



Utilization of waste marble to enhance volume change and strength characteristics of sand-stabilized expansive soil

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Abstract

In this paper, marble waste is evaluated as a secondary material to be utilized as potential stabilizer to improve the volume change and strength characteristics of sand-amended expansive soil, proposed as a possible landfill, pavement or sub-base material in a semi-arid climate. An experimental program was conducted on sand-expansive soil enhanced with marble waste, abundantly found as a by-product of construction industry, obtained from two different sources with different gradations, denoted as marble powder (MP) and marble dust (MD). One-dimensional swell, volumetric shrinkage, consolidation, unconfined compressive and flexural strength tests were conducted on expansive soil–sand mixtures with 5, 10 and 20% waste marble inclusions over curing periods of 7, 28 and 90 days. Test results showed that 10% marble powder and 5% marble dust by dry mass were the optimum amounts for mitigating the swell–shrink potential and compression index as well as yielding the highest unconfined compressive and flexural strength values. Moreover, the rate of reduction in swell potential versus the flexural strength over the curing periods studied is highest in 10% MP- and 5% MD-included specimens, the latter being more insensitive to this change. The soil mixtures displayed brittle behavior after marble addition, hence its utilization as a secondary additive to sand-amended expansive soil is recommended for soils exposed to lower flexural loads such as light traffic.

Keywords Expansive soil · Stabilization · Waste marble · Swell–shrinkage · Unconfined compressive strength · Flexural strength

Introduction

Swelling and shrinkage are the most important parameters in the investigation of volume change properties of expansive soils occurring with moisture variations due to climatic changes. Different materials are used to alleviate swelling–shrinking problems of soils on structures, such as lime, cement, and bitumen. Addition of lime decreases the swell potential of the soil, whereas cement stabilization increases shear strength, showing higher strength gain compared to lime-treated soils (Nelson and Miller 1992). Gueddouda et al. (2011) studied the effect of different combinations

of cement, lime and salt (NaCl) on the expansive clay and concluded that the most feasible and economic alternative is using lime–salt combination as an additive for improvement of the expansive clays. Abdullah and Alsharqi (2011), however, showed that only 2% cement addition over 28-day curing period would be enough to improve the expansive soil. Fattah et al. (2010) investigated on the improvement of the expansive soil using three different additives including cement, steel fibers, cement grouting and gasoline oil. They concluded that 5% of additives and 4% gasoline were sufficient for the treatment of soil. Sahoo and Prahdan (2010) observed that the maximum increase in strength of expansive soil was obtained with 8% lime addition and a marginal decrease in strength was observed with higher lime contents. Farooq et al. (2011) examined the effect of lime addition (0, 2, 4, 6 and 8%) and curing period (0, 7, 14 and 28 days) on unconfined compressive strength of expansive soil. They reported that the best result was obtained with the addition of 4% lime content for all curing periods. Conversely, Kiliç et al. (2015) deduced that 6% lime utilization decreased the percent swell, swell pressure and increased the unconfined

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compressive strength of clay over 90-day curing period. Önal (2015) studied the usage of lime as a stabilizer for the improvement of bearing capacity of the pond-based soils and concluded that unconfined compressive strength increased by adding 8% lime with the curing periods of 28, 56 and 180 days.

Recently, utilization of industrial waste materials as stabilizing agents became very popular for both recycling and soil improvement purposes, including fly ash, marble dust, rice husk ash, waste tyre and wood ash (Amit and Singh 2013). Tuncan et al. (2000) recommended the use of 20% lime, 10% fly ash and 5% cement utilization for stabilizing petroleum-contaminated waste soil as an effective sub-base material. Phanikumar (2009) compared influence of lime and fly ash on physical properties, compaction characteristics and swell of expansive clays. Test results showed that liquid limit reduced, whereas plastic limit increased with increment of lime and fly ash contents, hence resulting in a reduced plasticity index, and consequently swell potential. Maximum dry density increased and optimum water content reduced with both lime and fly ash additions. Suneel et al. (2010) focused on the long-term consolidation and strength behavior of fly ash-stabilized marine clay. Various fly ash percentages were used in the testing program and an increasing trend on shear strength properties with the increment of fly ash content was observed. Fly ash inclusion reduced the plasticity characteristics, optimum water content, compression index and coefficient of consolidation while increasing the unconfined compressive strength. Cömert et al. (2010) studied the treatment of sub-base soils with a mixture of fly ash, marble dust and waste sand addition, and concluded that the optimum ratios were 20% fly ash, 5–10% marble dust and 5% waste sand based on unconfined compression test results. Firat et al. (2012) concluded that fly ash, marble dust and waste sand improved swelling ratio, CBR and water conductivity, hence are effective stabilizers in road sub-bases. Gandhi (2013) compared marble dust and rice husk ash in the improvement of expansive soils and indicated that marble dust was more efficient than rice husk ash for Atterberg limits, free swell index, CBR and swelling pressure tests. Shrivastava et al. (2014) studied the influence of rice husk ash on the lime-stabilized black cotton soil. Liquid limit, plasticity index and free swell index values reduced after rice husk ash addition. Gupta and Sharma (2014) utilized sand, fly ash and marble dust with different proportions for the stabilization of black cotton soil and specified that this mixture can be used as a sub-grade material for the construction of flexible pavements in rural roads with low traffic volume.

Agrawal and Gupta (2011), Abdulla and Majeed (2014) and Akinwumi and Booth (2015) studied the effect of different percentages of marble dust in the stabilization of expansive soil and reported that use of marble in varying proportions decreased liquid limit, plastic limit and plasticity index

values. Zorluer and Usta (2003) used marble dust in five different percentages (0, 1, 3, 5 and 7%) by dry mass of soil and observed the swell potential reducing with an optimum marble dust addition of 5%. Başer and Çokça (2010) used waste limestone dust and waste marble dust for the improvement of expansive soil prepared as a mixture of kaolinite, bentonite and stabilizing agents. Laboratory results showed that swell percentage reduced and rate of swell raised with the additive percentage. The influence of marble dust utilization on swelling behavior was also investigated by Agrawal and Gupta (2011), Çimen et al. (2011), Sabat and Nanda (2011) and Abdulla and Majeed (2014) who reported that swell potential and swell pressure decreased with the increment of marble dust content.

Gurbuz (2015) focused on the stabilization of clayey soil using waste marble powder in sub-bases of the road construction. Waste marble powder was added to the clayey soil with various percentages (2.5, 5, 10, 15, 20 and 25%) to peruse the unconfined compressive strength and ductility behavior. Test results showed that the peak strength and ductility increased with the increment of marble content up to 10% and then it continued with a decreasing trend as marble content increased. Based on these results, 10% waste marble was chosen as an effective dosage. Akinwumi and Booth (2015) also observed a similar trend in unconfined compressive strength and in addition they have observed reduction in coefficient of permeability with the increment of marble content.

In the previous studies, waste marble was added to the expansive soil or it was used with a secondary waste material such as fly ash as a stabilizing agent. In this study, however, utilization of waste marble as a secondary material in sand-amended expansive soil is adopted, with the intention of recycling this industrial waste accumulating in the environment, as well as discovering a suitable mixture for landfill liner or sub-base stabilization of pavement and road constructions. Laboratory testing program consisted of swell–shrinkage, compressibility, unconfined compressive and flexural strength tests. In addition, evaluation of durability was examined with respect to different curing periods.

