Salamatpoor and Salamatpoor *Geo-Engineering (2017)8:8*
DOI 10.1186/s40703-017-0044-0

International Journal of Geo-Engineering

ORIGINAL RESEARCH

Open Access

Evaluation of adding crushed glass to different combinations of cement-stabilized sand

Sina Salamatpoor* and Siavash Salamatpoor

*Correspondence: s_salamatpoor@sci.iaun.ac.ir; sina.salamatpoor@gmail.com
Department of Civil Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran

Abstract

One of the methods that can stabilize clean sand type (SP) is blending the waste crushed glass and cement with these sands. In this paper, the laboratory tests are conducted on combination of clean sand, crushed glass, and cement in different condition for soil stabilization. Blends were stabilized by cement with 3, 5 and 10 weight percent of specimens. Different compounds of crushed glass used in this paper consists of 100% SP (poor graded sand) and ratio of glass to sand is in sequence, 10/90, 30/70 and 50/50 (G/S). A series of drained triaxial, direct shear, unconfined compressive strength and standard proctor tests on various combinations of glass and stabilizing sands with cement. The results show that increasing the percentage of crushed glass will reduce the amount w_{opt} samples in connection increases $\gamma_{d,max}$. It can also unconfined compressive strength (q_u). Relative density and strength parameters c and φ significantly increase. The minimum value of crushed glass which is improved the sandy soil properties is 10%. Also, by adding 10, 30 and 50% crushed glass to sandy soil which had stabilized 10% cement, the samples shear strength will be increased to 70, 98 and 244%, respectively. Therefore, adding crushed glass to the soil will correct unsuitable soil parameters with respect to ease of implementation, very easy access and reduce operational costs associated with its use in construction work.

Keywords: Crushed glass, Sand stabilized, Shear strength, Alternative material

Background

Soil stabilization is a method aimed at improving the quality of construction material properties to provide a range of pre-defined objectives. Soil stabilization is achieved through a variety of the most common being, physical stabilization. Waste material has been defined as any type of material produced by human and industrial activity that has no lasting value [1]. The growing quantities and type of waste materials, shortage of landfill spaces, and lack of natural earth materials highlight the urgency of finding innovative ways to recycling and reusing waste materials [2, 3]. Additionally, recycling and subsequent reuse of waste materials can reduce the demand for natural resources, which can ultimately lead to a more sustainable environment. One of the recyclable materials that are economically insignificant is crushed glass (CG), billion tons of which, around the world, will be buried in landfills. For example, in the United States, in 2001, approximately 11 million tons of glass entered the municipal waste stream, but only about 2.4

million tones (22%) of this glass was recovered and recycled. The reminder ended up in landfills. In Australia, approximately 850,000 tons of glass is used each year, but only 350,000 tons (40%) was recovered for recycling [4]. Therefore, the best countries in material recycling industry can only recycle 20–40% of used glasses, and the rest of them will be buried in landfills. In the other side, the biodegradation of glass normally takes about 450 years; therefore, this long time emphasizes on the need for the reuse of recoverable materials such as glass. Glass is manufactured from silica sand (SiO_2) and other compounds, and occurs naturally as black obsidian rock (volcanic deposit) and fulgurite (from lightning strikes). Recycled glass is the mixture of different colored glass pieces collected from municipal and industrial waste streams and is often mixed with a wide range of debris including food remaining, plastic and metal caps, ceramic, paper and soil [5, 6].

Also, recycled glass particles are generally angular shaped and contain some flat and elongated particles. It is believed that the waste stream, from which the glass particles have been produced, controls the quality of the material, especially the amount of debris in the mixture. Furthermore, the production process and crushing procedure play the most important roles in maximum particle size, debris level and flakiness index of recycled glass which, consequently, influence other geotechnical characteristics [7]. With regard to loose sandy ground, there are many sites for construction that are not appropriate because of their poor or bad engineering properties. However, there are different solutions for this problem such as strengthening the foundation and changing the location of the construction or improving site characteristics. Considering constant changes of the location is not always possible, and strengthening the foundation is too expensive. Therefore, the most commonly used approach is to stabilize and improve the strengths of site properties [3].

There are various methods for fixing, stabilizing and improving the parameters of loose sandy ground conditions including the use of different percentages of cement, blast furnace slag and fly ash, that all depends on the improvement and economic conditions and choosing them. Therefore, it is more logical to use materials since in addition to having lower cost, they are more easily accessible.

