

# The effect of grain size of ground glass particles on the strength of green stabilized sand

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Note

## Keywords

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

## Abstract

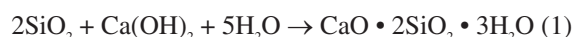
Regular soil improvement techniques customarily involve the use of ordinary Portland cement (OPC) despite the environmental issues related to the production process of such material. Hence, the establishment of alternative binders through the use of industrial and/or urban waste might be an option to 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  $\text{CO}_2$  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 possess 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  $\text{SiO}_2$ ) and amorphous structure, soda-lime waste glass can be grinded 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,  $\text{SiO}_2$  may combine with calcium hydroxide [ $\text{Ca}(\text{OH})_2$ ], yielding binding compounds (Massaza, 2004) such as calcium silicate hydrated (C-S-H) as described in Equation 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

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Submitted on March 10, 2020; Final Acceptance on July 29, 2020; Discussion open until March 31, 2021.

DOI: <https://doi.org/10.28927/SR.434669>



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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 silica 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 assess the impact of three distinct ground glass granulometries on the strength and stiffness of compacted sand - ground glass - carbide lime blends. For this, a  $2^k$  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 ( $2^k$  fac-

torial 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  $2^k$  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 [ $\text{Ca}(\text{OH})_2$ ] was used as an alkaline activator. Such lime is a by-product

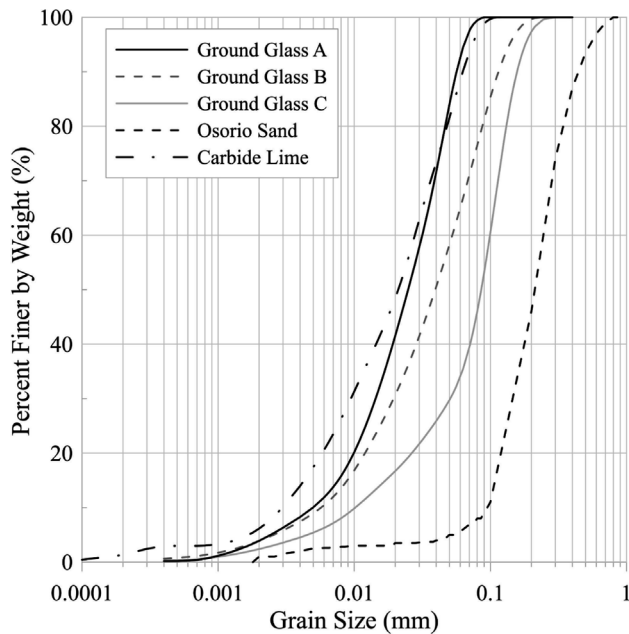
**Table 1.** Controllable factors.

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 ( $\text{kN/m}^3$ )	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		
Plasticity index	Non-plastic				
Specific gravity	2.47	2.47	2.47	2.19	2.65
Specific surface area <sup>*</sup> ( $\text{m}^2/\text{g}$ )	2.48	2.21	1.50	22.60	-
Coarse sand ( $2.00 \text{ mm} < d < 4.75 \text{ mm}$ ) (%)	-	-	-	-	-
Medium sand ( $0.425 \text{ mm} < d < 2.00 \text{ mm}$ ) (%)	-	-	-	-	10
Fine sand ( $0.075 \text{ mm} < d < 0.425 \text{ mm}$ ) (%)	-	20	50	-	87
Amount of silt ( $0.002 < d < 0.075 \text{ mm}$ ) (%)	99	79	50	97	3
Amount of clay ( $d < 0.002 \text{ mm}$ ) (%)	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.

