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Laboratory Evaluation of Finely Milled Brick Debris as a Soil Stabilizer

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Abstract: Brick is one of the most common building materials, and it is also one of the largest components of waste generated from both construction and demolition. Reuse of this waste would reduce the environmental and social impacts of construction. One potential bulk use of such waste is as a cementing agent for soil stabilization. However, this is currently limited by the need to mill the residue to a particle size below 0.035 mm. In this study, the behavior of two soil types stabilized using alkali-activated brick dust was investigated. The unconfined compression strength at different curing temperatures and moistures and the use of different types and concentrations of alkaline activators were investigated. It was found that the addition of brick dust resulted in an increase in the soil strength between 1.7–2.3 times with respect to the non-stabilized material, suggesting that the resulting materials will find practical applications in construction.

Keywords: construction waste; demolition waste; brick dust; alkali-activation; geopolymers; soil stabilization; strength improvement; binder materials; compressive strength

1. Introduction

Construction and demolition waste (CDW) represents a significant portion of the waste generated annually worldwide [1]. It is estimated that CDW in the European Union represents 30% [2], in Australia 57% [3], UK 50%, 30% USA, and 60% in Hong Kong [4] of solid waste. In many countries, the final disposal of these materials continues to be mainly in landfills [4], which generates severe environmental impacts. It has been demonstrated through the Life Cycle Analysis (LCA) that landfilling has a greater environmental impact than the alternative of reusing or recycling [5]. The reuse of CDW in construction has been promoted, and in some European countries it has been possible to reuse up to 90% [5]. The use of CDW as aggregates for the manufacture of concrete, mortars and pavements has been well explored [2,6–9], showing results that vary according to the quality of the aggregate and the production process used [7].

In most countries, bricks account for a high percentage of CDW. To reduce the environmental effect of tipping and reincorporate CDW into the production chain, it is increasingly reused in road construction [10–14]. This minimizes both the generation of CDW and the use of virgin raw materials whose extraction and processing impose a high resource cost. Globally, a wide range of studies have been conducted, which have proposed different approaches to the use of CDW in road construction. These uses include CDW–soil admixtures as an unbonded compacted material [12–17], CDW–soil admixtures stabilized with Portland cement [5,12], and CDW as aggregate in hydraulic concrete [8,18–20]. It has been established that when mixed with a larger volume of concrete debris, CDW can act as a granular base material [5,13,14]. A large of proportion of bricks in CDW deteriorates its performance; however, CDW can be used as a subbase material [17,21] or as a granular base when stabilized using Portland cement [12,22].

In such applications, CDW is treated as an inert aggregate. However, it is known that materials containing significant amounts of silica and aluminum, which include brick debris, can be activated using alkaline activators to produce geopolymers [19,22–24]. Several studies have demonstrated the synthesis of geopolymers from finely milled and alkali-activated brick debris (ABD), which can improve the strength of mortar and concrete [4,23,25]. However, to date, no research has investigated their use in soil stabilization or road construction.

Geopolymers are inorganic materials that are generated by a chemical reaction between aluminosilicate oxides and alkali metal silicate solutions under alkaline conditions. Their partially or fully amorphous polymeric structures comprise Si–O–Al bonds [23,26]. The formation of geopolymers depends on the particle size and mineralogy of the base material and on the synthesis conditions [23]. Most studies focusing on the use of geopolymers have been based on the activation of fine materials. The current understanding is that the material should have a particle size of less than 75 µm or less than 35 µm if better cementitious properties are demanded [27]. In general, the materials used have had D50 values of less than 25 µm [22,24], 20 µm [28], or 15 µm [23]. Evaluations of the grain size have reported that fractions finer than 150 µm (D50 < 15 µm) yield geopolymers with substantially greater compressive strength [23]. In this work, cubic specimens of paste were demonstrated to achieve a compressive strength of 49.5 MPa after 7 days of curing. Reducing the size grain from 400 to 140 µm (or D50 from 76 µm to 14 µm) resulted in an increase in strength from 38 to 58 MPa. The grain size is often represented by the specific surface or Blaine fineness. The optimum Blaine fineness for blast furnace slag is between 4.000 and 5.500 cm^2/g. Beyond 5.500 cm^2/g, the fineness has little effect on the mechanical strength [20]. In other studies, the strength has been found to increase when the Blaine fineness increases from 171 to 472 m^2/kg, especially at lower values [29]. At fineness between 15.67 and 25.55 m^2/g, a positive relationship was found between the surface area of metakaolin powders and the compressive strength of the geopolymers [30]. This has been attributed to an increased aluminate content in the geopolymer matrix and a more homogeneous microstructure. However, other studies have shown that materials with greater fineness require additional hydration, which increases porosity and lowers mechanical strength [31].

