Keywords
Carbide lime
Ground glass
Porosity/binder index
Pozzolanic reactions
Soil stabilization
Sustainable binders
Unconfined compressive strength

Abstract
Regular soil improvement techniques customarily involve the use of ordinary Portland cement (OPC) despite the environmental issues related to the production process of such material. Hence, the establishment of alternative binders through the use of industrial and/or urban waste might be an option to overcome part of those problems. Thus, present research evaluates the strength of a quartz sand stabilized with a binder composed by ground glass powder (having granulometries) and carbide lime. For this, a $2^k$ factorial design method was employed in order to define the experimental runs in which the effect of the following variables was assessed: dry unit weight, curing period, amount of carbide lime, ground glass content and ground glass milling granulometry. The results have shown the great influence exerted by the dry unit weight, the amount of ground glass powder and the curing period. The effects of ground glass granulometry and carbide lime were, as well, statistically significant. Moreover, the results were correlated to the porosity/binder index ($\eta/B_v$) in which great $R^2$ coefficients were obtained. In general, the proposed binder showed to be effective for soil stabilization purposes, especially if finer ground glass powders are employed.

1. Introduction

Customary soil improvement techniques frequently involve the usage of binders such as Ordinary Portland Cement (OPC) and densification through compaction (Ingles & Metcalf, 1972; Mitchell, 1981). Nevertheless, the production process of Portland cement releases great quantities of CO$_2$ due to demand for large amounts of energy and natural resources, being notably deleterious to the environment (Habert, 2014; Chen et al., 2010). Thus, the development of binders utilizing alternative materials that posses adequate physical-chemical properties (e.g. urban and/or industrial waste) arises as an alternative in order to partially overcome those issues.

Soda-lime glass corresponds to more than 85 % of the total amount of glass produced in a global scale per year as it is the major constituent of glass containers and as-like objects (Mohajerani et al., 2017, Schmitz et al., 2011). Hence, it is an important source of waste in urban areas, being a problem when not properly recycled. In Brazil, less than 50 % of the glass containers are recycled, while this rate is up to 40 % in USA, 87 % in Germany, and 95 % in Switzerland (CEMPRE, 2015). Ergo, in some countries there still a sizeable amount of glass disposed in landfills. Yet, due to its chemical composition (mainly SiO$_2$) and amorphous structure, soda-lime waste glass can be ground and employed in the composition of several binders as a pozzolanic material (Sales, 2015; Rangaraju et al., 2016; Mohajerani et al., 2017). Consequently, in an alkaline and hydrated environment, SiO$_2$ may combine with calcium hydroxide [Ca(OH)$_2$], yielding binding compounds (Massaza, 2004) such as calcium silicate hydrated (C-S-H) as described in Equation 1.

$$2\text{SiO}_2 + \text{Ca(OH)}_2 + 5\text{H}_2\text{O} \rightarrow \text{CaO} \cdot 2\text{SiO}_2 \cdot 3\text{H}_2\text{O}$$ (1)

Accordingly, notwithstanding of other applications for waste-glass material such as fine and coarse aggregate in concrete (Chen et al., 2006; Park et al., 2004; Malik et al., 2013), incorporation in asphaltic mixtures (Day et al., 1970; Hughes, 1990; Jony et al., 2011) and supplementary filler material (Arulrajah et al., 2017), several studies were conducted aiming to employ fine ground glass waste as a...
pozzolan. Pattengil & Shutt (1973) assessed the effect of partial replacement (in mass) of cement in concrete by distinct amounts of ground glass powder (0 %, 15 %, and 30 %). Metwally (2007) conducted a similar study by employing milled non-recyclable waste glass as a partial replacement of cement in concrete. Sales et al. (2015) assessed the pozzolanic activity of ground glass obtained of dissimilar colors of soda-lime glasses and did not find differences between the examined glass types. Consoli et al. (2019) evaluated the strength and stiffness of a cement composed by finely ground glass and carbide lime molded at distinct degrees of compaction. Baldovino et al. (2020) appraised the mechanical response of a sedimentary silty soil stabilized with ground waste glass and Portland cement using three curing times (7, 28 and 90 days). Consoli et al. (2018a) studied the performance of a quartz sand stabilized with distinct amounts of a finely ground glass (10 %, 20 %, and 30 % ) and carbide lime (3 %, 5 %, and 7 %) through strength, stiffness and durability tests, whereas Consoli et al (2020a) conducted a similar study but using three different silicas sands.

