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Laboratory analysis of loose sand mixed with construction waste material in deep soil mixing

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Abstract. Deep soil mixing, DSM technique has been widely used to improve the engineering properties of problematic soils. Due to growing urbanization and the industrial developments, disposal of brick dust poses a big problem and causes environmental problems. This study aims to use brick dust in DSM application in order to minimize the waste in brick industry and to evaluate its effect on the improvement of the geotechnical properties. Three different percentages of cement content: (10, 15 and 20%) were used in the formation of soil-cement mixture. Unlike the other studies in the literature, various percentages of waste brick dust: (10, 20 and 30%) were used as partial replacement of cement in soil-cement mixture. The results indicated that addition of waste brick dust into soil-cement mixture had positive effect on the inherent strength and stiffness of loose sand. Cement replaced by 20% of brick dust gave the best results and reduced the final setting time of cement and resulted in an increase in unconfined compressive strength, modulus of elasticity and resilient modulus of sand mixed with cement and brick dust. The findings were also supported by the microscopic images of the specimens with different percentages of waste brick dust and it was observed that waste brick dust caused an increase in the interlocking between the particles and resulted in an increase in soil strength. Using waste brick dust as a replacement material seems to be promising for improving the geotechnical properties of loose sand.

Keywords: cohesion-less soil; construction waste material; deep soil mixing; ground improvement; laboratory analysis; recycling & reuse of materials; reinforced soil

1. Introduction

Deep soil mixing (DSM) is one of the most effective methods to enhance the engineering properties of problematic soils such as expansive soils, soft clays, liquefiable soils and contaminated soils (Al-Tabba *et al*. 2000, Le Kouby *et al*. 2020, Lu *et al*. 2020, Hasheminezhad and Bahadori 2020). DSM is a type of ground improvement in which cementitious materials are mixed with the existing problematic soils in the study area and the strength and the compressibility characteristics of the problematic soils are improved (Horpibulsuk *et al*. 2004, Timoney *et al*. 2012, Haakeel *et al*. 2019). Many studies in the literature such as: Farouk and Shahien (2013); Fang *et al.* (2001); Rashid *et al*. (2017) investigated the efficiency of DSM technique on soft clays. DSM technique has been successfully applied in many construction fields of civil engineering (Le Kouby *et al*. 2020, Yi *et al*. 2019, Jung *et al*. 2020, Ma *et al.* 2020).

DSM produces cemented soil with high strength and low compressibility (Bruce and Bruce 2002, Tang *et al*. 2007, Chenari *et al.* 2018). It reduces seismic amplification and mitigates the liquefaction susceptibility in loose sands (Mann 2017, Tong *et al*. 2019). Wang *et al*. (2009); Esmaeili *et al*. (2020) introduced DSM technique as an efficient and economical method of soil improvement. Various laboratory and numerical models of DSM have been performed in order to understand the efficiency of DSM on problematic soils. Fatahi and Khabbaz (2012); Yilmaz *et al.* (2018) reported the effectiveness of DSM on the shear and compressive strength of soft soils. Sukontasukkul and Jamsawang (2012) studied the behaviour of flexural strength of soil-cement columns whereas Yapage *et al*. (2014) examined the embankment stability due to DSM application. In DSM applications, deep soil mixing columns are formed as a result of penetration of rotary auger into the soil and mixing a slurry or binder material with the in-situ soil (Esmaeili *et al*. 2014, Liu *et al*. 2017, Wang *et al.* 2020). DSM is divided into two main parts which are dry deep soil mixing, DDSM and wet deep soil mixing, WDSM (Timoney *et al*. 2012, Bredenberg 2017). The capacity of the obtained mixed depends on the soil type, the additive materials used in the mixture and the applied mixing methodology (Huang *et al*. 2015, Zhang *et al*. 2018). It also depends on the materials and the mixture properties, as well as the binder content (Chenari *et al.* 2018, Sukontasukkul and Jamsawang 2012). Several researchers (Bruce and Bruce 2002, Esmaeili *et al*. 2020) stated that the strength of DSM column increases with increasing mixing efficiency, increasing curing time and temperature, decreasing organic content of the ground and decreasing water content of the mix.

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In conventional design of DSM columns, the binder content is usually used as the controlling parameter and considered as a major factor affecting the strength development in DSM treated soils (Madhyannapu *et al.* 2009, Chang *et al.* 2016). Different replacement materials for cement have been used in DSM applications (Gupta and Kumar 2017, Yoobanpot *et al.* 2017, Arulrajah *et al.* 2018, Chhun *et al.* 2020). Some of the common replacement materials used in the previous studies were fly ash, slag, glass powder and silica fume which were found in nature as waste and much cheaper than the conventional cement (Arasan *et al*. 2015, Seifan *et al*. 2020).

Canakci *et al*. (2018) used glass powder as a replacement material for cement in DSM mixtures and found it to be an effective material for enhancing sand with different clay contents. Saberian *et al*. (2018) stated that using bentonite as a natural pozzolan in soil mixing stabilization is more eco-friendly than using cement only. Some other researchers such as Cristelo *et al*. (2011); Sukontasukkul and Jamsawang (2012) used different additives such as; lime, fiber and blast furnace slag with cement and achieved very good improvement in strength, stiffness, flexural performance and toughness in DSM application.

