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Using Waste Ceramic Dust in Stabilization of Clay Soils

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Abstract: A considerable amount of the globally produced ceramic goes to waste daily. Ceramic wastes that are sent to the landfills have negative effects on soil, water, and the environment, as they contain aluminum, silica and iron oxide. The waste water leaching to the soil contains insoluble particular matter or heavy metals and could damage the plants. The air emission of the ceramic waste dumping process is also very high and it has negative effect on environment and human health by spreading dust. Using waste ceramic dust in soil stabilization could be for better disposal of such waste. The usage of natural resources can be minimized as well as prevent additional environmental burden and emissions. For this purpose, three local clay soil samples from Erbil in North-Iraq were gathered and the effects of addition of waste ceramic dust on mechanical properties of these samples were experimentally examined in two different grading sizes. The ceramic dust with particle sizes passing sieve No.40 and sieve No.10, in the proportion of 0, 5, and 10% percentages were used. The study showed that with an increase in ceramic dust percentages, liquid limit, plastic limit, plasticity index, optimum moisture content of the clay decreased. On the other hand maximum dry density, unconfined compressive strength and California bearing ratio increased. The study showed that addition of No.10 gradation ceramic dust results in higher improvement compared to the same amount of ceramic dust in No.40 size. The current work concludes that soil stabilized with the right type and ratio of ceramic dust could be suitable for a sustainable highway construction subgrade by reducing the design thickness and potentially be more economic.

Keywords: Ceramic dust, soil stabilization, soil strength, environmental impacts, sustainable highway subgrade

1. Introduction

The excessive use of natural resources is becoming a challenge for the environment and society. The substitute materials that once were rejected as waste could be used again to conserve natural resources. In the years 2011-2012, the worldwide production of ceramic tiles was about 11,200 million square meters (Agrawal, 2017).

The commonly practiced form of disposal of ceramic tiles is dumping into landfills. This current procedure is causing environmental problems in contamination of land soil, groundwater, and the air. This issue is largely due to lack of regulation, lack of expertise, risk avoidance, and standard procedures in managing such wastes (Cabalar et al., 2017). Ceramic is produced in high concentration of silica, aluminum oxide, and iron oxide, comprising about 89.1% within its composition (Silva et al., 2014). In acidic soil when pH is lower than 5, aluminum enters the root tips and it stops root growth of the plant, it also can cause phytotoxicity (Panda et al., 2009). Nanoparticles are being regarded as an emerging occupational hazard in recent years. Exposure to them can occur during different processes of the tile industry such as during production, transportation, application and waste recycling. The danger of exposures to aerosol particles depends on the type of origin, the rate of transport of particles in the air and their removal or concentration in the workplace environment. Ingestion and skin absorption are also probable routes for causing damage during processing and disposal (Bessa et al., 2020).

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There has been increasing public interest in the general issues of waste disposal management in recent years, particularly with industrial waste and those wastes from building sectors (Chen & Idusuyi, 2015). Life Cycle Analysis (LCA) had shown that extensive environmental damage and footprint would be caused due to landfilling rather than recycling or reusing materials. Construction and Demolition waste (C&D) accounts globally for the largest proportion of solid wastes, which is 75%, while ceramic wastes have the highest percentage share of it with 54%. This proportion includes; ceramic floor tiles, wall tiles, sanitary ware, and household ceramics (Zimbili et al., 2014; Hidalgo et al., 2019). In developed countries, a lot of attention is paid to waste management and recycling, as recovering and reusing the waste material would be both economically and environmentally beneficial. The literature survey showed that 30% of the whole world's ceramic industry production goes to industrial waste. A lot of waste can be generated during production of all kinds of ceramic as well as during the sale, storage, and transportation processes (Shuying et al., 2014). The worldwide inventory of ceramic waste dust during the final polishing process of ceramic tiles exceeds 22 billion tons (El-Dieb et al., 2018). In some European countries, reusing construction and demolition waste has been possible to reuse up to 90% amount (Hidalgo et al., 2019). The ecological and environmental benefits of waste materials include; (1) reducing landfill disposal of unrecyclable waste by reusing them, (2) reducing the adverse effects of wastes on the environment and air pollution, (3) reducing the energy needed for the production, and using less natural resources. On the other hand, the alternative material source, its transport, and process, such fees and landfill management cost should be considered for the work (Canakci et al., 2016).

Iraq is estimated to produce 31,000 tons of solid waste every day, with a per capita solid waste exceeding 1.4 Kg per day. Baghdad, the capital of Iraq alone, has more than 1.5 million tons of solid waste each year. In the absence of adequate and appropriate methods and places for handling and recycling services, the current way for waste disposal in Iraq is landfilling with minimal concern for human health and the environment (Chabuk et al., 2015). For the population of 1,118,187, the daily volume of solid waste production in Erbil, a large city in Iraq, was approximately 1.27Kg/capita. Total revenue from recyclable solid waste was $333,488.85 a day in 2016. It has been observed that the city is still lacking in terms of efficient waste treatment technology. Erbil Landfill Site (ELS), situated near the Erbil-Mosul main road about 15 km away from Erbil city center, opened in 2001. The site receives more than 2000 tons of municipal solid waste per day (Aziz et al., 2019).