Materials and methods

Materials

The expansive soil used in this study was obtained from Nicosia, Cyprus, which is widely distributed in the region, imposing considerable damage to infrastructure and buildings. It consists of 42% clay, 48% silt and 10% sand, and it is classified as silt with high plasticity (MH) (ASTM D2487-11 2011).

The sand used was obtained from Famagusta Bay in the eastern coast of the island. The parameters of effective grain size (D_{10}), median grain size (D_{50}), coefficients of uniformity (C_u) and curvature (C_z) obtained from the sieve analysis (ASTM D422-63e2 2007) are 0.16 mm, 0.19 mm, 1.25 and 1.013, respectively. Based on these parameters, the Unified Soil Classification System (ASTM D2487-11 2011) yields a classification of poorly graded uniform sand (SP).

Marble waste, of different gradations, marble powder (MP) and marble dust (MD) obtained from two different production plants are used in this research as a secondary material added to expansive soil–sand mixture. It is the by-product of the expanding construction industry on the island, utilization of which can be a potential solution to its increasing accumulation. Particle size distribution analysis (ASTM D422-63e2 2007) showed that marble powder consists of 6% clay size, 32% silt size and 62% sand size particles, whereas marble dust includes 80% silt size and 20% sand size particles.

Chemical compositions of expansive soil, waste marble powder and waste marble dust are obtained from X-ray fluorescence (XRF) spectrometer and the test results are listed in Table 1.

Waste marble powder and waste marble dust include 55.7 and 54% CaO (lime) content, respectively, which is concurrent with the previous researchers who indicated that marble waste they have used for stabilization purpose possessed very high lime (CaO) content of up to 55% (Zorluer and Usta 2003; Başer 2009; Cömert et al. 2010). The reaction between calcium from lime with silica and/or alumina in the presence of water is called pozzolanic reaction. The cementitious products are calcium silicate hydrate (CSH), calcium aluminate hydrate (CAH) and calcium aluminosilicate hydrate (CASH) (Eades and Grim 1960; Eades et al. 1962). Lime-soil mixtures gain long-term strength due to pozzolanic reactions (Little 1999; Bhattacharja et al. 2003; Kampala and Horpibulsuk 2013) which provide remarkable improvement in the soil properties such as compressibility, shear strength, unconfined compressive strength and

stiffness (Rajasekaran and Rao 2002; Khattab et al. 2007; Consoli et al. 2009; Tang et al. 2011; Wang et al. 2017). In this study, the silica and alumina contents of the soil sample (Table 1) are adequate to get into pozzolanic reaction in the presence of water and calcium hydroxide derived from the CaO content of the marble.

X-ray diffraction (XRD) analysis was done to detect the minerals of expansive soil, marble powder and marble dust. The test results showed that expansive soil includes kaolinite, illite and chlorite, and also non-clay minerals of feldspar and calcite. Quartz, calcite, kaolinite and sepiolite are the common minerals for both of marbles.

Methods

Expansive soil and waste marble were pulverized and the sand was washed with distilled water for reducing the total soluble salt concentration. All materials were oven-dried before sample preparation. All of the tests were carried out on compacted soil specimens which were at their optimum water content and maximum dry density in accordance with standard Proctor compaction test (ASTM D698-12e2 2012). Sand was added to expansive soil in 1:1 ratio, then waste marble powder and marble dust were added in the percentages of 5, 10 and 20% by dry mass. The tests were conducted at 0-, 7-, 28- and 90-day curing periods. The soil samples are categorized as expansive soil–sand (NS), expansive soil–sand–marble powder (NSMP) and expansive soil–sand–marble dust (NSMD), and the experiments were performed on seven groups of soils. Definitions of soil groups are listed in Table 2.

One-dimensional swell tests (ASTM D4546-14 2014) were performed using 75 mm diameter and 15 mm height soil specimens under 7 kPa surcharge and full saturation condition. Upon completion of one-dimensional swell, compressibility tests (ASTM D2435-11 2011) were applied with incremental loading. Volumetric shrinkage test was performed on specimens upon completion of one-dimensional swell test, recording the wet mass and dimensions of soil

Table 1 Chemical composition of expansive soil, marble powder and marble dust

| Chemical composition | Expansive soil | Marble powder | Marble dust |
|------------------------------------|----------------|---------------|-------------|
| SiO ₂ (%) | 36.5 | 0.178 | 4.4 |
| CO ₂ (%) | 17.9 | 42.6 | 35.9 |
| CaO (%) | 16.2 | 55.7 | 54 |
| Al ₂ O ₃ (%) | 11.8 | 0.0708 | 0.977 |
| Fe ₂ O ₃ (%) | 6.87 | 0.0641 | 0.0891 |
| MgO (%) | 6.26 | 1.22 | 0.778 |
| Other elements | 4.47 | 0.1671 | 3.8559 |

Table 2 Definition of soil groups

| Soil groups | Definition |
|-------------|---|
| NS | 50% expansive soil + 50% sand |
| NS5%MP | 47.5% expansive soil + 47.5% sand + 5% marble powder |
| NS10%MP | 45.0% expansive soil + 45.0% sand + 10% marble powder |
| NS20%MP | 40.0% expansive soil + 40.0% sand + 20% marble powder |
| NS5%MD | 47.5% expansive soil + 47.5% sand + 5% marble dust |
| NS10%MD | 45.0% expansive soil + 45.0% sand + 10% marble dust |
| NS20%MD | 40.0% expansive soil + 40.0% sand + 20% marble dust |

specimens stored in a temperature-controlled room during desiccation, until the volume change ceased.

Flexural strength test (ASTM C348-14 2014) was applied on prismatic soil beam specimens which were prepared using a special mold with the dimensions of 40 mm × 40 mm × 160 mm. The soil beam samples were statically compacted at optimum water content to the maximum dry density already obtained by standard Proctor compaction test.

Test results and discussion

Physical properties

Consistency limits (ASTM D4318-10e1 2010), linear shrinkage (BS 1377-2:90 1990) and specific gravity (ASTM D854-14 2014) test results of all soil groups are depicted in Table 3.

In the MP group, liquid limit and plasticity index decreased with the increasing waste marble content, corroborating with the results of Akinwumi and Booth (2015), Abdulla and Majeed (2014) and Agrawal and Gupta (2011). On the other hand, in the MD group, liquid limit and plastic limit values increased while the plasticity index reduced with the increment of marble dust content, similar to findings of Başer (2009), Sivrikaya et al. (2014) and Gurbuz (2015). The plasticity index has been reduced by 17% in 10% MP and by 33% in 20% MD samples after 24 h of mellowing time, which are the lowest indices attained. The difference in the behavior of MP and MD-added expansive soil–sand mixtures arises from the amount of fines contained in each sample, the latter consisting of 42% more fines; therefore, larger surface area in contact with the expansive soil facilitates the pozzolanic reaction to take place. However, these values are not adequate enough to evaluate the pozzolanic reaction induced by marble waste, but merely represent the initial state of the mixtures before being compacted for

strength and volume change studies. Consequently, it can be deduced that the effect of waste marble on plasticity index of samples is insignificant when particle sizes are dominantly in the coarse range and when in non-cured state.