In the present study, unlike the materials used in the previous studies in the literature, construction waste material; brick dust, was utilized in deep soil mixing. Brick dust is considered to be an eco-friendly alternative material when it is used in DSM application. Brick dust contains sand and clay particles which consist of chemical compounds such as silica, alumina, carbonates and oxides which are needed for pozzolanic reaction (Khan *et al*. 2018). Because of its constituents, clay gains pozzolanic activity when it reacts with lime in the presence of water (Rogers 2011). Brick dust exhibited high strength in concrete and mortar due to its pozzolanic activity (Demir *et al*. 2011, Ge *et al*. 2015). The majority of the presented works in the literature are in the field of DSM application in soft clay stabilization, while a few studies have dealt with loose sandy soils (Esmaeili *et al*. 2014). Since DSM is an effective ground improvement application method, there is still a need for further study of the method with different materials as additives. In the present study, cement replaced by waste brick dust mixed with loose sand was used in DSM technique in order to investigate its effect on the improvement of loose sand. It was found that the waste material; brick dust which was used as a replacement material for cement was quite effective in improving the geotechnical properties of loose sand.

2. Materials and methods

2.1 Soil sampling

The soil sample used in the present study was collected from Famagusta beach, North Cyprus at a depth of about one meter from the ground surface. Table 1 gives the physical properties of the soil sample used in this study. Sieve analysis was carried out according to ASTM D6913 in order to determine the particle sizes, the effective size (D_{10}), the uniformity coefficient (C_u), and the coefficient of curvature (C_c). Fig. 1 shows the particle size distribution curve of the soil used in this study. Based on Unified Soil Classification System (USCS), the soil was classified as poorly graded sand, SP and with the in-situ relative density of 19.7%. It was defined to be a loose sand.

Table 1 Geotechnical properties of soil

Soil properties	Value
In situ bulk density (g/cm^3) [a]	1.6
Water content (%)	15
Unit weight of soil solids, γ_s (g/cm^3) [b]	2.67
Effective size, D_{10}	0.16
Effective size, D_{30}	0.18
Median particle size, D_{50}	0.2
Effective size, D_{60}	0.22
Uniformity coefficient, C_u	1.37
Coefficient of curvature, C_c	0.92
Classification (USCS)	SP
Maximum dry unit weight (kN/m^3) [c]	16.4
Minimum dry unit weight (kN/m^3) [d]	13.4
Relative density, D_r (%)	19.7

a ASTM D1556
b ASTM D854
c ASTM D7382
d ASTM D4254

2.2 Binder materials

The binder materials used in this study were cement and waste brick dust. The binder materials: cement and brick dust were used together as a ratio of the total weight of untreated sand. Lorenzo and Bergado (2006) and Gullu *et al.* (2017) stated that in order to obtain a better binder-soil mixture, the amount of binder material in the binder-soil mixture should not exceed 20% of the total weight of untreated soil. In the present study, considering their statements, the binder-soil ratios, B/S were selected to be 10, 15 and 20%. The binder materials were used in two forms: In the first form, only cement was used as a binder material whereas in the second form, cement was partially replaced by waste brick dust. In the soil-cement mixture, 10, 20 and 30% of the cement was replaced by waste brick dust. The replacement percentages were decided according to the previous findings of Ge *et al*. (2012) and O'Farrell *et al*. (2006). In Section 2.3, the percentages of cement and waste brick dust used in this study were described in detail.

2.2.1 Cement

In previous studies, different types of cement were used as the main binding material in deep soil mixing (Egorova *et al*. 2017, Karpisz *et al*. 2018, Lee *et al*. 2019). (Portland cement CEM 142.5 R) type was used in the present study. Table 2 describes the physical and chemical properties of the cement used in this study.

2.2.2 Waste brick dust

In the literature, many researchers used different waste materials as a binder material for enhancing the performance of problematic soils in deep soil mixing (Arasan *et al*. 2015, Arulrajah *et al*. 2018, Patterson and Wilk 2019). Several studies indicated that brick dust can be used effectively in concrete production as a cement replacement material. Using brick dust as a partial replacement improved the strength characteristics of concrete (Heidari and Hasanpour 2013, Wong *et al*. 2018).

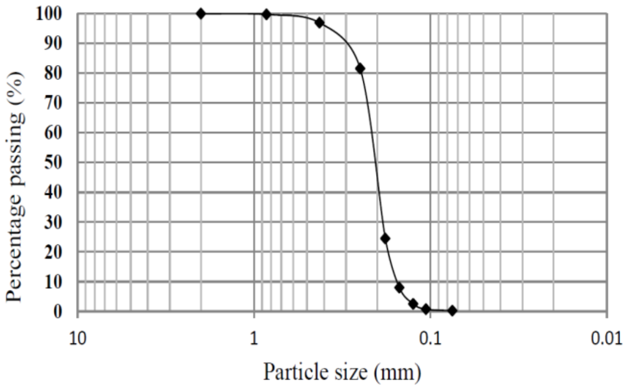

Fig. 1 Particle size distribution of soil sample

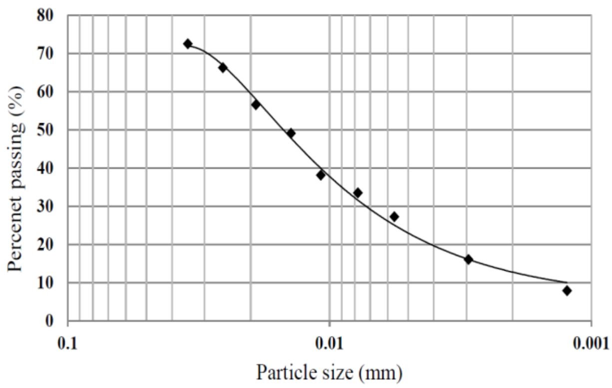

Fig. 2 Particle size distribution of waste brick dust

Table 2 Chemical and physical properties of cement

Properties	Value
SiO_2 (%)	19.95
Al_2O_3 (%)	5.06
Fe_2O_3 (%)	3.04
CaO (%)	63.09
MgO (%)	2.34
SO_3 (%)	3.32
Na_2O (%)	0.80
Loss on ignition (%) [a]	2.27
Unit weight of cement, γ_c (g/cm^3) [b]	3.13
Specific surface (cm^2/g) [c]	3810

