

# MECHANICAL STABILIZATION OF AEOLIAN SAND WITH CERAMIC BRICK WASTE AGGREGATES

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## Abstract

The use of ceramic brick waste is a sustainable and eco-friendly alternative for the stabilization of soils in comparison with other more traditional additives, such as cement. The addition of different types of construction wastes to soils has been so far mainly investigated for cementitious materials rather than for earthworks projects and civil infrastructures, and even less for aeolian sand. In this research, ceramic brick waste aggregates have been experimentally studied as an option to improve the geotechnical properties of aeolian sand from Jeddah (Saudi Arabia). Three different percentages of replacement have been considered, 15 %, 30 % and 45 %, since such high replacements have not been investigated in the literature. This research is focused on employing aeolian sand for earthworks applications. The experimental program is based on size analysis, compaction and California Bearing Ratio (CBR) tests specially modified to manage the represent different lateral confinement in the samples, and the results are confirmed by scanning electron microscope (SEM). Experimental results demonstrate an improvement of the overall geotechnical properties of the aeolian sand after mixing it with ceramic brick waste aggregates by means of the correction of the missing particle fractions and the addition of more aggregated particles, improving the coefficient of uniformity ( $C_u$ ) from 2.37 (aeolian sand) up to 3.56 (45 %-brick waste). The CBR obtained for the two higher replacements is around 33 % in confined conditions (triple than aeolian sand) and almost 1 % for unconfined conditions independently of the replacement. An optimal replacement of 30 % has been identified and the possible crushing and breakage of the waste aggregates are discarded. This mechanical stabilization can be considered feasible and environmentally suitable.

**Keywords:** Aeolian sand; Ceramic brick waste aggregate; Eco-friendly soil stabilization; Confined and Unconfined Conditions

## 1. Introduction

Aiming at a more sustainable construction approach, plenty of alternatives and research to reduce raw material consumption in construction, through reusing different types of wastes, have been developed within the last few decades. Some examples are municipal solid waste incinerator ash (fly ash) or ceramic tile wastes, which are nowadays extensively reused by the construction sector, while their disposal is therefore minimized or even often avoided. This approach presents important advantages from both the environmental and economical points of view, but strong uncertainties from the technical side arise in some cases, and that requires research to be conducted in order to explore and understand their suitability and technical possibilities.

On the other hand, the development of transportation infrastructures in arid regions is in growing demand and aeolian sand for construction purposes should be considered as a feasible material in those locations, where there is little to non-alternative materials. The main characteristics of this type of soil have been deeply described in the literature, which can be summarized as follows: aeolian sands are granular and cohesionless soils, with a very uniform particle size distribution (poorly-graded) and an evident prevalence of the fine fraction (ranging mainly from 0.08 mm to 0.40 mm), lacking edges in their particles. The natural water content is normally very low, its permeability ranges from  $3.4 \times 10^{-6}$  to  $1 \times 10^{-4}$  m/s, the predominant mineral composition is quartz with some low quantities of feldspars and calcites. The specific gravity ranges between 2.44 to 2.87, the cohesion is negligible, and friction angles are between 39 and 42 degrees [1].

These gradation properties present serious challenges when this material is to be employed in earthworks, such as road and railway embankments or fills, especially at those locations where the lateral confinement is low. Moreover, the compaction of this material is extremely difficult, because usually a clear optimum moisture content cannot be found in its compaction curves and even a minimum dry density value can appear at very low water contents [1]. In general, for aeolian sands reported in the literature, the maximum dry density varies between 1.642 and 1.765 g/cm<sup>3</sup>, and the corresponding optimum moisture content is between 11.0 and 14.5 % [1]. Besides, the on-site

bearing capacity of aeolian sand is usually not sufficient for most geotechnical engineering applications and therefore the use of alternative materials has to be considered. This is not an environmentally suitable option and sometimes this is not even feasible due to the lack of alternative proper materials on site. Therefore, different ground improvement techniques can be considered for enhancing their workability conditions and engineering performance.

In the framework of this research, two chemical stabilizers for the same aeolian sand have been successfully investigated previously, i.e. cement [2] and polymeric emulsion [3]. Cement is a well-known, widely employed additive for granular soils, and aeolian sand in particular [2, 4-9]. Despite its excellent performance in stabilized soils, cement presents several drawbacks, mainly high cost, scarce availability in some regions or non-eco-friendly material due to its high CO<sub>2</sub> emissions. Alternatively, other types of additives have been explored in the literature trying to overcome some of these problems. Some of the most extended ones are lime or bitumen stabilizations [10-17], whereas other types of additives, such as chemical stabilizers (polymeric emulsion, enzymes, lignosulfonates) [3, 18-26], reinforcing elements (fibres, geosynthetics, metal strips) [27-29] or slag residues material (solid waste incinerator ashes, ceramic tile waste) [30-31] have been scarcely or neither investigated nor used. A comprehensive and detailed review of different alternatives for the improvement of aeolian sand reported in the literature can be found in [1].

The partial replacement of raw material by other types of waste aggregates such as ornamental stone [32] or fine stone waste [33] has been mainly investigated for cementitious applications, paying special attention to the influence of the granulometric distribution on the properties of the final product. The considerable environmental impact of cement production has promoted the development of new research in this field. However, hardly any literature exists on the use of waste aggregate in road construction despite the large amount of fill material that these types of earthwork constructions require. Mehrjardi et al. [34] experimentally investigated the mechanical properties of recycled concrete aggregates (from concrete blocks and frames for buildings) and the rest of other construction and demolition wastes (without concrete elements after removing soluble and weak materials) for sub-base layers in roads, achieving promising results. Furthermore, Deboucha et al. [35] investigated the improvement of the geotechnical properties of common Algeria soils (with high compressibility and low bearing capacity) for their use as a base or sub-grade material for road construction after mixing it with ceramic waste (5-15 % of replacement), marble dust (2-5 % of

replacement) or cement (up to 2 %). These researchers observed a general improvement of the geotechnical properties for all mixtures in comparison with the original natural soil, especially when some cement was also added. However, the literature on the improvement of aeolian sand with waste aggregates is very scarce. As an example, Ameta et al. [31] stabilized dune sand from India using ceramic tile waste particles, which are mainly made of clay fired in a kiln and glazed, getting a polished and impermeable surface. In that research, different sizes of wastage particles (from 0.425 mm to 4.75 mm) as admixture up to 30 % of replacement were considered, achieving a higher improvement as the percentage of replacement and particle size were greater.

In the particular case of ceramic waste, plenty of different types of ceramic products are widely used in building construction, including brick walls, ceramic tiles and other types. Ceramic brick waste material represents the most extended component within the construction and demolition wastes worldwide, although they are normally disposed of as landfills. A vast generation of ceramic waste occurs along the whole product's life cycle, from the manufacturing, when up to 30 % of the daily production can be discarded, until building demolitions. Ceramic wastes occupy a significant fraction of the total construction waste production [36], hence the availability of enough amount of this waste is guaranteed, should it be required for other uses. However, this large volume of waste implies a strong environmental issue that should be attended to. In the last years, numerous research aims at investigating the re-utilization of this material in new construction procedures or elements.

In this research, the partial replacement of aeolian sand from Jeddah (Saudi Arabia) with ceramic brick waste material for enhancing the particle size distribution of the original soil has been explored. Non-chemical stabilization treatment has been undertaken herein, in contrast to some of the previous author's works, since ceramic brick waste can be considered as an aggregate material that induces mechanical stabilization. The ongoing stabilization research is aiming to improve the geotechnical properties of this aeolian sand, approaching sustainability and environmental challenges. The reduction in the consumption of raw materials and the re-valorization of wastes in the construction sector are two relevant approaches that firmly need to be considered nowadays.

Different percentages of replacement have been considered, ranging from 15 % to 45 %, since such high replacements have not been investigated in the literature, despite being feasible in some practical applications. The improvements achieved in terms of compaction and the California

bearing ratio (CBR) are investigated, to explore the utilization of this material for geotechnical applications, i.e. embankment fills, especially at those locations with low lateral confinement conditions, which represent the most critical situations. The laboratory tests carried out have been successfully supported by research previously published by the authors [2, 3], attending to the percentage of ceramic brick waste replacement and lateral confinement conditions. The improvement achieved in the engineering properties tested after mixing has been also supported by scanning electron microscope (SEM) analyses. Therefore, the possible degradation of the material has been also discussed, highlighting the role of ceramic brick waste.

## **2. Materials and Methods**

### *2.1. Characterization of Aeolian sand*

The aeolian sand employed in this research was collected from Jeddah desert dunes (Saudi Arabia). From its mineralogical composition point of view, this sand is mainly formed by quartz (73.8 %) with a low proportion of feldspar (3.3 %) and calcite. Regarding the size of its particles, this aeolian sand is characterized by a very uniform particle size distribution, ranging between 0.08 and 0.63 mm. This is non-plastic material with only 1.38 % of fines content classified as poorly graded (SP) [37]. The coarser fraction is rounded without sharp edges, whereas the fine fraction presents some edges and slabs and it is less rounded and more heterogeneous. Scanning electron microscope (SEM) images of this aeolian sand are shown in Fig. 1. This sand has a very low natural moisture content of approximately 0.27 % and null CBR in absence of lateral confinement. The main characteristics are also listed in Table 1.

### *2.2. Characterization of Ceramic brick waste*

Ceramic brick waste have been collected from a local construction and demolition waste plant in Caceres (Spain). Ceramic bricks are inexpensive rectangular blocks commonly employed in building construction. Since they are a very common and standard construction component, similar brick waste disposal can be found on other sites. This waste material has been generated during manufacturing processes (defective and broken units or surplus production directly discarded by the manufacturing plant), transportation, handling or storage, so it has not been mixed or contaminated with other demolitions waste.

Ceramic bricks are an inorganic, non-metallic, non-toxic, environmentally harmless, and non-water sensitive material. They are formed mainly from clay, which is mixed with water making it moldable for achieving the desired shapes. After, they are fired in a kiln up to 900 °C-1100 °C to provide strength, hardness and heat resistance to the final product. Normally, bricks are non-exposed so they are not glazed since a finished or treated surface is not necessary, unlike ceramic tiles or facing tiles.

