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Geopolymers Based On Recycled Ground Glass And Cement For Sedimentary Soil Stabilization

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ABSTRACT

The paper presents the stabilization of a soil with recycled-glass and Portland cement. For this, a sedimentary soil originating from the Guabirotuba Formation (Curitiba, Brazil) was used adding three amounts of cement in relation to the dry mass of the soil: 3, 6 and 9%. Additionally, 5%, 15% and 30% recycled-glass powder (GP) residue were the contents chosen to add to the soil-cement blend. The specimens were cured under 7, 28 and 90 days and submitted to unconfined compressive (q_u), splitting tensile (q_t) and durability against wet-drying cycles (M/S), and measuring the accumulated loss of mass (PMA). The results showed that the addition of the following factors increased the q_t, q_u and durability of soil-cement-GP mixes: cement content, GP content, molding dry unit weight and curing time. The strength is controlled by the porosity/cement ratio (η/C_{iv}) for each curing time and GP content. Dosage and estimation equations for qt and qu were proposed using the η/C_{iv} index adjusted to an exponent of 0.21. Finally, considering the PMA results, 23 of the 27 proposed blends are suitable for the construction of pavement sub-bases.

Keywords: Geopolymerization, Recycling, Glass Powder, Soil Stabilization, Durability.

1. INTRODUCTION

Recycling powdered glass waste represents a major problem for urban areas, both in developed and developing countries (Turgut 2013). Using recycled powdered glass waste in the production of geopolymers is a new technology considered in construction projects, especially in concrete. However, it has been little investigated for soil stabilization. Arulrajah et al. (2017) analyzed recycled glass (RG) as a supplemental filler in spent coffee bean geopolymers (GC) using fly ash and slag. Fly ash and slag at 30% by weight were used as precursors to induce geopolymerization in RG-CG mixtures. RG was added to geopolymer mixtures in proportions of 25%, 50% and 75% by weight. The authors concluded that an alkaline liquid ratio of 70% Na_2SiO_3 and 30% NaOH was used to induce geopolymerization in the obtained mixtures UCS (unconfined compressive strength) with a value of 10 MPa in 28-d of curing, and the RG- CG, FA and slag are an alternative building material and indeed promote a sustainable future for the construction industry.

Pourabbas Bilondi et al. (2018a) investigated the feasibility of using a geopolymer based on recycled glass powder (RGP) to improve the mechanical behavior of clayey soils. They used a low plasticity clayey soil mixed with various percentages (0-25% by weight) of RGP and sodium hydroxide as an alkaline activator. The alkaline activator was prepared with a different concentration of NaOH (1, 2, 3, 4, 5, 6, 7 and 8 M, M = Molar) and then added to the soil-RGP mixture. The authors studied the influences of curing temperature of 25 and 70°C and various curing periods (7, 28 and 91 days) in UCS. They concluded that the UCS values of all specimens stabilized with a geopolymer and NaOH concentrations were increased compared to the unstabilized soil sample. The UCS values were higher when the specimens were cured for a period of 91 days and the results confirmed that a rich source of silica (in an amorphous phase), such as glass powder, was necessary for better soil stabilization and formation of soil. gel-geopolymer.

Recently Pourabbas Bilondi et al. (2018b) employed calcium carbide residues (CCR) as an alkaline activator for clay-RPG mixtures. The effect of different factors such as CCR content, glass powder content (0-25%), initial synthesis temperature and curing time were investigated. The UCS of CCR-RGP samples improved significantly by increasing the CCR and RGP content to the optimal values of 7% and 15%, respectively. The authors also concluded that the UCS values of the geopolymeric specimens increased with increasing the initial synthesis temperature from 25°C to 70°C for both curing times (7 and 28 days). However, the effect of the high initial temperature of synthesis on the UCS of the specimens was less effective for 28 days of curing.

In agreement with the above, the use of cement together with recycled glass powder has not been investigated in the stabilization of soils of the Guabirotuba Formation. Thus, this study evaluates the potential of combining two binders: recycled glass powder (in powder form) and Portland cement of initial strength, as a possible geopolymer partially replacing Portland cement to improve the behavior of a sedimentary soil of the Guabirotuba Formation. .

2. MATERIALS AND METHODS

2.1 Materials

In the present research, four materials were used: soil, high initial strength cement, powdered glass residue (GP) and water.