a ASTM D7348
b ASTM C188
c ASTM C204

Table 3 Chemical and physical properties of the BD

Index properties	Value
SiO_2 (%)	38.64
Al_2O_3 (%)	12.2
Fe_2O_3 (%)	8.53
MgO (%)	6.18
CaO (%)	14.49
Na_2O (%)	1.21
K_2O (%)	1.89
Others (%)	16.86
Loss on ignition (%)	1.29
Silt content (%)	87
Clay content (%)	13
Unit weight of brick dust (g/cm^3)	2.78
Effective size, D_{10}	.0014
Effective size, D_{30}	.007
Median particle size, D_{50}	.015
Effective size, D_{60}	.02
Uniformity coefficient, C_u	14.28
Coefficient of curvature, C_c	1.75

In terms of pozzolanic activity, brick dust was found to be effective in achieving higher strength in concrete (O'Farrell *et al*. 2006, Ge *et al*. 2015). The demolition of brick masonry structures due to large-scale urbanization in North Cyprus has produced a huge amount of construction waste, including large quantities of clay brick which is normally ended in landfills. For conducting this study, the waste brick dust was obtained from the demolition and crushing activities at the construction sites in North Cyprus. In the present study, brick dust with particle diameters smaller than 75 μm was used as a partial replacement material of the cement. Table 3 gives the physical and chemical properties of the brick dust used in this study and Fig. 2 shows the particle size distribution of the waste brick dust.

2.3 Mix design program

Based on the existing studies in the literature, different mix proportions of soil-cement have been used in soil mixing application in order to reinforce different problematic soils (Ribeiro *et al*. 2016, Brasse *et al*. 2018; Saberian *et al*. 2018, Onal and Sariavci 2019, Al-Bared *et al.* 2020). Binder material is considered to be one of the most effective materials in the injection slurry of DSM (Wong *et al*. 2020). Lorenzo and Bergado (2006), Canakci *et al.* (2018) stated that, to achieve the best strength and economical usage, B/S ratio should not exceed 20% of the total weight of the untreated soil.

In this study, 12 different mix proportions were selected and studied. Table 4 illustrates the mix proportions of the testing program that have been performed in this study. As aforementioned, the cement content in the soil-cement mixture was partially replaced with waste brick dust by using three different replacement percentages: 10, 20 and

Table 4 Mix proportions of testing program

Mix designation	B/S* ratio (%)	W/B* ratio	Replacement percentage (%)		Density g/cm^3
			Cement (C)	Brick dust (BD*)	
10/BD0	10	1.2	100	0	1.7
10/BD10	10		90	10	
10/BD20	10		80	20	
10/BD30	10		70	30	
15/BD0	15	1.2	100	0	1.85
15/BD10	15		90	10	
15/BD20	15		80	20	
15/BD30	15		70	30	
20/BD0	20	1.2	100	0	2.0
20/BD10	20		90	10	
20/BD20	20		80	20	
20/BD30	20		70	30	

*B/S: Binder-soil ratio
*W/B: Water-binder ratio
*BD: Brick dust

30% of the total weight of cement. The mix proportions used in the present study and the B/S ratio with the replacement percentage of waste brick dust were given in Table 4.

Three different water-binder (W/B) ratios: 1.0, 1.2 and 1.5 were tested in order to get the best W/B ratio for achieving homogeneity in soil-binder mixtures. As a result of series of testing, it was found that, by using W/B ratio of 1.0, there was a difficulty in mixing the materials together. While, W/B ratio of 1.5 produced visible voids and bleeding during the molding of the soil-binder mixtures. The best homogenous mixtures were obtained with a W/B ratio of 1.2. With this ratio, the soil-binder materials were uniformly mixed without generating any visible voids in the soil-binder mixtures. Therefore, throughout this study, a W/B ratio of 1.2 was used for all the soil-binder mixtures. Fig. 3 shows the soil-binder mixtures prepared with different W/B ratios.