Before carrying ceramic brick waste to the laboratory, bricks blocks were broken and crumbled by a mobile crusher in the construction and demolition waste plant. The material obtained presents a very heterogeneous size particles distribution, as can be observed in Fig.2 a. Since relatively large particles were obtained after crushing, compared with the aeolian sand particle sizes and attending to the maximum particle size requirements for laboratory tests, the whole amount of crushed brick material was sieved by 6.3 mm-sieve, rejecting all the ceramic brick waste material higher than this cutoff. This threshold corresponds to a maximum particle size of around three times higher than the biggest particles in the aeolian sand. After that, the resulting fraction of ceramic brick waste material was uniformly mixed obtaining the particle size distribution shown in Fig. 3 and Table 2, compared with the aeolian sand. The ceramic brick waste particles are sharp-edged with a large range of particle sizes. In all cases, the maximum particle sizes of any aggregate considered in this research satisfy the requirements of the tests carried out in the experimental program. A detailed characterization of the ceramic brick waste is summarized in Table 3, and the corresponding scanning electron microscope images (SEM) are included in Fig. 2-b. The ceramic brick waste particles are sharp-edged with a large range of particle sizes, in contrast with the rounded shape and homogenous size of the particles of the aeolian sand.

### *2.3. Brief overview of the experimental program*

The experimental program was defined to investigate the improvement in the compaction and bearing capacity properties of the aeolian sand after a proper stabilization with different proportions of ceramic brick waste aiming for embankment construction and fill material. The whole experimental program was carried out in the Geotechnical Laboratory at the University of Extremadura (Caceres, Spain).

Three percentages of replacement have been considered, 15 %, 30 % and 45 %, with respect to the total dry weight of soil, being the percentages of aeolian sand in each admixture equal to 85

181 %, 70 % and 55 %, respectively. Percentages as high as 45 % have never been previously  
182 investigated as the replacement in improved materials. For comparison purposes, the original  
183 untreated aeolian sand, without adding ceramic brick waste, as well as the ceramic brick waste only  
184 (without sand), have also been tested. A total of five types of specimens have been tested, and to  
185 assure the repetitiveness of the results, two tests were conducted on each case.

#### 186 *2.4. Mixture preparation*

187 The initial natural moisture of the aeolian sand was found as 0.27 % whereas the natural  
188 moisture of ceramic brick waste was null. For preparing each specimen, the corresponding amounts  
189 of soil and ceramic brick waste were thoroughly mixed until achieving a uniform mixture. After that,  
190 the proper volume of water was added in each case and uniformly mixed again. Since the  
191 stabilization analyzed in this research does not imply a chemical transformation of the additive, no  
192 curing was necessary and the specimens could be tested with no delay.

#### 193 *2.5. Particle size distribution*

194 Aggregate materials can be characterized and compared through their particle size  
195 distributions. The size analysis followed in this research is described in [39]. From a sieve analysis,  
196 different index properties can be characterized as the coefficient of uniformity ( $C_u$ ), coefficient of  
197 curvature ( $C_c$ ) and D-values, where  $D_{10}$ ,  $D_{30}$  and  $D_{60}$  are the most relevant. On the other hand,  
198 density is a relevant index of the mechanical behaviour of a soil, which is greatly influenced by the  
199 void ratio and therefore, by the particle size distribution and fine contents.

200 Crushing and breaking of a particle due to the energy transfer during the compaction process  
201 is a relevant matter that can affect to the long-term performance of the material. They can be easily  
202 assessed by comparing the evolution of the corresponding particle size distribution before and after  
203 loading, paying special attention to the increment of the quantities for smaller fractions and fine  
204 contents. In this research, the particle breakage procedure reported by Hardin [40] has been  
205 considered, which is based on the granulometric curves. This can be considered as an  
206 approximated characterization, allowing us to determine if more exhaustive degradation tests of the  
207 material are necessary.

#### 208 *2.6. Compaction procedure*

209 Before conducting the CBR tests, the relationship between the maximum dry density and the  
210 corresponding optimum water content must be established by means of the corresponding

compaction curves. These relationships cannot be uniquely defined, in particular for fine materials, because they can vary noticeable depending on the dosage of additive. Two complete compaction curves have been obtained for each type of specimen and percentage of replacement, and the average curve has been finally obtained. In all cases, an automatic compactor was used and each curve was defined by at least five data properly distributed along the compaction curve.

The compaction procedure followed in this research corresponds to Modified Proctor [41] with several variations to control the influence of lateral confinement in the behavior of the samples. The variations of the Modified Proctor procedure have been successfully validated previously for cement-stabilized soil [2] and polymer emulsion-stabilized soil [3]. The main modification introduced with respect to the conventional Modified Proctor test is a reduction of the height of the samples up to 76.2 mm. The number of layers is also reduced from five to three for keeping the same energy of compaction per unitary volume with respect to the normalized test. The rest of the parameters involved in the test conform to the normalized Modified Proctor procedure [41].

#### *2.7. California Bearing Ratio tests under different lateral confinement conditions*

The California bearing ratio (CBR) of the stabilized soil with different proportions of ceramic brick waste has been investigated. The lateral confinement conditions can influence significantly on the mechanical response of aeolian sand, therefore two extreme situations have been considered: fully laterally confined (which turns into the more advantageous situation), and without lateral confinement (which corresponds to the more disadvantaged one). The novel procedure successfully followed in previous research [2, 3] has also been considered herein, which is supported on a modification of the standard CBR test [42]. For confined conditions the samples were maintained in the metallic-mold during the penetration stage of the CBR test, whereas for unconfined conditions, the specimens were tested after removing the lateral confinement provided by the metallic-mold to the bearing strength of the soil. The same modifications highlighted previously for the compaction procedure have also been maintained for the analysis of the CBR, keeping the rest of the parameters conforming to those of the normalized test [42]. For each CBR test, a total of three specimens are necessary for the different values of the energy applied, ranging from 25 %, 50 % and 100 % of the modified compaction energy through the number of blows by layer, 15, 30 and 60, respectively.

These modified CBR tests were carried out for the three percentages of replacement of ceramic brick waste considered and also both unmixed aeolian sand and 100%-ceramic brick waste specimens for comparison purposes. Two complete CBR tests were developed for each type of specimen and confinement condition. Each specimen was prepared according to the corresponding optimum water content obtained from the previous compaction test, trying to achieve the maximum dry density in each case. Since this soil corresponds to semi-arid regions, and due to the lack of plasticity of both aeolian sand and ceramic brick waste, CBR tests were carried out without previous immersion. A multi-function load frame was employed in all tests with an overload of 4.5 kg applied over each sample. During testing, the corresponding load-displacement curves were registered too.

### **3. Results and discussion**

The discussion focuses on the influence of the addition of recycled aggregates proposed and the employed replacements in comparison with the equivalent properties of both original materials, aeolian sand and ceramic brick waste. The correction of the proposed particle size distribution is also discussed. The influence of the lateral confinement condition is analysed thoroughly. The deformational response of the original materials and the three mixtures are also investigated. The interlocking between particles from both materials developed for each percentage of replacement and the engineering property responses observed are supported by an SEM analysis. And finally, the degradation of the mixture after applying several levels of compaction energy is reviewed, in order to assess the feasibility of the proposed stabilization.

#### ***3.1 Correction of the particle size distribution***

After adding different percentages of ceramic brick waste aggregates, the particle size distribution of the final mixtures significantly changes. These variations have been checked by sieving analyses of the original aeolian sand, ceramic brick waste without mixing, and the three percentages of replacement (labelled as 15 %-B, 30 %-B and 45 %-B) as depicted in Fig. 3. As can be observed from Fig. 3 and Table 2, the addition of aggregates results in reducing the lack of coarse fractions in the original aeolian sand while it matches with the finer fraction (approximately below that 0.2 mm). As previously mentioned, aeolian sand is a very uniform material that can be classified as poorly graded sand with a coefficient of uniformity of 2.37, whereas ceramic brick

waste material can be classified as a very well graded material with a coefficient of 18.89 [37]. For the three percentages of the proposed replacement, the final achieved mixtures are classified as poorly graded material, since the corresponding coefficients of uniformity are slightly increased to 3.56 despite the high percentages of replacement considered (up to 45 % - Table 4).

The changes induced in the particle size distribution have also been evaluated through the coefficients of uniformity ( $C_u$ ) and curvature ( $C_c$ ) and D-values,  $D_{60}$ ,  $D_{30}$  and  $D_{10}$ , which are summarized in Table 4 and depicted in Fig. 4.  $D_{60}$  increases progressively up to 50 %-mixture and rises abruptly for higher percentages of replacement.  $D_{30}$  increases very slightly showing a moderate increment for very high values of %-replacement, beyond the percentages analysed in this research, whereas  $D_{10}$  keeps constant. For the intervals of %-replacement analysed in this research, slight decrements can be observed in  $C_c$ , keeping between 1 and 1.15 in all cases, showing a moderate reduction for very high %-replacement.  $C_u$  increases linearly as %-replacement does, following a similar pattern to  $D_{60}$ , achieving 2.61, 2.98 and 3.56 for 15 %-B, 30 %-B and 45 %-B of substitution, respectively. Concerning  $C_u$ , the final aggregate mixtures are less uniformly graded as %-replacement is higher. Supporting the evolution of the different granulometric indices, it can be asserted that the lack of coarser fractions in aeolian sand has been amended with the addition of this type of waste aggregate.

### *3.2 Compaction test: Moisture content – dry density relationship*

The results of the compaction tests developed for the three percentages of replacement are presented in Fig. 5, where the dotted lines correspond to the two series undertaken for each percentage, while the solid line corresponds to the average result in each case. The notation followed is: X%B-Y, where X is the percentage of replacement, B refers to ceramic brick waste, Y denotes the corresponding number of series of test and “mean” denotes the average results in each case. For comparison purposes, the corresponding results of unmixed aeolian sand and unmixed ceramic brick waste have also been included. The pairs of optimum moisture content (OMC) – maximum dry density (MDD) for each case have been attached to the figure.