To obtain particulate material from brick debris, the debris must be ground. If a very fine particle size is required, milling may take several hours, increasing energy consumption and other costs. For example, to obtain particles of D_{50} = 15.1 µm and a specific surface of 1.3 m^2/g from a volcanic ash calcined at 945 °C, between 2 and 5 h of milling was needed [32]. Another study reports that when producing an ABD mortar, milling to obtain D_{50} = 24.25 µm may account for up to 16% of the kilograms of carbon dioxide equivalent (kg.CO2.eq) generated in the production process of mortar [22].

The mechanical performance of geopolymers is generally evaluated after curing at temperatures between 60 °C and 90 °C [22,33] or even at 100 °C [29,32]. Curing is also performed under high humidity as the concrete mixture is covered with plastic membranes or bags after preparation [22,23,25,28]. However, this is unrealistic under typical construction conditions [22,34].

From the authors' own experience, one of the main practical barriers to the wider use of geopolymers from CDW is the difficulty of obtaining materials with sufficient fineness. This study, therefore, investigated the use of materials with coarse granulometries in soil stabilization. Potential uses for such materials would be in road construction, restitution of eroded soils, and erosion control. The behavior of soil and ABD mixtures in which the grain size was greater than 75 µm was examined. Furthermore, the roles played by different factors and variables for determining the unconfined strength (UCS) were examined. Curing was performed at temperatures of 20 °C and 50 °C and humidities of 95% and 59%.

2. Materials and Methods

To investigate the cementitious effect, the effect of ABD, USC tests were carried out on cylindrical specimens made with mixtures of soil and ABD. During the research, it was identified that the variables to be considered were the time, humidity, and temperature of curing as well as the stabilizer concentration. Given the high number of variables with influence on UCS, a factorial design was developed using the software R, to identify the influence of each variable and its interaction. This analysis allowed for a comparison of all possible combinations of test specimens and dependent variables. In addition to the variables identified, two replications were considered. A matrix was generated combining the percentage of stabilizer addition (7%, 14% and 21%), alkaline activator (RC and NaOH), curing temperature (20 °C–30 °C and 40 °C–50 °C), curing humidity (59%—environment and 95%—moist room) and curing age (7 and 28 days). The factors and soils were randomized to reduce systematic errors. Based on this design, it was determined that the tests should be replicated 48 times for each soil type at curing times of 7 and 28 days. The optimal ratio by weight of BD to alkaline activator was determined by means of an experimental process as described by Rodriguez et al. [35]. Herein, the optimal ratio was given a constant value of 6:4 for RC and 1:5 for NaOH (equivalent to 2.5 M). The UCS of the stabilized material was compared with that of the non-stabilized materials.

Cylindrical specimens (diameter: 50 mm; height: 100 mm) were produced with admixtures of ABD with two types of soil. These were statically compacted to reach the maximum dry density of the modified proctor compaction test. All specimens were allowed to achieve a humidity of 25%, corresponding to the maximum optimum compaction moisture for such mixtures and cured: at room temperature (20 °C–30 °C) at 95% humidity, 40 °C–50 °C and 95% humidity, at 20 °C–30 °C and 59% humidity, and at 40 °C–50 °C and ambient humidity. Once curing was complete, UCS tests were performed using a Humbold HM 3000 press following ASTM standard D5102 [36]. Before failure, all specimens were allowed to achieve a humidity of 25%, corresponding to the maximum optimum compaction moisture for such mixtures.

Brick dust (BD) was obtained from two sources: (a) sweepings of the furnaces used in the manufacturing process and (b) residues from brick factories. In both cases, the materials were obtained as a result of the calcination of residual clays derived from the rock weathering of the geological formation known as Stock de Altavista. This is located in the northwest of Colombia, at the western end of the Aburrá Valley. Alkaline activation of BD was done using a hydrated lime residue from a company in the city of Medellín, herein after referred to as RC. Commercially sourced sodium hydroxide (NaOH) was used as a comparator. The two types of soils used were: soil of residual origin with a sandy texture (S1) and that with a silty texture (S3). Furthermore, the soils and BD were characterized using X-ray fluorescence (XRF) and X-ray diffraction (XRD) tests.

3. Results

Figure 1 illustrates the results of the granulometry tests, and Table 1 lists the Atterberg limits and presents the soil classification done using the AASHTO and USCS methods. Modified proctor compaction tests were performed for the two soil types and different ABD concentrations. The results are shown in Figure 2. Table 2 shows the XRF results focusing only on soil type (Loss ignition 2.7%) and Figure 3 shows the XRD results.