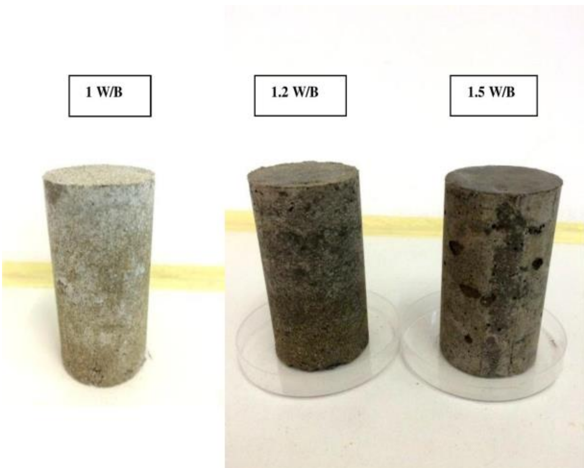

Fig. 3 Specimens prepared with different water-binder ratios

2.4 Sample preparation

Detailed procedures of sample preparation in soil mixing and sample curing are discussed in this section. In the preparation of soil-binder mixture, soil sample was dried in the oven at 50°C for 24 hours and the binder materials; cement and brick dust were calculated according to each mix proportion as described in Table 4. Soil sample with binder materials were thoroughly mixed by using a mixer of 50 rpm as shown in Fig. 4(a). Then the calculated amount of water was added to the mixture and mixed for 10 minutes to form a homogenous mixture without any soil lumps. As suggested by EuroSoilStab (2002); Jacobson *et al*. (2003); Kim *et al*. (2018) a cylindrical splitting mold of 50 mm in diameter and 100 mm in height was used to form the specimens.

A thin layer of oil was applied on the inner surface of the mold to extract the samples easily as shown in Fig. 4(b). Soil-binder mixture was placed in the splitting mold in five equal layers as shown in Fig. 4(c).
Each layer was compacted gently in order to achieve the required density as described in Table 4. Then the final surface was trimmed and leveled as described in Fig. 4(d). After 24 hours, the samples were extracted and kept in the air for one day to dry. Fig. 4(e) illustrates the dry samples after 24 hours. The specimens were soaked in water treatment bath at room temperature of 20 °C for 7 and 28 days. Fig. 4(f) shows the cured specimens.

2.5 Testing methodolgies

In the study, Vicat test was performed according to ASTM C191 standard at room temperature in order to evaluate the effect of waste brick dust on the setting time of cement paste. The bulk density of the specimens was determined after 28 days of curing of the specimens in water treatment bath. For measuring the surface area of the cement used in the present study, ASTM C204 standard was

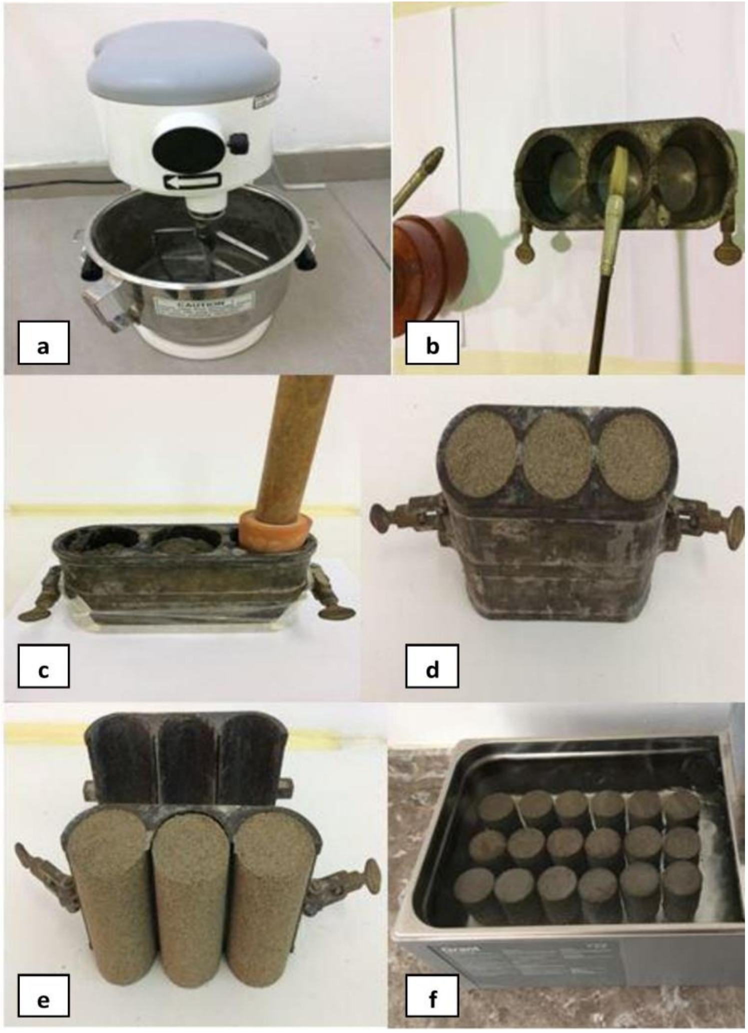

Fig. 4 Preparation of specimens: (a) electric mixer, (b) oiling the mold, (c) compaction of specimens, (d) specimens after trimming, (e) prepared specimens and (f) specimens in water treatment bath

adopted. Blaine air-permeability apparatus was used in order to determine the quantity of the air through a prepared bed of cement of definite porosity. Table 2 gives the surface area of the cement in terms of square centimeters per gram. The unconfined compressive strength (UCS) of the specimens were determined according to ASTM D1633 standard. The specimens' dimensions were 100 mm in height and 50 mm in diameter. After 28 days of curing, the specimens were left in the air until they became fully dry and then they were tested under uniaxial compression machine in order to investigate the effect of waste brick dust on the deformation behaviour and cracking propagation after failure. The resilient modulus, MR is used to characterize the stress–strain relationship of soils especially under repeated loading (Yang *et al*. 2008). In the present study, MR was predicted according to the equation suggested by Thompson (1965). The equation was in terms of unconfined compressive strength as described in details in Section 3.5. A microscopic study was performed and the specimens were examined under a stereoscopic microscope at 300X magnification and the obtained microscopic images were examined and discussed in the study.