It is known that the pozzolanic activity of a material is influenced, among other factors, by the specific surface area (SSA) of the pozzolan (Massaza, 2004). Yet, in spite of the several works conducted aiming to evaluate the performance of ground glass as a pozzolanic material, none of them assessed the influence of the grain size of the glass obtained after a milling process which is directly linked to the SSA. Thus, present research intends to assesses the impact of three distinct ground glass granulometries on the strength and stiffness of compacted sand - ground glass - carbide lime blends. For this, a 2 x factorial design was employed in which the content of carbide lime (CL), the dry unit weight, the amount of ground glass and the curing period were varied at two levels. This design approach (2 x factorial design) was separately conducted using each one of the obtained ground glass granulometries. Besides, the results were correlated to the porosity/binder content index (Consoli et al., 2018a, 2018b).

2. Experimental program

The experimental program was conducted in three parts. Initially, the soil, the carbide lime and the ground glass powders were characterized. Thereafter, unconfined compressive strength tests were carried out based on a 2 x factorial design approach (Montgomery, 2008). Finally, the strength results were statistically analyzed in order to assess the influence of the studied controllable factors (i.e. variables) which are depicted in Table 1.

2.1 Materials

The physical properties of the materials employed herein are summarized in Table 2 and the grain size distribution of each one is depicted in Figure 1. The grain size distribution results were obtained by means of laser diffraction analysis. According to ASTM D2487 (ASTM 2017), the soil is a poorly graded quartz sand with silt (SP-SM) which was obtained nearby Porto Alegre (south of Brazil). This sand is known as Osorio sand. Carbide lime [Ca(OH)₂] was used as an alkaline activator. Such lime is a by-product

Table 1. Controllable factors.

| Controllable factor                              | Levels |
|------------------------------------------------|--------|
| Granulometry of ground glass powder            | a, b and c |
| Amount of ground glass (%)                     | 10 and 30 |
| Amount of carbide lime (%)                     | 4 and 7 |
| Dry unit weight (kN/m³)                        | 15.5 and 17.5 |
| Curing period (days)                           | 7 and 28 |

Table 2. Physical properties of the materials.

| Physical properties | Ground glass powder | Carbide lime | Osorio sand |
|---------------------|---------------------|--------------|-------------|
|                     | Type A | Type B | Type C | Non-plastic |
| Specific gravity    | 2.47   | 2.47   | 2.47   | 2.19         | 2.65         |
| Specific surface area (m²/g) | 2.48 | 2.21   | 1.50   | 22.60       | -            |
| Coarse sand (2.00 mm < d < 4.75 mm) (%)      | -      | -      | -      | -            | -            |
| Medium sand (0.425 mm < d < 2.00 mm) (%)     | -      | -      | -      | -            | 10           |
| Fine sand (0.075 mm < d < 0.425 mm) (%)      | -      | 20     | 50     | -            | 87           |
| Amount of silt (0.002 < d < 0.075 mm) (%)    | 99     | 79     | 50     | 97           | 3            |
| Amount of clay (d < 0.002 mm) (%)            | 1      | 1      | -      | 3            | -            |
| Coefficient of uniformity                     | 2      | 8.33   | 10     | 10           | 2.5          |
| Coefficient of curvature                      | 0.55   | 1.33   | 2.5    | 0.9          | 0.9          |