For the three percentages of replacement, the compaction curves follow similar trends, approaching nearer to the pattern of the ceramic brick waste than the aeolian sand. In all the cases, the inclusion of ceramic brick waste aggregates highlights the optimum compaction point.

For the case of 15 %-B, a moderate increment of the MDD can be observed from 1630 kg/m<sup>3</sup> (aeolian sand [2]) to 1655 kg/m<sup>3</sup>, while the OMC almost does not change. For the cases of 30 %-B and 45 %-B, the increments of MDD are more significant, up to 1690 and 1681 kg/m<sup>3</sup>, respectively, achieving the value observed for the ceramic brick waste and even a bit higher than it for the case of 30 %-B. This implies that the void content of the mixture has been significantly reduced compared to the 15%-B or the original state of the sand. Other researchers have also observed slightly increments of MDD as the ceramic waste content or particle sizes are increased [31, 35]. However, for the highest percentage of replacement, the MDD can be slightly reduced because of the specific gravity of the ceramic waste which is slightly lower than the aeolian sand (Table 3), similar behaviors were also observed by Deboucha et al. [35]. The OMC is similar for all mixtures and the specimen of aeolian sand (13.7 % [2]) and significantly lower than for the ceramic brick waste (15.5 %). Although the variation in MDD and OMC is moderate, it can be observed a non-linear relationship between MDD and OMC with respect to %-replacement, as can be observed in Fig. 6a and c, where a maximum MDD and a minimum OMC can be pointed out for the case of 30 %-B. After that, for higher percentages of replacement, MDD tends to be constant whereas OMC tends to increase linearly. The variation of MDD for the evolution of the coefficient of uniformity for different %-mixtures has been plotted in Fig. 6b, where an evident linear trend can be observed up to  $C_u$  around 3 (which corresponds to 30 %-B) reaching the maximum MDD and reducing slightly for the highest percentages of replacement tested, similarly to Fig.6a.

### 3.3 California bearing ratio (CBR) tests under different lateral confinement conditions

#### 3.3.1 CBR results

The results obtained for all tested series according to the previously described CBR procedure are shown in Fig. 7, for both confinement conditions and the five proportions of aggregates considered in this research, pointing out the mean values for each case with solid lines. This figure reveals the influence on the bearing strength of the confinement conditions, the percentage of substitution and the energy of compaction, which is applied by means of the number of blows by layer: 15, 30 and 60 blows/layer which corresponds to the 25 %, 50 % and 100 % of the energy of compaction of Modified Proctor, respectively. The CBR achieved for the 100 % of the energy of compaction and each percentage of replacement have been plotted in Fig. 8 for confined

specimens and in Fig. 9 for unconfined ones, and the results are listed in Table 5. For the case of aeolian sand without lateral confinement, the CBR ratio is null because the sample tested out of the compaction mold is crumbling with a reduce pressure because the aeolian sand lacks of any collaborative mechanism such as cohesion, tensile capacity or binder.

For the samples tested with lateral confinement, the addition of ceramic brick waste aggregates significantly improves the CBR of the Jeddah aeolian sand, reaching higher CBR as the %-brick waste replacement increases, from 11.4 % in the case of aeolian sand up to triple this value for 30 %-B and 45 %-B. Comparing with a cement stabilization with this aeolian sand [2], the CBR for 30 %-B and 45 %-B replacement is almost the half of the corresponding value for a 2 % of cement addition. Deboucha et al. [35] reported values of CBR four times higher than CBR obtained in this research for 15 % of replacement, although it must be highlighted that the CBR for the original soil is also more than four times higher than the aeolian sand since they analysed a well-graded silted soil ( $C_u=13.07$ ) with low degree of plasticity. Higher values of CBR are reported when ceramic wastes are enriched with 2 % of cement. The improvements achieved in terms of CBR for 15 % of ceramic waste replacement respect to the original stage of each soil is 1.4 and 1.6 times for silted soil [35] and aeolian sand, respectively.

It must be highlighted that the CBR linearly increases with the percentage of replacement until 30 %-B, where the CBR is maintained despite the increment of the percentage of replacement, this finding is coherent with the results obtained for the MDD. Ameta et al. [31] also reported positive almost-linear trends between CBR and the percentage of replacement or the particle diameter size. However, the values of CBR achieved were significantly lower to the results presented in this research for similar percentage of replacement despite dune-sand is also tested but ceramic tiles wastes and Standard Proctor Test are employed instead. The highest results, around 94.2 %, are obtained for the unmixed ceramic brick waste. For confined conditions, the variation of the CBR ratio with the % of replacement shows a linear adjustment plotted in Fig. 8 and defined by Eq. 1, with a suitable correlation coefficient ( $R^2$ ) equal to 0.961.

$$\text{Confined condition: CBR (\%)} = 0.836 \text{ Brick(\%)} + 6.1 \quad (1)$$

On the other hand, for unconfined cases, the CBR ratios obtained for the three percentages of replacement considered are very similar, approximately equal to 1 %, almost the half of the

corresponding value in the case of addition of 2 % of cement [2]. Although this value is low, this stabilization treatment makes it possible to test the unconfined specimens. For this condition, the case of 100 %-B presents a CBR up to 8.2 %.

The improvement achieved in CBR for each percentage of replacement can be quantified with respect to the original aeolian sand as the quotient between them. For the confined condition, the improvement is 1.6 for 15 %-B and 2.9, approximately, for 30 %-B and 45 %-B. For unconfined conditions, the improvement has been quantified with respect to the result of the confined aeolian sand, since the aeolian sand without lateral confinement cannot be tested. The improvement results are included in Table 5.

A relevant influence of the coefficient of uniformity on the CBR ratio is highlighted in Fig. 10, since a non-linear trend can be observed, mainly for the confined case. A slight increment of  $C_u$ , from 2.37 (aeolian sand) to 2.98 (30 %-B), has tripled the CBR ratio of Jeddah aeolian sand for the confined case, whereas for unconfined conditions, the increment obtained is similar for the three values of %-brick waste.

Attending to the CBR, the ceramic brick waste material presents outstanding properties compared with aeolian sand, and hence the mixture of both materials collaborates to improve the overall aeolian sand behaviour. Even for the most disadvantaged condition of confinement, the addition of ceramic brick waste to aeolian sand improves relatively its bearing strength, enlarging its possibilities and reducing the construction wastage.

### *3.3.2 Load-displacement curves*

During the modified CBR procedure previously described, the load-displacement curves have also been obtained, and are depicted in Figs. 11 and 12. The deformational behaviour of the mixtures can be investigated through these results, attending to the degree of lateral confinement, energy of compaction and %-brick waste replacement. The influence of the ceramic brick waste aggregate on this issue can be highlighted since the response for untreated sand and unmixed ceramic brick waste specimens have also been included in both figures, however, the confined results for untreated aeolian sand have been added only in Fig. 11 because the unconfined tests were not possible to execute.

The deformational patterns observed for confined and unconfined tests are very different. In the case of confined conditions, Fig. 11, the increment of %-replacement increases significantly the improvement of the CBR of the sand, although several observations should be pointed out since the load-displacement patterns for aeolian sand and ceramic brick waste are very distinct. In the first case, a linear initial increment can be observed until a displacement around 6 mm, keeping almost constant or even slightly decreasing after this value. This pattern of response is characteristic of a ductile material. On the other hand, the load-displacement curve for 100 %-brick waste presents a monotonic increment, similar to linear elastic material, and the CBR of this material increases for higher levels of energy of compaction. With respect to the three mixtures analysed, similar patterns to aeolian sand can be observed characterized by a first linear increased stage following a constant response. The end of this linear state appears for larger values of displacement as the percentage of additive is higher, up to 7.5 mm for 45 %-B, as a consequence of the linear response of the ceramic brick waste material. The influence of the energy of compaction is negligible for the lowest values of %-brick replacement and it is a bit more relevant between 15 blows/layer and higher levels of energy for the highest percentage of replacement. In brief, after mixing, the stabilized aeolian sand keeps its ductile behaviour with moderate enlargement of its elastic region but with a significant improvement of its CBR as the percentage of replacement is higher. Only for a very high percentage of replacement, the influence of the energy of compaction could be partially relevant.

In the opposite case, for the unconfined condition shown in Fig. 12, a progressive transformation toward the ceramic brick waste load-displacement pattern can be observed as the percentage of replacement is higher. In the case of 100 %-brick waste, a clear maximum load value occurs for a displacement of around 2 mm, which is followed by a progressive decrement until achieves a very low residual load until the end of the test. The influence of the energy of compaction is well-defined from the beginning of the test, around the optimum value and until achieving the residual load stage, but it is progressively dissipated as the displacements are longer. Due to the absence of lateral confinement, the material presents an evident brittle response. In the cases of the three tested mixtures, an optimum (similar to the ceramic brick waste pattern) is revealed in each case as the percentage of replacement raises, approaching the load-displacement response patterns of 100 %-brick waste but not to its magnitude. In the case 15 %-B, the influence of the

energy of compaction is negligible whereas it is more relevant for the 45 %-B. The patterns of load-displacement observed for unconfined samples during the penetration CBR stage are due to the increasing radial fragmentation of the samples into blocks, progressively reducing the contribution of the lateral confinement around the material under the piston.

#### *4.4 3.4 Microstructural characterization*

The microstructural behaviour between aeolian sand and ceramic brick waste particles has been investigated by a scanning electron microscopy (SEM) analysis. The corresponding micrograph images for the three percentages of replacement considered (15 %, 30 % and 45 %) are shown in each row of Fig. 13. These images reveal the interlocking between particles, where the voids are filled as the percentage of replacement is higher, increasing the particles aggregates, especially from unmixed aeolian sand and 15 %-B to 30%-B. These variations are less significant between 30 %-B to 45 %-B. The interlocking and filling of the voids progressively modify the microstructural composition of the mixture and also support the correction of the particle size distribution highlighted above and the macroscopic behaviors observed in the laboratory tests carried out for the characterization of different engineering properties.