There are neglected waste materials from the ceramic tile industry that could be useful in soil stabilization (Agrawal, 2017). The use of ceramic waste to enhance soil properties is a cost-effective and safe process (Panwar & Ameta, 2016). This process will not only enhance soil properties, it will also solve the problems associated with its disposal. Expected improvement of stabilization can be summarized as; (1) Quality improvement: by reducing swelling and plasticity index of soil while increasing strength and durability by better gradation, (2) Thickness reduction in road subbase designs: Construction thickness might be reduced if the requirement of the base or subbase course is sufficient, (3) Effective control of ceramic waste dust for a safe and healthy environment, (4) Support using waste materials in the sustainable construction sector (Makusa, 2013). The effect of ceramic waste dust on index properties, California Bearing Ratio (CBR), compaction characteristics, shear strength, and swelling of expansive soil were studied by Rajamannan et al. (2013). In their study they observed that the Atterberg limit, swelling pressure, and optimum moisture content (OMC) decreased as the ceramic waste dust increased in the mix. At the same time, the unconfined compressive strength (UCS) increased and CBR value rose by 150%. Finally, the use of ceramic waste dust changed the soil classification from high plasticity CH group to low plasticity CL. The study concluded that ceramic waste dust up to 30% is very economical and valuable for enhancing soil strength for flexible pavement subgrade building. Sabat (2012) also studied the impact of addition of ceramic waste dust to clay soils and found that it could be used as filler materials and concluded that from a mineralogical, chemical, and morphological aspect, ceramic waste dust gives better properties to the sample without having a negative effect on its water absorption and compressive strength. Chen & Idusuyi, (2015) stabilized lateritic soil with ceramic waste dust additives from 0 to 30% and concluded that the addition of this form of dust decreases liquid limit (LL), plastic limit (PL), plasticity index (PI), and optimum moisture content (OMC). On the other hand, maximum dry density (MDD), and CBR for both soaked and unsoaked samples increased. The study recommends that from an economics and reinforcement perspective, a ratio of up to 30% ceramic dust can be utilized in the soil for better stabilization. The study also referred to that a significant part of the environment can be sustained over time, and waste tiles can find beneficial use in sustainable highways and road constructions.

For this research, improved stabilization of three clay soil samples is attempted with different percentages of ceramic dust. The intent was to examine the impact of the addition of two different grading sizes of ceramic waste dust on clay soil properties, using Atterberg limits, compaction, unconfined compressive strength, and unsoaked California bearing ratio (CBR) as a measurement parameter. Although most of the researchers referred used to up to 30% ceramic dust can be beneficial for weak samples soil stabilization, in the present work, only up to 10% ceramic dust was used to find out the effect of the grading of ceramic dust on strength properties of three different low expansive clays.

As stated, the advantage of using ceramic dust is it is cheap, environmentally friendly method in collecting and processing, and can be used as a strong, sustainable material in highway construction facilities. While there is no ceramic factory in Iraq that might have created a large number of waste tiles daily, many companies bring tiles from outside the country and sell them, in which during the whole process, broken tile waste is created. Furthermore, the demolition of various structures results in lots of tile ceramic waste which is not disposed in a regulated manner. Using low amounts of ceramic in subway construction could help the environmental friendly disposal of such waste.

2. Material and Methodology

The clay soil samples used in the experiment were three disturbed samples collected in Erbil-north Iraq after removing 50cm of the top soil. The collected samples were put in plastic bags, the first sample named S1 was taken from BSV1 near Kawrgosk about 30 min away from Erbil city center, the second sample S2 was from Sarta 5 near Darashakran, and finally, the third sample S3 was taken from Sarta 6 near Darashakran as shown in Fig. 1. The broken ceramic tiles were collected from the wastes of a company in Erbil-Iraq. A Los-Angeles abrasion machine was then used to grind the ceramics to smaller parts and the obtained grains got passed from sieve No.10 (2mm) and sieve No. 40 (0.425 mm). The three clay samples were oven-dried at 60°C temperature to avoid any alteration in clay mineral properties.