*Obtained via BET analysis.
of the production of acetylene-gas and was obtained in an industry located in the region of Porto Alegre. Further information regarding the physical, chemical and mineralogical characterization of the carbide lime can be found on Saldanha et al. (2018). The ground glass powder was obtained via milling transparent waste glass in a ball mill following a regular procedure. This encompassed a fixed time (5 h), a defined amount of glass (1.5 kg) and specific quantity of milling balls. After the milling process was accomplished, the powder was separated in three distinct fractions (corresponding to different granulometries) via screening using sieves. The first fraction (A) corresponded to the particles smaller than 75 μm, the second fraction (B) corresponded to the portion greater than 75 μm and smaller than 149 μm and the third amount (C) was composed by particles greater than 149 μm. The chemical composition of the glass was obtained via X-Ray Fluorescence (XRF) and revealed that it is mainly composed by SiO₂ (75 %), CaO (17 %), Al₂O₃ (3 %) and Na₂O (2 %). The X-ray Diffraction pattern (Figure 2) was obtained in the fraction (A) and is typical of an amorphous material (Music et al., 2011).

2.2 Methods

The studied variables (and their levels) were defined based on the previous work of Consoli et al. (2018a), which was performed using the same sand, carbide lime and type of soda-lime glass (transparent). Therefore, the following variables were assessed: dry unit weight ($γ_d$), amount of carbide lime (CL) and ground glass powder quantity (GG). The amounts of ground glass (GG) and of carbide lime content (CL) are both based upon the total dry mass of the specimen. The molding moisture content ($w$) was set as 10 %. Table 3 exhibits the experimental runs (dosages) and duplicates were molded within each experimental design (treatment).

2.3 Specimens molding and curing

Cylindrical specimens (50 mm in diameter and 100 mm in height) were molded for the unconfined compressive strength tests according to the undercompaction method (Ladd, 1978). Each specimen was individually molded following a randomized order aiming to guarantee the statistical independence of the error. The molding process started by the weighing of the dry materials (sand, ground glass powder and carbide lime). Right after they were mixed until a uniform consistency was acquired. Next, distilled water was added and the materials were thoroughly mixed until a homogeneous mass was created. After this mixing, three small portions of this mass were taken in order to verify the molding moisture content. Following, each specimen was statically compacted in three layers inside a split mold to the specified dry unit weight. Then, the specimen was removed from the mold, weighed, measured (precisions of nearly 0.01 g and 0.1 mm) and sealed in a plastic bag to be cured in a humid room with controlled environment (at 23 ± 2 °C with relative moisture of about 95 %). Each specimen was considered suitable for testing if they met the following limits: dry unit weight within ±1 % of the target value, molding moisture content within ±0.5 % of the target value and dimensions within ±1 % of the target values.

In order to compute each specimen porosity ($η$), the Equation 2 can be employed. In this, $γ_d$ refers to the dry unit weight, $S$ to the sand quantity, GG to the amount of ground glass powder and CL to the carbide lime content. Besides, each substance possesses its own specific grains weight as fol-
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2.4 Unconfined compressive strength tests

One day before the curing period was accomplished (6 or 27 days) the specimens were submerged in a water tank (23 ± 2 °C) along 24 h in order to minimize possible suction effects (Consoli et al., 2011). Following, the strength tests were conducted based on the ASTM C39/C39M (ASTM, 2020) using an automatic loading press with maximum capacity of 50 kN. A displacement rate equal to 1.14 mm/min was adopted and the maximum load was recorded for each tested specimen with a resolution equal to 0.005 kN.

3. Results and discussion

3.1 Unconfined compressive strength

Figure 3a presents the unconfined compressive strength ($q_u$) results for the specimens cured along 7 days, while Figure 3b exhibits the results for a curing period equal to 28 days. For both curing periods, the $q_u$ results are correlated to the porosity/volumetric binder content index ($\eta/B_v$) as previously proposed by Consoli et al. (2018b).

