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PERFORMANCE CHARACTERISTICS OF LOW CARBON WASTE MATERIAL TO STABILISE SOIL WITH EXTREMELY HIGH PLASTICITY

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Abstract. The application of low-carbon and natural materials to mitigate the undesired properties of difficult soils is considered as a sustainable solution to the issues regarding these soils. Selecting some natural materials, of low carbon type, from the rubble of demolished buildings or debris from the construction of new buildings and recycling them in a poor or weak soil stabilisation process is a very little explored field of research in Iraq. This paper investigated the geotechnical characteristics of extremely high plasticity soil (EHPS) improved with a low-carbon building stone debris (BSD). Five dosages from coarse and fine soil-size ((BSDC) and (BSDF)) of BSD have been prepared to use in the EHPS-BSD mixtures. The laboratory tests included Atterberg limits, linear shrinkage, unconfined compression, consolidation, and swelling. The effect of the BSD on the time to zero-water content and the maximum swell was included. The efficiency of the BSD was proved by the amelioration of the compressibility and strength, and by reducing the shrinkage, swell pressure, and the potential of swelling. The shrinkage, compressibility, and swelling properties of the EHPS were reduced depending on the gradation and content of BSD. The gradation of BSD had a major role in strength development and controlling the time required to reach the final shrinkage and maximum swell stage.

Keywords: Low carbon materials, extremely high plasticity soil, swelling shrinkage.

1. Introduction

High plasticity soils (HPS) have unsought properties upon wetting and drying like shrinkage and expansion. These soils exhibit a considerable shrinkage/swelling when their water or moisture content is subjected to a seasonal fluctuation [1, 2]. The unsought properties of HPS have negative effects on the strength and compressibility of these soils, as such, HPS are considered as unfavourable and unsuitable soils to be used as foundation materials. The construction of different engineering infrastructures on HPS represents a big challenge for engineers. Where HPS occur, they are difficult as layers for roads or as foundations for light structures. Due to the unfavourable properties of HPS, their difficult nature, and their widespread presence across the world, these soils have gained worldwide attention. Therefore, high plasticity soils need an enhancement in their index and mechanical properties [2–4].

There are numerous ways one can utilise and adopt in the enhancement processes of properties of difficult soils, such as electrical, mechanical, chemical, physical, and biological treatment methods. For more sustainable technologies, recycling of waste material for the soil stabilization is also applied. However, mitigating the particle volume changes in the HPS by chemical alternation is among the most effective stabilisation techniques that gained the acceptance of geotechnical engineers [5–22]. The efficiency of the stabilising material (economic and design) is an important factor that affects the chemical stabilizer selection. Also, the impacts of the selected stabilizer on the environment should be kept in mind. Improvement technologies of difficult soils have to be used within a manner that take into account the environmental aspects so as not to cause adverse effects to the environment (soil, air, and water). Hence, an improvement and stabilisation of soils using low-carbon natural materials are highly encouraged [2, 22, 23]. Using such materials is considered a sustainable solution to the problems of difficult soils [23].

There is a number of materials defined as "low carbon materials", LCM. Among these materials are lime, rice-husk (reactive ash), fly ash, silica fume, granulated slag, blended cement, natural stones, stone dust, and several liquid materials like "sodium silicate-based" [23–26]. Materials like "ground-granulated blast-furnace slag", which have low carbon emissions, have been used in improving expansive soil. Such an application causes a positive reduction in the emissions of carbon dioxide. The solid block units produced from the compaction of the mixture of soil, lime, and water are considered as the LCM and eco-friendly construction material [2, 27]. The use of high volumes of coal fly ash, silica fume, rice-husk (reactive ash), or granulated slag in the cement manufacturing process produced a low carbon cement called blended cement. Also, the compacted mixture of stone dust, fly ash, and lime is used to produce a block with a high density, such a block has been considered as LCM. Natural materials like stones, biomass, and soil are considered ideal building materials [18, 19]. Such materials were considered as ideal due to their low emission of carbon, recycling potential, reusability, and a low carbon footprint. The "cement stabilized rammed earth" is another material that was proven to be low-carbon material [28]. Also, the autoclaved dredged mud-brick is another LCM. This material is produced by mixing 10 % of fly ash, 12 % of steel slag, and 15 % of calcium carbide with dredged soil [29]. Furthermore, the "ground granulated blast furnace slag – GBS" has been considered as a sustainable LCM. The rammed earth (including different additives like lime or gravel and sand), for wall construction purposes, has been used as LCM. In addition, some of the natural stones were, also, referred to as being LCM [25, 30]. In the last years, [31], a low carbon liquid additive named "sodium silicate-based" has been used to improve the compressibility and strength properties of soils. The application of "sodium silicate-based" was considered as a sustainable solution to the problems of expansive soil. This is due to the composition of this material, it is mainly composed of elements like Si, Na, Fae, and Al, therefore, it is classified as LCM. Based on the chemical composition of the material, tile factory waste was also classified as an LCM and considered as a successful stabiliser to improve the properties of clay soil. It was found that the waste of tiles is mainly composed of sodium, silicon, oxygen, and magnesium [31]. Recent studies emphasised the geoenvironmental issue regarding the stabilisation of expansive soils. These studies show the necessity of sustainability of soil stabilisation processes. Avoiding parameters (like dosage and type of additive) that cause adverse effects on the environment (like emission of carbon) should be considered. It is undesirable to use additives with a high carbon or heavy metal content in the soil stabilisation processes [32].