Table 1. Data for soil and BD characterization.

	S1	S3	BD
US sieve N°10-opening: 2 mm (% finer)	84	-	-
US sieve N°40-opening: 425 µm (% finer)	50	-	94
US sieve N°200-opening: 75 µm (% finer)	21.84	86.28	35
Specific gravity	2.77	2.70	2.7
Liquid Limit (%)	37.0	66	-
Plastic index (%)	11.0	17	-
USCS clasification (ASTM D2487)	SM	MH	-
AASHTO clasification (ASTM D3282)	A-1b	A-7-5	-

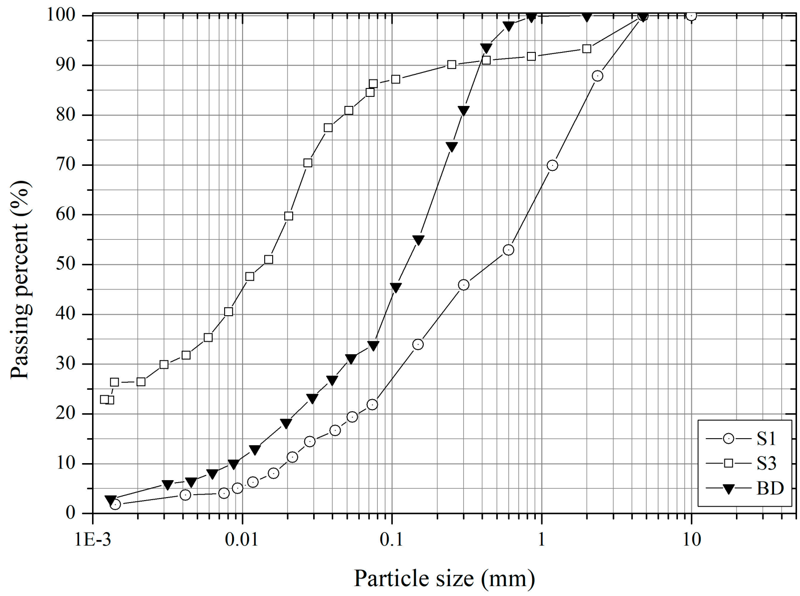

Figure 1. Particle size distribution for soils and BD sieve and hydrometer analysis.

Table 2. Chemical composition of soils from X-ray fluorescence (XRF) tests (ASTM C114).

Oxide	Composition %			Oxide	Composition %		
	Soil S1	Soil S3	BD		Soil S1	Soil S3	BD
SiO_2	52.11	41.53	48.30	NiO	0.02	0.02	
Al_2O_3	19.26	35.45	28.60	Na_2O	2.57	-	3.30
Fe_2O_3	10.18	20.47	11.00	V_2O_5	0.05	0.09	
TiO_2	1.27	1.51	1.40	WO_3	0.04	0.05	
K_2O	0.86	0.65	0.60	MnO	0.18	0.04	
ZrO_2	0.04	0.05	-	MgO	5.09	-	1.60
CaO	8.04	0.05	2.00	SnO_2	-	0.02	
Cr_2O_3	0.03	0.02	0.10	ZnO	0.01	0.02	
CuO	0.01	0.02	-	P_2O_5	0.23	-	1.10
				SO_3	-	-	0.20