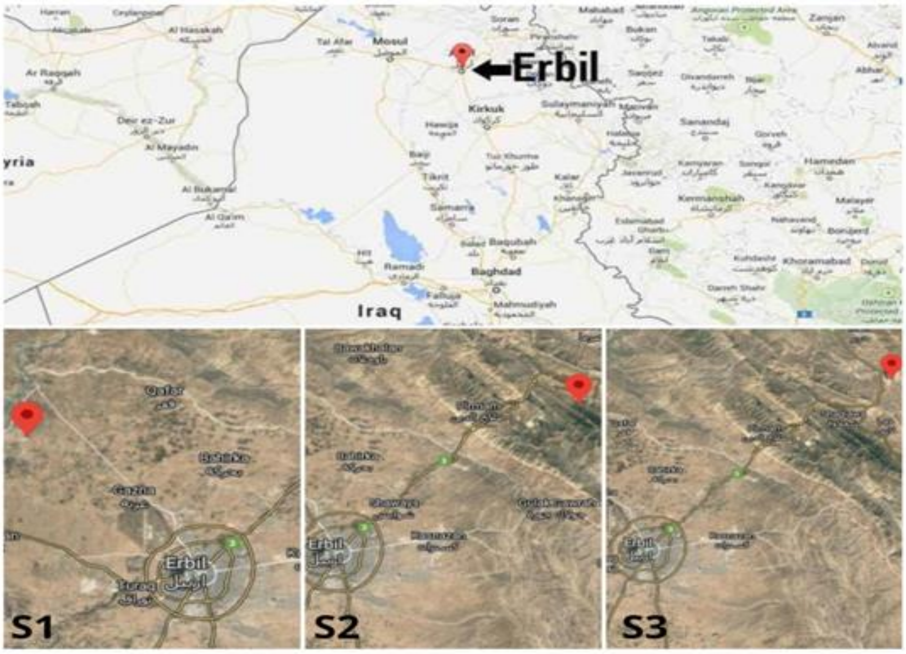


Fig. 1 - Location of the study area within the districts of Erbil-Iraq

Specific Gravity test was done according to ASTM D854. The experimental method is associated with calculating the specific gravity of soils used to assess the degree of saturation and unit weight of moist soils for both soil and ceramic dust. Table 1 shows the result for the specific gravity of the samples and ceramic dust.

Table 1 - Specific gravity of soil sample and ceramic dust

Sample Name	Specific gravity
S1	2.68
S2	2.68
S3	2.69
Ceramic dust	2.63

Hydrometer analysis test were done according to ASTM D422 (Fig.2). This procedure is used to determine the particle size distribution of fine soil particles

(a) **(b)**

Fig. 2 - Hydrometer test for soil samples S1, S2 and S3: (a) Oven-dried clay samples; (b) Filled hydrometer cylinder.

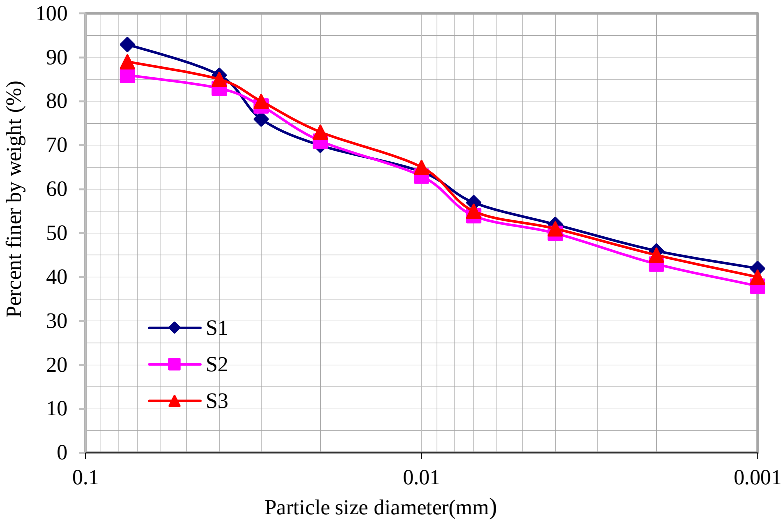


Fig. 3 - Particle size distribution curve for the obtained clay samples

In Fig.3, it can be seen that the soil samples contain 46, 43, and 45% clay size particles for S1, S2 and S3 respectively. According to the USCS classification plasticity chart, all samples are classified under the CL group category as silty clay soils with low plasticity.

The Atterberg limits tests were conducted according to ASTM D4318. These tests were performed to determine the liquid limit, plastic limit and plasticity index of the fine-grained soil samples. The Atterberg limits in soil differ based on the moisture absorbing minerals existing in the soil.

Standard proctor compaction test was performed according to ASTM D698. In the Standard proctor test, soil passing sieve No.4 was taken and mixed with both sizes of ceramic dust with various amounts of water added to the mixture. 15 types of mixtures were prepared for the test.

Unconfined compression strength was done according to ASTM D2166. This test gives an estimated value for cohesive soils' strength in terms of total stress. It helps geotechnical engineers to have a rather easy and quick perspective about long-term efficiency designs of the treated the soil. For the test, dried clay samples were prepared at their optimum water content, and compacted inside the molds with diameter and height of 38x 76.6 mm respectively. The compacted samples were then put inside the UCS loading machine.

Unsoaked California bearing ratio (ASTM D1883), test procedure involves measuring the CBR for subgrade pavement, subbase, and base components of laboratory compacted samples. It is a characteristic strength function of soil to assess the mechanical strength of the soil by penetration (Zorluer & Gucek, 2020). For each sample, three mixtures were prepared at their optimum water contents and were compacted. In order to reach different densities the sample was first compacted in five layers, each layer with 10 blows, the second sample with 25 blows, and the third sample with 56 blows. In Fig. 4, we can see the impact of 10cm penetration depth after the test. To find the soaked CBR value, the samples must be soaked in water for at least four days before the test, so that for doing many CBR tests with limited number of molds it needs quite long time to achieve the results, and if the treated soil is needed to be used in a project that could affect causing a rise in construction cost, the mentioned delay can be eliminated by doing the unsoaked test and then converting it into soaked ones, many researchers have suggested different empirical relationship to correlate CBR with various soil variables (Lakshmi et al., 2016). The calculation for the unsoaked California bearing ratio (UCBR) was done according to equation .1.