Compaction test

Table 4 presents the compaction parameters, such as optimum water content and maximum dry density, which reveal that maximum dry density raised while optimum water content reduced as the marble powder content increased in the MP group, which supports the findings of Akinwumi and Booth (2015). Addition of 5, 10 and 20% MP to expansive soil–sand mixture of 1:1 ratio increased the content of coarse particles by 3, 9, and 10% respectively. Therefore, the water retention capacity of the mixture reduced, consequently reducing the optimum water contents. In MD-added samples, the fines increased by 8–12%, hence increasing the optimum water contents of the mixtures. Likewise, the maximum dry densities followed an increasing trend in MP group, while reducing in MD group, similar to the findings of Sabat and Nanda (2011). The aggregation of soil with the inclusion of marble dust induced increment in pore volume, therefore, the dry density reduced. The increment in optimum water content has occurred as a result of the necessity of additional water within the flocculated soil due to the pozzolanic reaction between soil and lime content of MD, thus substantiating the similar findings of Kumar et al. (2007) and Jha and Sivapullaiah (2015).

Volume change properties

One-dimensional swell

One-dimensional swell percentage versus time graphs were obtained from one-dimensional swell tests on specimens with three marble percentages at different curing times. The swell percentages with respect to logarithm of time plots are depicted in Figs. 1 and 2 for marble powder and marble dust,

Table 3 Physical properties of soil mixtures

| | Liquid limit (%) | Plastic limit (%) | Plasticity index (%) | Linear shrinkage (%) | Specific gravity |
|---------|------------------|-------------------|----------------------|----------------------|------------------|
| N | 65 | 36 | 29 | 18 | 2.69 |
| NS | 32 | 20 | 12 | 9 | 2.69 |
| NS5%MP | 30 | 17 | 13 | 10 | 2.65 |
| NS10%MP | 29 | 19 | 10 | 10 | 2.69 |
| NS20%MP | 26 | 15 | 11 | 9 | 2.68 |
| NS5%MD | 35 | 21 | 14 | 12 | 2.69 |
| NS10%MD | 37 | 27 | 10 | 12 | 2.52 |
| NS20%MD | 38 | 30 | 8 | 9 | 2.58 |

Table 4 Compaction test results

| | Optimum water content (%) | Max. dry density (kg/m ³) |
|---------|---------------------------|---------------------------------------|
| NS | 17.5 | 1690 |
| NS5%MP | 15.5 | 1740 |
| NS10%MP | 15.0 | 1790 |
| NS20%MP | 15.3 | 1781 |
| NS5%MD | 18.0 | 1705 |
| NS10%MD | 21.0 | 1590 |
| NS20%MD | 24.0 | 1540 |

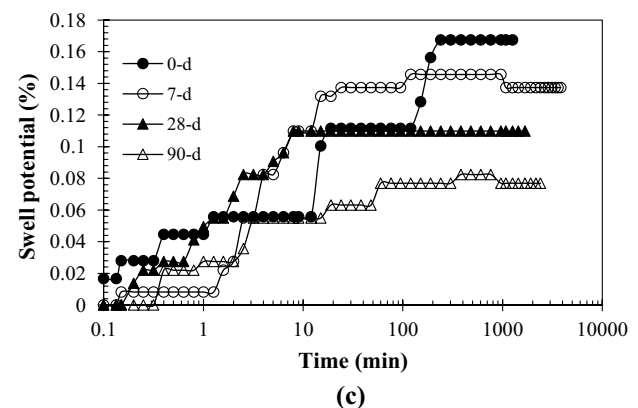
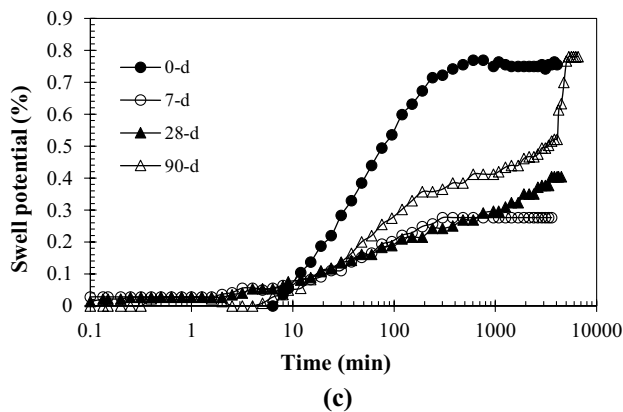
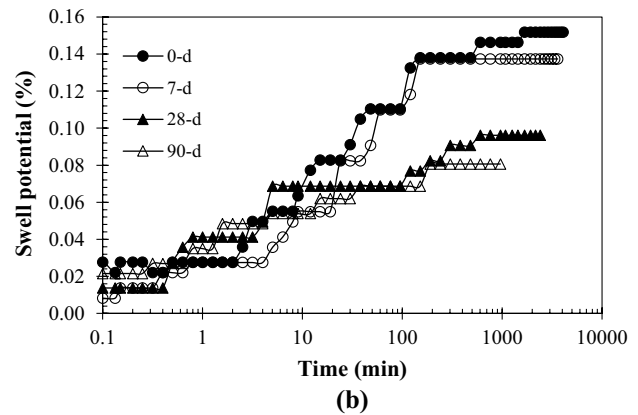
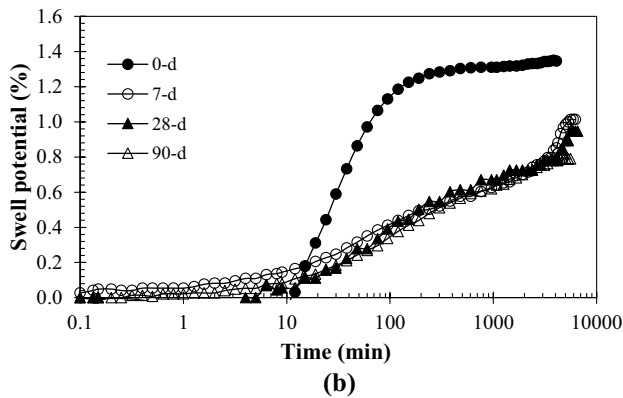
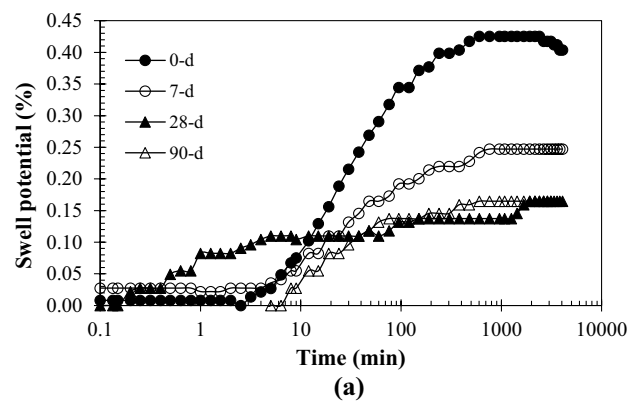
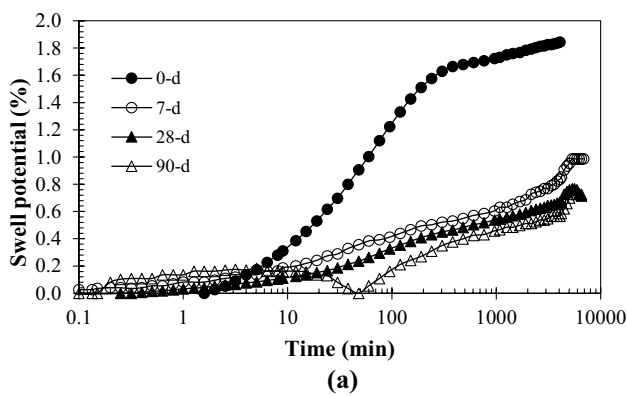