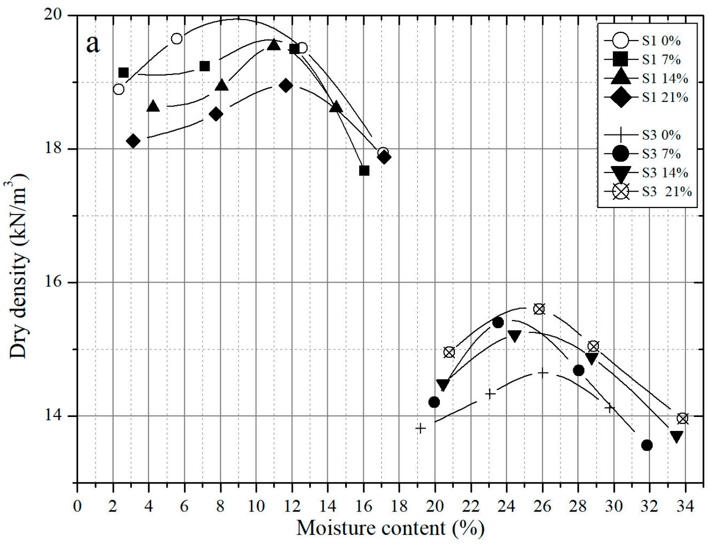

Figure 2. *Cont.*

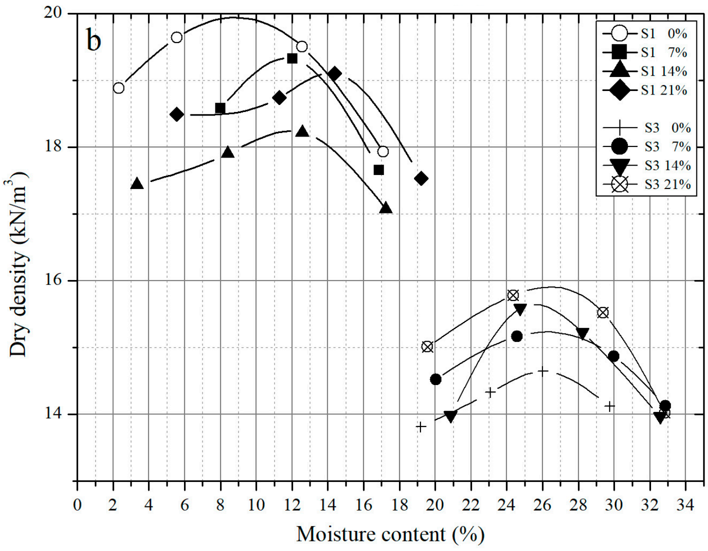

Figure 2. Compaction curves of soils stabilized with (**a**) RC and (**b**) NaOH.

Based on the compaction tests, specimens were constructed for UCS testing. In total, 96 UCS tests were performed after curing for 7 and 28 days. Figures 3 and 4 present the results obtained according to the soil type, curing time, and combinations of variables described in the previous section. The compressive strength ranged from 0.14 to 2.70 MPa. For comparison, UCS tests were performed on specimens of soil compacted without the addition of ABD (SR), only with the addition of NaOH and only with 3%RC. Four determinations were made for each soil, obtaining average UCS values of 0.38, 0.77 and 0.45 MPa for S1 and S3 respectively. In Figures 3 and 4, the result is shown as a dark line called SR. For each soil with NaOH, mean UCS values of 0.23, 1.48 and 0.43 were obtained for S1 and S3 respectively. For each soil with 3%RC, UCS values of 0.92, 0.57 and 1.5 were obtained for S1 and S3 respectively.

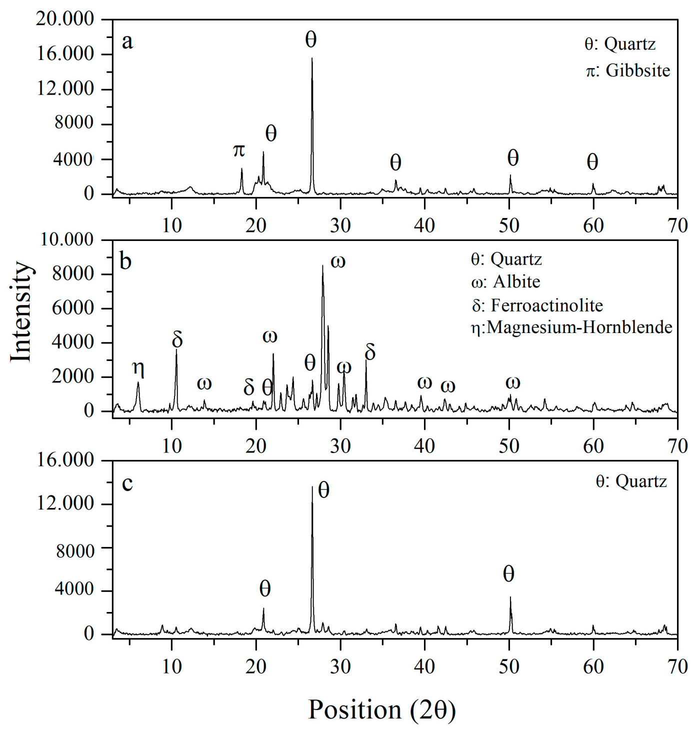

Figure 3. X-ray diffraction (XRD) results: (**a**) silt soil (S3), (**b**) sandy soil (S1), (**c**) and brick dust (BD).