$$\text{Corrected UCBR\% at (2.5 and 5 mm)} = \frac{\text{Dial gauge readings}}{\text{Plunger Area}} \times \frac{100}{\text{Standard pressures}} \quad (1)$$

Fig. 4 - The sample shape after 10cm penetration for unsoaked California bearing ratio

3. Result and Discussion

Many researchers have identified the specific gravity of ceramic waste to range between 2.27 to 2.82 (Panwar et. al, 2017). In this study, the specific gravity of ceramic dust was found to be 2.63. Depending on the percentage of ceramic and clay soil with their calculated specific gravity, each mix's specific gravity was found according to the empirical equation .2 (Iravanian, 2008). Results for the specific gravity of all the mix are shown in Table 2.

$$Gs_{mix} = \frac{100}{\frac{\text{Soil\%}}{Gs_{soil}} + \frac{\text{Ceramic Dust\%}}{Gs_{ceramic\ dust}}} \quad (2)$$

Table 2 - Specific gravity result for soil samples with different proportions of ceramic dust

Sample	CD%	Gs mix
S1		2.68
S2	0%	2.68
S3		2.69
S1		2.677
S2	5%	2.677
S3		2.687
S1		2.675
S2	10%	2.675
S3		2.684

In Fig. 5, 6 and 7 shows that untreated samples of clay have higher liquid limit and plastic limit values. At the same time, as 5% of ceramic dust passing sieve No.40 was added to the mix, the liquid limit and plastic limit started to decrease, by adding 10% of ceramic dust, the liquid limit and plastic limit values fell more slightly with a linear equation, that means the lean clay with high plasticity have been changed to a lower plasticity clay without a change in soil classification category. The reduction in Atterberg limits is mostly due to the replacement of soil particles by ceramic dust (Cabalar et al., 2017).