As the percentage of replacement is increased, a higher amount of particles of bigger size are introduced into the mixture, achieving a more uniform particles size distribution, and promoting the creation of aggregated particles, since the surface of higher particles is wrapped by more quantity of fines particles, improving the connection between aggregates after the compaction procedure. The roughness and edges of the added ceramic brick particles aggregates, identified by SEM (Fig. 2) also promote this behavior. Recent reported researches, supported on different advanced experimental techniques, have also highlighted similar patterns about the influence of the superficial characteristics on the improvement on the behavior of soils [43-48].

#### *4.5 3.5 Degradation of aggregate mixtures*

The long-term performance of the waste aggregates employed has been analysed to assess the degradation of this stabilization proposal in practical constructions. Crushing and particle breakage due to compaction procedures during construction could appear to alter the original gradation of the mixture. According to the widely employed method proposed by Hardin [40], the particle crushing after a stress stage can be quantified by comparing the particle size distribution

before and after being tested. Hardin proposed the relative breakage particle index,  $Br$ , defined by the area under the particle size distribution of a soil, assuming that a soil can be crushed until all particles achieved a size of 0.074 mm, and considering that the distribution of the larger particles is more relevant to the overall response of the soil since small particles (normally silt and clay) are not very susceptible to breakage.

The analysis for the case of 30 %-B of replacement is depicted in Fig. 14, where the initial gradation of the mixture and gradations after applying 25 % and 100 % of compaction energy can be compared. The aeolian sand and ceramic brick waste gradations have been added for reference and the Hardin's threshold has been slightly adapted up to 0.08 mm, for coherence with the sieve analysis criterion followed in this research. As can be observed in Fig. 14, after applying different levels of compaction energy, the changes in the resulting particle size distributions are negligible and therefore the index  $Br$  is nearly null. Attending to other granulometric indices, the variations in  $D$ -values are also very small, whereas the coefficients of uniformity and curvature present a very slight change before and after compaction, from 2.98 to 2.86 and from 1.06 to 1.10, respectively. Therefore, an excellent long-term behaviour of the stabilization proposed is feasible since non-relevant gradation alterations are expected.

#### **4. Conclusions**

In this research, the mechanical stabilization of aeolian sand (without chemical binder) by replacing different proportions of sand with ceramic brick waste aggregates (15 %, 30 % and 45 %), has been experimentally analysed and discussed. This stabilization is aimed to improve the poor geotechnical properties of the aeolian sand in terms of compaction and CBR under different lateral confinement conditions, which has been also scarcely investigated so far. The main conclusions drawn from this research are listed next:

- The ceramic brick waste material is a well graded material whereas the aeolian sand presents a notable lack of coarse fractions. The coefficient of uniformity ( $C_u$ ) of the resulting mixtures is slightly incremented as the addition of brick waste increases, ranging from 2.37 (aeolian sand) up to 3.56 (45 %-brick waste), reaching a less uniformly-graded composition.  $D_{60}$  is affected significantly by %-replacemen, whereas this influence is more

moderate for  $D_{30}$  and negligible for  $D_{10}$ . Based on the variation of these gradation indices, the lack of coarser fraction in aeolian sand is improved.

- The increment of MDD with respect to aeolian sand is moderate, varying between 1.5 % (15 %-B) and 3.7 % (30 %-B), which is governed by a non-linear tendency with respect to %-replacement and  $C_u$ . No relevant improvement is observed between 30 %-B and 45 %-B in terms of MDD. The highest MDD and the lowest OMC can be observed for 30 %-B.
- The CBR of the mixtures increases for a higher %-ceramic brick waste replacement with respect to aeolian sand up to three times under confined conditions. The CBR for unconfined samples do not significantly improve with the %-replacement. The ceramic brick waste material presents the highest of the CBR results obtained.
- The CBR obtained for 15 %-B and confined condition can be enough for most parts of common embankments whereas, the CBR obtained for 30 %-B and 45 %-B can be suitable for embankments with high performance. The CBR obtained for unconfined conditions are too low although the workability conditions of aeolian sand are enhanced.
- A linear agreement has been found between CBR and %-brick waste in confined conditions, whereas between CBR and  $C_u$ , the trend observed is non-linear for the %-replacements tested. A slight increment in  $C_u$ , from 2.37 to 3.56, has tripled the CBR ratio of aeolian sand for confined samples.
- The addition of different %-brick waste replacement also modifies the deformational behaviour of aeolian sand. In the case of the confined condition, aeolian sand presents a ductile response independent of the energy of compaction whereas, ceramic brick waste material presents a linear elastic behaviour influenced by the energy of compaction. The mixtures present a ductile behaviour which enlarges its elastic region for higher %-replacement. The influence of energy of compaction is not relevant in general. For unconfined cases, the materials present mainly a brittle response and the energy of compaction is more relevant for higher %-replacements.
- In the microstructural behaviour of the mixture, different phenomena, like interlocking between particles, filling of voids and creation of more aggregated particles between aeolian sand and ceramic brick waste particles, have been supported by SEM micrographs.

500           These behaviours are more relevant as the percentage of replacement is higher, up to 30  
501           %-B.

502           - According to Hardin's criterion, the possible crushing and breakage of the waste  
503           aggregates can be discarded.

504           The experimental results presented guarantee the outstanding properties of ceramic brick  
505           waste as a mechanical stabilizer for aeolian sands, collaborating to improve its geotechnical  
506           properties and enhancing the scarce coarse fraction of this type of sand, enlarging its  
507           possibilities and reducing the construction waste and raw material consumption. An optimal  
508           replacement is achieved at around 30 %. Therefore, this stabilization is an environmental and  
509           feasible technical alternative.

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513           their gratitude to Grupo Santano (Caceres, Spain), the construction & demolition waste recycling  
514           plant where the ceramic brick waste material employed in this research was collected. Finally, the  
515           authors would like to thank Dr Vicente Montes Jiménez for the SEM micrographs of this study  
516           developed through the research project funded by the government of Extremadura (IB20042).

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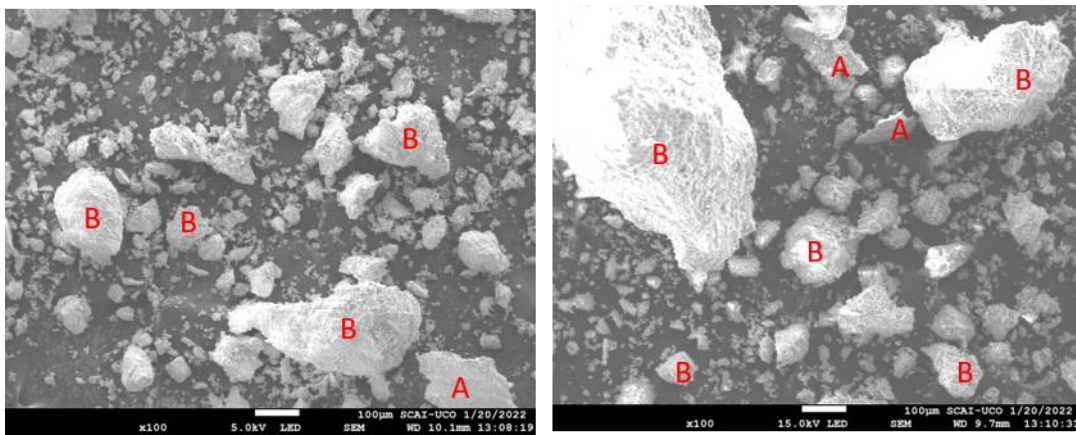
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**Figure 1.** Jeddah aeolian sand and scanning electron microscope images (SEM) (90x micrographs-A: rounded and uniform size particles of aeolian sand)

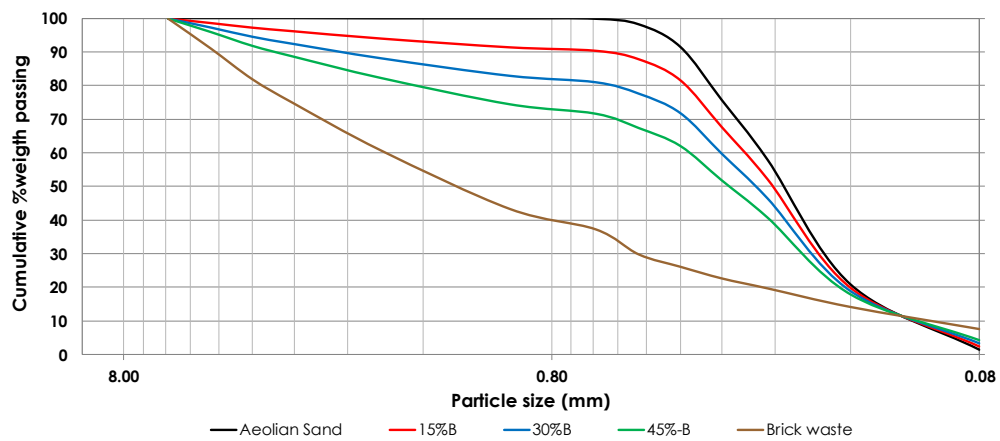


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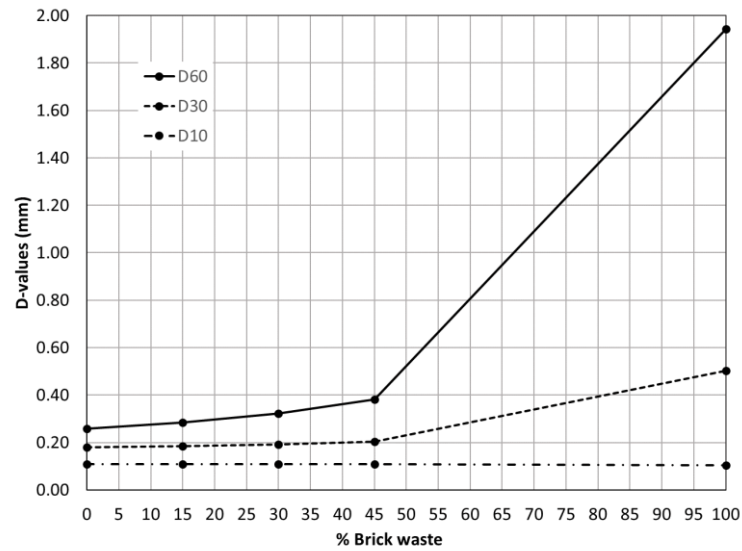


b)