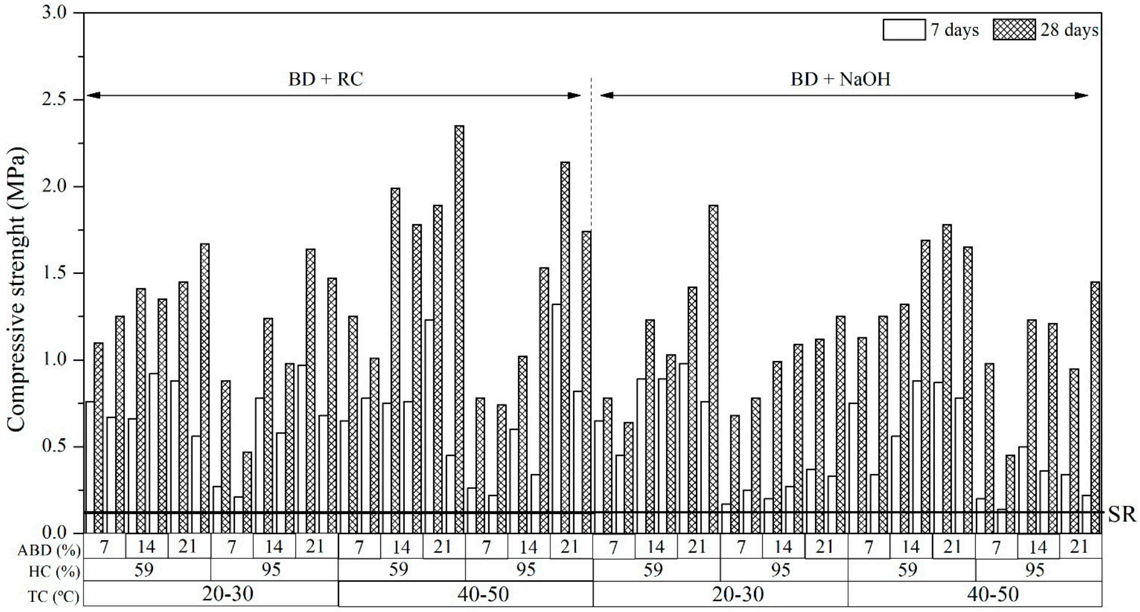

Figure 4. UCS tests for soil S1 with 7 and 28 days of curing, grouped by the activating agent, humidity (HC), and temperature of curing (TC).

4. Discussion

From Figure 2, it can be seen that the addition of ABD changed the compaction process in the two soils. In the case of S1, the maximum dry density decreased and the optimum humidity increased. This can be explained by the greater fineness of S1 and ABD mixture when compared with S1 alone. It is well known that the specific surface of a material increases as its fineness increases. Hence, greater humidity is required for compaction and density decreases [37]. The opposite trend was observed for S3, with the maximum dry density increasing and the optimum humidity decreasing. This can be explained by an increase in the amount of larger particles. The resulting pozzolanic reactions modify the structure of a fine granular material by promoting flocculation. Such a process occurs when soils are stabilized with lime [38]. The flocculated structure facilitates the compaction of a fine granular soil, allowing higher dry densities to be achieved at a higher moisture content.

The UCS results are shown in Figures 4 and 5. It can be observed that after 28-day curing, the highest average strength was recorded for S1. After 28-day curing, the average values were 1.27 MPa for S1, and 1.24 MPa for S3. After 7 days of curing, the average values were 0.58 MPa for S1 and 0.57 MPa for S3. These values were in agreement with the results reported for soil blocks with the addition of a mixture of lime and BD [27] in which resistance was of the order of 1–2 MPa and durability was greater than that of other systems based on lime, cement and sand. An important difference was that in this work, most BD particles were retained in a 75-µm sieve (Figure 1), whereas previous research [27] recommended a BD particle size less than 75 µm, preferably less than 35 µm. These results were closer to those reported in a previous study [31], suggesting that greater fineness requires additional hydration, which increases porosity and reduces mechanical strength.