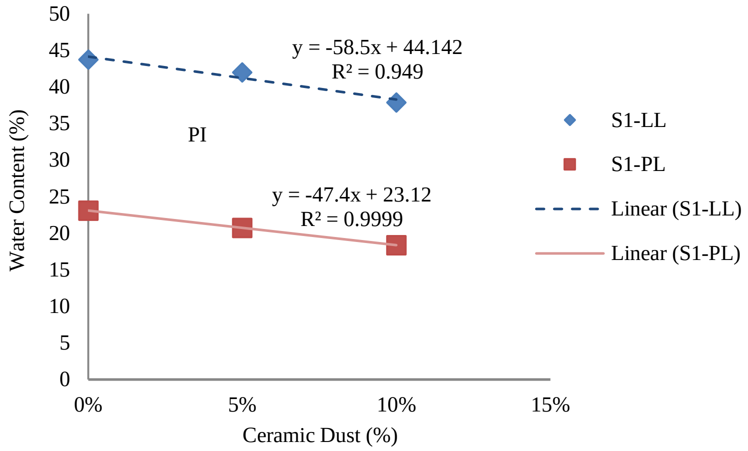


Fig. 5 - Liquid limit, plastic limit, and plasticity index for sample S1

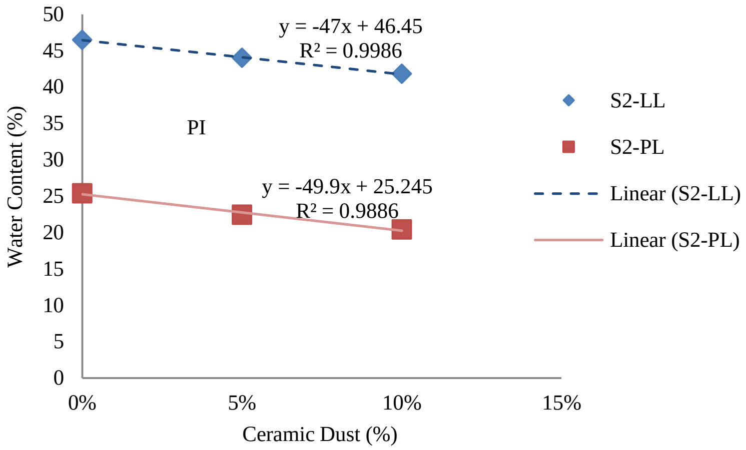


Fig. 6 - Liquid limit, plastic limit, and plasticity index for sample S2

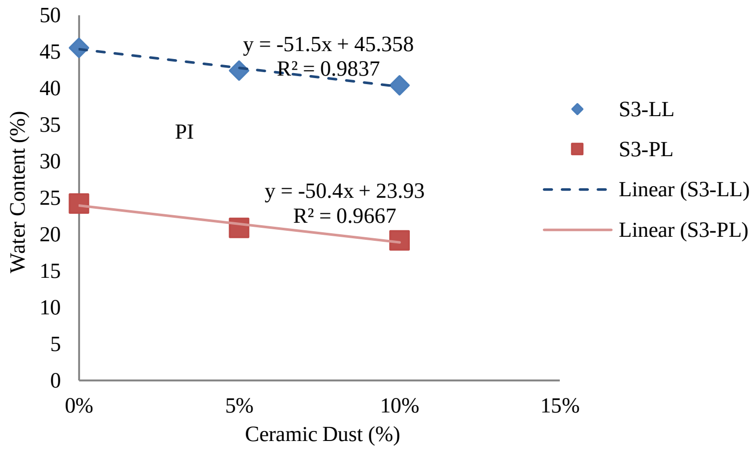


Fig. 7 - Liquid limit, plastic limit, and plasticity index for sample S3

Table 3 - Results of standard proctor compaction for the obtained sample

Sample	CD%	Ceramic size	MDD (g/cm^3)	OMC %
S1	0	0	1.832	16.15
S2			1.774	13.84
S3			1.920	14.16
S1	5%	#40 (0.425mm)	1.881	13.23
S2			1.815	12.22
S3			1.951	12.89
S1	10%	#40 (0.425mm)	1.919	11.13
S2			1.875	11.35
S3			1.992	10.63
S1	5%	#10 (2mm)	1.897	12.56
S2			1.891	11.87
S3			1.971	12.25
S1	10%	#10 (2mm)	1.952	10.52
S2			1.938	10.23
S3			2.025	9.96

CD: Ceramic dust*

Table 3 shows that untreated clay samples have less dry density than samples containing 5% ceramic dust while their optimum water content is much higher than the samples containing 5% ceramic. On the other hand, samples containing 10% ceramic dust have a higher dry density than untreated clay containing 5% ceramic dust. Also, the optimum water content is less. A direct positive relationship between the optimum water content and plasticity index was observed in all samples, which is also supported in the literature (Hassan et al., 2017).

As shown in Fig.8, 9, and 10, by adding more ceramic dust from 0 to 10%, it can be seen that OMC decrease. Meanwhile in causes an increase in MDD. Increase of dry density and decrease of the absorbed water within a clay soil is a desired point as it results in improving the mechanical properties of the treated soil. The positive changes are mainly due to the ceramic dust particles that have been fired at high temperatures, so they give better strength to the mixture and are inert once adjacent to water. Both ceramic sizes mixtures showed better optimum water contents comparing to the untreated clay samples, while the coarser size of ceramic dust, which are the sizes passing sieve No.10, showed higher dry density, and less water content values compared to the mixtures with the finer size of ceramic dust in all mixtures. This observation can be due to the gradation of the particles, as they contain larger particles having a smaller total surface area, water absorption can be minimized. On the other side, after compaction, it will give a higher dry density at lower water content than the finer size of ceramic dust.

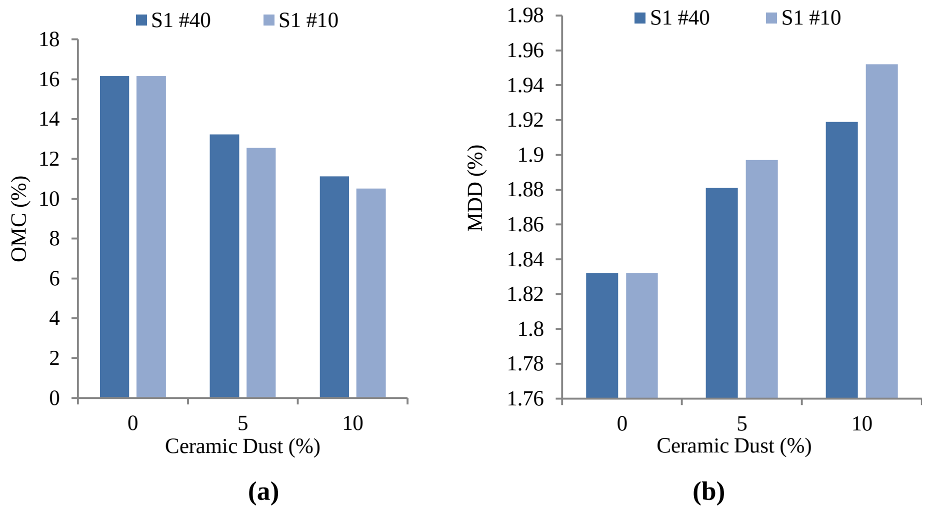
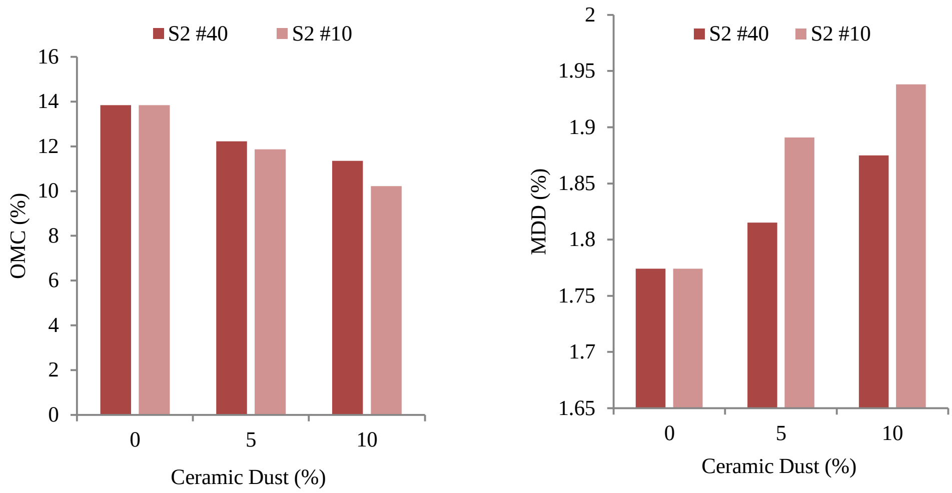
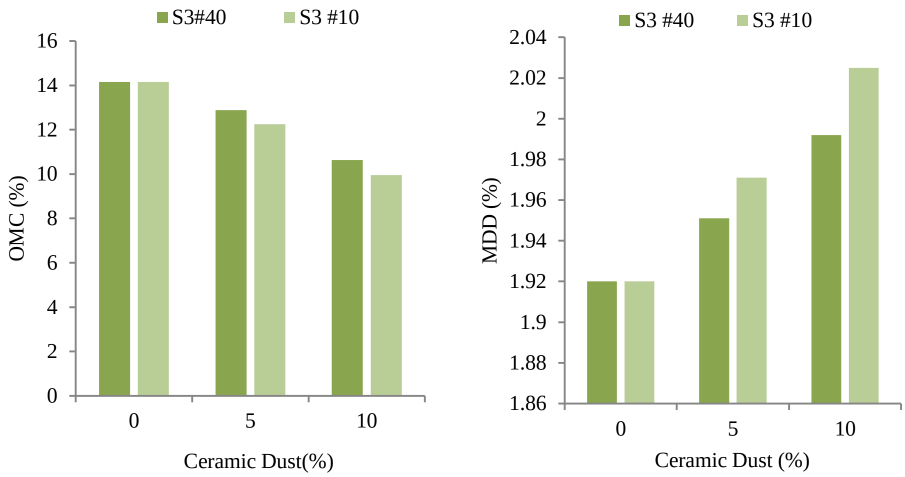