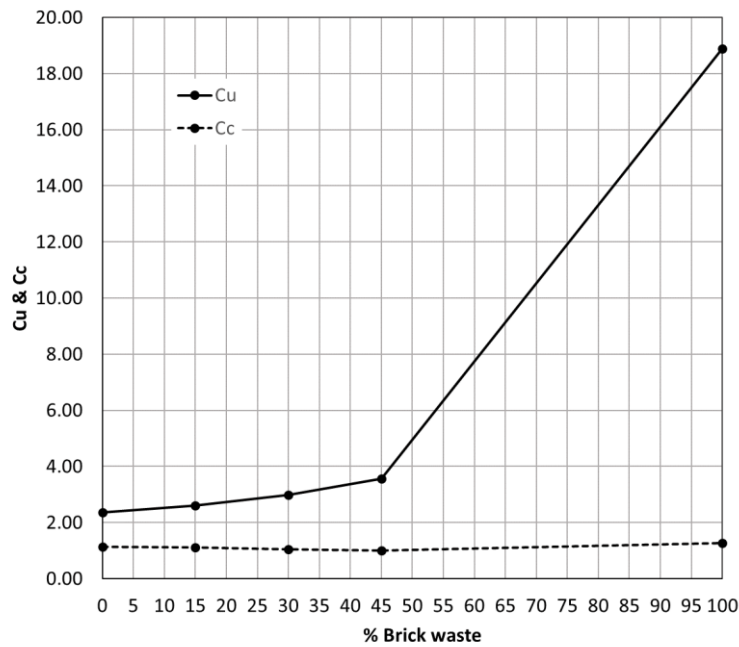
**Figure 2.** Ceramic brick waste: a) original material state, crushing process and final material composition before sieving at geotechnical lab b) Scanning Electron Microscope (SEM) for ceramic brick waste (100x micrographs - A: sharp-edged particles, B: roughness and different particle sizes)



**Figure 3.** Particle size distribution of aeolian sand, ceramic brick waste material and mixtures with 15 %, 30 % and 45 % of replacement

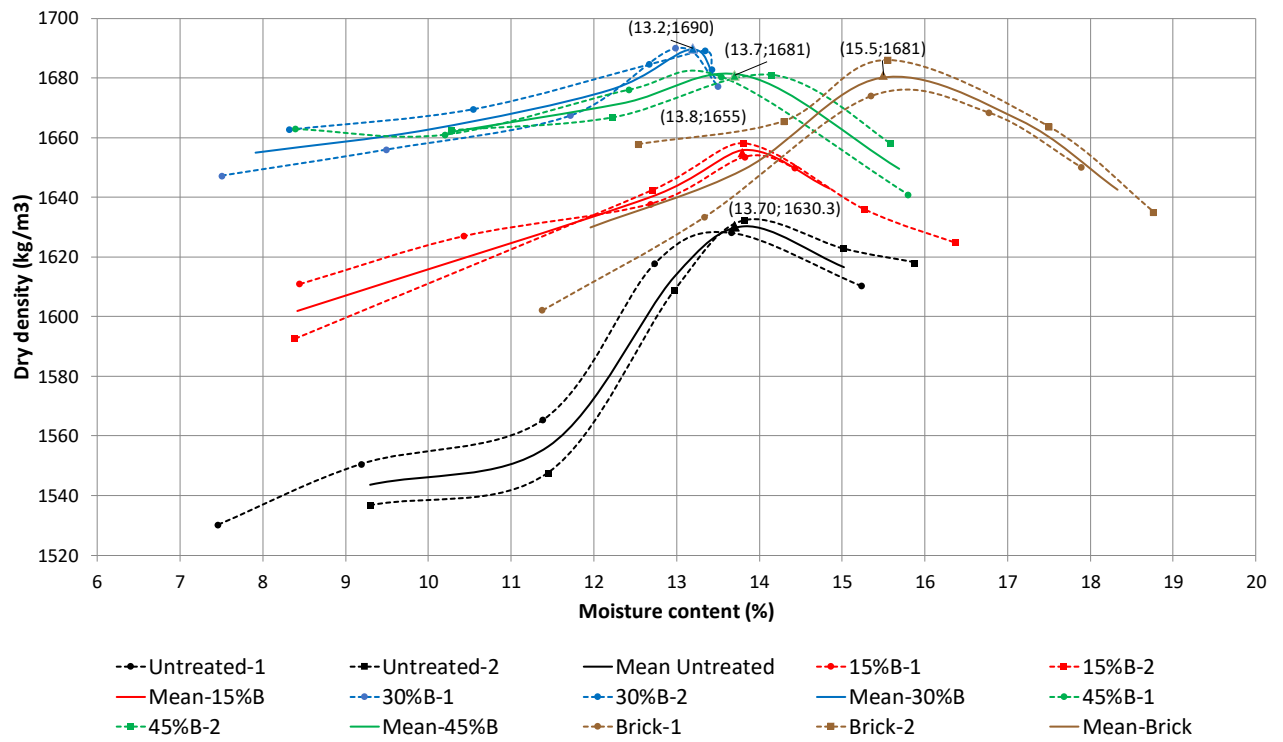


a)

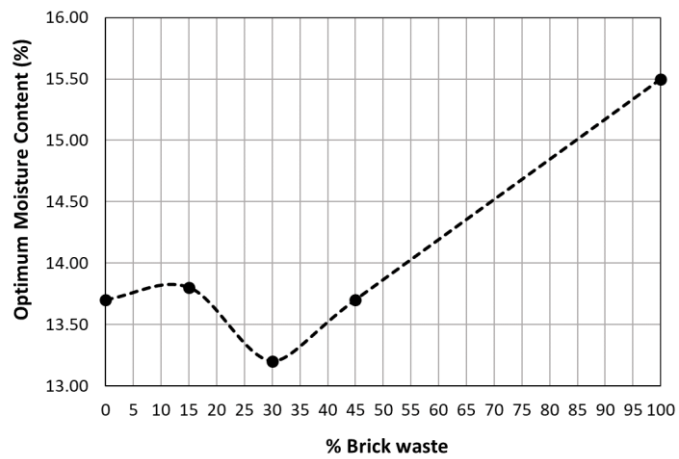
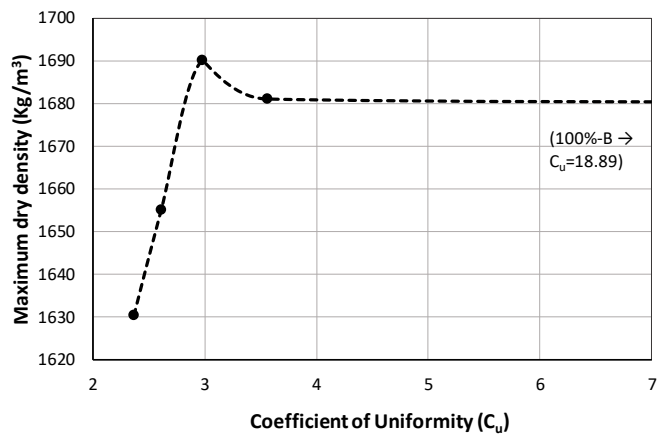
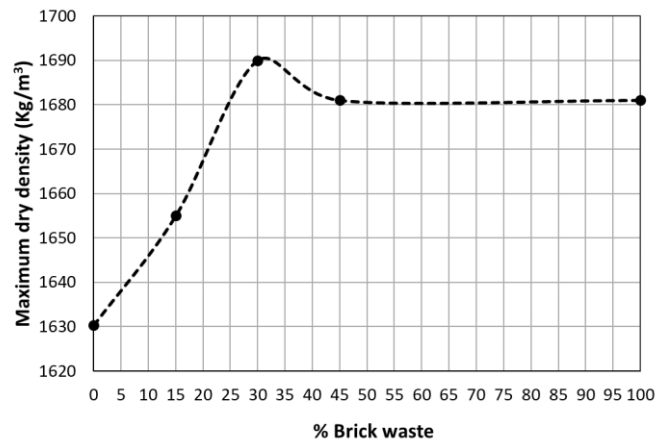