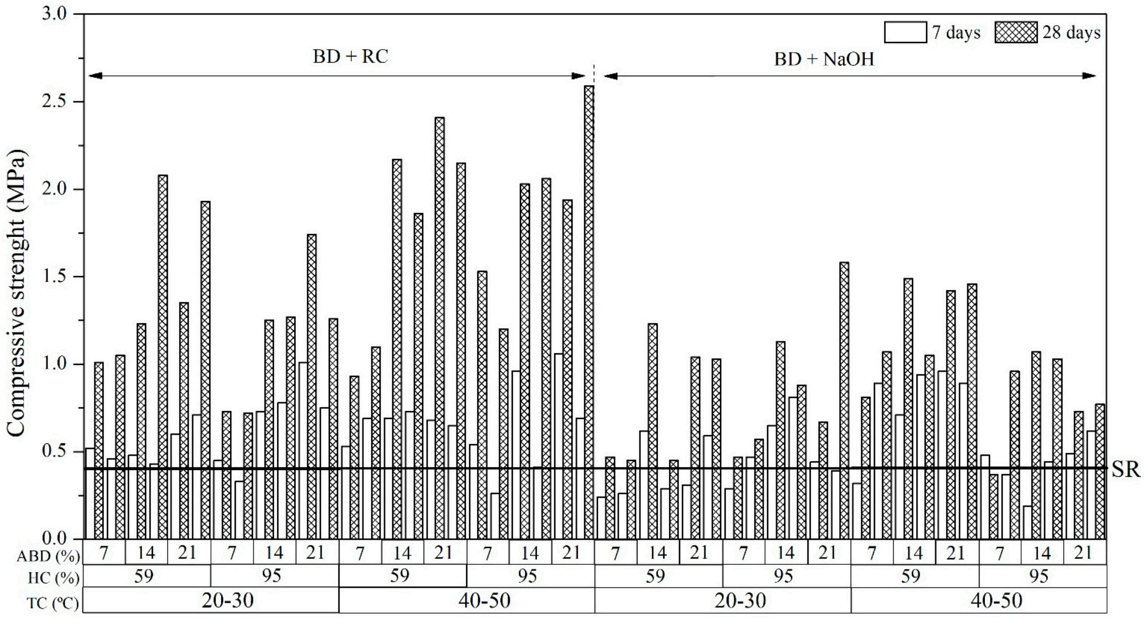

Figure 5. UCS tests for soil S3 with 7 and 28 days of curing, grouped by the activating agent, humidity (HC), and temperature of curing (TC).

As can be seen in Figures 4 and 5, overall, the addition of ABD produced a soil strength greater than that of non-stabilized soil. In these figures, the horizontal black line marked "SR" represents the average resistance of the unstabilized soils. The stabilizing effect of ABD can be seen in the average increases of 235% for S1 and 176% for S3. These increases were attributed to pozzolanic reactions in the presence of ABD. The difference between the soil types can be explained by the higher SiO content of S1 (52.11%) compared with that of S3 (41.53%) and to the lower concentrations of Al2O3 at 19.26% and 35.45%, respectively (Table 2). Figure 2 shows the quartz phases in BD. High-magnitude peaks suggest mineralogical phases with high stability and indicate weak thermodynamic reactivity with external chemical agents. The diffractogram suggests that the precursor is semi-crystalline, with the presence of quartz (SiO_2) as the main phase. The interval between 16 and 37 in (2θ) identifies the amorphous phase in BD. This is significant as it allows new cementing phases to form when BD reacts with NaOH or RC.

As can be observed, some UCS values of 7-day stabilized S3 were lower than those of RS. These values corresponded broadly with activation by NaOH and were mainly observed when the curing temperature was below 20 °C–30 °C. They can be explained by the higher temperatures required for activation with NaOH. The UCS values obtained for RC were higher than those obtained for NaOH. The highest strengths were found when the curing conditions were a humidity of 59% and temperatures between 40 °C and 50 °C. To disaggregate the contribution of each variable, analysis of variance (ANOVA) was performed. The null hypotheses were that the curing temperature, curing humidity, alkaline activator used, and percentage added would have no effect on the unconfined compression. Alpha was set to $p = 0.05$ at a confidence level of $\beta = 95\%$. Table 3 summarizes the results after the verification of independence and normality.

Table 3. P-values by soil type.

Soil	S1		S3	
Model	*p*-values (7 days)	*p*-values (28 days)	*p*-values (7 days)	*p*-values (28 days)
Temperature	0.982	0.001	0.038	0.001
Moisture	0.001	0.001	0.633	0.198
Activator	0.005	0.002	0.045	0.001
Percentage of stabilizer	0.001	0.001	0.002	0.001

Across the two soil types, similar trends were found for the curing moisture, alkaline activator used, and percentage added. Figures 6 and 7 show the results for the alkaline activator. As can be seen, RC was more effective than NaOH. The results for curing humidity showed a greater environmental influence at 59% than at 95%. Greater percentage addition produced an increase across the board, but the effect was stronger between 7% and 14% than between 14% and 21%. The curing temperature was also confirmed to have a significant effect, with higher temperatures associated with increased UCS. The exception was 7-day-cured S1 in which no change was observed.