Fig. 8 - (a) Optimum water content versus the ceramic dust percent in both sizes; (b) Maximum dry density versus the ceramic dust percent for both sizes for sample S1



(a) **(b)**

Fig. 9 - (a) Optimum water content versus the ceramic dust percent in both sizes;(b) Maximum dry density versus the ceramic dust percent for both sizes for sample S2



(a) **(b)**

Fig. 10 - (a) Optimum water content versus the ceramic dust percent in both sizes; (b) Maximum dry density versus the ceramic dust percent for both sizes for sample S3

In Fig. 11, 12, and 13 it can be seen that with additional added 5% ceramic dust to the samples, the unconfined compressive strength starts to increase compared to the untreated sample for S1, S2, and S3. On the other hand, by adding 10% ceramic dust, strength increased more for both sizes of ceramic dust. The coarser size of ceramic dust showed higher unconfined compressive strength values than the finer size, mainly due to the higher MDD.

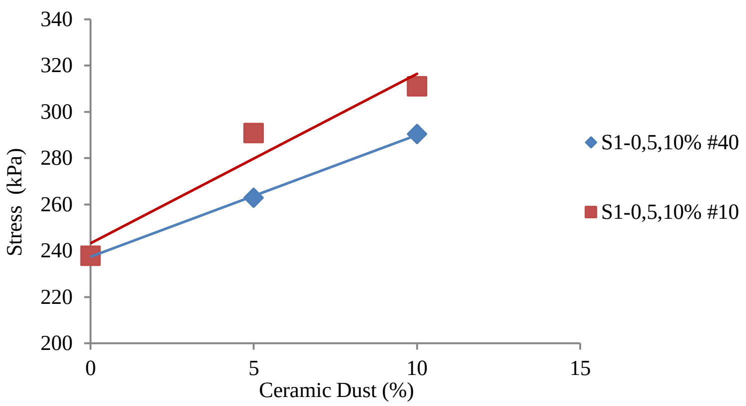


Fig. 11 - Stress versus the ceramic dust percent for the S1 sample with both ceramic dust sizes

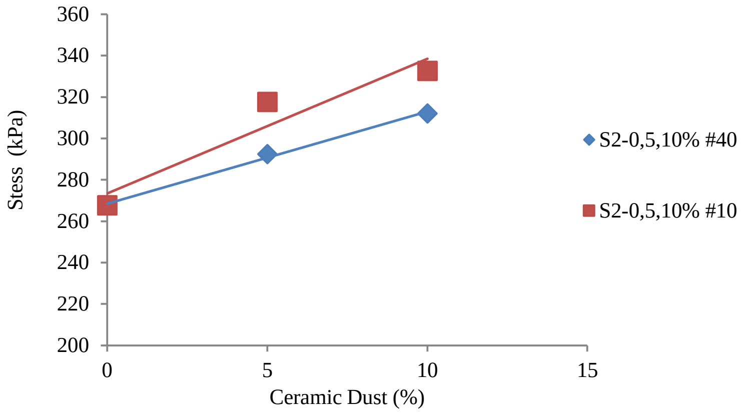


Fig. 12 - Stress versus the ceramic dust percent for the S2 sample with both ceramic dust sizes