Fig. 1 Aging effect on swell curves of **a** 5% MP, **b** 10% MP and **c** 20% MP

Fig. 2 Effect of curing time on swell curves of **a** 5% MD, **b** 10% MD and **c** 20% MD

respectively. The plots reveal that the primary swell percentages are significantly reduced with curing time. The secondary swell, which displays a progressive increase in the 0-day cured specimens, with the rate of 0.20%/min, stabilizes easily within nearly 4 days with 5 and 20% MP and 3 days with 10% MP included and 90-day cured specimens. Studying the swell percentage versus logarithm of time curves of MD-treated specimens, it can clearly be seen that there is no secondary swell tendency whatsoever. This behavior is the result of aforementioned pozzolanic reactions occurring faster and more effectively in MD specimens which include higher content of fines. The major component of

swell percentage, the primary swell, and the time taken for primary swell to be completed are obtained from the swell-logarithm of time curves and are summarized in Table 5.

20% MP has yielded the lowest primary swell percentage of 0.35% at 90-day curing period. However, the change of swell percentage with curing was not consistent, which was perceived to have occurred due to surplus of marble content. Furthermore, 20% MP specimen revealed a secondary swell tendency which has ended up in a total swell strain of 0.78. Utilization of 10% MP, however, showed a gradual reduction in swell strain with curing time and no additional

Table 5 Primary swell results of the soil groups

| Curing time | Swell parameters | NS | MP | | | MD | | |
|-------------|-------------------|------|------|------|-------|------|------|------|
| | | | 5% | 10% | 20% | 5% | 10% | 20% |
| 0 day | Primary swell (%) | 0.67 | 1.64 | 1.24 | 0.497 | 0.43 | 0.15 | 0.17 |
| | Time (min) | 204 | 203 | 90 | 1300 | 200 | 150 | 250 |
| 7 days | Primary swell (%) | – | 1.03 | 1.01 | 0.276 | 0.25 | 0.14 | 0.15 |
| | Time (min) | – | 5500 | 5000 | 300 | 400 | 150 | 22 |
| 28 days | Primary swell (%) | – | 1.00 | 0.94 | 0.40 | 0.16 | 0.10 | 0.11 |
| | Time (min) | – | 5500 | 2500 | 3000 | 1800 | 600 | 8 |
| 90 days | Primary swell (%) | – | 0.98 | 0.56 | 0.35 | 0.16 | 0.08 | 0.08 |
| | Time (min) | – | 5000 | 420 | 180 | 60 | 190 | 380 |

secondary swell component, which appeared to be the most suitable marble content for sustainable results. Therefore, it can be concluded that 5% is not adequate for cementation and 20% is an excessive amount for the treatment, therefore, 10% is the optimum amount for this type and gradation of marble waste. In the MD group, which contains an appreciable amount of fines in the marble component, swelling percentage of each marble content showed a decreasing trend with aging and all of the test results are in “low swell” category (Snethen et al. 1977). The fine marble particles have been more effective in this group, and 5% waste inclusion was observed to be sufficient to provide pozzolanic reactions causing agglomeration of particles, hence formation of flocculated and stronger fabric between the soil particles (Jha and Sivapulliah 2015). These observations agree with past research on the efficacy of marble dust utilization in soil treatment, reducing swell potential (Zorluer and Usta 2003; Başer and Çokça 2010; Agrawal and Gupta 2011; Çimen et al. 2011; Sabat and Nanda 2011; Abdulla and Majeed 2014).

Volumetric shrinkage

Volumetric shrinkage strain ($\Delta V/V_0$, where ΔV is the volume change and V_0 is the initial volume of the specimen) versus time results of cured MP and MD groups are displayed in Figs. 3 and 4, respectively, and the maximum volumetric shrinkage strains are listed in Table 6.

Comparing the test results, it is observed that lower shrinkage values were obtained with the addition of 10% MP in all curing time periods. In MD group, however, 5 and 10% MD inclusions have given similar results, whereas 5% MD has lower results after 28 and 90-day aging periods. On the other hand, 20% MD included sample had inconsistent results with the curing time. Based on these findings, it can be deduced that 5% MD is more effective in reducing the volumetric shrinkage strain. These results are compatible with the recommendation of safe volumetric shrinkage strain value of about 5% for soil liners (Kleppe and Olson 1985; Daniel and Wu 1993;

Tay et al. 2001; Osinubi and Eberemu 2010; Moses and Afolayan 2013). A similar shrinkage strain value can be presumed for compacted road sub-base for limitation of crack formation, hence shrinkage settlements.

Shrinkage occurs due to desiccation by loss of water through evaporation, and cracking starts from the soil surface to deeper soil, diminishing at the end of the tensile zone (Tang et al. 2010). Excessive shrinkage causes cracking and deterioration of compacted soil structure which results in settlements and increase of hydraulic conductivity, which are undesirable attributes in road bases and landfills. Therefore, the shrinkage behavior should be examined with respect to variation of water content against time. One good parameter which can be used as a measure of affinity of mixtures to excessive shrinkage is the swell–shrinkage index, which identifies the shrink–swell potential of soils (Briaud et al. 2003). In this study, 90-day cured soil specimens are selected in the investigation of evaporation graphs to observe the behavior in longer periods, hence to assure the sustainability of the waste marble stabilization. Table 7 depicts shrink–swell indices determined from the evaporation curves given in Fig. 5.

Studying the evaporation curves, it can be deduced that during desiccation, initially the water content of soil samples were reduced linearly, the rate of drying reducing with marble content, which is more defined in MD group. After the completion of rapid drying period, the drying continued at a slower rate, finally reaching a constant value. The water evaporation was fast approximately in the first 5000 min for MP and MD groups. The required times to reach equilibrium while drying at room temperature were 7000 and 8000 min for MP and MD groups, respectively, hence slower drying occurring in MD group which has undergone a more efficient pozzolanic process due to higher fine content.

Table 7 gives the shrink–swell index parameter (I_{ss}), determined from the initial and final water content values, which indicate that all combinations in the MP group are less than the maximum allowed value of 20%, whereas only 5% MD included sample satisfies this recommended requirement.