The volumetric binder content ($B_v$) is designated as the sum between the volumetric contents of carbide lime ($V_{CL}$) and pozzolan ($V_{GG}$), both divided by the total volume of the specimen ($V$) as presented in Equation 3.

$$\eta = 100 - \left( \frac{100}{\eta_{GG} + \eta_{CL}} \right) \left( \frac{100}{\frac{V_{CL}}{V} + \frac{V_{GG}}{V}} \right)$$

(2)

Table 3. Experimental runs.

| Experimental run | $\gamma_s$ (kN/m$^3$) | CL (%) | GG (%) | Type | $\eta/B_v$ |
|-----------------|------------------------|--------|--------|------|------------|
| 1               | 15.5                   | 4      | 10     | A    | 4.46       |
| 2               | 15.5                   | 4      | 10     | B    | 4.46       |
| 3               | 15.5                   | 4      | 10     | C    | 4.46       |
| 4               | 15.5                   | 4      | 30     | A    | 1.83       |
| 5               | 15.5                   | 4      | 30     | B    | 1.83       |
| 6               | 15.5                   | 4      | 30     | C    | 1.83       |
| 7               | 17.5                   | 4      | 10     | A    | 3.20       |
| 8               | 17.5                   | 4      | 10     | B    | 3.20       |
| 9               | 17.5                   | 4      | 10     | C    | 3.20       |
| 10              | 17.5                   | 4      | 30     | A    | 1.31       |
| 11              | 17.5                   | 4      | 30     | B    | 1.31       |
| 12              | 17.5                   | 4      | 30     | C    | 1.31       |
| 13              | 15.5                   | 7      | 10     | A    | 3.58       |
| 14              | 15.5                   | 7      | 10     | B    | 3.58       |
| 15              | 15.5                   | 7      | 10     | C    | 3.58       |
| 16              | 15.5                   | 7      | 30     | A    | 1.66       |
| 17              | 15.5                   | 7      | 30     | B    | 1.66       |
| 18              | 15.5                   | 7      | 30     | C    | 1.66       |
| 19              | 17.5                   | 7      | 10     | A    | 2.56       |
| 20              | 17.5                   | 7      | 10     | B    | 2.56       |
| 21              | 17.5                   | 7      | 10     | C    | 2.56       |
| 22              | 17.5                   | 7      | 30     | A    | 1.18       |
| 23              | 17.5                   | 7      | 30     | B    | 1.18       |
| 24              | 17.5                   | 7      | 30     | C    | 1.18       |

Figure 3. Unconfined compressive strength results (a) 7 days of curing (b) 28 days of curing.
The $\eta/B_v$ index inputs into a single parameter the influence of porosity and the amount of binder on the mechanical behavior of the compacted mixtures. The relative importance between the compactness and the binder quantity may be adjusted, if necessary, through an exponent applied to the $B_v$. As formerly attained in other studies (Henzinger et al., 2018, Consoli et al., 2018a, 2018b, 2019, Ekinci et al., 2019), a power equation was obtained between the unconfined compressive strength and the $\eta/B_v$ parameter considering each type of employed ground glass and each curing period. Hence, an equation of the following type was obtained, in which the scalar “$A$” and the coefficient of determination ($R^2$), considering each curing period and each ground glass type, are presented in Table 4.

\[
q_u (\text{kPa}) = A \times 10^{2 \left( \frac{\eta}{B_v} \right)^{-1.55}}
\]  

(4)

Regardless the ground glass type, the only difference between the attained power equations relies on the scalar “$A$”. This must account for the differences related to the curing period and, as well, to the type of ground glass powder. Such trend is in accordance to what was formerly demonstrated by Diambra et al. (2017). Hence, within the same ground glass type, higher strength values were observed for the highest curing period. Otherwise, considering the same curing period, greater strengths were attained when the finer ground glass powder was used. The causes and implications of such outcomes are discussed in the next section.