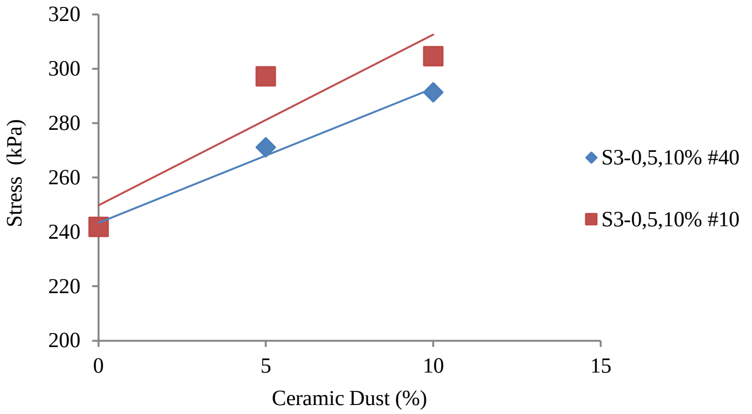


Fig. 13 - Stress versus the ceramic dust percent for the S3 sample with both ceramic dust sizes

Fig.14 shows that both ceramic dust sizes have increased UCBR values compared to untreated soil. At the same time, the coarser size of ceramic had slightly higher UCBR values. The UCBR increase with different amounts of ceramic dust and sizes could be due to the several reasons. One is that, the stabilized clay has higher stiffness due to high ceramic grain stiffness, less plasticity, more friction and therefore higher interlocking between clay and ceramic dust particles. The coarser size of ceramic has a lower surface area and less water absorption capacity in the mixture.

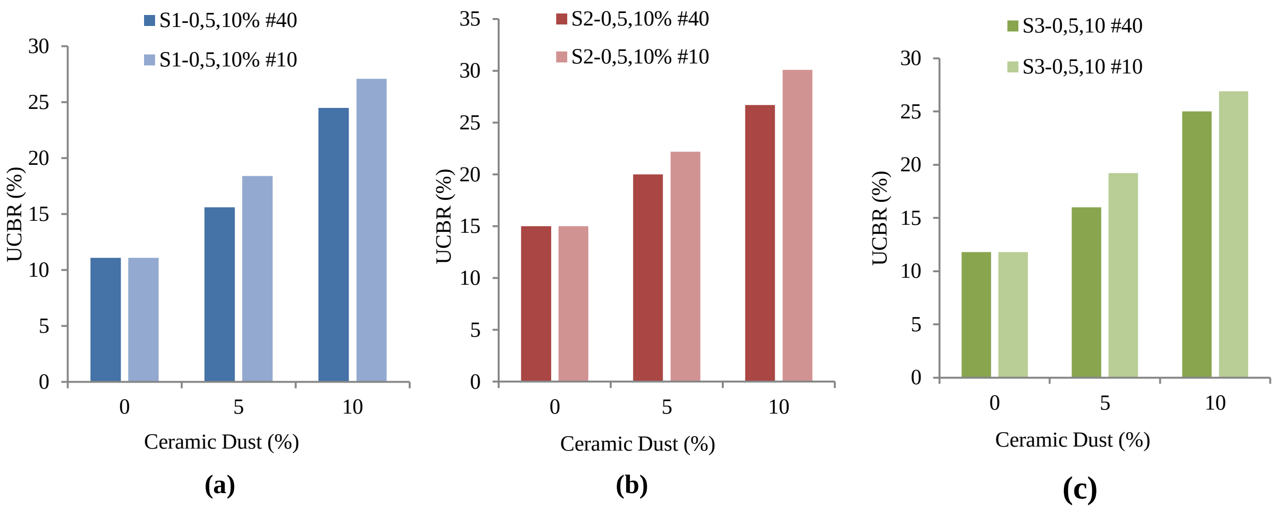


Fig. 14 - Unsoaked California bearing ratio versus the different amount of ceramic dust in both size of ceramic for(a) S1, (b)S2,(c)S3

Osouli (2017) did the unsoaked CBR test for calculating the soaked CBR. He used some correction factors for plasticity index, percent passing No.200, and dust ratio, while Lakshmi et al. (2016) conducted CBR on CL type of soil with the soaked and unsoaked condition. They found that the minimum value for CBR reduction in soaked samples were 86% of unsoaked samples. This phenomenon is due to the presence of excess water in soaked CBR, the water helps the plunger penetrate easier at lower time duration. The minimum value of 86% was used to predict the soaked CBR values for obtained samples and then the results were compared them to different standards, as shown in Table 4. Sign (√) refers to sample that is accepted to be used according to the standard. In contrast (×) sign, the sample cannot be used in highway subgrade construction according to the standard mentioned.