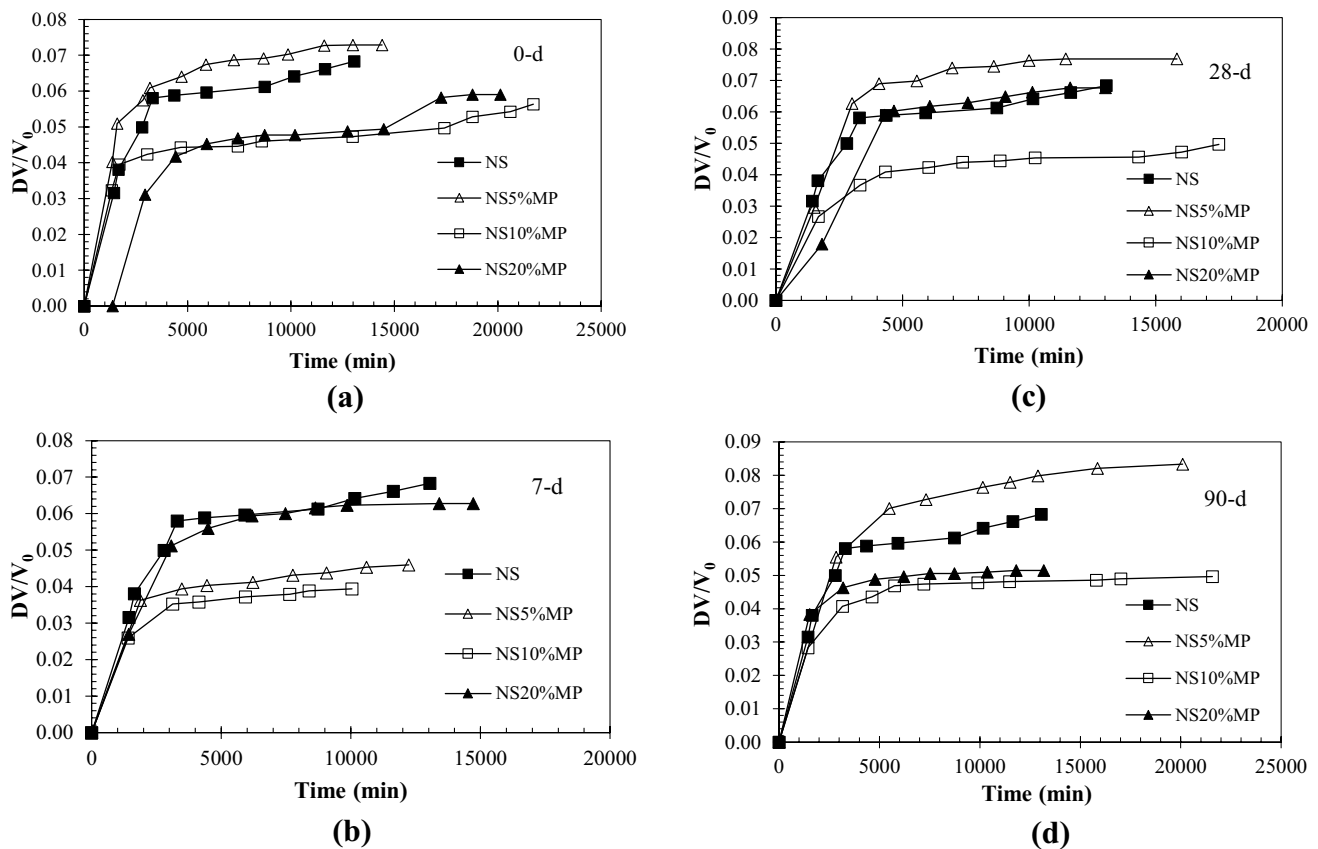


Fig. 3 Volumetric shrinkage strain versus time of MP group for a 0-day, b 7-day, c 28-day and d 90-day curing periods

Compressibility

Void ratio versus effective consolidation pressure curves were obtained for MP and MD groups at different curing periods from which consolidation parameters were derived. The variation of compression index values with different marble contents according to different curing times is presented in Fig. 6. When the test results are compared, utilization of 10% MP and 5% MD has given the lowest results for all of the curing times. Compressibility results of NS10%MP and NS5%MD satisfied “slightly compressible” case for all of the curing periods (Coduto 2001). Hence, waste marble usage has been very effective in reducing the compressibility through pozzolanic reactions causing cementation, hence durability against consolidation pressures.

Based on the experimental findings, evidently the best combinations of marble waste with the soil mixture are NS10%MP and NS5%MD, giving the best results in the volume change characteristics. Therefore, the saturated hydraulic conductivity values were calculated for these material combinations using one-dimensional consolidation data and the results are given in Table 8. The saturated hydraulic conductivity values obtained are well below the regulatory limit for landfill liner design (EPA 2000), which is 1×10^{-7} cm/s

for all ranges of effective confining pressures, reducing with the increasing pressures and curing times. The NS5%MD specimen has yielded lower values than the NS10%MP specimen.

Strength properties

Unconfined compression test

Unconfined compression tests were performed for MP and MD groups at different aging periods, and the results of unconfined compressive strength versus failure strain are displayed in the form of bar charts in Fig. 7. In MP group, it is observed that 5 and 10% MP-added specimens have higher UCS than 20% MP included samples at all curing periods. UCS of NS is 245 kPa, which increased to 346 and 384 kPa after inclusion of 5 and 10% MP, respectively, whereas it decreased to 187 kPa with the usage of 20% MP dosage. Curing time has no significant effect on the UCS values in MP mixtures, however, there is a marked increment of strength in MD specimens with time, mainly with 5 and 20% marble inclusions. Strength of NS is raised with the marble powder addition of up to 10% and followed a decreasing trend with 20% MP addition. This can be attributed to