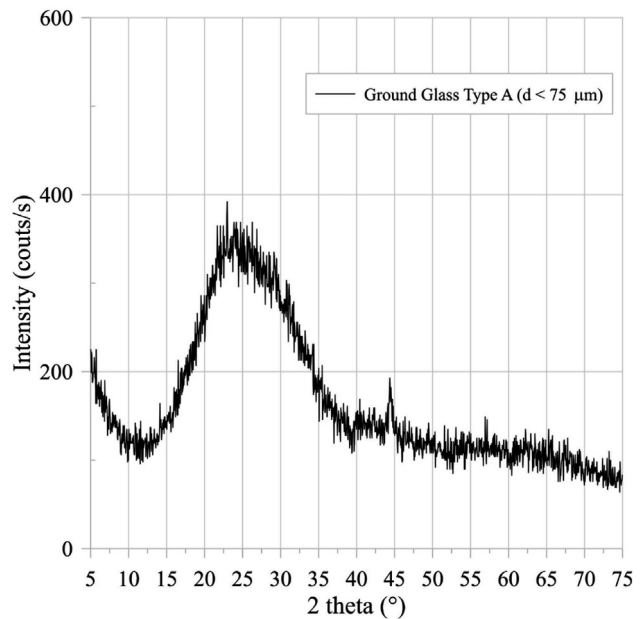


**Figure 1.** Grain size distribution of the employed materials.

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  $\mu\text{m}$ , the second fraction (B) corresponded to the portion greater than 75  $\mu\text{m}$  and smaller than 149  $\mu\text{m}$  and the third amount (C) was composed by particles greater than 149  $\mu\text{m}$ . The chemical composition of the glass was obtained via X-Ray Fluorescence (XRF) and revealed that it is mainly composed by  $\text{SiO}_2$  (75 %),  $\text{CaO}$  (17 %),  $\text{Al}_2\text{O}_3$  (3 %) and  $\text{Na}_2\text{O}$  (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 ( $\gamma_d$ ), 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 dupli-



**Figure 2.** X-ray diffraction test of ground glass.

cates 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  $23 \pm 2$  °C with relative moisture of about 95 %). Each specimen was considered suitable for testing if they met the following limits: dry unit weight within  $\pm 1$  % of the target value, molding moisture content within  $\pm 0.5$  % of the target value and dimensions within  $\pm 1$  % of the target values.

In order to compute each specimen porosity ( $\eta$ ), the Equation 2 can be employed. In this,  $\gamma_d$  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-

**Table 3.** Experimental runs.

Experimental run	$\gamma_d$ (kN/m <sup>3</sup> )	CL (%)	GG (%)	GG Type	$\eta/B_{iv}$
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

lowing: soil ( $\gamma_s$ ), carbide lime ( $\gamma_{CL}$ ) and ground glass powder ( $\gamma_{GG}$ ).

$$\eta = 100 - 100 \left[ \left( \frac{\gamma_d}{\frac{s}{100} + \frac{GG}{100} + \frac{CL}{100}} \right) \left( \frac{\frac{s}{100}}{\gamma_s} + \frac{\frac{GG}{100}}{\gamma_{GG}} + \frac{\frac{CL}{100}}{\gamma_{CL}} \right) \right] \quad (2)$$

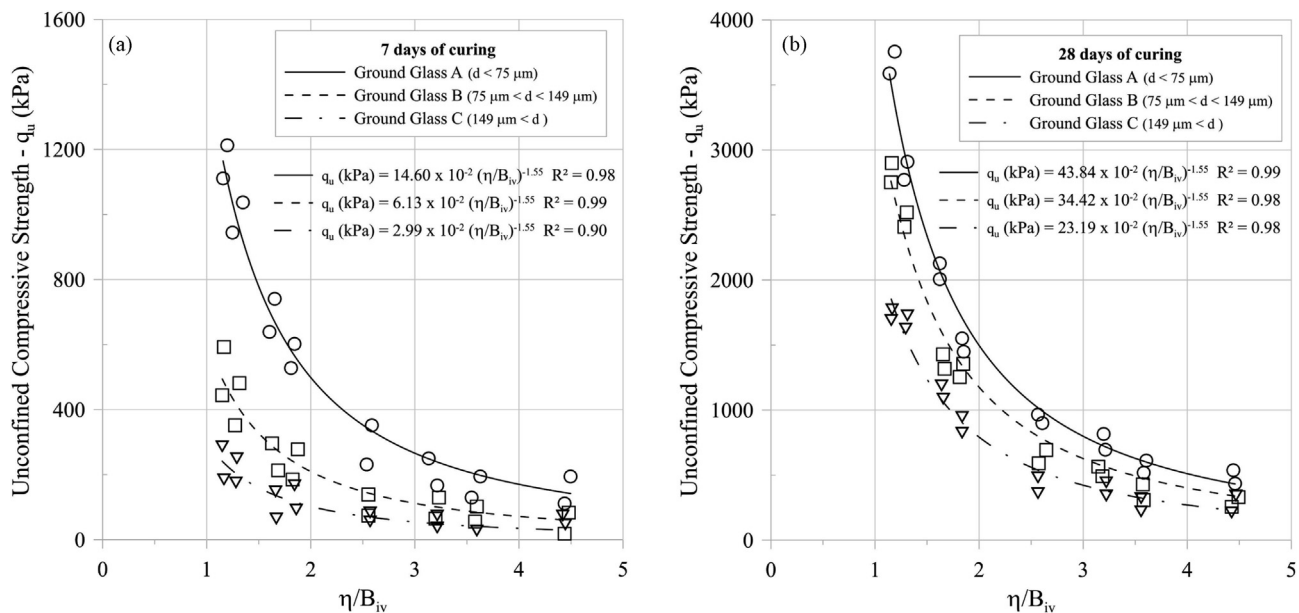
### 2.4 Unconfined compressive strength tests