Dupas and Pecker [8] studied the static and mechanical properties of sand–cement in order to stabilize sand and avoid the risk of liquefaction. They found that adding 5% PC (Portland cement) increased the adhesion in sandy soil up to 200–300 κPa. Kukko [9] considered the use of different cementitious materials such as PC, blast furnace slag, and fly ash to enhance the strength of several different soils and concluded that the strength of stabilized materials was highly dependent on the cementitious materials content.

Wartman et al. [10] conducted a laboratory study to evaluate the feasibility of using CG to improve the engineering characteristics of fine-grained, marginal materials, such as kaolin, and quarry fines (i.e., the fine from a concrete sand quarry). Wartman et al. [10] found that frictional strength of the fine-grained soils considerably increased by addition of CG and suggested that this concept could be used to improve the engineering properties of other marginal materials. In a similar vein, Grubb et al. [11] found that the addition of CG to dredged material (DM) caused significant improvements in the physical properties of DM, including reduction in moisture content, organic content, and plasticity index as well as coarsening the grain size distribution. They found that the addition of CG to DM caused significant improvements in CPT results and using CG is more economical than other methods of DM stabilization such as using PC.

This paper reports on a laboratory evaluation to stabilize ingredients of CG and sandy soil (SP) with cement as a soil stabilization method and suitability of the blended products as general, embankment, and structural fill materials for transportation, airport, building and land reclamation in urban areas. Increase in the amount of crushed glass in stabilized SP by cement leads to rise in amount of the γ_{dry}, soil strength parameters c and ϕ, relative density, unconfined compressive strength and can also cause decrease in the amount of w_{opt}, which shows these parameters for construction works are suitable for detecting workability.

Soil classification and geotechnical properties

Glass used in this article defined as "postconsumer material" comprised of the mixed colored glass fragments resulting from the breakage of glass containers (predominantly food, juice, beer and liquor bottles) that cannot be reused by bottle manufacturers. The glass was crushed by los angles abrasion machine and sieved through a 12.7 mm (1.2 in.) sieve. Fine fraction of all recycled glass samples was identified as non-plastic material and as such Atterberg limits results could not be obtained. Also, the sand that is used for experiments is Babolsar natural sand, which underlies a densely populated seismic region of the southern coast of the Caspian Sea in Mazandaran, Iran. The reconstituted specimens of the sand were prepared using the bulk samples taken from the borrow pits on the beach. (For more information about the behavior of clean sand Babolsar refer to the articles, [12, 13]).

It was decided to present the aggregation of CG in a way to improve aggregation of sand. Therefore, CG aggregation was proposed according to Table 1. Also, the grain size distributions of CG, SP, and CG–SP blends were determined according to Unified Soil Classification System (USCS). The grain size distribution curves are presented in Fig. 1, and the percent gravel and sand are summarized in Table 1. As expected, the grain size distribution of the SP grew progressively coarser with the addition of CG. The smaller the size of crushed glass particles becomes, the more they are similar to the shape of natural aggregate. This means that larger glass particles are more flaky shaped and, consequently, more similar to their original shape before being crushed.

With regard to SP aggregation, according to previous studies on soil stabilization with cement, it was decided to use 3, 5 and 10% of Portland cement (PC) type 2 for stabilization.

Compaction characteristics

Compaction is an important construction criterion since all engineered fills are compacted in some fashion, and the compaction effort is monitored for quality control [7]. Dry density and optimum water content are controlled to achieve proper compaction. In

Table 1 Classification of SP and CG–SP blends

Description	Gravel (%)	Sand (%)	Fines (%)	USCS
Sand	0	99.81	0.19	SP
10/90 (G/S)	4	94.7	1.3	SP
30/70 (G/S)	9	88.6	2.4	SP
50/50 (G/S)	15	81.3	3.7	SP