To characterize the materials, the following tests were performed: soil and glass powder granulometry according to the American standard ASTM D2487 (ASTM, 2011), Atterberg limits of the soil according to the Brazilian standards NBR 7180 (ABNT, 2016) and NBR 6459 (ABNT, 2016), the actual specific gravity of the soil grains according to the ASTM D854 (ASTM, 2014) and the real specific gravity of the cement and glass powders according to the Brazilian standard NBR 16605 (ABNT, 2017).

The soil used is a soil characteristic of the metropolitan region of Curitiba belonging to the Guabirotuba Formation. The soil is mostly composed of sedimentary silt, yellow in color and was collected on a road slope 2.5 meters deep from the natural ground level in the municipality of São José dos Pinhais (southeast of Curitiba).

The cement used was high initial strength (ARI) CPV.

The powdered glass residue was collected in a glass shop in Curitiba and dried in an oven at 70°C for 42 hours. The residue was subjected to milling using a ball mill for 4 hours. Finally, the ground product was sieved using the diameter of 0.075 mm, thus obtaining the powdered product.

Distilled water was used for the characterization of the materials, compaction tests, preparation of the compression-tensile-durability test specimens and saturation of the samples, thus avoiding undesired reactions.

2.2 Cement Percentages, GP and Cure Times

Three cement contents were used in relation to dry soil mass: 3, 6 and 9% according to local experience in stabilizing the soils of the Guabirotuba Formation with cement (Moreira et al. 2019). Additionally, 5%, 15% and 30% of glass were the percentages chosen in relation to the dry mass of the soil. The simple compressive strength and tensile strength by diametral compression of the compacted mixtures were evaluated after 7, 28 and 90 days of curing. Finally, for durability tests, the mixtures were cured for 7 days.

For this research, three (3) specific dry molding weights were chosen: 13.50 kN/m^3, 14.50 kN/m^3 and 15.50 kN/m^3. A battery of tests was carried out previously, compacting specimens at 14.50 kN/m3, adding 6% cement, 15% glass, cured in 28 days and varying the moisture content (ω) from 20% to 38% . It was found that 26% moisture is the value where the mixtures obtain the highest value at simple compression and indirect tension without exceeding the 100% saturation line as can be seen in Figure 1 (b). Thus, all samples were compacted with 26% moisture content, varying the specific molding weights and cement percentages. Molding points, percentages of C, GP and cure times for all tests are shown in Table 1.

Table 1. Molding points, percentages of C, GP and cure times.

γ_d (kN/m^3)	ω (%)	C (%)	GP (%)	Saturação/%	t (days)
13.5	26	3, 6, and 9	5, 15, and 30	0.73	7, 28, and 90
14.5	26	3, 6, and 9	5, 15, and 30	0.88	7, 28, and 90
15.5	26	3, 6, and 9	5, 15, and 30	0.97	7, 28, and 90

2.3 Simple Compression, Tensile and Durability Tests

Specimens of 50 mm and 100 mm in diameter and height were molded, respectively, for compression and traction tests. For the durability tests, specimens measuring 10 cm in diameter and 12.73 cm in height were molded. First, the soil was dried completely in an oven and then the amount of cement and powdered glass residue were added. The dry mixture of soil+C+GP was carried out until homogeneous. The amount of water necessary to reach 26% moisture in the mixture was weighed and added. Next step, the specimens were compacted using 3 layers using stainless steel molds and a manual hydraulic press with a capacity of 10 ton. Finally, the specimens were extracted from the molds and were weighed and measured. The samples had to respect the following maximum errors to be used in the resistance/durability tests: dimensions of the samples with a diameter of ±0.5 mm and a height of ±1 mm, specific dry weight (γ_d) of ±1% and moisture content (ω) of ±0.5%. For each molding point, GP content, C and curing time, 3 specimens were molded.

To carry out the simple compression and tension tests, an automatic press with a capacity of 10 kN was used. The tests were performed with an automated system, measuring mainly the applied force (2.7 N resolution) and the deformation with a sensitivity of 0.01 mm, with a test speed of 1.10 mm/min. 5 hours before each test, the specimens were previously immersed in water to avoid the influence of suction as much as possible. The simple compression test procedures followed the Brazilian standard NBR 5739 (ABNT, 2018) and the tensile tests followed the recommendations of NBR 7222 (ABNT, 2011).