Moreover, in order to validate the results obtained herein, a normalization procedure was carried out following the procedure previously adopted by Consoli et al. (2017, 2020b). Thus, all the $q_u$ values obtained in the present research were normalized by a respective $q_u$ value related to a $\eta/B_v$ equal to 3. The index value equal to 3 was chosen because it lies within the $\eta/B_v$ boundaries that vary from 1.0 to 4.5. The results obtained herein, in conjunction with the ones attained by Consoli et al. (2018a), are plotted in Figure 4 in the normalized form. The single equation ($R^2 = 0.95$) was obtained through the employment of such approach:

\[
\frac{q_u (\eta/B_v = 3)}{q_u (\eta/B_v = 3)} = 5.49 \left( \frac{\eta}{B_v} \right)^{-1.55}
\]  

(5)

3.2 Statistical analysis

In order to statistically assess the significance of the controllable factors (and their interactions), an analysis of variance (ANOVA) was conducted at a significance level ($\alpha$) of 5 %. In addition, the Pareto chart of the standardized effects was employed (Figure 5) aiming to graphically demonstrate the magnitude of the standardized effects of the studied variables and the second order interactions. In this graph, a reference line delimits the significant factors at the adopted $\alpha$. Such line is the quantile in the Students t-distribution and depends upon $\alpha$.

| Table 4. Summary of parameters for Equation 4. |
|---------------------------------------------|
| Ground glass type | Curing period (days) | A (kPa) | $R^2$ |
|-------------------|----------------------|--------|-------|
| A                 | 7                    | 14.60  | 0.98  |
| B                 | 7                    | 6.13   | 0.99  |
| C                 | 7                    | 2.99   | 0.90  |
| A                 | 28                   | 43.84  | 0.99  |
| B                 | 28                   | 34.42  | 0.98  |
| C                 | 28                   | 23.19  | 0.98  |

Figure 4. Normalized strength results.

Figure 5. Pareto chart of the standardized effects.
Through the analysis of the results depicted in Figure 5, it is clear that all the factors influence the strength of the studied blends at the adopted α. However, the curing period (E), the amount of ground glass powder (B), their interaction (BE) and the dry unit weight (A) are the most relevant factors in controlling the unconfined compressive strength of the amended soil. In addition, although statistically significant, the effects exerted by the ground glass type (D) and by the amount of carbide lime (C) are sensibly smaller compared to those exerted by the other variables.

The kinetics of the pozzolanic reactions explains the great influence of the curing period on the strength of the tested specimens. Namely, higher curing periods enable the fixation of greater quantities of carbide lime, yielding the formation of cementitious binding compounds that contribute to enhance the strength of the blends, regardless the ground glass powder type (Saldanha & Consoli, 2015; Saldanha et al., 2016; Bilondi et al., 2018). In this sense, neglecting the change in fabrics due to distinct amounts of glass powder, the availability of greater quantities of reactive material (i.e. pozzolan) facilitates the yielding of cementitious materials along the curing period. This explains the appreciable effect of the amount of ground glass powder and its interaction with curing period in altering the strength of the tested blends.

The substantial influence of the dry unit weight is related to the compactness of the specimens. That is, lower porosity values imply in greater degrees of interlocking between the particles and, therefore, in broader strength values. Besides, the proximity between the particles that compose the mixture influences the kinetics of the pozzolanic reactions, facilitating it. This explains the interactions of the dry unit weight with curing period (AE) and with the ground glass powder quantity (AB). As well, the amount of carbide lime (C) had little influence in altering the quc, probably because the minimum amount of 4 % might be sufficient for the pozzolanic reactions development considering the curing periods employed herein. Similar trend was observed by Consoli et al. (2018a, 2018b, 2019, 2020). Nonetheless, for distinct curing conditions (i.e. higher curing period and/or temperature) this might not be true.