Selecting some natural materials of LCM type from the rubble of demolished buildings or debris from the construction of new buildings and recycling them in a poor or weak soil stabilisation process is a very little explored field of research in Iraq. In this work, low-carbon natural building stone debris (BSD) was selected as a solid additive to ameliorate the geotechnical characteristics of extremely high plasticity soil (EHPS). Extensive laboratory testing was carried out. BSD was prepared in two different sizes to use in EHPS-BSD mixtures, these are coarse soil-size and fine soil-size, denoted as BSDC and BSDF, respectively. Five dosages of each BSD size used, ranging from 10 % to 50 %, with an increment of 10 %, were prepared. Experiments included Atterberg limits, linear shrinkage, unconfined compression, consolidation, and swelling tests. Also, the effect of curing on the development of soil strength has been included.

Soil Properties	Values
Color	Yellow
Specific Gravity, Gs	2.58
Sand fraction (0.06-2 mm, %)	0
Silt fraction (0.002–0.06 mm, %)	18
Clay fraction (less than 0.002 mm)	82
Liquid limit, w_L (%)	139
Plastic limit, w_p (%)	43
Plasticity Index, Ip (%)	96
Soil Activity, A	1.17
BSCS	CE
Optimum water content (%)	35
Maximum dry density, g/cm^3	1.23
Silicon, Si (%)	20.71
Aluminium, Al (%)	6.68
Calcium, Ca (%)	3.38
Magnesium, Mg (%)	2.14
Iron, Fe (%)	0.62
Sodium, Na (%)	0.75
Nitrogen, N (%)	1.57
Oxygen, O (%)	60.88
Carbon, C (%)	0.00

Table 1. Properties and characteristics of the EHPS.

2. Materials and methods

2.1. Extremely high plasticity soil (EHPS)

The soil selected in this study is plastic clay soil, it is a naturally occurring problematic soil with a clay content higher than 80 %. The disturbed soil sample used in this study was obtained from Al-Anbar province (Latitude 32° 31' N and longitude 41° 54' E), Iraq. The basic properties of the soil have been determined and are shown in Table 1. According to BS 5930, the selected soil was classified as "clay of extremely high plasticity" "CE". Throughout this paper, the selected soil of extremely high plasticity has been denoted as (EHPS). The EHPS has a high plasticity index ($Ip =$ 96 %) with an activity value (A) of 1.17. Based on Ip and A values and the potential expansivity, the EHPS can be classified as "Very High", [33].

The chemical composition of EHPS, Table 1, indicates that the element of silicon is the most abundant, also, EHPS has a high content of calcium component, with the other elements being aluminium, iron, etc. The qualitative X-Ray diffraction (X.R.D.) analysis indicated that montmorillonite and Quartz are the main constituents of the soil, [34]. The value of "cation exchange capacity" for EHPS is 80 meq/100 g. As it can be seen, the results of physical, chemical, mineralogical tests indicate that the studied EHPS is potentially expansive.

2.2. Building stone debris (BSD)

In Iraq, natural stones are an essential building material used in construction. They are used for the

Material Property	DBSC	DBSF
Color	very pole brown	light yellowish brown
Specific Gravity, Gs	2.78	2.71
Liquid limit, w_L (%)	28	32
Plastic limit, w_P (%)	–	–
Plasticity Index, Ip (%)	NP	NP
D10 (mm)	0.13	0.001
D30 (mm)	0.18	0.0028
D50 (mm)	0.23	0.0065
D60 (mm)	0.26	0.01
Cu	2	10
Cc	0.99	0.78
British Soil Classification System, BSCS	SP	M
USCS	SP	ML
CaO	63.41	
Fe2O3	20.09	
SiO2	5.30	
K2O	1.19	
MnO	0.15	

Table 2. Properties and characteristics of BSD.

DBS Content, %	10	20	30	40	50
Designation	DBSC10 DBSF10	DBSC20 DBSF20	DBSC30 DBSF30	DBSC40 DBSF40	DBSC50 DBSF50

Table 3. Designation of the produced EHPS-BSD mixtures.

masonry of buildings. Also, natural stones are preferred for finishing and facing works. Mostly, natural massive rocks are the main source of the building stones in Iraq. The building stone debris (BSD) was selected as a solid additive to ameliorate the geotechnical characteristics of extremely high plasticity soil (EHPS).