For the durability tests, each M/S cycle started with the cycle of wetting the samples in water at 23°C for 5 hours in distilled water. After wetting, the samples were removed and placed in an oven for 42 h for drying at 70°C. After the drying cycle, the samples were subjected to brushing (with a brush specified in ASTM D559-15) to measure mass loss. Two cycles of 18 to 19 brushes were performed on the side faces, and 4 brushes on the two transverse faces of the test cups, applying an average force of 1.5 kg, which was monitored on a precision balance. To avoid as many operational error variables as possible, all brushing tests were performed by the same operator during the 12 cycles for 24 days. Durability testing procedures followed the American standard ASTM D559 (ASTM, 2015).

3. RESULTS AND DISCUSSIONS

3.1 Materials Characterization

Table 2 presents the soil properties, Figure 1(a) presents the granulometric curve and Table 3 the soil chemical composition. It is noted [according to the Brazilian standard NBR 6502 (ABNT, 1995)] that 60% of the particles are silt (0.002 mm < diameter <0.06 mm), 25% are sand and a small portion of 5% clay was also found during the sedimentation test. According to the Unified Soil Classification System (SUCS), the soil is classified as an elastic sandy silt (MH) with an average plasticity index of 14.86%.

The cement used was of high initial strength (ARI), with a high percentage of calcium oxide (CaO), strength at 7d of 42 MPa and at 28d of 53 MPa. The cement density was calculated to be 3.11. The chemical composition of cement is shown in Table 3.

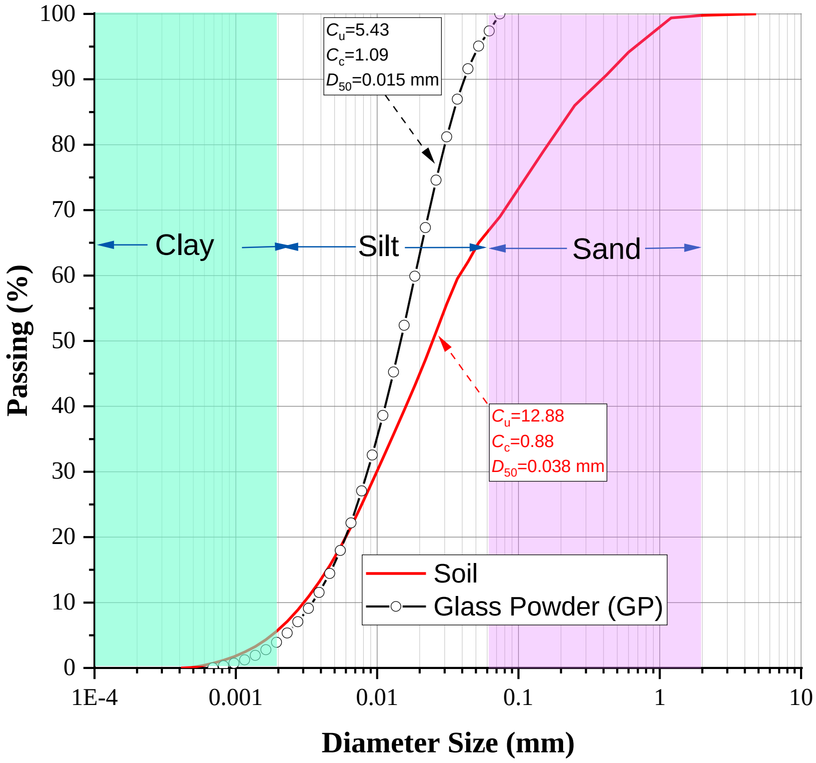
The powder residue was characterized and the results are shown in Table 2 and Table 3. In addition, mineralogical tests were carried out finding an amorphous formation with 98% silica content. Finally, the glass powder was classified as silt (ML) with a density of 2.40 g/cm^3. The PG granulometric curve is shown in Figure 1 (a).