One day before the curing period was accomplished (6 or 27 days) the specimens were submerged in a water tank ( $23 \pm 2 \text{ }^\circ\text{C}$ ) 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 ( $\eta/B_{iv}$ ) as previously proposed by Consoli *et al.* (2018b). The volumetric binder content ( $B_{iv}$ ) 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.



**Figure 3.** Unconfined compressive strength results (a) 7 days of curing (b) 28 days of curing.

$$B_{iv} = \frac{V_{GG} + V_{CL}}{V} \quad (3)$$

The  $\eta/B_{iv}$  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  $B_{iv}$ . As formerly attained in other studies (Henzinger *et al.*, 2018, Consoli *et al.*, 2018a, 2018b, 2019, Ekinici *et al.*, 2019), a power equation was obtained between the unconfined compressive strength and the  $\eta/B_{iv}$  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.

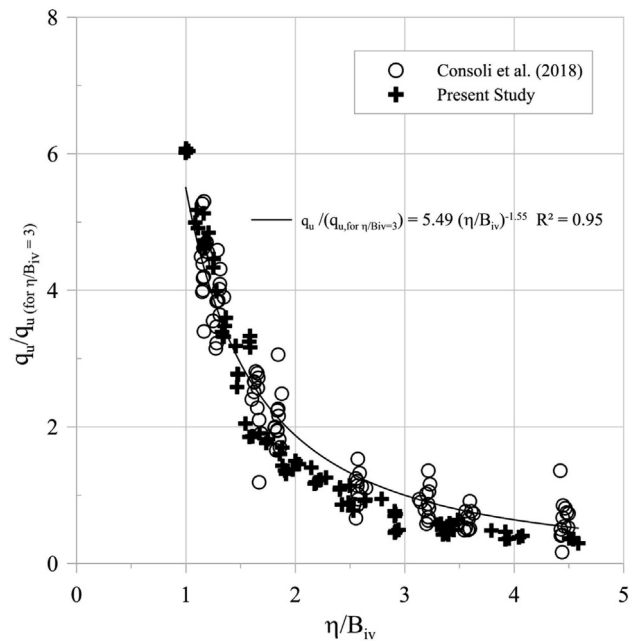
$$q_u \text{ (kPa)} = A \times 10^2 \left( \frac{\eta}{B_{iv}} \right)^{-1.55} \quad (4)$$

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  $\eta/B_{iv}$  equal to 3. The index value equal to 3 was chosen because it lies within the  $\eta/B_{iv}$  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:

**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

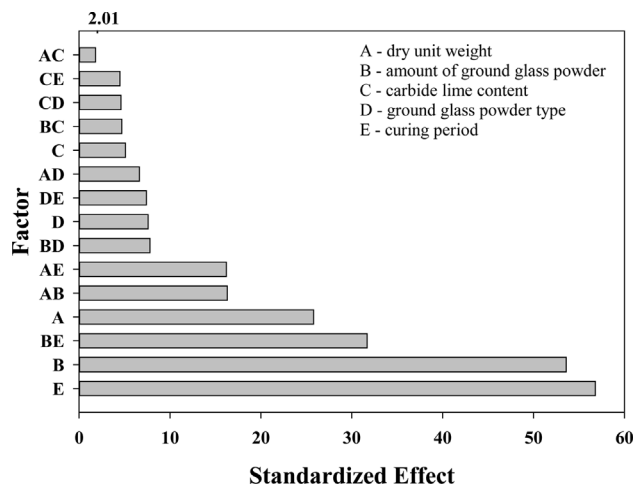


**Figure 4.** Normalized strength results.

$$\frac{q_u}{q_{u(\frac{\eta}{B_{iv}}=3)}} = 5.49 \left( \frac{\eta}{B_{iv}} \right)^{-1.55} \quad (5)$$