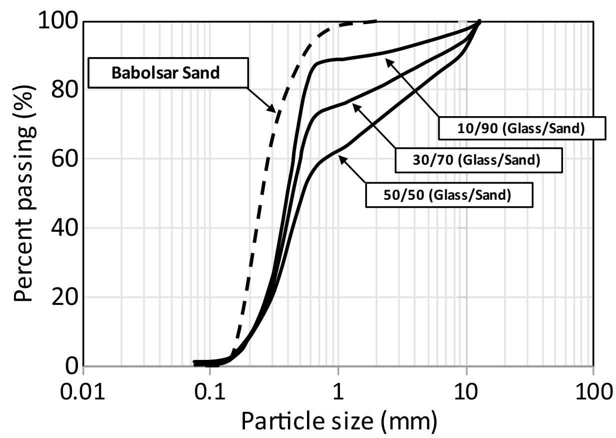

Fig. 1 Grain size distribution for CG, SM and CG–SM blends

this study, laboratory moisture–density relationships were developed for stabilized SP and CG–SP blends following the standard proctor method, ASTM D698 [14], using five or six moisture–density points. Table 2 summarized the maximum dry densities ($\gamma_{d,max}$) in SI (kN/m^3) unit, and the optimum moisture content (w_{opt}). Also, Fig. 2a–c, shows the compaction curves for 3, 5 and 10% of PC efforts, respectively. It was observed that the dry density increased in all samples with increase in cement content. This was due to the basic fact that the soil–cement mix might have difference in specific gravity than the original one.

Optimum water contents ranged from 9.8 to 14.9% and maximum dry density ranged from 16.6 kN/m^3 as glass content increased (i.e., maximum dry density as a function of moisture content for a fully saturated sample). With increased CG content, the w_{opt} decreased and the $\gamma_{d,max}$ increased, and the shape of the compaction curve was treated toward those associated with conventional coarse solids and aggregates.

The flatness of the curves suggests stable compaction characteristics and good workability over a wide range of water content given that crushed glass is relatively insensitive to moisture content. The trends in the lines of optimums for the CG–SP blends are summarized in Fig. 3. The impact of CG on compaction characteristics of 100% SP was clearly evident. The fine cement particles influenced the compatibility of soil–cement material. This soil–cement interaction resulted in the cementitious products and its gained strength.

Table 2 Compaction and properties of stabilized SP and CG–SP blends

Description	Stabilized with 3% cement		Stabilized with 5% cement		Stabilized with 10% cement	
	$\gamma_{d,max}$ (kN/m^3)	$\omega_{opt\,(\%)}$	$\gamma_{d,max}$ (kN/m^3)	$\omega_{opt\,(\%)}$	$\gamma_{d,max}$ (kN/m^3)	$\omega_{opt\,(\%)}$
Sand	16.6	14.93	16.9	14.75	17	14.94
10/90 (G/S)	17.24	12.75	17.48	13.12	17.73	13.35
30/70 (G/S)	18.17	10.26	18.74	10.95	19.44	11.61
50/50 (G/S)	18.71	8.78	19.52	9.82	20.66	10.6