Table 2. Physical properties of soil and GP

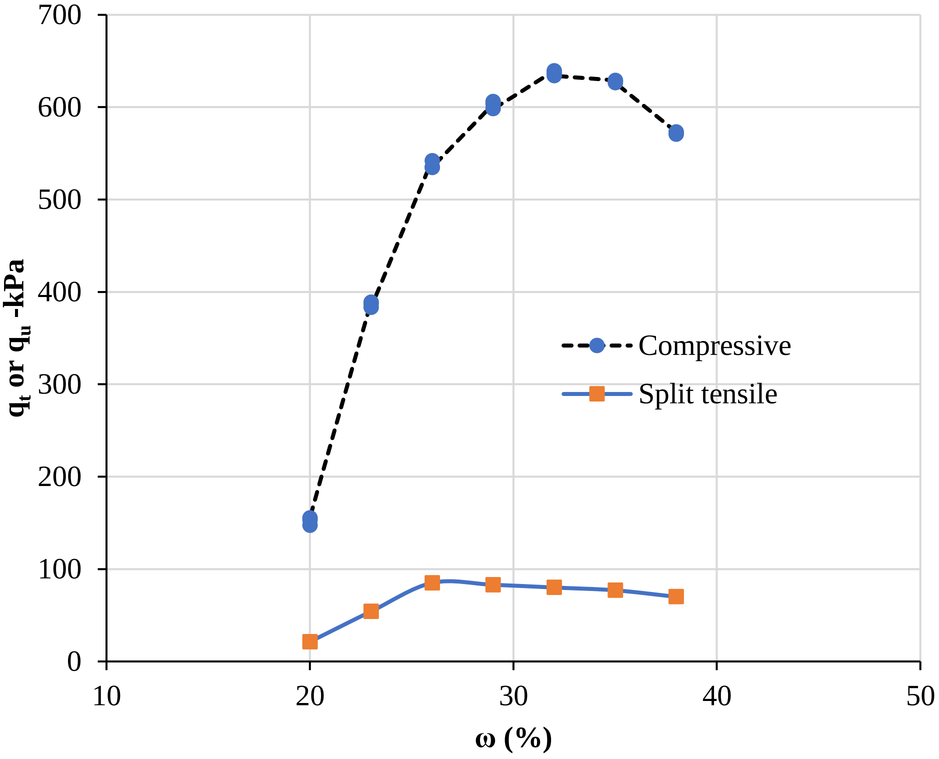
Properties	Soil	GP
Liquid Limit, %.	50.82	–
Plasticity Limit, %.	35.96	–
Plasticity index, %	14.86	–
Actual grain density	2.62	2.40
Coarse sand (0.6 mm< diameter<2 mm), %.	5	–
Medium sand (0.2 mm< diameter <0.6 mm), %.	12	–
Fine sand (0.06 mm< diameter <0.2 mm), %.	18	–
Silt (0.002 mm < diameter <0.06 mm), %.	60	95
Clay (diameter < 0.002 mm), %.	5	5
Effective diameter (D_{10}), mm	0.003	0.0035
Average diameter (D_{50}), mm	0.038	0.015
Coefficient of uniformity (C_u)	12.67	5.43
Coefficient of curvature (C_c)	0.88	1.09
Classification (SUCS)	MH	ML
Color	Yellow	White

Table 3. Chemical composition of soil, GP and cement

Compund	Concentration by weight (%)		
	Soil	GP	Cement (C)
SiO_2	48.78	74.22	18.96
Al_2O_3	44.51	1.83	4.30
Fe_2O_3	0.61	0.21	2.95
K_2O	0.84	–	–
TiO_2	0.92	–	–
SO_3	4.12	–	3.18
CaO	–	10.62	60.76
Na_2O	–	11.28	–
MgO	–	1.18	3.26
Loss on Ignition	0.22	0.66	–



(a)



(b)

Figure 1. (a) Soil and recycled glass powder (GP) granulometric curve. (b) Influence of moisture content on compressive and tensile strength in soil-cement-GP mixtures

3.2 Mechanical strength of soil-cement-GP mixtures

Figures 2 (a)- (b) show the results of the influence of the porosity/cement index on the qt and qu of the compacted soil-GP mixtures for 7, 28 and 90 days of curing, respectively. There is an increase in the mechanical strength of the mixtures when the amount of cement powder and the curing time are increased. It is also verified that the growth of qt and qu is related to the cement content. On the other hand, the strengths qt and q also increase when the dry specific weight of the mold is increased.