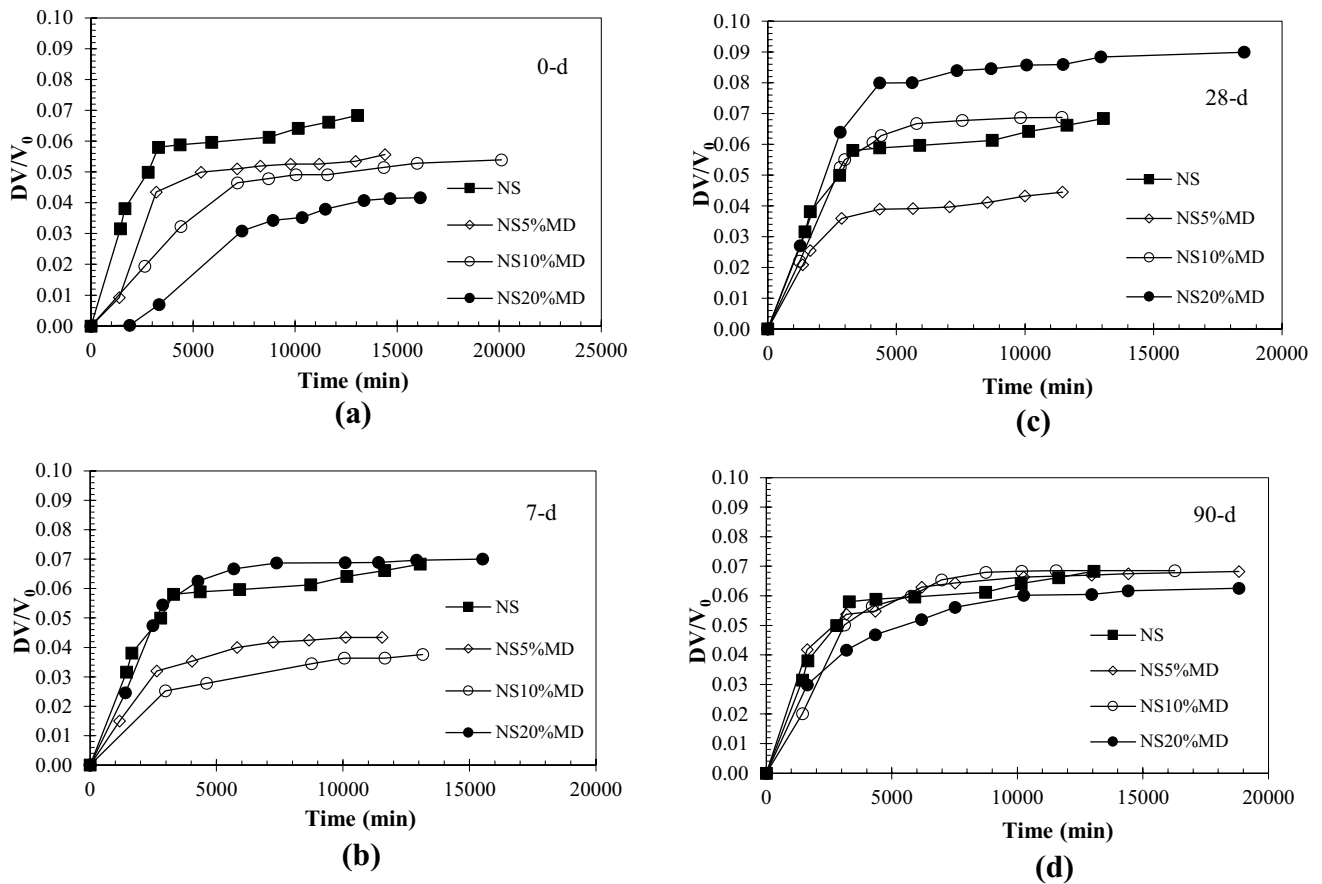


Fig. 4 Volumetric shrinkage strain versus time of MD group for a 0-day, b 7-day, c 28-day and d 90-day curing periods

Table 6 Volumetric shrinkage strain results

| Material | 0 day | 7 days | 28 days | 90 days |
|----------|-------|--------|---------|---------|
| NS | 0.068 | – | – | – |
| NS5%MP | 0.073 | 0.046 | 0.077 | 0.080 |
| NS10%MP | 0.056 | 0.039 | 0.050 | 0.049 |
| NS20%MP | 0.059 | 0.063 | 0.068 | 0.052 |
| NS5%MD | 0.056 | 0.043 | 0.044 | 0.067 |
| NS10%MD | 0.052 | 0.036 | 0.069 | 0.068 |
| NS20%MD | 0.042 | 0.070 | 0.088 | 0.063 |

Table 7 Evaporation results of 90-day cured soils

| | Initial water content (%) | Final water content (%) | Shrink–swell index (I_{ss}) |
|---------|---------------------------|-------------------------|---------------------------------|
| NS | 21.00 | 2.20 | 18.80 |
| NS5%MP | 19.35 | 2.74 | 16.61 |
| NS10%MP | 20.65 | 2.15 | 18.50 |
| NS20%MP | 18.20 | 3.09 | 15.11 |
| NS5%MD | 21.36 | 2.14 | 19.22 |
| NS10%MD | 23.80 | 2.50 | 21.30 |
| NS20%MD | 26.18 | 2.05 | 24.13 |

reduction in the cohesion between marble powder and clay particles, as also stated by Gurbuz (2015). In MD-added specimens, it appeared that 20% more fines added to the expansive silt led to improvement of the cohesive component which might be explained by the increased strength in 90-day cured specimens.

Strain at failure is an important parameter in the assessment of the ductility behavior, and it is compared with respect to curing time and marble content in Fig. 8. In MP group, 20% marble-added samples have given the highest failure strain yet the lowest UCS values in all curing periods. At 5 and 10% MP dosages failure strain values reduced with the increase of aging, whereas the UCS values are higher. On the other hand, failure strain indicates a decreasing trend with the increment of marble content and curing time in MD group. It is also noted that the UCS and failure strain results of MD are more consistent than the results of MP. Addition of 5% MD reached the highest UCS and failure strain values.

Secant modulus, E_{50} , which is the slope of the straight line drawn from the origin to the point representing 50% of the peak compressive strength, can be used to characterize stiffness of the soil. The secant modulus of NS and waste marble added soil groups are presented in Table 9. These

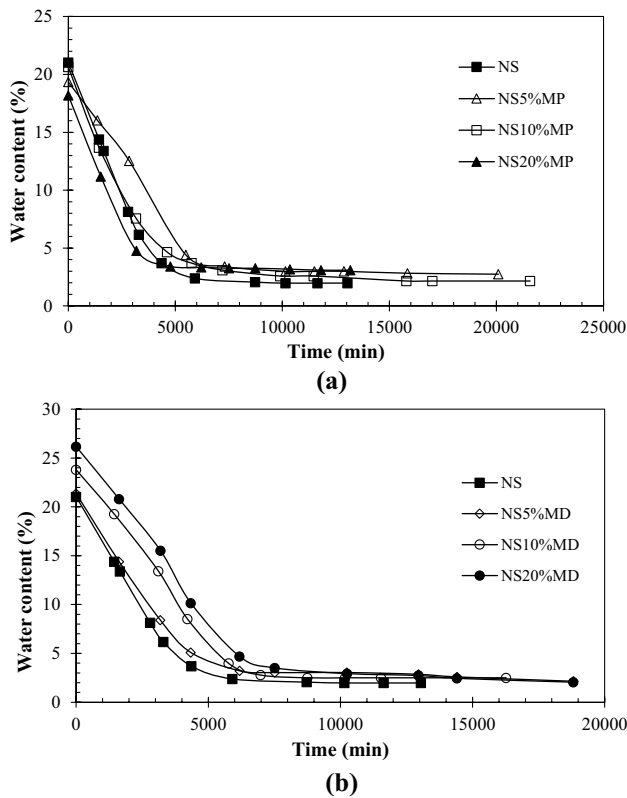


Fig. 5 Evaporation graphs with 90-day cured a MP and b MD groups

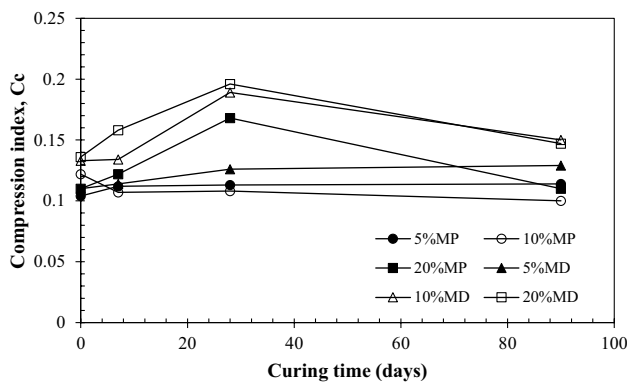


Fig. 6 Compression index values of MP and MD groups with curing time

values are calculated for 0- and 90-day cured samples to observe influence of aging on the stiffness of material. The test results showed that the stiffness of waste marble-added soils increased with curing time and the material became stiffer due to the pozzolanic reaction.