3. Results and discussion

The results obtained in this study are discussed in this section. First, the laboratory tests were performed to evaluate the effect of waste brick dust on the setting time of cement paste replaced by different percentages of waste brick dust and then the bulk density of the soil-cement-waste brick dust mixture were determined and the effect of these binder materials on unconfined compressive strength, UCS and the modulus of elasticity, E_s of the treated specimens were investigated.

3.1 Setting time

In order to evaluate the effect of waste brick dust on the setting time of cement paste, Vicat test was performed according to ASTM C191 standard. According to the standard, the setting time test was first performed on the control sample (cement paste only) and then the cement paste was replaced by different percentages of waste brick dust (10, 20 and 30%). Fig. 5 shows the effect of different percentages of waste brick dust on the final setting time of

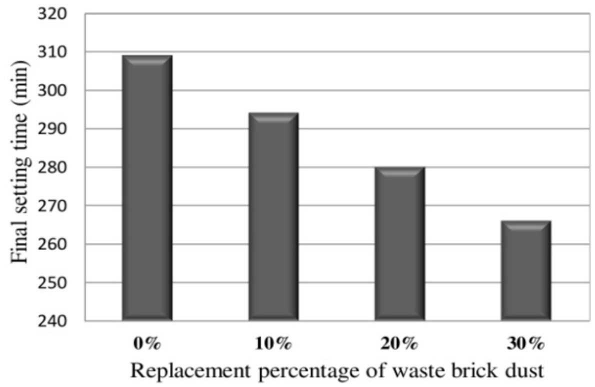

Fig. 5 Effect of replacement percentages of waste brick dust on the final setting time

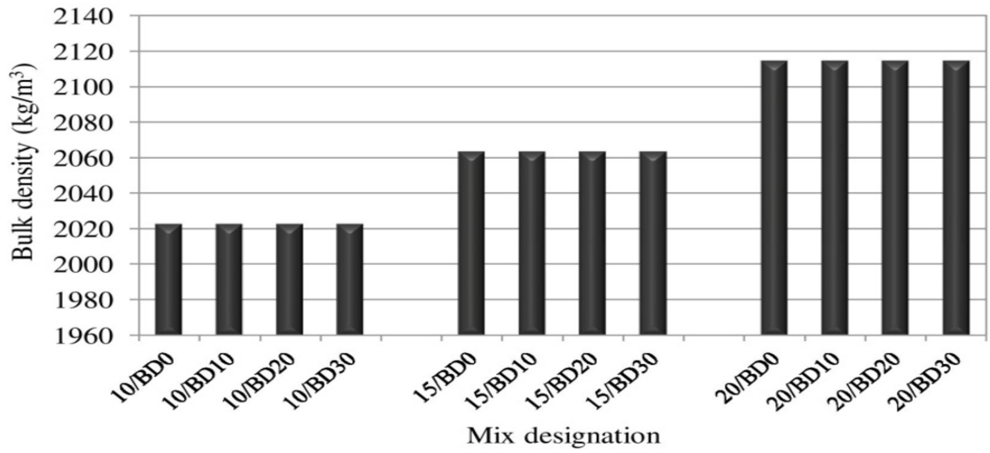

Fig. 6 Effect of replacement percentages of waste brick dust on bulk density

cement paste. According to the results obtained, it was observed that a reduction in the final setting time of cement-waste brick dust mixtures was obtained due to the increase in the waste brick dust content. The increasing replacement percentages: 10, 20 and 30% of waste brick dust in cement paste decreased the final setting time of control sample by 4.8, 9.3 and 13.9%, respectively. The replacement of cement with waste brick dust in cement paste caused the cement-waste brick dust mixtures to absorb more water compared with the mixture of cement paste only and resulted in faster rate of hardening. This could be explained due to the faster rate of release of silica and alumina present in the waste brick dust which resulted in reduction in the final setting time of cement-waste brick dust mixtures. Moreover, the high-water absorption of waste brick dust in the cement-waste brick dust mixture was attained and this led to faster rate of hardening of cement-waste brick dust mixture. This finding was in good agreement with the findings of Rakhimova and Rakhimov (2015) who stated that the increase in the rate of geopolymerization reaction in cement paste replaced by brick dust resulted in the shortening of the final setting time of this mixture.

3.2 Bulk density

Fig. 6 shows the bulk density of the soil-cement-waste brick dust mixture at 28 curing days. The figure indicates that the B/S ratio (10, 15 and 20%) has a direct effect on the bulk density. It is directly proportional to the bulk densities. As the B/S ratio increases, there is a continuous increase in the bulk densities. The bulk density values were in the range of 2022 – 2113 kg/m3. Considering the effect of only waste brick dust on the bulk density, it has been observed that there was no significant effect on the bulk densities. Due to the light weight of waste brick dust and lower density, waste brick dust does not show any considerable effect on the density of the mixtures at the same B/S ratios which is considered to be an advantage in terms of obtaining a constant density without degradation in the structure of mixture.