It was further confirmed that the choice of the alkaline activator had a significant effect. This agreed with the results reported in a previous study [39], where clay powder burned at temperatures below 950 °C and combined with caustic soda NaOH or slaked lime $Ca(OH)_2$ was shown to have binding properties. The introduction of alkaline activators, such as sodium hydroxide in these residues, improves the mechanical stabilization of the soil by raising the pH. This induces pozzolanic reactions and the binding of gels, thereby binding the soil particles [40]. The curing temperature was also confirmed to have a significant effect, with higher temperatures associated with increased UCS. The exception was 7-day-cured S1 in which no change was observed. This confirmed the results reported in previous research [41,42], which experimentally demonstrated that the UCS of geopolymers increased as the temperature was increased from 20 °C to 60 °C, while the time required to achieve resistance fell. This may be accounted for by an increase in the rate of initial polymerization at higher temperatures.

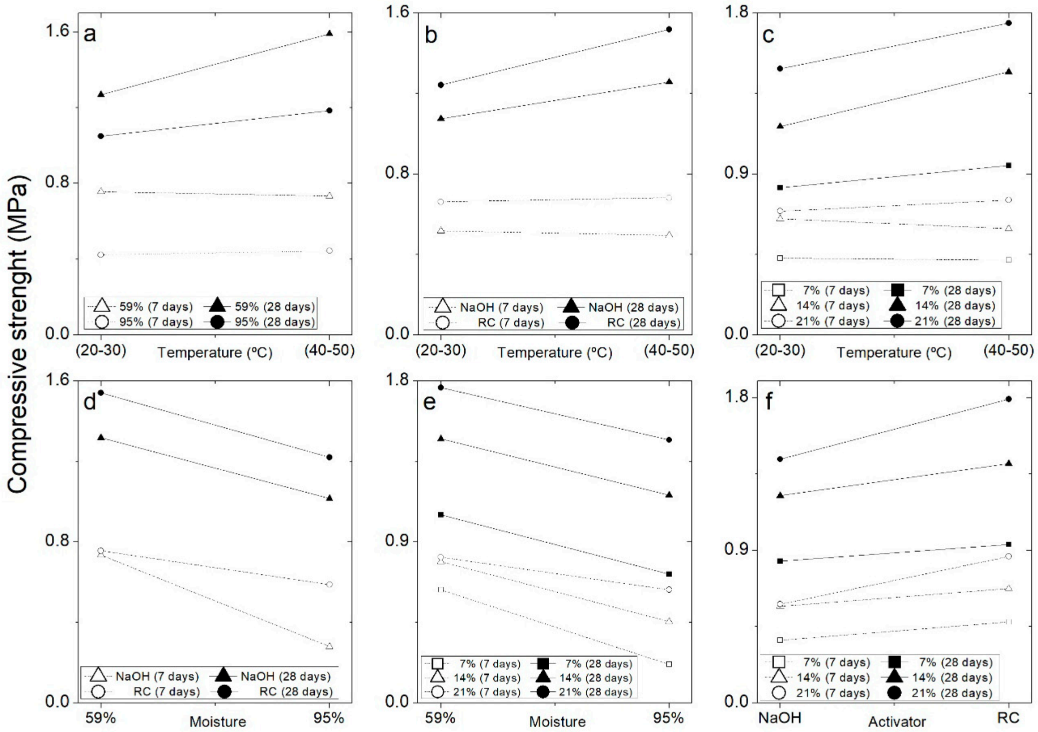

Figure 6. Effects on USC at 7 and 28 days of curing for soil S1. (**a**) Effect of temperature and moisture. (**b**) Effect of temperature and alkaline activator. (**c**) Effect of temperature and percentage of stabilizer. (**d**) Effect of moisture and alkaline activator. (**e**) Effect of moisture and percentage of stabilizer. (**f**) Effect of alkaline activator and percentage of stabilizer.