The BSD used was obtained and collected from a dumping area at one of the construction sites in Baghdad city, the capital of Iraq. BSD was prepared in the laboratory in steps including cleaning, drying, crushing, and sieving. After cleaning the surface of the BSD from foreign materials, drying at a temperature of 105° C took place, the BSD was crushed in two stages. A small hammer was first used to crush the BSD manually, while in the second stage, BSD was crushed mechanically. Subsequently, the crushed BSD was divided into two sets. The crushed BSD in the first set was sieved on sieve No. 40, the remaining material was then subjected to further mechanical crushing, then sieved again to ensure all material passed through the sieve 40. The crushed BSD from the second set was subjected to further crushing using the Los Angeles machine. The resultant material was sieved on sieve No. 200, and the residual material was then returned to the Los Angeles machine for further crushing. Such a process was continued until all the material passed the sieve No. 200.

To study the effect of the gradation of BSD on the geotechnical properties of the soil, two different gradations were prepared, the first one is the coarse gradation that included the materials passing through the sieve No. 40, denoted BSDC, while the second gradation is the gradation of fine material, obtained from materials passing the sieve No. 200, denoted BSDF.

The basic properties of the BSD are shown in Table 2. Clearly, the BSD is a non-plastic material and has higher Gs values than EHPS. BSD's chemical components show that, notably, the Ca, Fae, and Si are the main elements of BSD. Accordingly, it can be confirmed that the selected stabilising agent in this work shows a low-carbon content, in other words, it is an eco-friendly agent.

2.3. Preparation of specimens and laboratory testing programme

The EHPS was mixed with different dosages of BSDC and BSDF (Table 3). For this purpose, the dosages of 10 %, 20 %, 30 %, 40 %, and 50 % by weight of the dry soil were added to the EHPS. The EHPS-BSD mixtures were prepared by mixing the dosages of BSD with EHPS to form completely homogeneous mixtures. In general, the dry mixing method was used to prepare testing soil specimens. The designation of each produced sample is shown in Table 3.

The laboratory tests included Atterberg limits, linear shrinkage [35], compaction test, unconfined com-

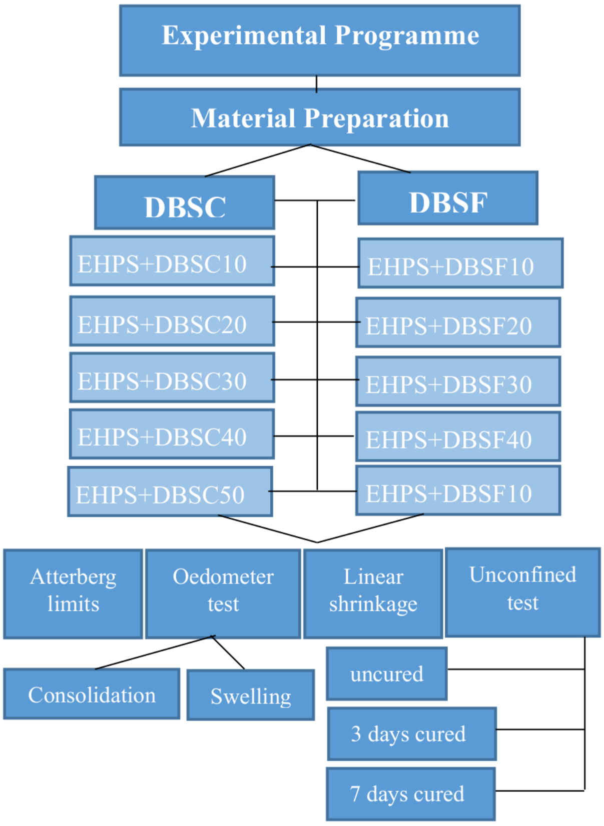

Figure 1. Testing programme.

pression [36], consolidation, and swelling tests [36]. The effect of curing on the unconfined compression test samples has also been included in the testing programme (see Figure 1).

Specimens were cured for 3 and 7 days. For basic tests, disturbed mixtures were used, while for engineering tests, compaction was applied to achieve the specified dry unit weights and corresponding water contents.

The compacted specimens were extruded from a standard compaction mould. The homogenous wet mixtures were prepared at an optimum water content, then compacted to a corresponding maximum unit weight inside a standard compaction mould. The specimens for engineering tests were obtained by pushing the 3.6 cm diameter and 7.2 cm height steel mould of unconfined tests inside the compaction mould. The obtained specimens were either directly tested for unconfined-compressive-strength [36] or cured for three and seven days and then tested. It should be noted that all cured specimens were weighted with a precision of 0.01 g after the preparation and after the completion of the curing period to ensure minimum variations and maximal consistency. The difference in weight was very little (in the second decimal of the weight), and this indicates a great accuracy of the curing process.