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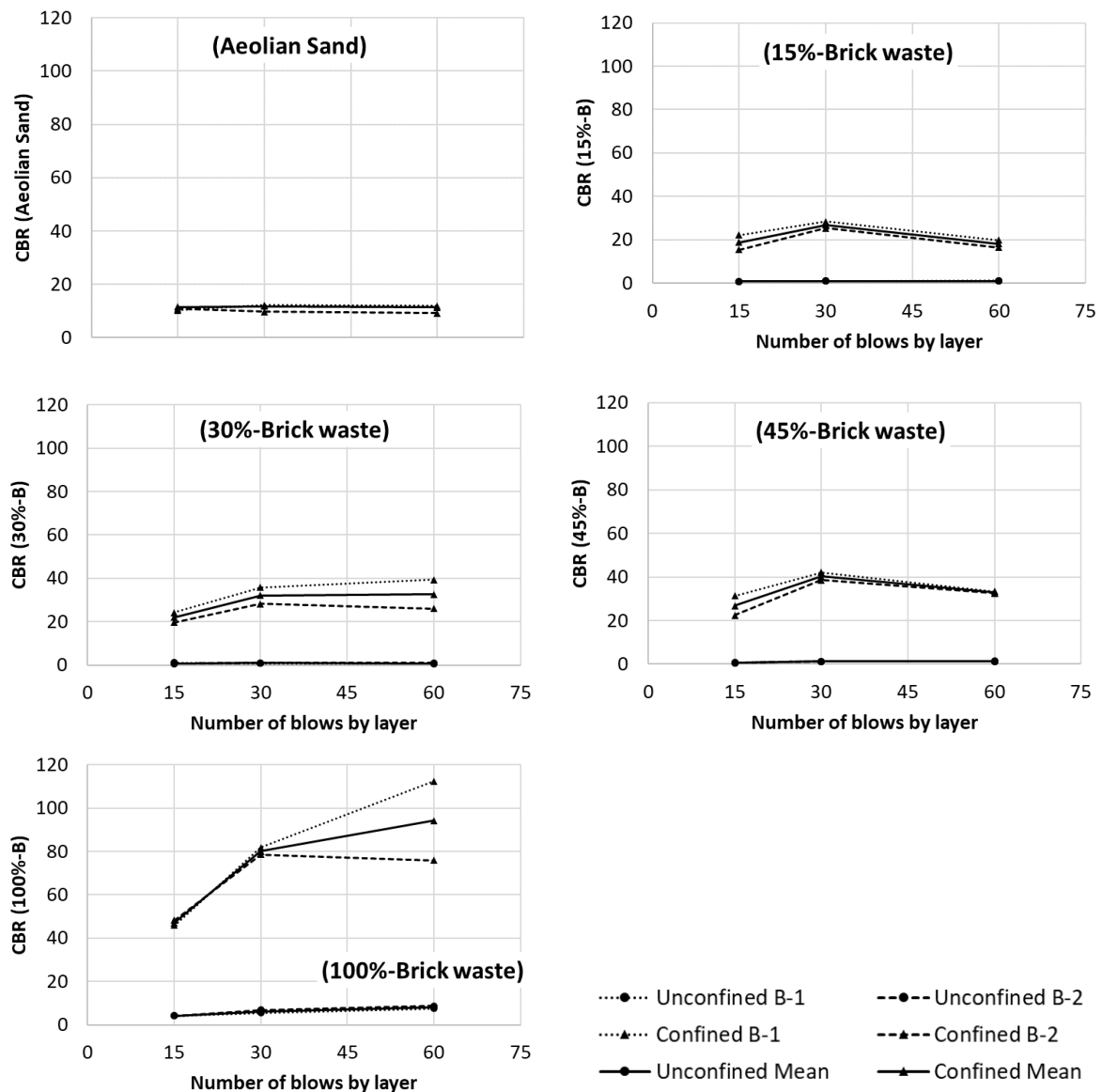
**Figure 4.** Changes in the gradation indices of the aeolian sand for different percentage of ceramic brick waste replacement: a)  $D_{60}$ ,  $D_{30}$  and  $D_{10}$ ; b) coefficient of uniformity ( $C_u$ ) and coefficient of curvature ( $C_c$ )



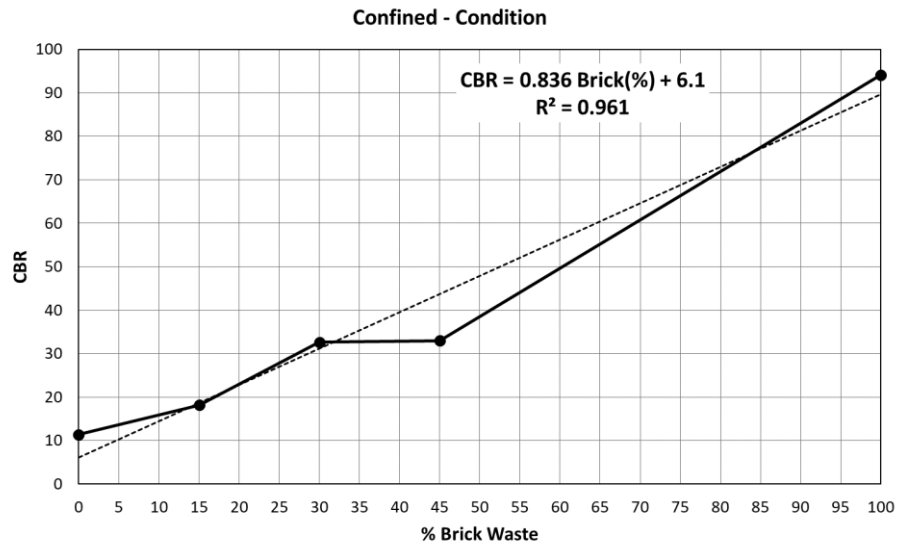
**Figure 5.** Compaction curves of aeolian sand, ceramic brick waste and mixtures for different percentages of replacement



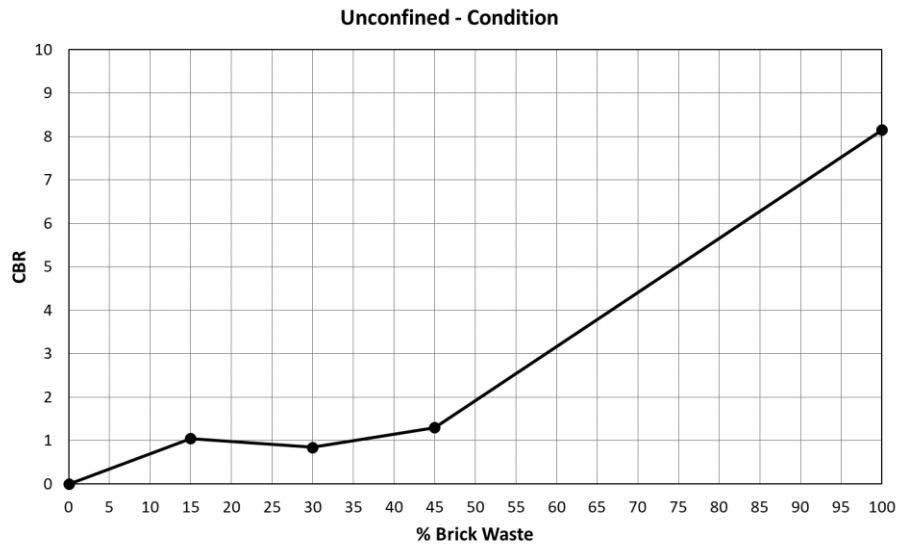
**Figure 6.** a) Variation of maximum dry density respect to the percentage of ceramic brick waste replacement; b) Variation of maximum dry density respect to coefficient of uniformity; c) variation of the optimum moisture content respect to the percentage of ceramic brick waste replacement



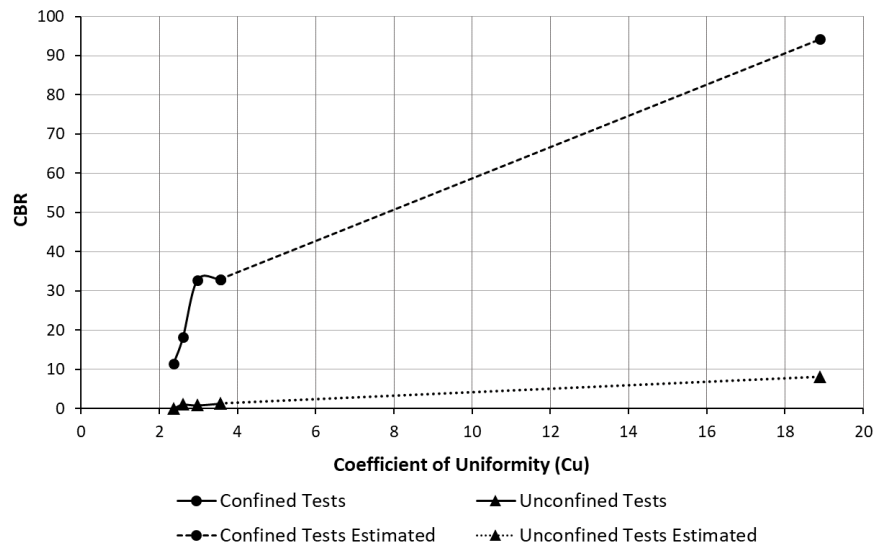
**Figure 7.** CBR ratios (%) respect to the energy of compaction and the percentage of replacement in both confined and unconfined conditions. Aeolian sand and unmixed ceramic brick waste results have been included for comparison



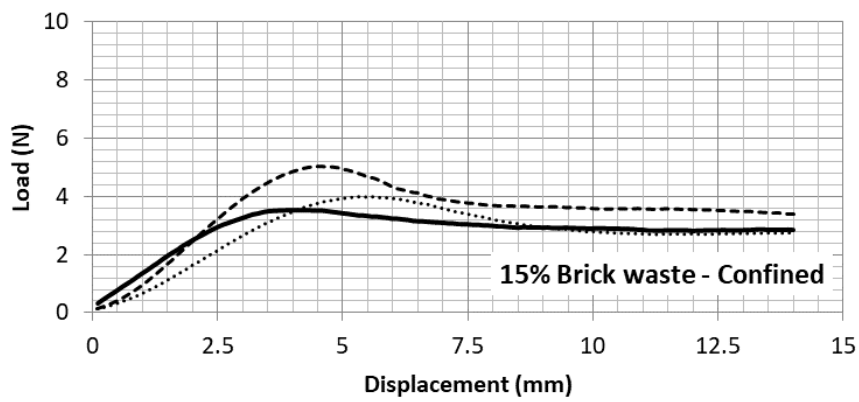
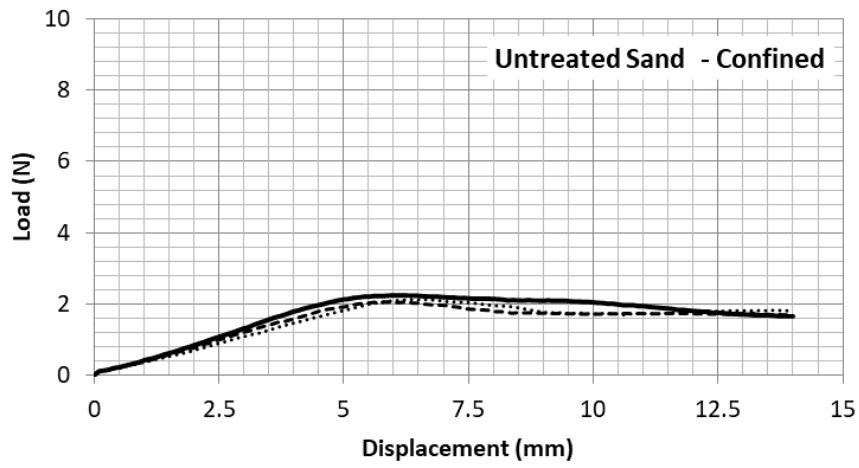
**Figure 8.** CBR ratio (%) respect to the percentage of replacement for the 100 % of compaction energy for confined conditions