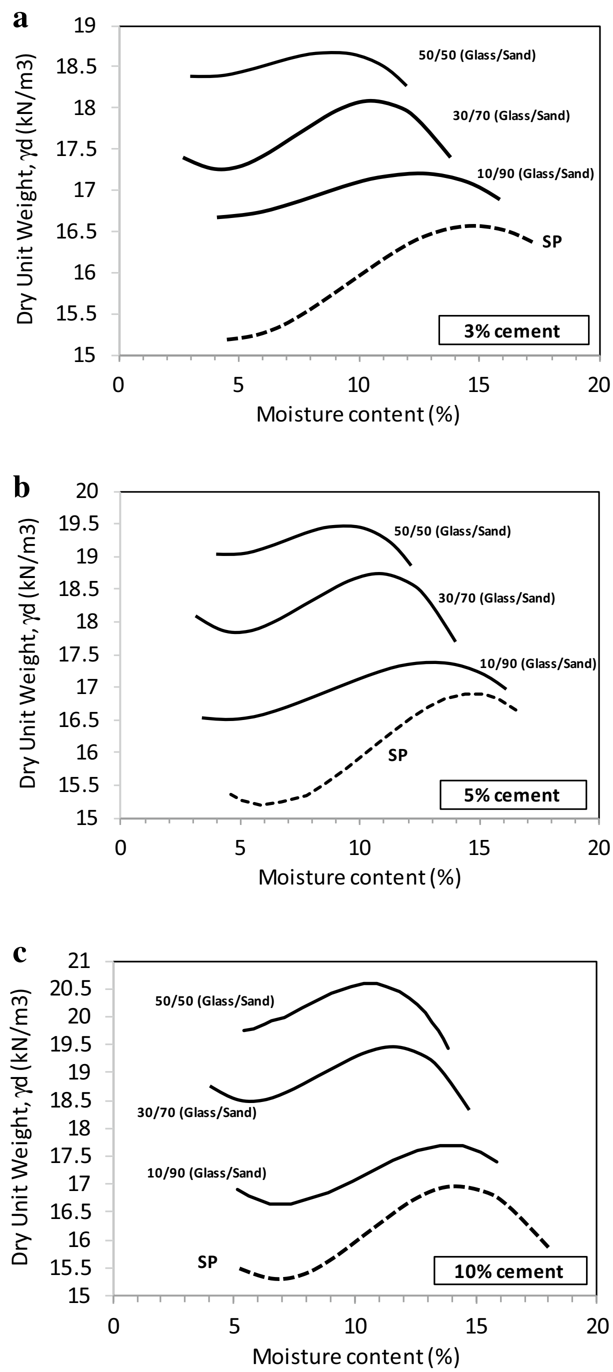

Fig. 2 Standard Proctor compaction for **a** 3%, **b** 5%, **c** 10% cements stabilized SM and CG–SM blends

For example, increasing in the amount of cement from 3 to 10% could contribute to increase in the sandy soil $\gamma_{d,max}$ from 16.6 to 18.71 kN/m^3 (about 3%). While this proportion of cement, Addition of the crushed glass in mixed 50% CG–SP will increase amount $\gamma_{d,max}$ from 18.71 to 20.66 kN/m^3 (approximately 11%).Therefore, (as shown in Fig. 3) the values of $\gamma_{d,max}$ increased in a nearly linear fashion with CG increment, which

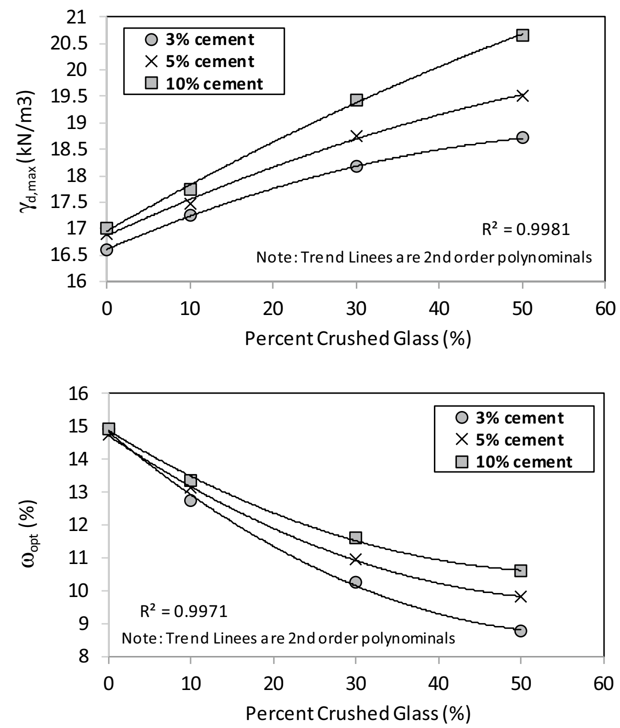

Fig. 3 Line of optimums for cement stabilized SM and CG–SM blends

showed that the CG–SP blends were denser than the individual material. Also, during the compaction tests, it is probable to crushed the CG under hammer load. Associated this subject in laboratory, it was revealed that the amount of particles crushable due to compaction test was negligible (around 2%).

Direct shear strength testing

Direct shear test was performed on stabilized SP and CG–SP blend samples in general in accordance with ASTM D3080 [15] standard. According to Disfani et al. [16] the specimens for direct shear tests were compacted in three layers inside the shear box using a rubber-tipped tamping rod following wet compaction method (partially saturated). Generally, the degree of compaction to be applied during preparation of a soil specimen for direct shear test depends on the relevant field compaction control requirement [17]. The selected normal stresses and confining pressures corresponded to shallow to moderate depth overburdened the conditions. The test results are summarized in Table 3. Also Fig. 4 shows the strength parameters' curves for 28 days curing. Samples were allowed to consolidate under the applied normal stress for few hours under the saturated condition. Afterwards, a displacement controlled shear phase at a rate of 0.5 mm/min was applied. It took about 15 min for samples to reach failure/peak shear stress.