Table 4 - Predicted Soaked California bearing ratio for obtained samples and standards CBR values (ASTM D1883, IRC SP:72, BS 1377, AASHTO T180)

Sample	Ceramic dust%	Size of ceramic	Soaked CBR %	ASTM standard CBR Limit (1 to 15%)	IRC Standard CBR Limit (2 to 15%)	BS Standard CBR Limit (3 to 4%)	AASHTO standard CBR Limit > 4%
S1			1.6	√	×	×	×
S2	0	0	2.1	√	√	×	×
S3			1.7	√	×	×	×
S1			2.2	√	√	×	×
S2	5%	#40 (0.425mm)	2.8	√	√	×	×
S3			2.2	√	√	×	×
S1			3.4	√	√	√	×
S2	10%	#40 (0.425mm)	3.7	√	√	√	×
S3			3.5	√	√	√	×
S1			2.6	√	√	×	×
S2	5%	#10 (2mm)	3.1	√	√	√	×
S3			2.7	√	√	×	×
S1			3.8	√	√	√	×
S2	10%	#10 (2mm)	4.2	√	√	√	√
S3			3.8	√	√	√	×

In Table 4. it's shown that the untreated samples S1, S2, and S3 have CBR values of 1.6, 2.1, and 1.7%. According to the Subgrade Design and Construction for a clay soil having a LL>40 and PI>10, the CBR values between 1 to 15 can be suitable for highway subgrade application, however the rating is given as very poor (Schaefer, 2008). After adding 10% ceramic dust of finer size, CBR values increased and reached to 3.4, 3.7, and 3.5% which are still acceptable limit but in higher value. On the other hand, by adding 10% of the ceramic coarser size, the CBR values of S1, S2 and S3 increased to 3.8, 4.2, and 3.8% respectively. According to IRC SP:72 standard CBR values more than 2% could be used as a subgrade with, yet, 3-4% CBR value is categorized as a poor rated grading (IRC, 2007). According to AASHTO T180 minimum CBR value should be 4% for using it in a highway subgrade, which was reached in S2 with 10% ceramic dust of 2mm grading (AASHTO, 2004). Therefore, the treatment of soil with ceramic dust in resulted in improvement in the considered standards. It can also be concluded that coarser size of ceramic gives a higher CBR value that can lead to a better rating, less thickness design, and reduces cost by using a higher CBR value for using them in construction of a sustainable highway subgrade. According to British Standard (BS1377, 2016), the predicted suitable value for CBR is about 3 to 4% for a CL type of soil. Due to this, the untreated samples cannot be used for subgrade, and the soil can be only accepted after it gets to be stabilized by containing 10% of ceramic dust in both sizes to improve the CBR value. As expected, the coarser size has a better CBR value due to their larger particles.

In general, it can be said that up to 10% amount of coarser size of ceramic dust had shown improved properties in increasing compaction, unconfined compression and CBR values, with reducing the samples plasticity and water absorption. About the CBR results despite the improvement, it seems that higher percentages of ceramic dust will get a better grading result, when we compare the tested CBR results with ASTM standard, we can see that it improved to higher CBR values at the same group of rating. In this study the higher percentages of ceramic dust was not used, as in the study area there aren't any factory for production of ceramic. The amount of waste ceramic tiles in Erbil city have not been calculated by any researcher, so that up to 30% ceramic will be hardly affordable for a long highway project, however there are still a considerable amount of tiles exist and ends up in landfills.

4. Conclusion

Industrial wastes can be used effectively for soil stabilization. Ceramic waste, which represents a higher percentage of building waste worldwide, can be used in road construction, reducing the environmental impact of waste. The research findings mainly showed that the clayey soil's engineering properties had improved considerably due to stabilization with ceramic dust. The following conclusions can be drawn based on the findings and discussions of the study.

1. By additions of ceramic dust, the research further aims to solve the disposal problem of these wastes, which also creates a threat to the environment and human health.
2. The addition of ceramic dust from up to 10% decreased the LL by 13, 10, and 11% for S1, S2, and S3, respectively. In the same way PL was decreased by 20, 19, and 20% for S1, S2, and S3, respectively.
3. The MDD of the sample S1, S2, and S3 increased with adding ceramic waste dust from 0 to 10%, while OMC of the sample S1, S2 and S3 were decreasing, so the compaction parameters were improved by the addition of both sizes of ceramic dust. Comparing both sizes, the effect of treatment was more visible in coarser size of ceramic on MDD increase and OMC reduction.
4. The UCS increases with the increase in the percentage of the ceramic dust in both sizes of ceramic, in the finer size about 22, 16, and 20% in S1, S2, and S3 samples respectively. While the coarser size showed more improvement and higher strength due to larger particles and a higher dry density, there was 30, 24 and 25% improvement for S1, S2, and S3 samples.
5. The CBR values goes on increasing with the increase in the percentage of ceramic dust. There are 120, 78, and 111% increase in CBR value for S1, S2, and S3, respectively, with the finer size of ceramic compared to untreated soil. For the coarser size of ceramic unsoaked CBR were increased more with 144, 100, and 127% for S1, S2, and S3, respectively. When 10% of ceramic dust was added, this can significantly decrease the design thickness of the highway pavement.
6. About 10% percent of ceramic dust can be useful in soil stabilization and help to reduce environmental pollution both by using waste materials and reducing the use of available natural resources.
7. The use of solid waste in soil stabilization improves the soil's geotechnical properties. By achieving a higher CBR value, the soil samples can be used as subgrade for highways with smaller design thickness.

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