The compressibility of EHPS-BSD mixtures was studied by carrying out a set of oedometer tests (one-dimensional-consolidation test [36]; each wet homogenous EHPS-BSD mixture was statically compacted inside the oedometer ring (5 cm diameter and 2 cm height) to obtain the required unit weight. A set of swell-tests was carried out in accordance with [36] to study the volume changes of EHPS-BSD mixtures. The preparation of swell test specimens was similar to that of the consolidation test specimens. However, the height of the specimen for the swell test (1.65 cm) is smaller than the height of the ring (2 cm). This is, as stated by HEAD [37], to ensure a total lateral confining throughout the test. The swelling was measured using a dial gauge of 0.002 mm/division. After soaking, the following intervals were fixed to record the swelling: (0.5 min, 1 min, 2 min, 4 min, 8 min, 16 min, 30 min, 60 min, 120 min, 180 min, 240 min, 1440 min, 2880 min, 4320 min, 5760 min, 7200 min, and 8640 min).

3. Results and discussion

3.1. Plasticity of EHPS-BSD mixtures

The results of Atterberg's limits (liquid limit (w_L), plastic limit (w_P), and plasticity index (Ip) for EHPS mixed with two graded types of BSD are provided in Figure 2. There is a clear improvement of the properties of the EHPS when mixed with BSDC and BSDF. There is a characteristic reduction in w_L due to the addition of the BSDC and BSDF. However, a higher reduction in w_L values can be noted in EHPS-BSDC mixtures as compared to EHPS-BSDF mixtures. The percentual decrease in w_L of EHPS was about 50 %

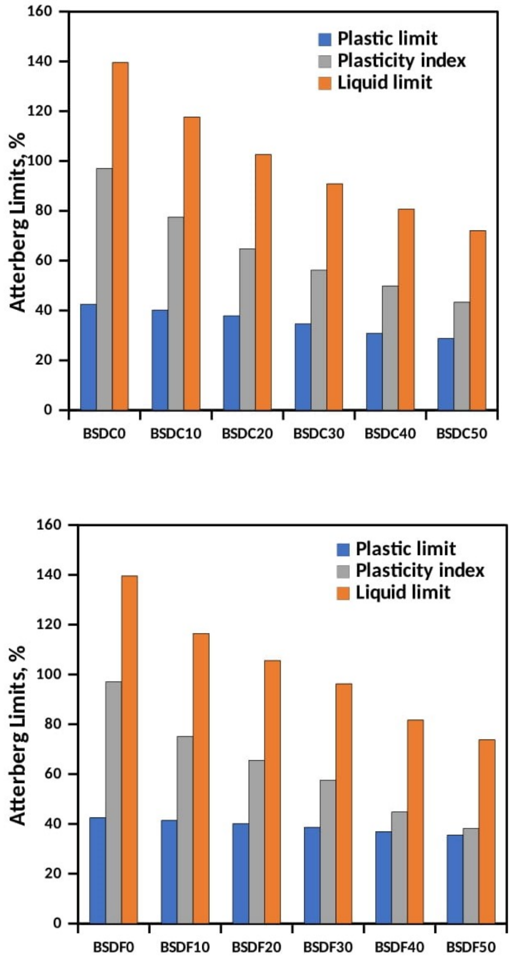

Figure 2. Variation of Atterberg limits with various BSD percentages.

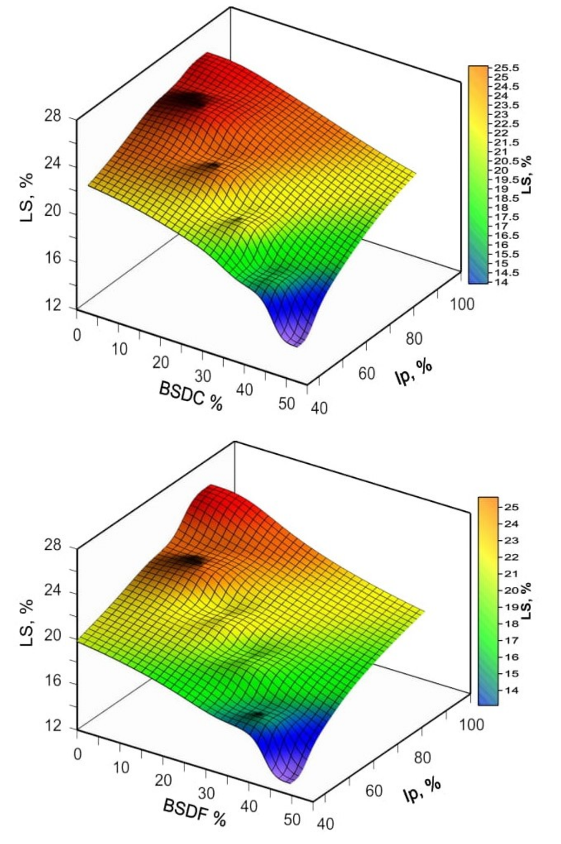

Figure 3. Variation of LS with various BSD percentages.