Figure 4 shows the variations in friction angle and cohesion as a function of CG for each blend. As expected, the stress friction angle and cohesion of the blends generally increased with addition of CG. The coefficients of variation (R^2) are extremely close to 1, which indicates that the regressions fit the data well. The friction angle (φ) of the

Table 3 Direct shear test strength parameters of stabilized SP and CG–SP blends

Description	Stabilized with 3% cement		Stabilized with 5% cement		Stabilized with 10% cement	
	c (κPa)	φ (degree)	c (κPa)	φ (degree)	c (κPa)	φ (degree)
Sand	18.2	37.2	21.1	41.3	47.7	59
10/90 (G/S)	26.2	41.1	32.7	44.3	52.1	68.8
30/70 (G/S)	35.3	52.8	42.2	59.4	–	–
50/50 (G/S)	36.7	53.78	46.7	61.1	–	–

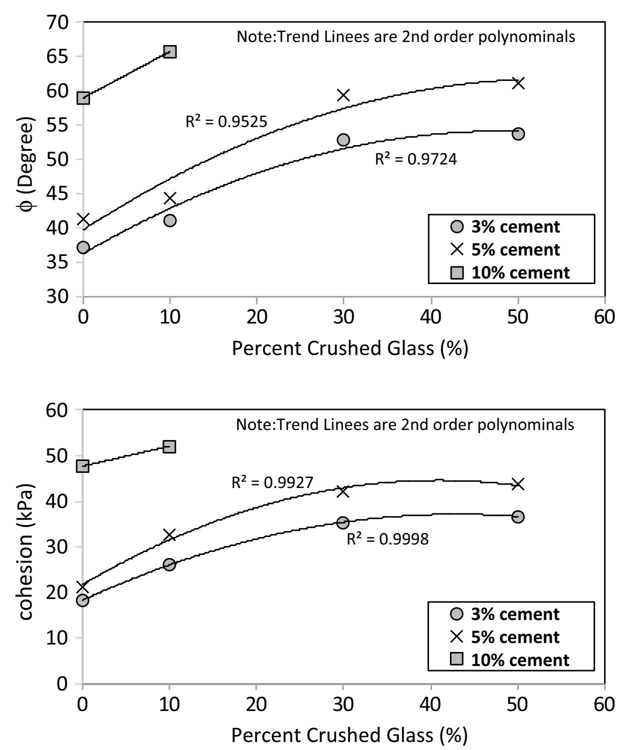

Fig. 4 Strength parameters (φ, c) for stabilized SM and CG–SM blends

stabilized SP increased significantly as the percentage of CG increased. Considering that CG aggregates have sharp corners, by addition of CG, fastening between aggregates grew up, and the adhesion between the aggregates may also increase the shear resistance.

Also, the cohesion (c) of stabilized SP increased significantly as the percentage of CG increased, which can be due to pozzolanic reaction between the cement and fine particles of glass (see Fig. 4). Glass powder (finer than 0.0725 mm) can act like a pozzolanic material adjacent cement. But as seen in Fig. 4, maximum increscent in c occurred by adding 30% (almost) CG for the higher percentages of CG cohesion will be decreased. However, the results of the obtained friction angle and cohesion were somewhat unusual.

As seen, the failure does not happen in specimens containing 30 and 50% crushed glass and stabilized SP at 10% cement (These points are not plotted in Fig. 2), and it would be considered due to the high resistance of these samples. Also, for samples stabilized with 3 and 5% cement, increasing the amount of crushed glass from 30 to 50% does not bring a major difference in the angle of friction and adhesion sandy soil (<2 and 5%, respectively). Therefore, we can say the best amount of glass to be used in the tests is 30%, and more than this does not exert any effect on behavior and sample resistance. Wartman et al. [10] suggested that the impacts of CG on the strength of fine-grained soils may be delayed until the CG particles cease floating in the fine-grained matrix and develop particle-to-particle interactions, which, subsequently, dominate strength.

Uniaxial and triaxial tests

Unconfined compressive strength and drained triaxial shear tests have been conducted on the stabilized SP and CG–SP blend specimens after curing at 28 days to evaluate their uniaxial compressive (q_u) and compressive shear strengths.

Unconfined compressive tests performed on SP and CG–SP blend specimens in general accordance with ASTM D2166 [18]. Sample size for the experiments was 49 mm diameter and 98 of length. The specimens were loaded at a rate of 1 mm/min. The test results are summarized in Table 4 and represented in Fig. 5.