3.3 Unconfined compressive strength, UCS

The effect of waste brick dust on the unconfined compressive strength, UCS is presented in Fig. 7. The unconfined compressive strength of the soil-cement-waste brick dust mixtures showed variation with changing B/S ratio and replacement percentages of waste brick dust. The results showed that the optimum replacement percentage of waste brick dust was at 20% in all B/S ratios. At 28 curing days, the UCS values of the mixtures with 10/BD20, 15/BD20 and 20/BD20 ratios increased from 2374.35 kPa to 2509.73 kPa, 3769.80 kPa, and 5331.87 kPa, respectively. By increasing the percentage of waste brick dust to 30, a decrease in UCS was obtained. The UCS values of the mixture with 10/BD30, 15/BD30 and 20/BD30 ratios were

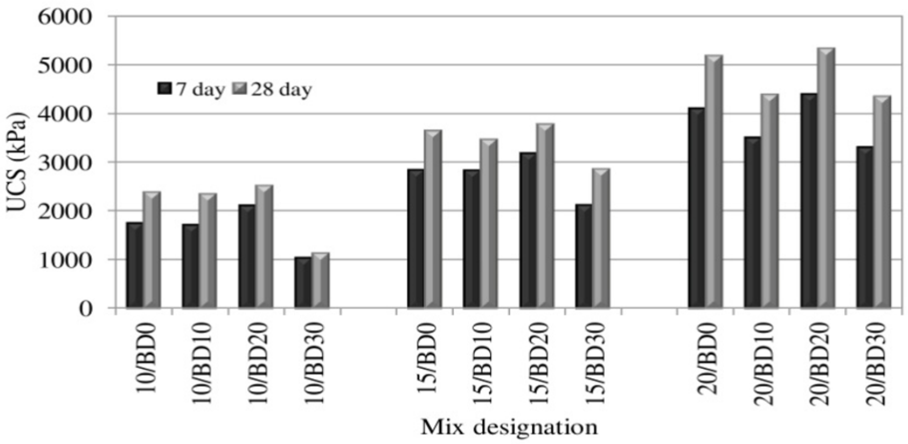

Fig. **7** UCS of treated specimens with different replacement percentages of waste brick dust

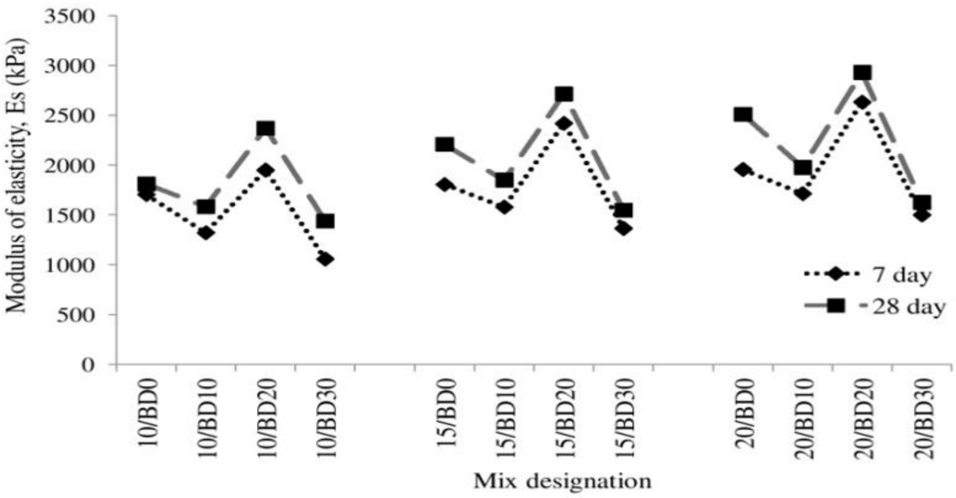

Fig. 8 The effect of replacement percentages of waste brick dust on the modulus of elasticity

2343.10 kPa, 3457.38 kPa and 4384.21 kPa. The most effective percentage of waste brick dust replacement in increasing UCS was 20 above which there was no further increase in UCS. This indicates that the presence of silicon dioxide, SiO2 in waste brick dust with a replacement percentage of 20 is sufficient for the completion of the pozzolanic reaction that will take place in the soil-cement-waste brick dust mixtures. Beyond this percentage, the waste brick dust acts as a filler and does not contribute to the strength. This finding was in good agreement with the findings of (Khan *et al.* 2018) who stated that the excessive amount of brick dust can show inferior behaviour in terms of compressive strength. On the other hand, reduction in UCS at 10% replacement of waste brick dust could be explained due to the insufficient SiO2 content which was inadequate to activate the pozzolanic reaction in the soil-cement-waste brick dust mixtures as reported by (Wong *et al.* 2018).

3.4 Modulus of elasticity

Fig. 8 shows the values of the modulus of elasticity, Es of the soil-cement-waste brick dust mixtures. Based on the obtained results, it can be seen that with increasing B/S ratios, a continuous increase in modulus of elasticity, Es of all soil-cement-waste brick dust mixtures were obtained. The modulus of elasticity of the mixtures ranged between 1057.69 kPa and 2631.57 kPa at 7 curing days, and 1437.5 kPa and 2929.3 kPa at 28 curing days. The obtained Es values are in good harmony with the values obtained by (Saberian *et al.* 2018). In terms of replacement cement with waste brick dust, it can be seen that there was a slight decrease in the modulus of elasticity of all mixtures with 10% replacement whereas with 30% replacement, a sharp decrease in the modulus of elasticity of all mixtures was obtained. In all B/S ratios, the highest modulus of elasticity value was obtained with a 20% replacement of waste brick dust. As Rosato (2003) stated, the increase in the modulus of elasticity of the mixtures is a good indication for the strength and stiffness improvement of the mixtures.