and 49 % for BSDC50 and BSDF50, respectively. This is also the case for w_P values, w_P decreased with increasing the content of both types of BSD. But a distinct response can be seen to the addition of BSDC in comparison with BSDF. As shown in Figure 2, w_P decreased considerably with the addition of BSDC. The gross effect on the improvement of plasticity with BSD is a decrease in the Ip of EHPS-BSD mixtures. As for the w_L, Figure 2 clearly shows that the improvement effect of BSDF was better than that of an equal amount of BSDC. While the Ip of EHPS decreased below 35 % for BSDF50, the EHPS mixed with the identical quantity of BSDC had Ip value of 40 %. In general, an increased BSD percentage led to a decrease in the Ip. The same finding is, also, reported by [38] for expansive soil treated with "pyroclastic rock dust". As such, an immediate alteration in EHPS workability can be caused by the exchanging of calcium ions, released by the CaO from the BSD structure, with other ions on the structure of the EHPS. Such a cation exchange caused the w_L to decrease and as a result, reduce Ip. Such a reduction in Ip produced a more tenuous texture of EHPS-BSD mixtures and this makes the EHPS in-situ handling easier.

3.2. Linear shrinkage (LS) result

According to the procedure presented by BS 1377 [36], Linear Shrinkage (LS) values for EHPS-BSD mixtures were determined. Test specimens were prepared at a high water content (near the w_L) and placed in the designed mould under lab conditions. The changes that take place in the air and water phases of specimens have been analysed, and shrinkage paths have been examined for LS. Figure 2 shows the variation of LS and Ip with different contents of BSD. As can be seen, when the content of BSD increased from 0 % to 50 %, the LS reduced, decreasing the Ip. Particularly, the LS of BSDC50 and BSDF50 mixtures decreased by 45.7 % and 48.8 %, respectively, in comparison to unaltered EHPS specimens. A re-examination of Figure 3 showed that the efficiency of BSDF was higher than that of BSDC in decreasing the shrinkage values of EHPS, however, the trend of decreasing LS is comparable for both the BSDC and BSDF.

The study of LS included the time to reach the final drying stage (the zero-water content). The effect of the type and content of BSD on the time needed to reach the final shrinkage stage has been investigated. For each EHPS and EHPS-BSD mixtures, the water content during the drying stage was calculated at

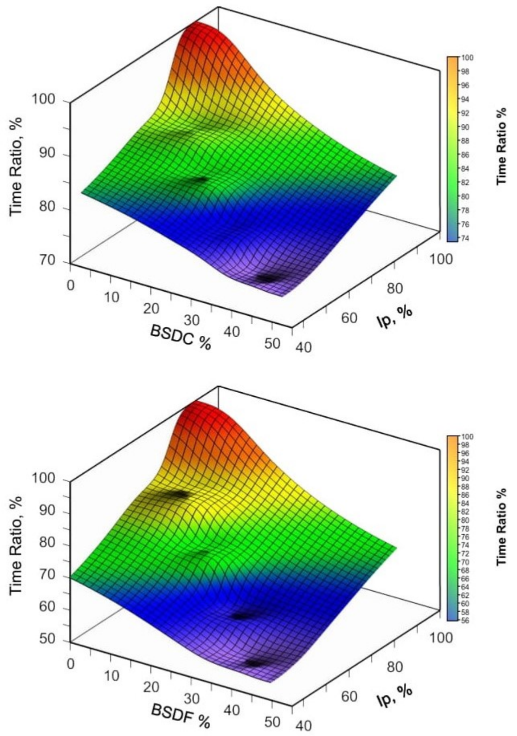

Figure 4. Effect of BSD and Ip on the time ratio of EHPS.

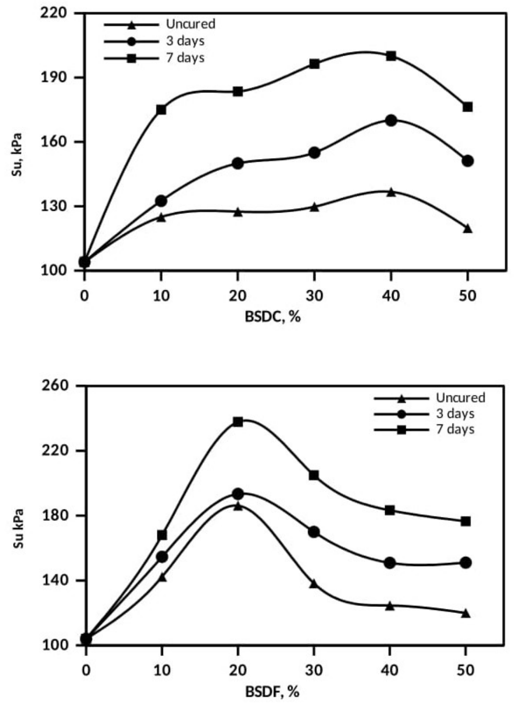

Figure 5. The effect of the type and content of BSD and curing period on S_u of EHPS.

specified time periods, then, the ratio of final drying time for each mixture (t_n) to that of unaltered soil (t_f) was calculated and named as "time ratio". The variation of the time ratio with various Ip and BSD contents is shown in Figure 4. As illustrated, the addition of BSD decreases the time required to reach the final shrinkage stage, this decrease depends mainly on the type and content of BSD. The EHPS-BSDF mixtures required a shorter time than the EHPS-BSDC mixtures. The BSDF50 required only 50 % of the time, while the BSDC50 required 70 %.