Flexural strength test

According to Vaníček (2013), Onyejekwe and Ghataora (2014) and Angraini et al. (2015), behavior of structures, such as highways, landfills and embankments under the effect of heavy loads, imposing tensile stresses, must be well understood. In this article, tensile strength is indirectly studied by flexural strength test. Flexural strength tests were carried out for all soil groups with different curing times which yielded load–deflection curves. The peak flexural load of each mixture was used in the calculation of flexural strengths by Eq. 1. Toughness is defined as the energy absorbed during flexural loading, and is represented by the area enclosed under the load versus deflection curve up to the deflection of L/150 mm (Onyejekwe and Ghataora 2014; Jamsawang et al. 2014). Increase in the deflection value is an indication of ductile behavior, hence improved toughness. Ductility and toughness are the two important parameters for pavement materials to prevent sudden failure after peak due to traffic load (Disfani et al. 2014). Flexural strength, deflection and toughness results are summarized in Table 10 for NS, NSMP and NSMD soil groups.

$$f = \frac{1.5PL}{bd^2} \tag{1}$$

where *P* is the maximum flexural load, *L* is the span length, *d* is the depth and *b* is the width of the flexure beam.

Flexural strength showed an increasing trend while the deflection at failure decreased with the curing time in MP and MD groups. In addition, toughness reduced with aging for both MP and MD groups. In MP group, 10% inclusion has given the best results for all of the parameters, whereas in MD group 5% addition provided the highest flexural strength in all curing periods. Therefore, it was concluded that while aging was enhanced the flexural strength, ductility and toughness have decreased, displaying a brittle

Table 8 Saturated hydraulic conductivity results

| Curing time | | <i>k_{sat}</i> (cm/s) | | | |
|-------------|---------|-------------------------------|-------------------------|-------------------------|-------------------------|
| | | 98–196 (kPa) | 196–392 (kPa) | 392–784 (kPa) | 784–1568 (kPa) |
| 0 day | NS | 4.97 × 10 ⁻⁸ | 2.82 × 10 ⁻⁸ | 1.60 × 10 ⁻⁸ | 9.01 × 10 ⁻⁹ |
| | NS10%MP | 5.70 × 10 ⁻⁸ | 5.78 × 10 ⁻⁸ | 1.84 × 10 ⁻⁸ | 1.13 × 10 ⁻⁸ |
| | NS5%MD | 3.74 × 10 ⁻⁸ | 2.20 × 10 ⁻⁸ | 1.20 × 10 ⁻⁸ | 7.05 × 10 ⁻⁹ |
| 90 days | NS10%MP | 6.30 × 10 ⁻⁸ | 3.81 × 10 ⁻⁸ | 2.08 × 10 ⁻⁸ | 1.23 × 10 ⁻⁸ |
| | NS5%MD | 5.03 × 10 ⁻⁸ | 3.09 × 10 ⁻⁸ | 1.91 × 10 ⁻⁸ | 1.28 × 10 ⁻⁸ |

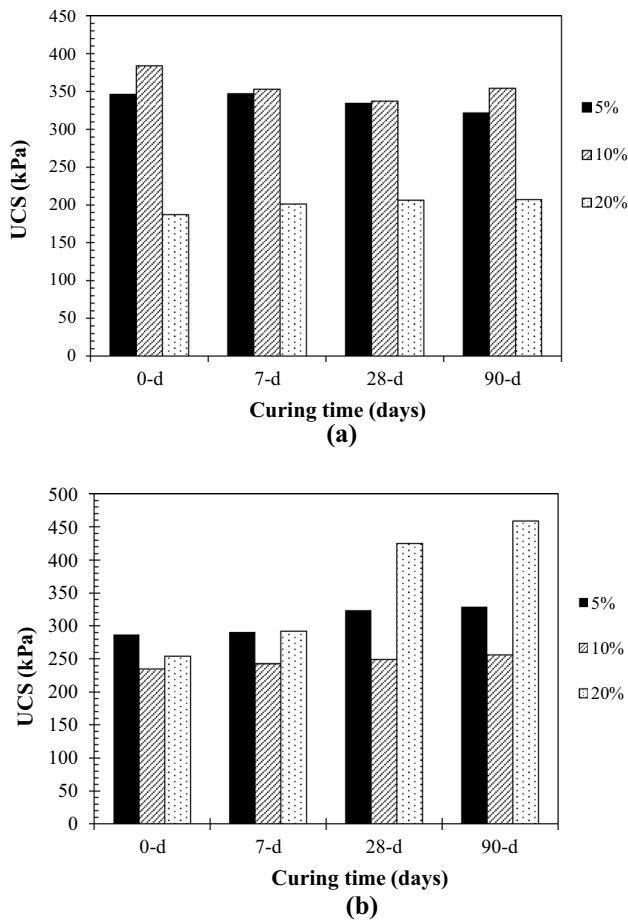


Fig. 7 Unconfined compressive strength results of **a** MP and **b** MD groups

behavior under tension, similar to findings of Chinkulki-niwat and Horpibulsuk (2012) and Kampala and Horpi-bulsuk (2013). The significant increment of flexural strength was obtained within 90-day curing period for all soil combinations. The increment in flexural strength is 94, 50 and 52% for NS5%MP, NS10%MP and NS20%MP samples, respectively. In addition, the same behavior is observed in MD group for which flexural strength of NS5%MD, NS10%MD and NS20%MD is increased by 50, 32 and 57%, respectively.

Relationships between swell potential and flexural strength presented in Fig. 9 for MP and MD groups indicate that flexural strength is indirectly proportional to swell potential. In the 10% optimum MP-included mixture, 50% increment in flexural strength resulted in 55% reduction in swell potential over the 90-day curing period. Conversely, while the flexural strength of 5% optimum MD-included mixture has increased by 50%, swell potential decreased by 65%. The latter reduction is appreciably larger due to higher content of finer particles in MD, with higher surface area, hence more reactive during aging period.