3.5 Resilient modulus

Resilient modulus, MR is a good indicator for material property especially in characterizing pavements for their structural analysis and design. It can illustrate the stress-

Table 5 Resilient modulus (MPa) of treated specimens

Mix designation	Curing time	
	7 days	28 days
10/BD0	284.45	363.22
10/BD10	280.58	359.35
10/BD20	329.65	380.01
10/BD30	196.64	208.26
15/BD0	420.04	520.76
15/BD10	418.75	497.52
15/BD20	462.65	536.26
15/BD30	330.94	422.62
20/BD0	576.29	710.58
20/BD10	502.68	612.44
20/BD20	613.73	729.95
20/BD30	478.15	607.28

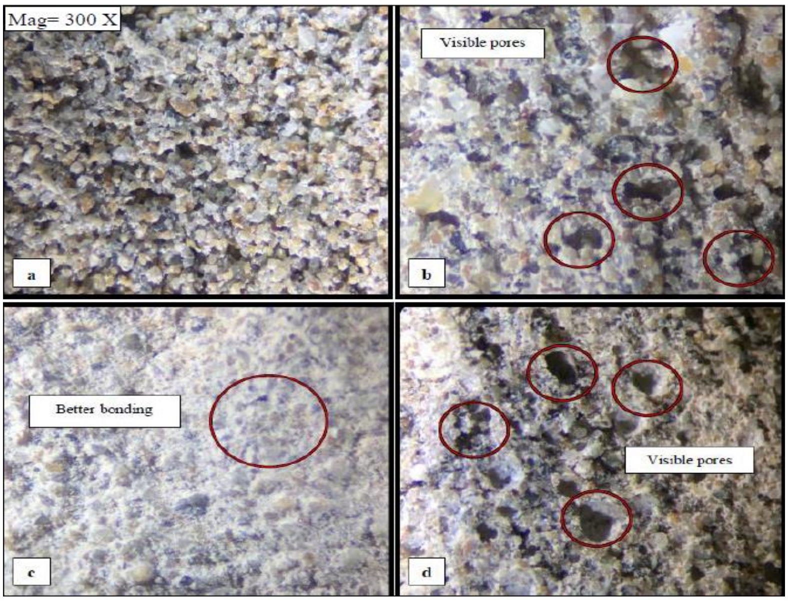

Fig. 9 Microscopic images of the specimens with cement and waste brick dust: (a) 20/BD0, (b) 20/BD10, (c) 20/BD20 and (d) 20/BD30

dependent elastic modulus of different soil materials (Nazzal and Mohammed 2010 and Venkatesh *et al*. 2018). MR was used by different researches to measure the elastic response of soils mixed with different additives (Sas *et al*. 2012, Park *et al*. 2014). MR value can be estimated directly from laboratory testing or indirectly through correlation with other laboratory tests (Rahim 2005). Direct determination of MR requires a complex and time-consuming testing and because of this, MR is estimated based on correlations with some material properties such as index properties of the soil, California Bearing Ratio, CBR and unconfined compressive strength (Thompson 1965, George 2004). Thompson (1965) suggested the below equation, Eq. (1) for MR in terms of the unconfined compressive strength

$$MR(MPa) = 0.124qu(kPa) + 68.8 \qquad (1)$$

Depending on the values obtained from the unconfined compression stress test, the MR values were calculated by using the above equation and the results were presented in Table 5. The calculated values of MR showed the similar response trend with the modulus of elasticity values as described in Fig. 8. The highest value of resilient modulus is obtained at 20% replacement of waste brick dust in all mixtures while 10% replacement of waste brick dust resulted in lower values of the resilient modulus. At the peak stress values, the particles in soil-cement-waste brick dust mixtures orientated into denser state and resulted in higher MR values. 30% waste brick dust replacement resulted in MR values lower than the other brick dust replacements because of the weaker particle interlocking generated in this mixture.

In order to explain the obtained test results, test specimens were examined under a stereoscopic microscope and the microscope images of specimens were examined

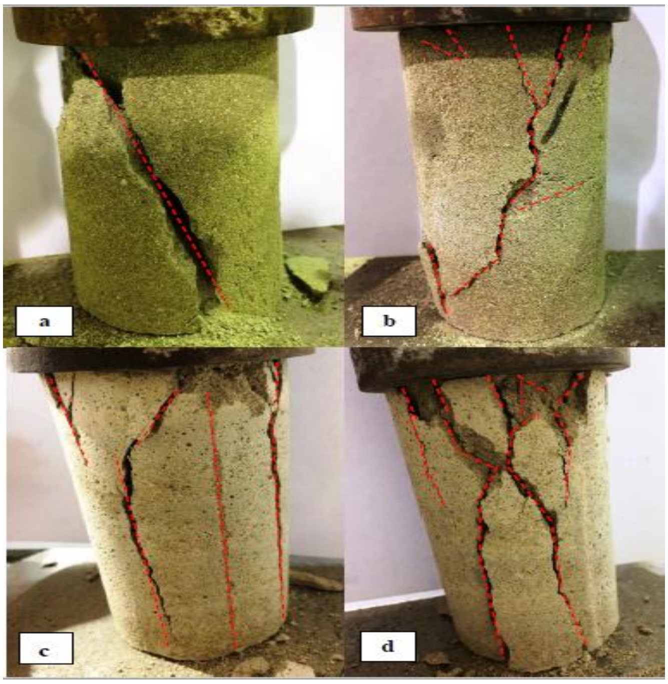

Fig. 10 Deformation behaviour of the treated specimens with waste brick dust: (a) 20/BD0, (b) 20/BD10, (c) 20/BD20 and (d) 20/BD30