3.3. Shear strength of EHPS-BSD mixtures

According to the result of the unconfined compression test, the variation of the shear strength of EHPS (S_u) with the type and amount of BSD has been studied. The S_u values were calculated for the uncured EHPS-BSD samples tested directly after the preparation and for samples cured for three and seven days. As illustrated in Figure 5, for uncured EHPS-BSDC samples, there is a slight change in S_u after the addition of BSDC, which indicates the importance of the curing period on the generation of a pozzolanic reaction. This was proved by curing the EHPS-BSDC samples for three and seven days, Figure 5, in which a significant increase in S_u values has been noted. This may be attributed to a change in the soil matrix due to the formation of cementation agents as a result of pozzolanic reaction during the curing period. In contrast, the early generation of strength was noted for both uncured and cured EHPS-BSDF samples. The gradation of BSD has a major role in strength development. The start of the pozzolanic reaction is mainly affected by the fineness of pozzolanic additives. In fact, the pozzolanic reaction is starting earlier for materials with a paramount fineness, as such materials have a noticeably larger surface area [39–41].

The influence of curing periods on S_u of EHPS-BSD samples is well very noticeable in Figure 5. A significant improvement in S_u can be noted for EHPS-BSDF samples in comparison to EHPS-BSDC samples. In fact, this improvement is not absolute, it depends on the content and the type of the BSD. It was found that the shear strength begins to develop and increase with the increase in the content of both types of BSD until it reached an optimal value. Beyond this value, the shear strength begins to decrease, but the final result of the shear strength remains higher than that of the unaltered soil. Regardless of the curing period, the optimal EHPS-BSD mixtures for this work were BSDC40 and BSDF20. Based on the observation, it can be concluded that the content of BSD, up to an optimal value, supports the pozzolanic reaction required to form the cementitious materials for the amelioration of the S_u. A further addition of BSD then showed the same result as adding sand or silt materials, such materials lead to a reduction in the shear strength of the EHPS-BSD mixtures.

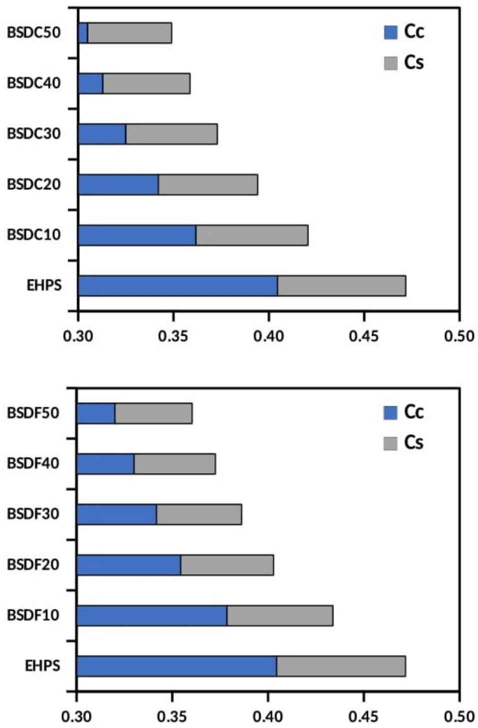

Figure 6. The effect of the type and content of BSD on Cc and Cs of EHPS.

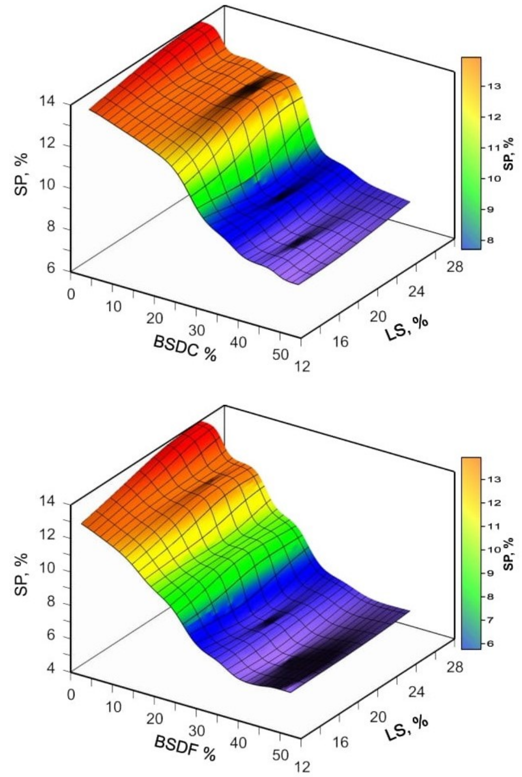

Figure 7. Variation of SP and LS with various BSD percentages.