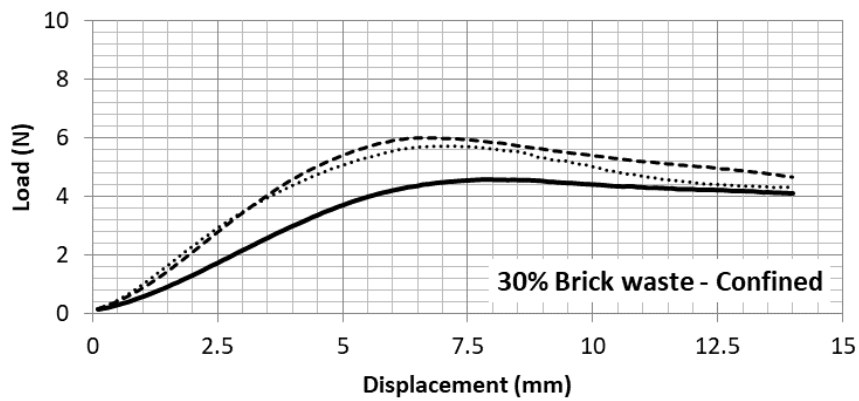
**Figure 9.** Variation of CBR ratio (%) respect to the %-replacement for unconfined condition and 100 % of compaction energy

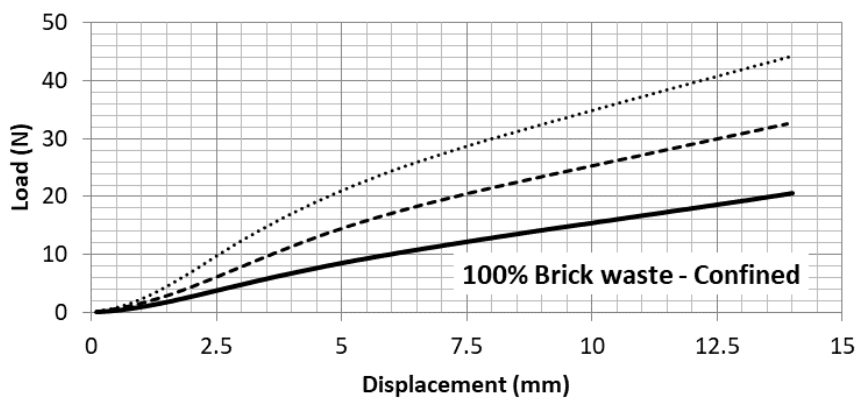
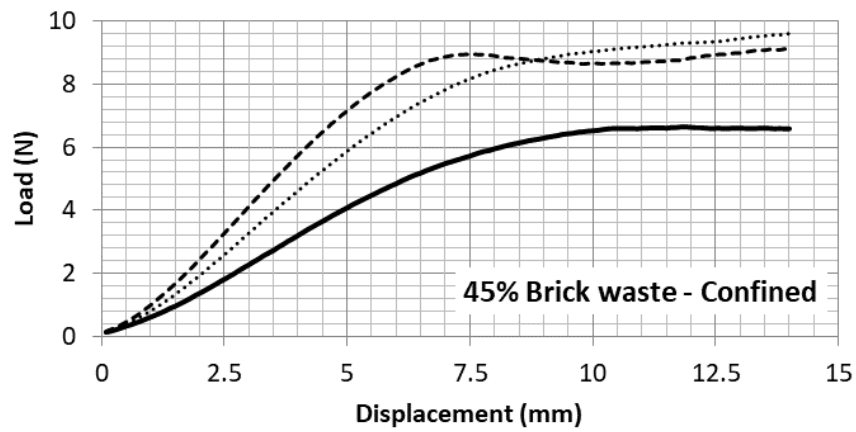


**Figure 10.** Evolution of CBR (%) for confined and unconfined conditions respect to the coefficient of uniformity ( $C_u$ ) obtained for each aggregate mixture



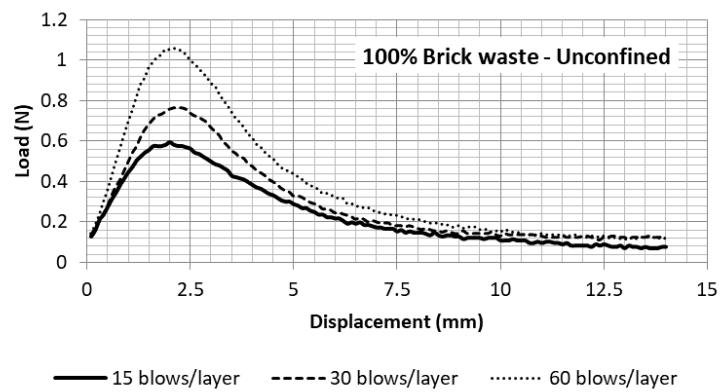
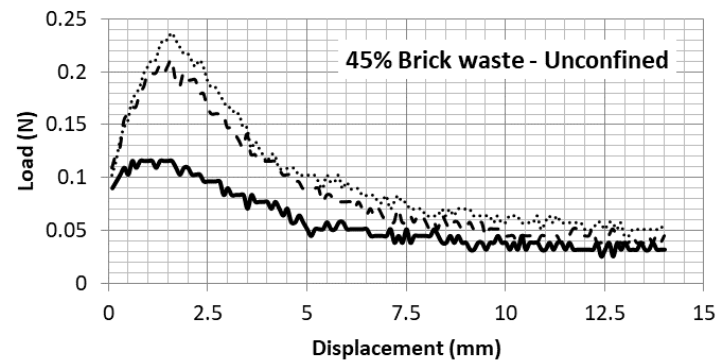
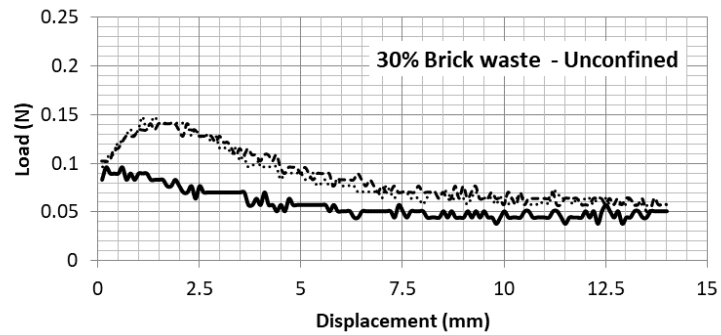
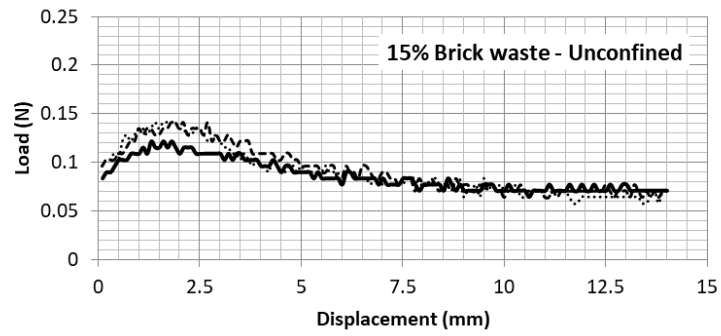
— 15 blows/layer    - - - 30 blows/layer    ..... 60 blows/layer





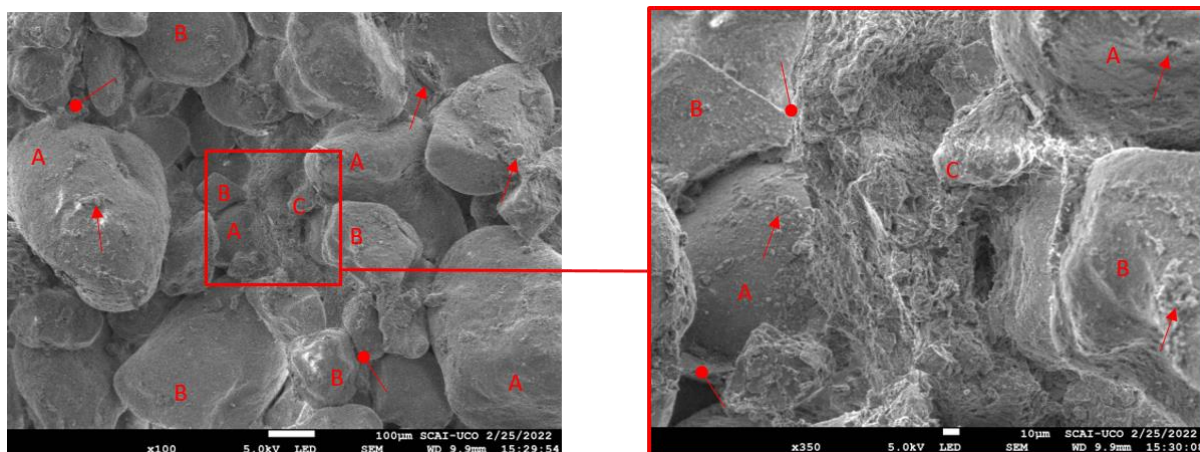
— 15 blows/layer    - - - 30 blows/layer    ..... 60 blows/layer

**Figure 11.** Load-displacement curves during CBR tests for confined specimens and different compaction energies (blows by layer)



**Figure 12.** Load-displacement curves during CBR tests for unconfined specimens and different compaction energies (blows by layer)