As seen in figure, the addition of CG caused a significant increase in unconfined compressive strength values (q_u) of stabilized SP. On the other hand, by increasing the amount of cement from 3 to 10%, the rate of increase (mutation rate) in unconfined compressive strength surprisingly decreased. As for the samples stabilized with 3% cement, the unconfined compressive strength for sandy soil is 3.9 kN/cm^2. By adding 50% crushed glass to it, the resistance increases to 16.4 kN/cm^2 (about 4.3 times), while this ratio increases 3.7 and 3.4 times respectively for 5 and 10% cement. This may be

Table 4 Unconfined compressive strength parameter of stabilized SM and CG–SP blends

Description	Stabilized with 3% cement q_u (kg/cm^2)	Stabilized with 5% cement q_u (kg/cm^2)	Stabilized with 10% cement q_u (kg/cm^2)
Sand	3.9	5.2	8.21
10/90 (G/S)	6.2	8.1	10.01
30/70 (G/S)	8.1	9.8	14.7
50/50 (G/S)	16.4	19	28.12

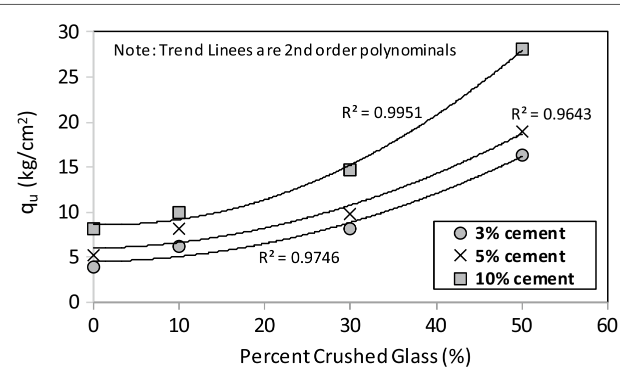

Fig. 5 Unconfined compressive strength for stabilized SM and CG–SP blends

due to the replacement of cement with sand grains and increasing pozzolanic reactions between grains.

In another part of tests, a series of shear strength tests were performed under drained triaxial (CD) compression. The tests were performed on isotropically consolidated specimens using an automated triaxial testing, control and acquisition system. The tests were performed at effective confining pressure level of 210 κPa. The remolded specimens were placed in thin lifts and were compacted using a rubber-tipped pestle to at least 90% of maximum dry unit weight and within ±5% difference with the optimum water content obtained in standard compaction tests. The rubber membrane having 0.3 mm thickness was kept in position by applying suction between the mold and the membrane. A low level of vacuum was applied to the specimen, and then sample height and diameter were measured. The target height and diameter of samples were tried to be 100 and 50 mm, respectively (ratio of 2). There is a high possibility of puncturing the membrane by sharp angular glass particles during placement and compacting. To avoid this, the desired unit weight was kept around 90%, the outside of the first membrane was covered with a thin layer of silicon grease, and a second membrane was placed on top of the first one [16]. The cell was installed, and the water supply was opened to fill out the cell with water the confining pressure of about 10 κPa was applying while the vacuum was removing simultaneously. The sample was blowing with carbon dioxide for easier saturation. (e.g., to obtain a good degree of saturation, the technique of carbon dioxide worked out by Lade and Duncan [19] was used). Then, de-aired water was flushed through the sample, and a prescribed back pressure was applied to achieve the 95% or more saturation. After consolidation, the specimens were tested under a strain-controlled loading rate of about 1 mm/min to axial strain of approximately 25%, yielding a typical time to failure of about 20 min. Also, Fig. 6 shows prototyping process for Babolsar sand.

Figure 7 shows the behavior deviatoric stress and volumetric strain as a function of axial strain for stabilized SP with 5 and 10% of cement and combining CG–SP in an effective confining pressure round show 210 κPa. As seen, the deviator stress gradually reaches a peak value and then levels off to a slightly lower residual value (Fig. 7a). And in connection with it, a volumetric strain volume decreases in small amount at first, (contractive) and then, with continuing tests, shows increasing the volume (dilative) (Fig. 7b). CG–SP blends and stabilized SP such behavior is similar to the behavior of dense sand [20]. Also, these figures show samples stabilized by 5% cement with dash lines and samples stabilized by 10% cement with bold lines. Increase in percentage of crushed glass can make major increase in shear resistance and dilatation in samples. For example, increasing cement from 5 to 10% in sandy soil samples increases shear resistance by 30% and, in relation with that, increasing crushed glass in stabilized sand samples in amount 10, 30, 50% increases shear resistance in order about 70, 98, 244%.