### 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  $\alpha$ .



**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  $\alpha$ . 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  $q_u$ , 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 ( $C_u$ ) 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 ( $C_u = 2$ ), whereas the coarser ground glass powders exhibited higher  $C_u$  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  $\eta/B_v$  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 influent 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  $\eta/B_v$  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 ( $C_u$ ) 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 influent 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

porous environment is favorable to the development of pozzolanic reactions.

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

## Acknowledgments

The authors wish to express their gratitude to the Brazilian Research Council CNPq (INCT, Produtividade em Pesquisa, Universal), to FAPERGS-CNPq (PRONEX) and MEC-CAPIES (PROEX) for their financial support of the research group.

## References

- ASTM D2487-06. (2006). Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). *ASTM International, West Conshohocken, PA*. <https://doi.org/10.1520/D2487-06>
- ASTM C39M-20. (2020). Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. *ASTM International, West Conshohocken, PA*. [https://doi.org/10.1520/C0039\\_C0039M-20](https://doi.org/10.1520/C0039_C0039M-20)
- Arulrajah, A., Kua, T.A., Horpibulsuk, S., Mirzababaei, M., & Chinkulkijniwat, A. (2017). Recycled glass as a supplementary filler material in spent coffee grounds geopolymers. *Construction and Building Materials*, 151(1), 18-27. <https://doi.org/10.1016/j.conbuildmat.2017.06.050>
- Baldovino, J.J.A., Izzo, R.L.S., Silva, É.R., & Rose, J.L. (2020). Sustainable use of recycled-glass powder in soil stabilization. *Journal of Materials in Civil Engineering*, 32(5), 4020080. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0003081](https://doi.org/10.1061/(ASCE)MT.1943-5533.0003081)
- Bilondi, M.P., Toufigh, M.M., & Toufigh, V. (2018). Using calcium carbide residue as an alkaline activator for glass powder-clay geopolymer. *Construction and Building Materials*, 183(20), 417-428. <https://doi.org/10.1016/j.conbuildmat.2018.06.190>
- CEMPRE. (2015). CEMPRE review 2015. *CEMPRE - Compromisso Empresarial para Reciclagem, São Paulo, SP* (in Portuguese).
- Chen, C.H., Huang, R., & Yang, C.C. (2006). Waste E-glass particles used cementitious mixtures. *Cement and Concrete Research*, 36(3), 449-456. <https://doi.org/10.1016/j.cemconres.2005.12.010>
- Chen, C., Habert, G., Bouzidi, Y., & Jullien, A. (2010). Environmental impact of cement production: Detail of the different processes and cement plant variability evaluation. *Journal of Cleaner Production*, 18(5), 478-485. <https://doi.org/10.1016/j.jclepro.2009.12.014>