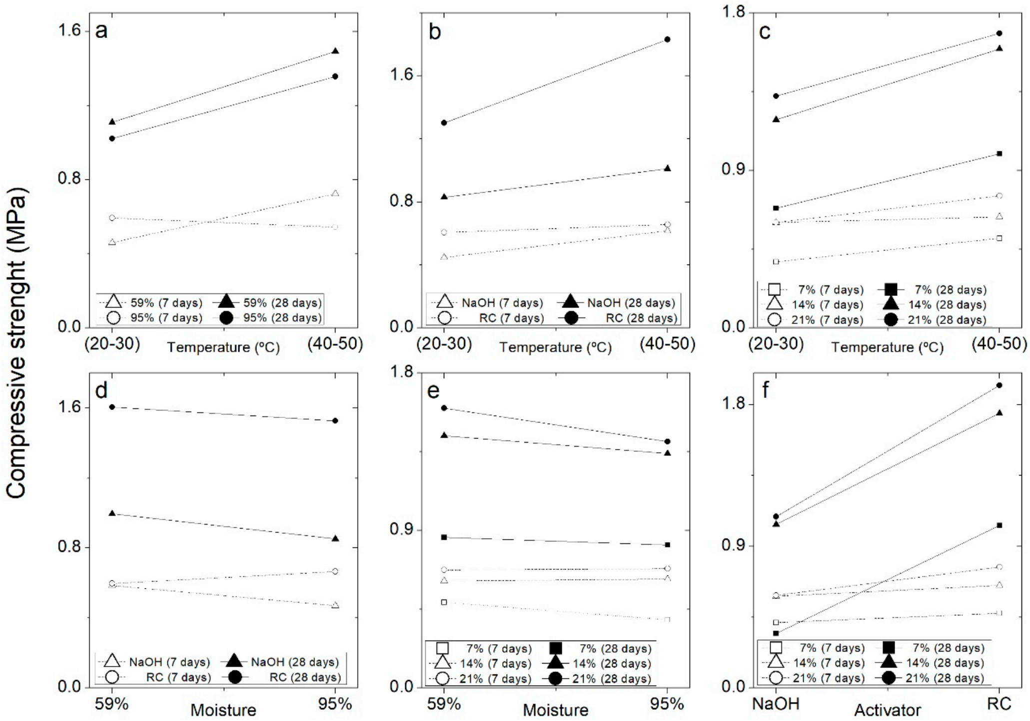

Figure 7. Effects on USC at 7 and 28 days of curing for soil S3. (**a**) Effect of temperature and moisture. (**b**) Effect of temperature and alkaline activator. (**c**) Effect of temperature and percentage of stabilizer. (**d**) Effect of moisture and alkaline activator. (**e**) Effect of moisture and percentage of stabilizer. (**f**) Effect of alkaline activator and ad percentage of stabilizer.

5. Conclusions

This research demonstrated the technical feasibility of using BD for soil stabilization. Its use during compaction was associated with an improvement in the strength and workability of the soils. This approach offers a route for utilizing a form of waste that is abundant in cities wherein brick is the basis of construction. Since it does not require a considerably fine grain size, our approach should be economically attractive in industrial applications.

The addition of ABD was shown to improve the compactability of soils with a higher clay content. This was achieved by increasing the densities that can be obtained and decreasing the required water content. This is a desirable effect as it will facilitate the use of soils with sticky characteristics.

The ABD also produced a substantial increase in soil strength. UCS increases greater than 176% were achieved, with the greatest increase of 235% observed for silty soil.

RC was found to be a more effective activator than NaOH. This is significant as it may reduce the environmental impacts associated with the inappropriate disposal of this residue. The addition of ABD was most effective when the concentration was lower than 14%, which decreased as the concentration was further increased. The curing temperature was found to have a strong influence on resistance; hence, improved performance can be expected in warm climates.

These results demonstrate the advantages of the alkaline activation technique for the use of waste and the possibility of a sustainable solution, because it reduces the demand for virgin raw materials, which consume significant amounts of energy during extraction and processing. The addition of ABD was most effective when the concentration was lower than 14%, which decreased as the concentration was further increased. Curing was shown to be an influential factor. Significant moisture loss produces shrinkage in the material, which in turn leads to premature cracking of the stabilized soil, especially in road building. The curing temperature was found to have a strong influence on resistance; hence, improved performance can be expected in warm climates.

In future works, evaluations will be made considering SEM, DRX and typical pavement tests to study the performance of these materials as granular bases and subbases and the evolution of the cementing process.

Author Contributions: All authors participated in most aspects of the research and the manuscript preparation. The main authors PhD Cesar Hidalgo and PhD Gloria Isabel Carvajal provided advice on the methodology proposed. F.M. performed the laboratory tests and processed the data of the different determinations. The discussion related to the validation of the proposed methodology and the analysis was carried out jointly by all authors. "Conceptualization, C.H. and G.C.; methodology, C.H.; formal analysis, C.H., G.C., and F.M.; investigation, C.H., G.C. and F.M.; resources, G.C., and C.H.; data curation, F.M.; writing—original draft preparation, C.H.; writing—review and editing, C.H. and G.C.; project administration, G.C.; funding acquisition, G.C.".

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Conflicts of Interest: All authors declare that they do not have any conflict of interest with any people or organizations that may inappropriately influence their work.

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