3.4. Compressibility of EHPS-BSD mixtures

The compressibility of EHPS-BSD mixtures has been examined in the one-dimensional-consolidation test. The compression index (Cc) and swelling index (Cs) values obtained from this test are plotted in Figure 6. There is a clear effect of BSD on the compressibility of EHPS, regardless of the gradation type of BSD, both Cc and Cs were reduced with an increasing BSD content. For BSDC50 and BSDF50, the addition of BSD reduces (21 to 25 %) the Cc values, while the reduction in Cs values ranged from (35 to 40 %). In other words, a lesser value of consolidation settlement can be expected for EHPS due to the addition of BSD.

The reaction of BSD with EHPS coincides with the reaction of "pyroclastic rock dust" with an expansive soil. The addition of pyroclastic rock alters the clay minerals due to larger sand-sized grains, and this leads to a reduction of the water absorption rate, as a result, an immediate modification in soil swell properties takes place [38].

3.5. Swelling of EHPS-BSD mixtures

The efficiency and performance of the BSDC and BSDF in mitigating the potential of EHPS to swell have been included in this work. The results of the swell-test for the designated specimens were used to determine the swell potential (SP) and the swelling pressure (Ps). Figure 7 highlights the variation of SP with BSD content; the LS values are also presented in this figure. It is clear that both BSD types are efficient in mitigating the SP values. There is a non-linear decrease in SP and LS values with an increasing BSD content. However, the values of SP for EHPS-BSDF specimens are significantly lesser than those for EHPS-BSDC specimens. For the BSDF50 specimen, the SP value was 6 %. For the comparable coarse-gradation BSD type specimen (i. e., BSDC50), the SP value was 7.7 %. Researches on the stabilisation of soils using additives with a high CaO content showed that such additives lead to, in addition to a cation exchange, flocculation, and agglomeration of soil grains. As a result of these two phenomena, larger particles form by flocking of the small particles together [42, 43]. The clear result of using such additives is a considerable reduction in the volume changes in the soil.

Figure 8 illustrates the axial strain-log pressure curves for EHPS-BSD mixtures. The swell pressure (Ps) values were determined from these curves. The variation of Ps with the applied pressure is shown in Figure 8. It can be seen that, under various applied pressures and for both BSD types, all the EHPS-BSD specimens showed the same trend in axial strain-log pressure curves. It was noted that the time to achieve 99 % of the maximum soil swell decreases with increasing the content of BSD, for BSDC50, the time was about 40 % of that required to reach the maximum swell of unaltered EHPS. However, as the applied pressure increased, the reduction in Ps for each EHPS-BSD specimen significantly decreased, beyond a par-

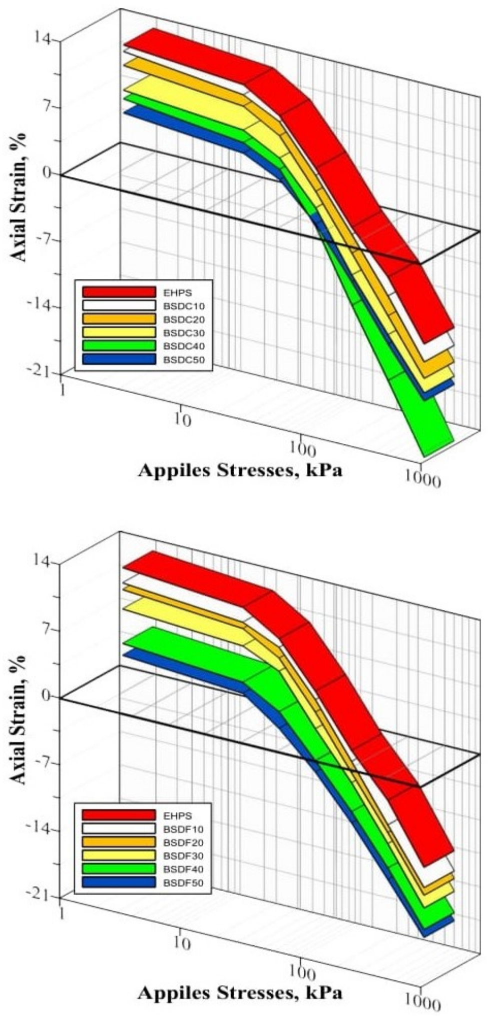

Figure 8. Axial strain-log pressure curves for EHPS-BSD mixtures.