- Consoli, N.C., Dalla Rosa, A., & Saldanha, R.B. (2011). Variables governing strength of compacted soil-fly ash-lime mixtures. *Journal of Materials in Civil Engineering*, 23(4), 432-440. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0000186](https://doi.org/10.1061/(ASCE)MT.1943-5533.0000186)
- Consoli, N.C., Marques, S.F.V., Floss, M.F., & Festugato, L. (2017). Broad-spectrum empirical correlation determining tensile and compressive strength of cement-bonded clean granular soils. *Journal of Materials in Civil Engineering*, 29(6), 06017004. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0001858](https://doi.org/10.1061/(ASCE)MT.1943-5533.0001858)
- Consoli, N.C., Winter, D., Leon, H.B., & Scheuermann Filho, H.C. (2018a). Durability, strength, and stiffness of green stabilized sand. *Journal of Geotechnical and Environmental Engineering*, 144(9), 04018057. [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0001928](https://doi.org/10.1061/(ASCE)GT.1943-5606.0001928)
- Consoli, N.C., Marin, E.J.B., Samaniego, R.A.Q., Heineck, K.S., & Johann, A.D.R. (2018b). Use of sustainable binders in soil stabilization. *Journal of Materials in Civil Engineering*, 31(2), 06018023. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0002571](https://doi.org/10.1061/(ASCE)MT.1943-5533.0002571)
- Consoli, N.C., Carreta, M.S., Leon, H.B., Scheuermann Filho, H.C., & Tomasi, L.F. (2019). Strength and stiffness of ground waste glass-carbide lime blends. *Journal of Materials in Civil Engineering*, 31(10), 06019010. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0002862](https://doi.org/10.1061/(ASCE)MT.1943-5533.0002862)
- Consoli, N.C., Festugato, L., Scheuermann, H.C., Miguel, G.D., Neto, A.T., & Andreghetto, D. (2020a). Durability assessment of soil-pozzolan-lime blends through ultrasonic pulse velocity test. *Journal of Materials in Civil Engineering*, 32(8), 04020223. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0003298](https://doi.org/10.1061/(ASCE)MT.1943-5533.0003298)
- Consoli, N.C., Carretta, M.S., Festugato, L., Leon, H.B., Tomasi, L.F., & Heineck, K.S. (2020b). Ground waste glass-carbide lime as sustainable binder stabilizing three different silica sands. *Géotechnique*, 1-14. Advance online publication. <https://doi.org/10.1680/jgeot.18.P.099>
- Cordeiro, C.G., Toledo Filho, R.D., Tavares, L.M., Fairbairn, E.N.R. & Hempel, A. (2011). Influence of particle size and specific surface area on the pozzolanic activity of residual rice husk ash. *Cement and Concrete Composites*, 33(5), 529-534. <https://doi.org/10.1016/j.cemconcomp.2011.02.005>
- Day, D.E., Malish, W.R., & Wixsom, B.G. (1970). Improved bonding of waste glass aggregate with bituminous binders. *American Ceramic Society Bulletin*, 49(12), 1038-1041.
- Diambra, A., Ibraim, E., Peccin, A., Consoli, N.C., & Festugato, L. (2017). Theoretical derivation of artificially cemented granular soil strength. *Journal of Geotechnical and Geoenvironmental Engineering*, 143(5), 04017003. [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0001646](https://doi.org/10.1061/(ASCE)GT.1943-5606.0001646)
- Ekinci, A., Scheuermann Filho, H.C., & Consoli, N.C. (2019). Copper slag-hydrated lime-Portland cement stabilized marine deposited clay. *Proceedings of the*