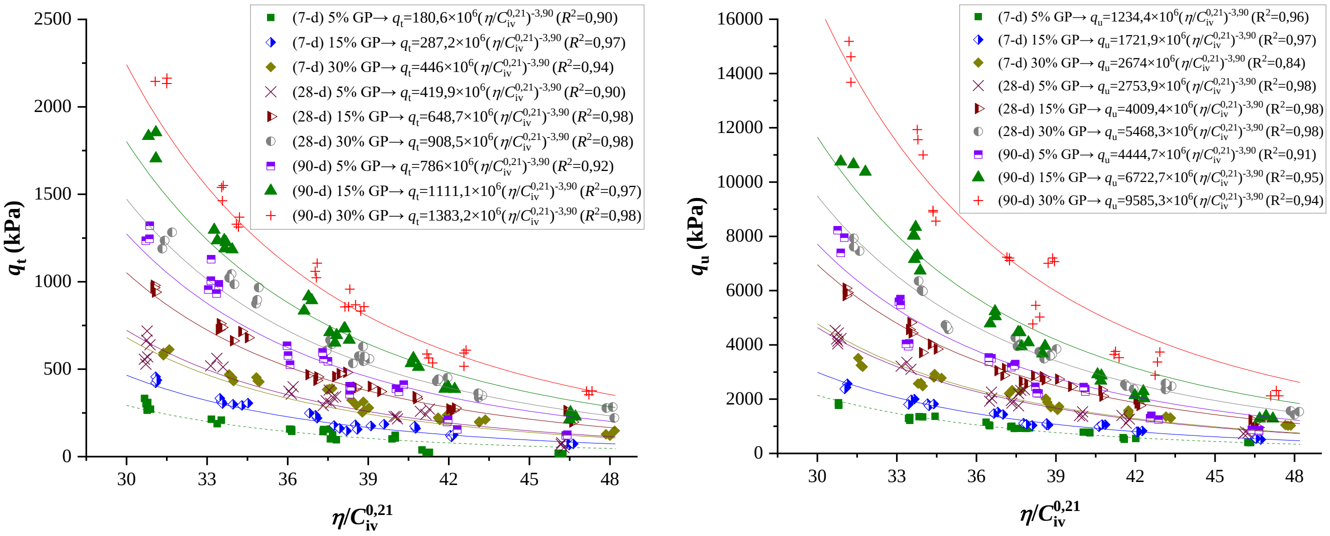
Analyzing Figures 1 (a)-(b) strength increases with curing time. In 7 days (using 15%GP and 9%C), the maximum strength qu obtained is 3.2 MPa while in 90 days of curing the strength is 12 MPa, an increase of 275%. Additionally, comparing all strengths and molding points for both qu and qt from 7 days to 90 days curing, the increases average 300%.

When adding the glass powder, the pozzolanic reactions increase causing the formation of higher percentages of C-S-H (hydrated calcium silicates). Thus, the improvement of the bond between the soil particles by the geopolymeric gel of the cement with the glass powder has been the main factor for the increase of the resistance of the specimens. This factor was responsible for the increase in strength of geopolymer materials in clays in previous studios made by Pourabbas Bilondi et al. (2018a, 2018b).

To make q_u-η/Civ and q_t-η/C_{iv} compatible, the values of C_{iv} had to adjust to an exponent of 0.21. This exponent added the coefficient values of determination of the equations and depends on the type of soil.

Figure 2 shows how strength qu and q_t potentially increases with increasing cure time. The decrease in η/C_{iv} adds the values of qu and q_t and vice versa due to the decrease in voids and increase in the volume of cement and glass powder. The addition of qu and q_t with the addition of glass can be compared with the soil-cement strength previously studied by Baldovino et al. (2020a, 2020b). For example, for 28 days of curing, soil-cement mixtures with 3% cement, compacted at a density of 14.5 kN/m^3, obtain a value of qu=500 kPa. By adding 15% glass, the strength increases to 2000 kPa. The same goes for the other mixtures. When adding the glass powder, the pozzolanic reactions increase causing the formation of higher percentages of C-S-H.

Note that the growth follows the form: $q_u \vee q_t = A_q \left[\frac{\eta}{(C_{iv})^B}\right]^b$. Where A_q is a constant that depends on the GP content and curing time, and B and C are empirical constants that depend on the type of soil and type of cement. In the case of qu and qt, the constants B and b remained constant because there were no unproportioned increases in mechanical strength due to the increase in curing time. The value of A_q increases with increasing GP for both qu and qt. That is, the strength of the mixtures was positively affected by the addition of GP. Looking at Figures 2(a)-(b), it is obvious how 30%GP and 5%GP cured for 7 and 28-days have the same effect on q_u and q_t.



