C. *An Introduction to Geotechnical Engineering* 733. (Prentice-hall Englewood Cliffs, NJ). 1981.
46. Barman, D. & Dash, S. K. Stabilization of expansive soils using chemical additives: a review. *J. Rock. Mech. Geotech. Eng.* **14**, 1319–1342. https://doi.org/10.1016/j.jrmge.2022.02.011 (2022).
47. Sharma, A. & Sharma, R. Effect of addition of construction–demolition waste on strength characteristics of high plastic clays. *Innov. Infrastruct. Solut.* **4**, 27. https://doi.org/10.1007/s41062-019-0216-1 (2019).
48. Singh, N. & Bisen, S. S. Soil stabilization and modification using waste paper sludge. *Int. J. Creat. Res. Thoughts* **9**, 76–83 (2021).
49. Moghal, A. A. B. et al. Effect of calcium-based derivatives on consolidation, strength, and lime-leachability behavior of expansive soil. *J. Mater. Civ. Eng.* **32**, 04020048. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003088 (2020).
50. Rogers, C. D. F. & Glendinning, S. Lime requirement for stabilization. *Transp. Res. Rec.* **1721**, 9–18. https://doi.org/10.3141/1721-02 (2000).
51. Ahmadi Chenarboni, H., Hamid Lajevardi, S., MolaAbasi, H. & Zeighami, E. The effect of zeolite and cement stabilization on the mechanical behavior of expansive soils. *Constr. Build. Mater.* **272**, 121630. https://doi.org/10.1016/j.conbuildmat.2020.121630 (2021).
52. Wu, Z. et al. Strength and micro-structure evolution of compacted soils modified by admixtures of cement and metakaolin. *Appl. Clay Sci.* **127**, 44–51. https://doi.org/10.1016/j.clay.2016.03.040 (2016).
53. Elias, N. Strength development of soft soil stabilized with waste paper sludge. *Int. J. Adv. Technol. Eng. Sci.* **3**, 141–149 (2015).
54. Kumar, A. & Gupta, S. Soil stabilization by utilization of hypo sludge and lime. *Int. J. Sci. Res. Sci. Eng. Technol.* **2**, 192–195 (2016).
55. Akbulut, N. *Graduate School of Natural & Applied Sciences* Ph.D. thesis, Hasan Kalyoncu University. (2020).
56. Okoro, C. C., Vogtman, J., Yousif, A., Agnaou, M. & Khoury, N. in *Geo-Front. 2011 Adv. Geotech. Eng.* 1202–1209 (2011).
57. Ahmadi Chenarboni, H., Lajevardi, S. H., Molaabasi, H. & Zeighami, E. Consolidation behavior of the expansive clay treated with cement and zeolite. *J. Cent. South. Univ.* **29**, 3140–3157. https://doi.org/10.1007/s11771-022-5147-x (2022).

Author contributions

M.T.: Conceptualization, Methodology, Writing-Original draft, Investigation, Visualition, Supervision, Data Curation, Reviewing and editing.İ.G.: Conceptualization, Data curation, Writing-Original draft, Reviewing and editing, Visualization.A.Z.:Data curation, Writing-Original draft, Software, Reviewing and editing.V.E.U.:Data curation, Software, Reviewing and editing, Supervision.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to M.T.

Reprints and permissions information is available at www.nature.com/reprints.

Terms and Conditions

Springer Nature journal content, brought to you courtesy of Springer Nature Customer Service Center GmbH (“Springer Nature”).

Springer Nature supports a reasonable amount of sharing of research papers by authors, subscribers and authorised users (“Users”), for small-scale personal, non-commercial use provided that all copyright, trade and service marks and other proprietary notices are maintained. By accessing, sharing, receiving or otherwise using the Springer Nature journal content you agree to these terms of use (“Terms”). For these purposes, Springer Nature considers academic use (by researchers and students) to be non-commercial.

These Terms are supplementary and will apply in addition to any applicable website terms and conditions, a relevant site licence or a personal subscription. These Terms will prevail over any conflict or ambiguity with regards to the relevant terms, a site licence or a personal subscription (to the extent of the conflict or ambiguity only). For Creative Commons-licensed articles, the terms of the Creative Commons license used will apply.

We collect and use personal data to provide access to the Springer Nature journal content. We may also use these personal data internally within ResearchGate and Springer Nature and as agreed share it, in an anonymised way, for purposes of tracking, analysis and reporting. We will not otherwise disclose your personal data outside the ResearchGate or the Springer Nature group of companies unless we have your permission as detailed in the Privacy Policy.

While Users may use the Springer Nature journal content for small scale, personal non-commercial use, it is important to note that Users may not:

1. use such content for the purpose of providing other users with access on a regular or large scale basis or as a means to circumvent access control;
2. use such content where to do so would be considered a criminal or statutory offence in any jurisdiction, or gives rise to civil liability, or is otherwise unlawful;
3. falsely or misleadingly imply or suggest endorsement, approval , sponsorship, or association unless explicitly agreed to by Springer Nature in writing;
4. use bots or other automated methods to access the content or redirect messages
5. override any security feature or exclusionary protocol; or
6. share the content in order to create substitute for Springer Nature products or services or a systematic database of Springer Nature journal content.

In line with the restriction against commercial use, Springer Nature does not permit the creation of a product or service that creates revenue, royalties, rent or income from our content or its inclusion as part of a paid for service or for other commercial gain. Springer Nature journal content cannot be used for inter-library loans and librarians may not upload Springer Nature journal content on a large scale into their, or any other, institutional repository.

These terms of use are reviewed regularly and may be amended at any time. Springer Nature is not obligated to publish any information or content on this website and may remove it or features or functionality at our sole discretion, at any time with or without notice. Springer Nature may revoke this licence to you at any time and remove access to any copies of the Springer Nature journal content which have been saved.

To the fullest extent permitted by law, Springer Nature makes no warranties, representations or guarantees to Users, either express or implied with respect to the Springer nature journal content and all parties disclaim and waive any implied warranties or warranties imposed by law, including merchantability or fitness for any particular purpose.

Please note that these rights do not automatically extend to content, data or other material published by Springer Nature that may be licensed from third parties.

If you would like to use or distribute our Springer Nature journal content to a wider audience or on a regular basis or in any other manner not expressly permitted by these Terms, please contact Springer Nature at

onlineservice@springernature.com