- Institution of Civil Engineers - Ground Improvement*, 1-30. <https://doi.org/10.1680/jgrim.18.00123>
- Habert, G. (2014). *Assessing the Environmental Impact of Conventional and 'Green' Cement Production*. Woodhead Publishing Limited.
- Henzinger, C., Schuhmacher, S.A., & Festugato, L. (2018). Applicability of the porosity/binder index to nonhomogeneous mixtures of fine-grained soil with lignite fly ash. *Journal of Materials in Civil Engineering*, 30(9), 06018013. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0002447](https://doi.org/10.1061/(ASCE)MT.1943-5533.0002447)
- Hughes, C.S. (1990). Feasibility using recycled glass in asphalt - report VTRC90-R3. *Virginia Transportation Research Council, Charlottesville, VA*.
- Igwe, O., Sassa, K., & Wang, F. (2006). The influence of grading on the shear strength of loose sands in stress-controlled ring shear tests. *Landslides*, 4(1), 43-51. <https://doi.org/10.1007/s10346-006-0051-2>
- Ingles, O.G., & Metcalf, J.B. (1972). *Soil Stabilization: Principles and Practice*. Butterworths.
- Jony, H.G., Al-Rubaie, M.F., & Jahad, I.Y. (2010). The effect of using glass powder filler on hot asphalt concrete mixture properties. *Engineering and Technology Journal*, 29(1), 44-57.
- Krim, A., Arab, A., Chemam, M., Brahim, A., Sadek, M., & Shahrour, I. (2017). Experimental study on the liquefaction resistance of sand-clay mixtures: Effect of clay content and grading characteristics. *Marine Georesources & Geotechnology*, 37(2), 129-141. <https://doi.org/10.1080/1064119X.2017.1407974>
- Ladd, R.S. (1978). Preparing test specimens using under-compaction. *Geotechnical Testing Journal*, 1(1), 16-23. <https://doi.org/10.1520/GTJ10364J>
- Massaza, F. (2004). Pozzolana and pozzolanic cements. In *Leas Chemistry of Cement and Concrete* (pp. 471-631). Hewlett.
- Malik, M.I., Bashir, M., Amad, S., Tariq, T., & Chowhary, U. (2013). Study of concrete involving use of waste glass as partial replacement of fine aggregates. *IOSR Journal of Engineering*, 3(7), 8-13.
- Metwally, I.M. (2007). Investigations on the performance of concrete made with blended finely milled waste glass. *Advances in Structural Engineering*, 10(1), 47-53. <https://doi.org/10.1260/136943307780150823>
- Mitchell, J.K. (1981). Soil improvement: State-of-the-art report. *Proc. 10<sup>th</sup> International Conference on Soil Mechanics and Foundation Engineering, Stockholm*. Publications Committee of X ICSMFE, 509-565.
- Montgomery, D.C. (2009). *Design and Analysis of Experiments*. John Wiley & Sons.
- Mohajerani, A., Vajna, J., Cheun, T.H.H., Kurmus, H., Arulrajah, A., & Horpibulsuk, S. (2017). Practical recycling applications of crushed waste glass in construction materials: a review. *Construction and Building Materials*, 156(15), 443-447. <https://doi.org/10.1016/j.conbuildmat.2017.09.005>
- Music, S., Filipovic-Vincekovic, N., & Sekovanic, L. (2011). Precipitation of amorphous SiO<sub>2</sub> particles and their properties. *Brazilian Journal of Chemical Engineering*, 28(1), 89-94.
- Park, S., & Lee, B. (2004). Studies on expansion properties in mortar containing waste glass and fibers. *Cement and Concrete Research*, 34(7), 1140-1152. <https://doi.org/10.1590/S0104-66322011000100011>
- Pattengil, M., & Shutt, T. (1973). Use of ground glass as pozzolan. *Proc. Symposium on Utilization of Waste Glass in Secondary Products, Albuquerque*. Univ. of New Mexico.
- Rangaraju, P.R., Rashidian-Dezfouli, H., Nameni, G., Amekuedi, G.Q. (2016). Properties and performance of ground glass fiber as a pozzolan in Portland cement concrete. *Proc. 11th International Concrete Sustainability Conference, Washington*. National Ready Mixed Concrete Association, 1-12.
- Saldanha, R.B., & Consoli, N.C. (2015). Accelerated mix design of lime stabilized materials. *Journal of Materials in Civil Engineering*, 28 (3), 06015012. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0001437](https://doi.org/10.1061/(ASCE)MT.1943-5533.0001437)
- Saldanha, R.B., Mallmann, J.E.C., & Consoli, N.C. (2016). Salts accelerating strength increase of coal fly ash-carbide lime compacted blends. *Géotechnique Letters*, 6, 23-27. <https://doi.org/10.1680/jgele.15.00111>
- Saldanha, R.B., Scheuermann Filho, H.C., Mallmann, J.E.C., Consoli, N.C., & Reddy, K.R. (2018). Physical-mineralogical-chemical characterization of carbide lime: An environment-friendly chemical additive for soil stabilization. *Journal of Materials in Civil Engineering*, 30 (6), 06018004. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0002283](https://doi.org/10.1061/(ASCE)MT.1943-5533.0002283)
- Sales, R.B.C., Sales, F.A., Correa, E.C.S., Patricio, P.S.O., Mohallem, N.D.S., & Aguilar, M.T.P. (2015). Study of the influence of chemical composition on the pozzolanicity of soda-lime glass microparticles. *Materials Research*, 18(2), 43-47. <http://dx.doi.org/10.1590/1516-1439.343914>
- Walker, R., & Pavía, S. (2011). Physical properties and reactivity of pozzolans, and their influence on the properties of lime-pozzolan pastes. *Materials and Structures*, 44, 1139-1150. <https://doi.org/10.1617/s11527-010-9689-2>

## List of symbols

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



$V_{GG}$ : 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

$\gamma_{GG}$ : unit weight of ground glass powder