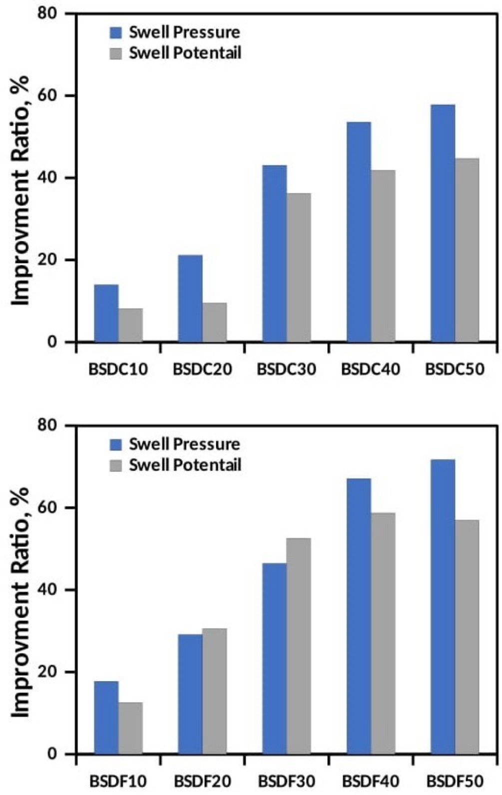

Figure 9. Improvement ratio for swell pressure and swell potential for EHPS-BSD mixtures.

ticular pressure value, the axial strain was converted from swell (positive zone) to compression (negative zone).

As shown, the BSD mitigated the effect of the swell potential and swell pressure to various degrees. To evaluate the efficiency and performance of BSDC and BSDF in improving the EHPS, the degree of improvement or the improvement ratio (IR) in SP and Ps values have been calculated as shown below:

$$IR = \frac{SPi - SPf}{SPi} \times 100 \tag{1}$$

$$IR = \frac{Psi - Psf}{Psi} \times 100 \tag{2}$$

Where

IR improvement ratio (%)

SPi swell potential of unaltered EHPS specimen

SPf swell potential of unaltered EHPS specimen

Psi swell pressure of unaltered EHPS specimen

Psf swell pressure of unaltered EHPS specimen

The variation of the improvement ratio with designated mixtures is shown in Figure 9. The statistical parameters for results shown in Figure 8 are shown in Table 4. As it can be seen, the BSD reduced the SP and Ps to different degrees. As the BSD increased, both SP and swell pressure decreased. However, the performance of the fine-sized BSD is better than that of the coarse gradation BSD. The maximum improvement ratio of SP and swell pressure by using BSDF was 57.0 % and 71.7 %, respectively. While the best performance of BSDC in improving the SP and swell pressure was 44.7 % and 57.8 %, respectively. These maximum improvement ratios were obtained for mixtures designated as BSDF50 and BSDC50. Such improvement, can be, while taking into account the aforementioned reasons, attributed to the formation of cementitious materials, as a result of the pozzolanic reaction, thus increasing the resistance of the soil to expansion [38, 44]. Overall, the addition of BSD altered the structure of expansive particles and caused a mitigation of the soil swelling potential.

4. Conclusions

In this experimental research, the following findings have been obtained:

(1.) There is a characteristic reduction in w_L due to the addition of the BSDC and BSDF. The percentual decrease in w_L of EHPS was about 50 %

Parameters	Ps		SP	
	DBSC	DBSF	DBSC	DBSF
mean	162	145	11	9
COV	34	46	26	38
standard deviation	55	67	3	3

TABLE 4. Various statistical parameters for SP and Ps.

and 49 % for BSDC50 and BSDF50, respectively. This is also noted for w_P and Ip values. The Ip of EHPS declined below 35 % when mixed with BSDF50, while the EHPS mixed with the identical quantity of BSDC resulted in Ip value of 40 %. BSD made the texture of EHPS more tenuous.

(2.) The improvement of EHPS with BSD reduces the amount of shrinkage. Increasing the BSD content from 0 % to 50 % reduced the LS, at a 50 % BSD content, the percentual decrease in LS was 45.7 % (for BSDC) and 48.8 % (for BSDF). BSDF50 reduced the time required by the EHPS to reach the final shrinkage by approximately 50 %.

(3.) The addition of BSD improved the S_u of EHPS, the soil became stiffer and harder with the addition of BSD. However, the curing period, the type, and the content of BSD had an important role.

(4.) The consolidation parameters of EHPS were reduced due to the addition of BSD, the reduction was 21 to 25 % in Cc and 35 to 40 % in Cs.

(5.) There is a non-linear decrease in the swelling potential of EHPS with an increasing content of BSD. For the BSDF50 and BSDC50, the SP reduced to 6 % and 7.7 %, respectively. The maximum reduction in swell pressure due to using BSDF and BSDC was 71.7 % and 57.8 %, respectively.

Overall, the addition of BSD altered the structure of expansive particles and caused a mitigation of the soil swelling potential. However, BSDF was more effective. Finally, the building stone debris can present a sustainable low-carbon stabiliser significant in geotechnical applications.

List of symbols

Cc compression index
Cs swelling index
Ip plasticity index [%]
IR improvement ratio [%]
LS linear shrinkage [%]
Psi swell pressure of unaltered EHPS specimen
Psf swell pressure of unaltered EHPS specimen
SPi swell potential of unaltered EHPS specimen
SPf swell potential of unaltered EHPS specimen
S_u shear strength [kPa]
w_L liquid limit [%]
w_p plastic limit [%]

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