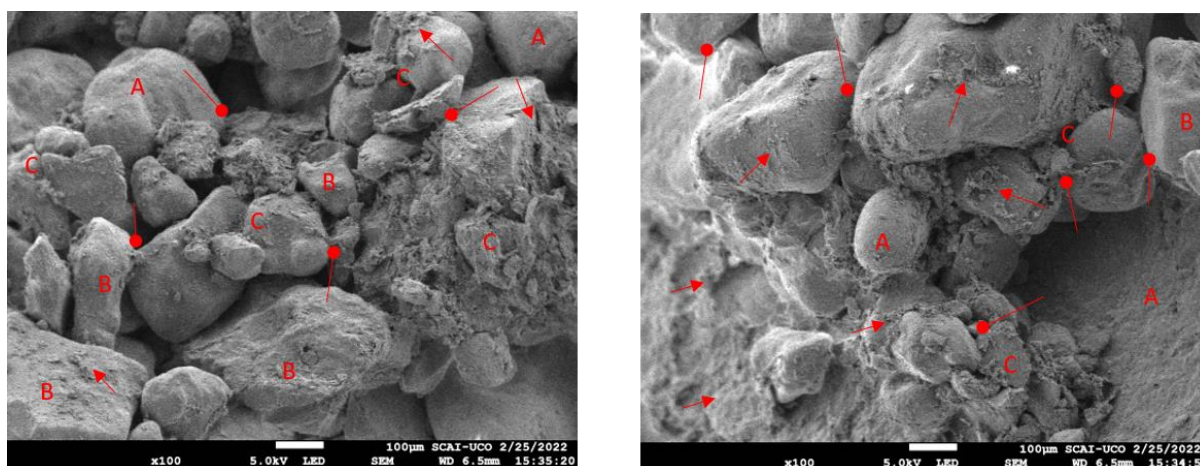
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738 a) 15 %-B (micrographs x100 and x350)

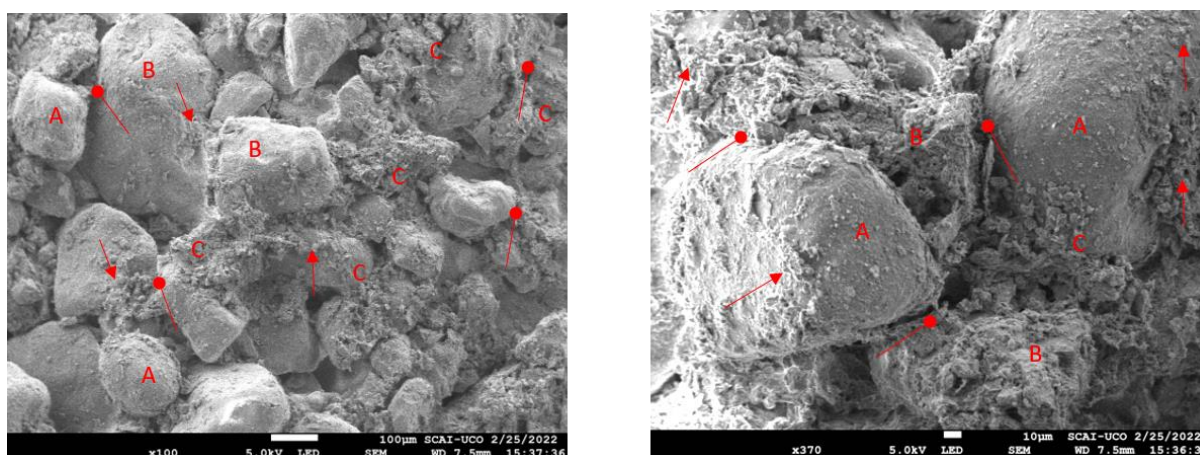
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741 b) 30 %-B (micrographs x100)

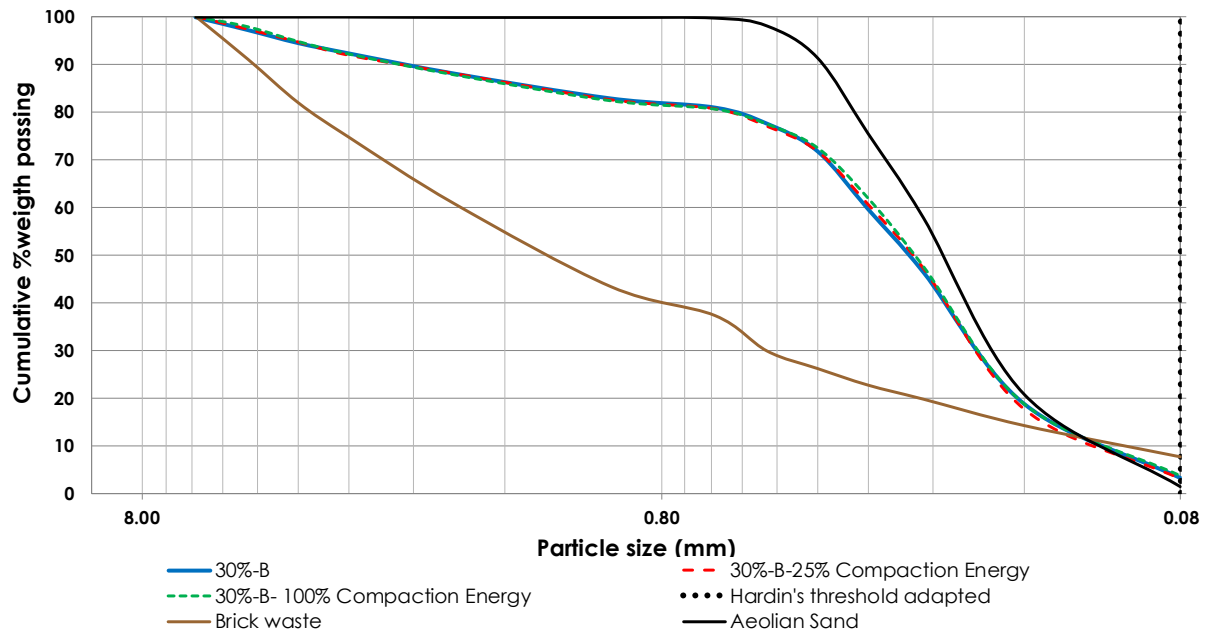
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744 c) 45 %-B (micrographs x100 and x370)

**Figure 13.** Scanning Electron Microscope (SEM) for the three percentage of replacement considered (A: particles of aeolian sand; B: particles of ceramic brick waste; C: aggregated particles; End-triangle arrow: wrapped surfaces; End-circle arrow: interlocking between particles)



**Figure 14.** Particle size distribution for the mixture of 30 % of replacement before and after applying 25 % and 100 % of compaction energy.

754 **Table 1.** Summary of the physical properties of Jeddah aeolian sand (after [2])

Soil property	Value
Specific gravity ( $G_s$ )	2.67
Natural moisture content (%)	0.27
$D_{10}$ (mm)	0.109
$D_{30}$ (mm)	0.179
$D_{60}$ (mm)	0.258
$C_u$	2.37
$C_c$	1.14
Carbonate (qualitative analysis with acid test)	YES
Colour	Reddish
Classification soil (USCS) [36]	SP – Poorly graded sand
Classification soil (AASTHO) [37]	A3

755 Note:  $D_{10}$ =grain diameter at 10 % passing;  $D_{30}$ =grain diameter at 30 % passing;  $D_{60}$ =grain diameter at

756 60 % passing;  $C_u$ = coefficient of uniformity;  $C_c$ : coefficient of curvature

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**Table 2.** Cumulative %-weight passing after sieving analysis of aeolian sand and ceramic brick waste

Sieve Size (mm)	Aeolian Sand	15 %-B	30 %-B	45 %-B	Ceramic brick waste
6.3	100.00	100.00	100.00	100.00	100.00
5	100.00	98.66	97.31	95.97	91.05
4	100.00	97.29	94.58	91.87	81.93
3.2	100.00	96.21	92.42	88.63	74.73
2	99.92	94.04	88.16	82.28	60.72
1	99.91	91.43	82.94	74.45	43.33
0.63	99.78	90.40	81.02	71.64	37.26
0.5	98.12	87.87	77.63	67.38	29.82
0.4	91.43	81.64	71.85	62.06	26.16
0.32	75.63	67.69	59.75	51.81	22.69
0.25	57.84	52.12	46.41	40.69	19.72
0.16	20.80	19.81	18.81	17.82	14.18
0.08	1.38	2.32	3.25	4.19	7.61

**Table 3.** Summary of the properties of the ceramic brick waste

Material property	Value
Specific gravity ( $G_s$ )	2.56
Bulk density ( $\text{kg/m}^3$ )	1990
Water absorption (%)	11.4
$D_{10}$ (mm)	0.10
$D_{30}$ (mm)	0.50
$D_{60}$ (mm)	1.94
$C_u$	18.89
$C_c$	1.26
Classification soil (USCS) [36]	SW-SM – Well graded sand with little fines

Note:  $D_{10}$ =grain diameter at 10 % passing;  $D_{30}$ =grain diameter at 30 % passing;  $D_{60}$ =grain diameter at 60 % passing;  $C_u$ = coefficient of uniformity;  $C_c$ : coefficient of curvature

**Table 4.** Representative values of coefficient of uniformity ( $C_u$ ), coefficient of curvature ( $C_c$ ),  $D_{60}$ ,  $D_{30}$  and  $D_{10}$  after sieving for aeolian Sand, 15 %, 30 % and 45 % of replacement of ceramic brick waste and ceramic brick waste without mixing

	Aeolian Sand	15 %-B	30 %-B	45 %-B	Ceramic brick waste
$D_{60}$ (mm)	0.26	0.28	0.32	0.38	1.94
$D_{30}$ (mm)	0.18	0.18	0.19	0.20	0.50
$D_{10}$ (mm)	0.11	0.11	0.11	0.11	0.10
$C_u$	2.37	2.61	2.98	3.56	18.89
$C_c$	1.14	1.10	1.06	1.00	1.26

786 **Table 5.** Mean values of modified CBR results (MmCBRC and MmCBRU) and indices of improvement  
787 (CBC<sub>x</sub> and UBC<sub>x</sub>) for both confined and unconfined conditions, for different percentages of replacement  
788 (15 %-B, 30 %-B, 45 %-B), and aeolian sand and ceramic brick waste material without mixing

%-Brick waste replacement	CBR (%) – (Confined Tests)	CBR (%) – (Unconfined Tests)	<i>CBR improvement ratio-confined condition</i>	<i>CBR improvement ratio-unconfined condition</i>
Aeolian sand	11.4	Not possible (0.00)	1.00	0.00 (Null)
15 %	18.2	1.1	1.59	0.09
30 %	32.7	0.9	2.86	0.07
45 %	33.0	1.3	2.89	0.11
Ceramic brick waste (100 %)	94.2	8.2	8.26	0.71

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