(a) **(b)**

Figure 2. Influence of the porosity/cement ratio on (a) tensile strength by diametrical compression and (b) diametrical compression

3.3 Durability of soil-cement-GP mixtures

Figure 3 shows the cumulative mass loss (MAP) of the mixtures influenced by the number of M/S cycles. It is observed that the mixtures with 3%C and with the smallest amounts of GP and dry specific weight of mold lost 7% of their mass after the 6th cycle. PAM is directly related to the amount of GP and C used and initial voids in the specimen. For chemically stabilized silty soils with paving application, the PAM value should not exceed 7-8%, according to PCA (1992). All mixtures, except 4 mixtures molded with 3% cement (i.e., $\gamma_{135}C_3GP_5$, $\gamma_{135}C_3GP_{15}$, $\gamma_{145}C_3GP_5$ and $\gamma_{135}C_3GP_5$ (where γ= dry specific gravity of mold, C=cement and GP=glass powder) meet this requirement. % is considered the most appropriate cement content whenever compacted at 14.5 kN/m^3 using 15%GP to stabilize the yellow silt of the Guabirotuba Formation, based on the mechanical and durability properties of this soil type.

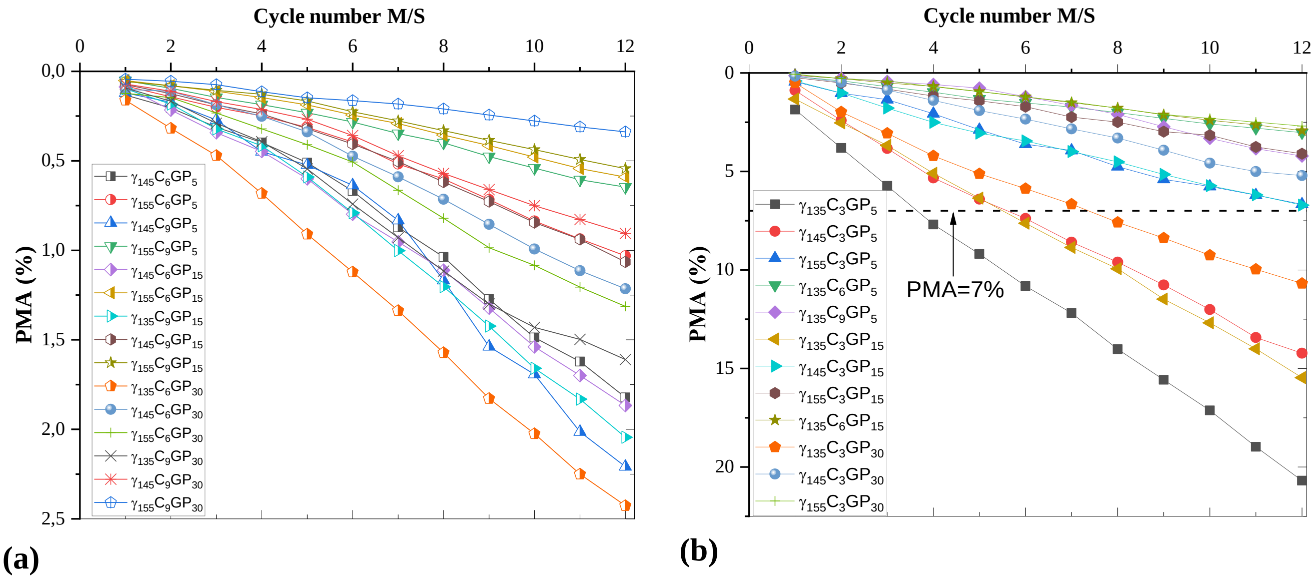


Figure 3. Influence of the number of M/S cycles on the PMA of soil-cement-GP mixtures. (a) PMA less than 2.5%. (b) PMA greater than 2.5%.

4. CONCLUSION

This work presented the mechanical behavior of soil-cement-glass mixtures. The porosity/cement index was used to describe the growth of q_u and q_t. According to the results the following conclusions can be attached:

– The simple compressive strength and indirect tensile strength of the specimens of soil-cement mixtures increased with the increase of the glass powder content from 5% to 30% and with the increase of the molding dry density. In addition, a potential trend was how best to represent the growth of qu and qt as the cement content varied from 3 to 9%. On the other hand, the decrease in the porosity of the samples also increased q_u and q_t.

– The porosity/volumetric cement content ratio (η/C_{iv}) proved to be an efficient parameter to study the mechanical behavior of soil-cement-glass powder mixtures. An exponent of 0.21 over the volumetric cement content ($\eta/C_{iv}^{0.21}$) provided a better fit of the samples tested under simple compression and indirect tension.

– It is suggested to use for geotechnical engineering projects, in terms of durability, the compacted mixtures above a dry specific weight of 14.5 kN/m^3, using 15%GP and 3%C.

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