and discussed. Fig. 9 presents the microscopic images of the four specimens with 20% of B/S ratio treated with 10, 20 and 30% replacement of waste brick dust at 28 curing days. Fig. 9(a) shows the microscopic image of the treated specimen with cement only (20/BD0). When this image was compared with the other images of the specimens with different percentages of waste brick dust replacement, it can be seen that the specimens treated with 20% of waste brick dust Fig. 9(c) resulted in less pore void space than the other specimens. The microscopic images of the specimens with 10 and 30% waste brick dust showed that these specimens contained larger pore spaces than the other specimens. The microscope image of the optimum percentage of waste brick dust (20/BD20) in Fig. 9(c) indicated that this percentage of waste brick dust used in the sand-cement mixture filled all the pore spaces of the sand particles in the mixture and covered all the surfaces of the sand particles.

This resulted in an increase in the interlocking of the sand particles and consequently resulted in a more dense structure. The cementitious compounds generated in the optimum percentage of waste brick dust (20/BD20) were considered to be a source for strength and stiffness development in the specimens. On the other, in the specimens with 10 and 30% replacement of waste brick dust, due to the visible pore spaces and the weak bonding between the sand particle as shown in Figs. 9(b)-9(d), insufficient cementitious compounds resulted in less stiffness and less MR values compared to the specimens treated with 20% waste brick dust.

3.6 Deformation behaviour

The deformation behaviour of the soil-cement-waste brick dust mixtures was investigated by using the unconfined compression test specimens after failure. The unconfined compression test specimens were tested under uniaxial compression and the effect of waste brick dust on the deformed shapes of the specimens and the cracking propagation of the specimens after failure were investigated. Fig. 10 illustrates the deformation behaviour of soil-cement-waste brick dust mixtures in mix designations: 20/BD0, 20/BD10, 20/BD20 and 20/BD30. The figure illustrates the deformed shapes of the specimens at failure. Fig. 10(a) shows the failure deformation of the specimen with 0% of waste brick dust in mix designation 20/BD0. The obtained deformation type is a typical shear failure as shown in Fig. 10(a). Whereases at 10% of waste brick dust in mix designation 20/BD10, a fracture surface with small cracks were observed as shown in Fig. 10(b). At 20% replacement of waste brick dust in mix designation 20/BD20, it was found that the crack path was along the vertical direction of the axial stress, which was typically axial splitting tensile failure as shown in Fig. 10(c). This finding was in good agreement with Yang *et al*. (2009), who stated that this type of tensile failure was due to brittle deformation of specimens. On the other hand, at 30% replacement of waste brick dust in mix designation 20/BD30, the deformation resulted in fracture surfaces with lots of cracks as shown in Fig. 10(d). The increasing amount of waste brick dust altered the deformation and cracking pattern of the treated specimens as shown in Figs. 10(b)-10(d). All the treated specimens with waste brick dust yielded more fracture surfaces than the cement mixed specimen: 20/BD0. In mix designations: 20/BD10 and 20/BD30, the tested specimens resulted in several short narrow tension cracks together with broad vertical cracks compared to the mix designations: 20/BD20. As Yadav *et al.* (2019) reported, such cracks are responsible for the sudden failure with less energy absorption of the specimen before failure. The resulted deformation and the crack pattern of the specimens with 10 and 30% waste brick dust replacement resulted in lower unconfined compressive strength due to the weak bonding and the improper strength and stiffness development of the specimens. These findings are in good agreement with the findings of Li *et al.* (2005) who associated the decrease in the unconfined compressive strength of the marble samples with the cracks generated in the specimens.

4. Conclusions

This study utilized waste brick dust as a replacement material of cement for enhancing the mechanical and strength properties of loose sandy soil to be more favorable for deep soil mixing. From the results obtained, the following conclusions can be drawn:

- In terms of recycling materials, based on the obtained geotechnical properties of the soil-cement-waste brick dust specimens, it was found that waste brick dust has good potential to be used as a cement replacement material in deep soil mixing technique.
- In terms of setting time, increasing percentage of the waste brick dust replacement decreased the final setting time of the mixtures due to the high water absorption of waste brick dust.
- Increasing B/S ratio resulted in an increase in the bulk density of all mixtures and caused the specimens to become denser. On the other hand, increasing the replacement percentage of the waste brick dust alone did not result in considerable effect on the bulk density.
- The effective silicon dioxide content required to be available for the pozzolanic reaction was found to be at the soil-cement-waste brick dust mixtures with a brick dust replacement of 20%. The highest unconfined compressive strength was obtained at this optimum percentage of waste brick dust replacement (20%).
- The best improvement in modulus of elasticity of the soil-cement-waste brick dust mixtures was obtained with waste brick dust replacement of 20%. The response trend of modulus of elasticity was in good agreement with the unconfined compressive strength values.
- The resilient modulus was varied in the same way as modulus of elasticity. 20% of waste brick dust replacement resulted in denser and stiffer specimens which resulted in higher resilient modulus.
- When the deformation behaviour of the soil-cement-waste brick dust mixtures was investigated, it was found that at 10% and 30% of waste brick dust replacement, the specimens resulted in fracture surfaces and cracks due to the inadequate strength whereas at 20% of waste brick dust replacement, the specimen was deformed in axial splitting tensile failure due to its high capability of crack resistance.

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