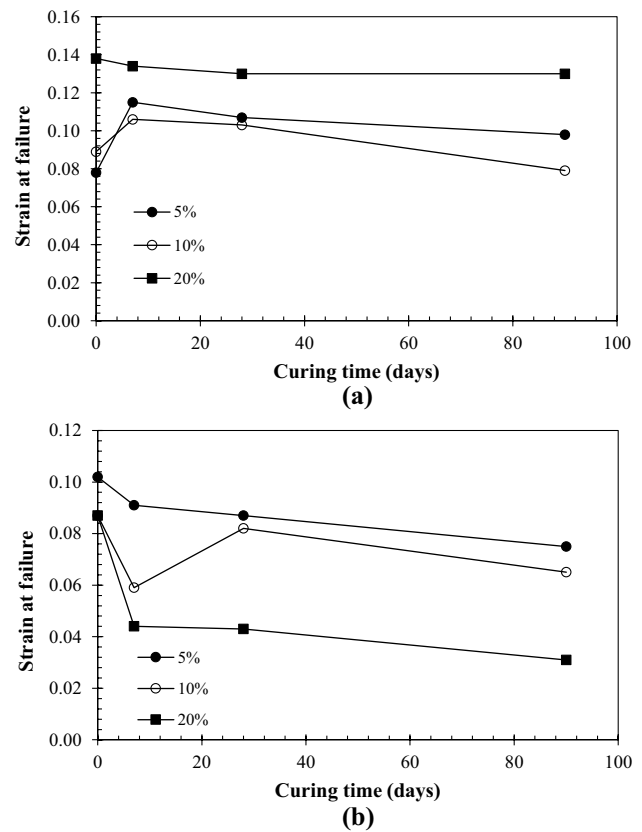


Fig. 8 Strain at failure results of **a** MP and **b** MD groups

Table 9 Secant modulus (E_{50}) results

| Material | E_{50} (kPa) | |
|----------|----------------|---------|
| | 0 day | 90 days |
| NS | 5169 | – |
| NS5%MP | 6654 | 9758 |
| NS10%MP | 8000 | 8178 |
| NS20%MP | 1798 | 3044 |
| NS5%MD | 3596 | 11,786 |
| NS10%MD | 3456 | 9846 |
| NS20%MD | 3850 | 18,254 |

Conclusions

An experimental program was undertaken to study the efficacy of two types of waste marble addition to sand-stabilized expansive soil for further enhancement of the physical properties, volume change and strength characteristics. Conclusions derived from the experimental findings are summarized below:

1. Utilization of 10% MP and 5% MD were observed to provide the best improvement in reducing swell percent-

Table 10 Flexural strength parameters

| Curing time | Flexural parameters | NS | MP | | | MD | | |
|-------------|---------------------|------|------|------|------|------|------|------|
| | | | 5% | 10% | 20% | 5% | 10% | 20% |
| 0 day | <i>f</i> (kPa) | 79 | 51 | 66 | 46 | 81 | 50 | 48 |
| | ΔH (mm) | 0.49 | 0.27 | 0.36 | 0.32 | 0.58 | 0.47 | 0.34 |
| | <i>T</i> (Nmm) | 11 | 6 | 13 | 8 | 12 | 8 | 7 |
| 7 days | <i>f</i> (kPa) | – | 70 | 99 | 65 | 68 | 45 | 52 |
| | ΔH (mm) | – | 0.26 | 0.34 | 0.25 | 0.24 | 0.23 | 0.15 |
| | <i>T</i> (Nmm) | – | 10 | 12 | 7 | 7 | 5 | 4 |
| 28 days | <i>f</i> (kPa) | – | 93 | 80 | 70 | 85 | 43 | 57 |
| | ΔH (mm) | – | 0.25 | 0.29 | 0.20 | 0.21 | 0.25 | 0.28 |
| | <i>T</i> (Nmm) | – | 7 | 10 | 7 | 7 | 4 | 5 |
| 90 days | <i>f</i> (kPa) | – | 99 | 106 | 58 | 96 | 56 | 72 |
| | ΔH (mm) | – | 0.26 | 0.29 | 0.27 | 0.17 | 0.15 | 0.14 |
| | <i>T</i> (Nmm) | – | 9 | 10 | 7 | 7 | 4 | 5 |

f flexural strength, ΔH deflection, *T* toughness

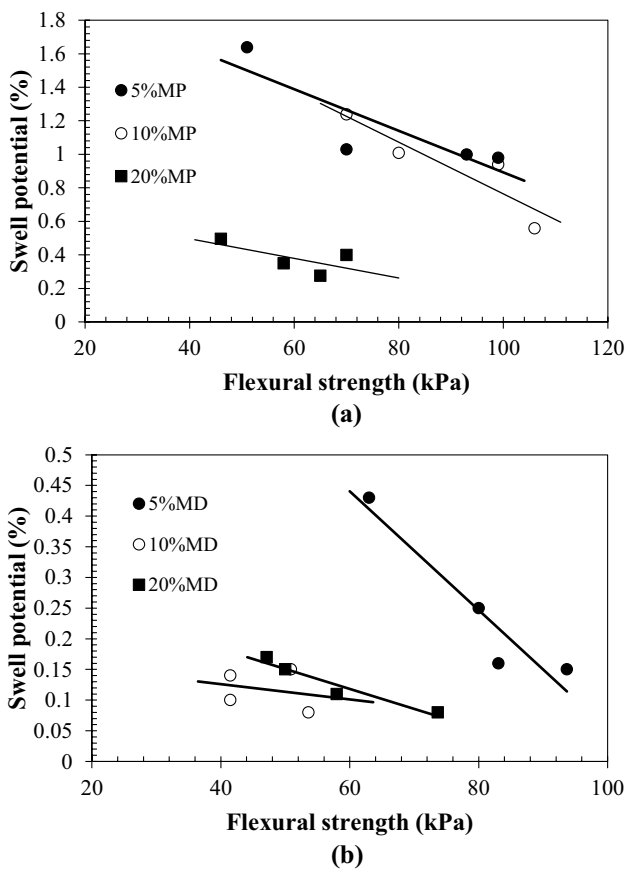


Fig. 9 Relationship between swell potential and flexural strength of **a** MP and **b** MD groups

age, by 66 and 61%, respectively, in 90 days. However, the swell potential of MD group is about 75% less than the MP group at 0 day which remained almost the same after 90-day curing.

- Lower volumetric shrinkage strains were obtained with the addition of 10% MP and 5% MD within each curing period. However, 5% MD displayed better results and lower shrink–swell index.
- On the basis of compressibility results, inclusion of 10% MP and 5% MD have given the lowest results for all of the curing times, the lowest compression index being recorded for 10% MP inclusion.
- Hydraulic conductivity values are observed to be well below 1×10^{-7} cm/s for both 10%MP and 5% MD specimens under different pressure ranges and within all curing periods.
- The unconfined compressive strength values of the specimens containing the optimum values of 10% MP and 5% MD indicate that these percentages enhanced the strength, maintaining values of 350 and 300 kPa, respectively.
- Addition of 10% MP and 5% MD provided the highest flexural strength values for all curing times, whereas toughness is observed to have reduced slightly with the addition of marble, the specimens becoming more brittle.
- A linear relationship was observed between swell potential and flexural strength, over 90-day curing period, swell potential decreasing with the increasing flexural strength and aging, the highest rate of reduction being noted in the optimum marble inclusions of 10% MP and 5% MD.

The overall conclusion is that marble waste produced as a by-product of construction industry can be recycled by efficiently utilizing in soil stabilization of road sub-base materials in a semi-arid climate, where expansive soils are abundantly prevailing. Based on the experimental findings,

use of marble dust has proved to be more efficient in stabilization than the marble powder.

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