Although not so impacting, the type of ground glass showed to be statistically significant. This is mostly explained by the higher specific surface area observed in the finer powder which is intimately linked to the reactivity of the material and, consequently, to the kinetics of the pozzolanic reactions (Massaza, 2004; Cordeiro et al., 2011; Walker & Pavia, 2011). Besides, through the uniformity coefficients (Cv) of the distinct ground glass powders (Table 2), it is possible to infer that the increment in the strength is not related to change of gradation existing between the three tested ground glass granulometries. Usually, higher strengths are attained for well-graded or gap-graded soils (Igwe et al., 2006; Krim et al., 2017). This was not the case herein if the gradations of the ground glass powders are individually considered. Namely, the best performance was observed amongst the finest powder (Cv = 2), whereas the coarser ground glass powders exhibited higher Cv values and worse strength values. That is, no relationship could be observed between unconfined compressive strength and gradation of the pozzolan.

4. Conclusions

The present research was carried out aiming to assess the influence, among other variables, of the granulometry of the ground glass powder used in conjunction with carbide lime to stabilize a quartz sand. Hence, from the results presented herein, the following conclusions can be drawn considering the experimental limits:

Good correlations were obtained between the unconfined compressive strength and the η/Bv index as the coefficients of correlation were, in general, greater than 97 %. Moreover, the results could be normalized and followed a unique curve.

The curing period was the most influential factor in altering the strength response of the studied specimens. This is clearly related to the kinetics of the pozzolanic reactions that occur between the carbide lime and the ground glass powder. Therefore, up to a certain limit, greater amounts of binding compounds will precipitate for higher curing periods, contributing to enhance the mechanical strength of the sand - binder blends.

Although not so impacting in comparison with the other experimental variables, the type of ground glass powder (i.e. the granulometry) was statistically significant in altering the strength of the studied blends. This is related to the higher surface area obtained for the finer grain size distribution which enhances the pozzolan’ reactivity. Such trend was easily demonstrated when the unconfined compressive strength results were correlated to the η/Bv index, being the adjustment scalar “A” higher for the finer granulometries.

Possible effects of different gradation existing between each ground glass granulometry type can be neglected as no apparent relationship between uniformity coefficients (Cv) and strength was obtained. Therefore, the specific surface area appears as the main factor of influence regarding the performance when different grain sizes distributions of glass were employed.

In general, either an increase in the amount of ground glass powder and a decrease in the porosity has led to higher unconfined compressive strength values. Statistically, the amount of ground glass showed to be more influential regarding the strength of the studied mixtures, which is explained by the availability of reactant material to induce the formation of cementing binding compounds. Nonetheless, the Pareto graph has also shown the great effect exerted by the dry unit weight and, as well, by the interaction between amount of pozzolan and dry unit weight. Thereafter, a less

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porous environment is favorable to the development of pozollanic reactions.

The ground glass powder showed to be an effective pozollanic material to be used for sandy soil stabilization purposes. This is especially valid if finer portions of it are used.

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### List of symbols

| Symbol | Description                  |
|--------|------------------------------|
| S      | soil content                 |
| CL     | carbide lime content         |
| C_u    | uniformity coefficient       |
| C_v    | curvature coefficient        |
| GG     | ground glass powder content  |
| q_u    | unconfined compressive strength |
| R^2    | coefficient of determination |
| V      | total volume of specimen     |

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\( V_{og} \): volume of ground glass powder
\( V_{cl} \): volume of carbide lime
\( \eta \): porosity
\( B_v \): volumetric binder content (expressed in relation to the total specimen volume) which means the volumetric content of ground glass plus carbide lime
\( \eta / B_v \): porosity/binder index
\( \gamma_d \): dry unit weight
\( \gamma_s \): unit weight of soil grains
\( \gamma_{cl} \): unit weight of carbide lime grains
\( \gamma_{og} \): unit weight of ground glass powder