Conclusion

The results of this laboratory evaluation of blending crushed glass and sandy soil indicated that blending CG with cement stabilized SP can significantly improve the properties of the stabilized SP by adding CG as little as 10%.

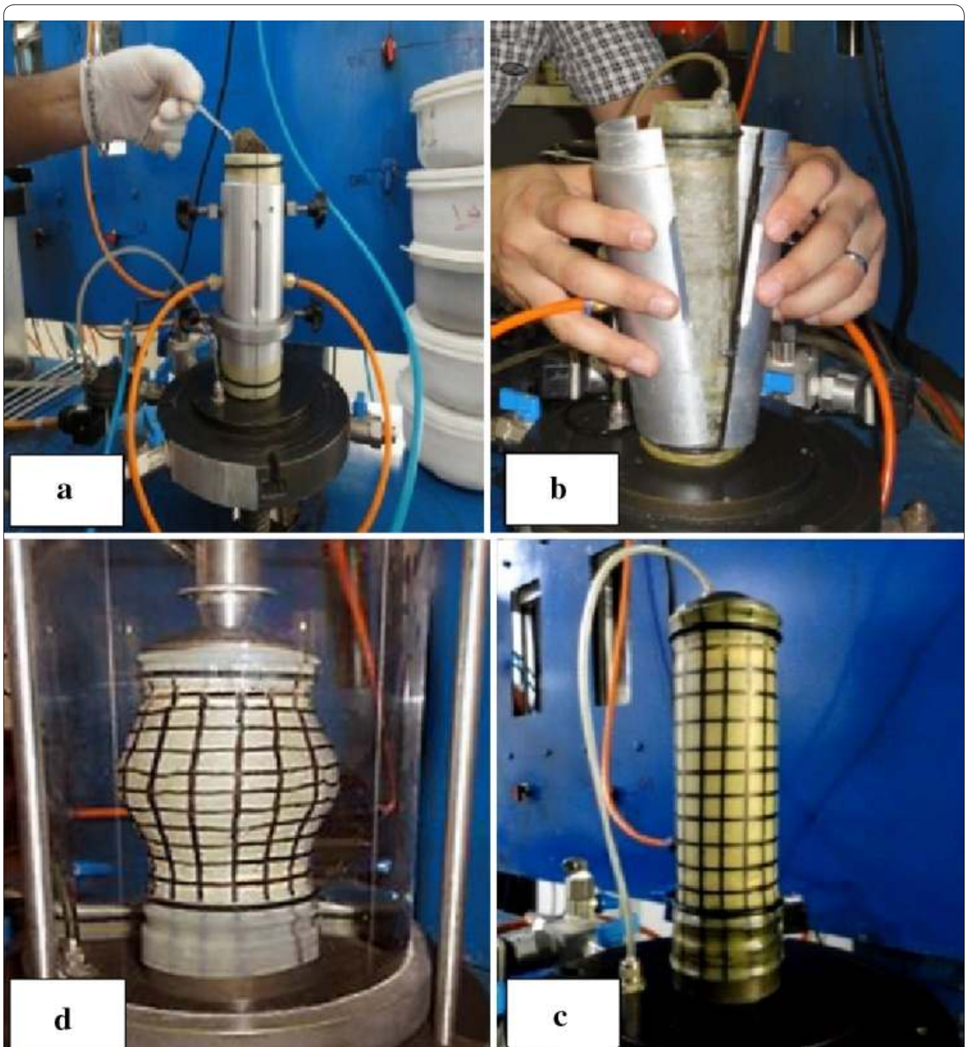

Fig. 6 The process of sample preparation (**a**) pouring sand into mold, (**b**) open the mold and applying suction to sample maintenance, (**c**) prepare samples for testing and (**d**) at the end of the test specimens deformed

Therefore, by adding a percentage of crushed glass, some mechanical properties of soil in embankments as a viable alternative materials, transportation, airports, marine structures and redevelopment in urban environments used can be improved.

The significant findings are summarized below:

1. The addition of CG caused improvement in the physical properties of SP, including reduction in moisture content as well as coarsening the grain size distribution. There were increase in $\gamma_{d,max,}$ and corresponding decrease in w_{opt} for all cement stabilized CG–SP blends.
2. Increasing crushed glass in sand combination stabilized by cement increases dilatation of samples, (due to the increased density) as change in amount of crushed glass from 10 to 30%, increases shear resistance in dried triaxial test about 98%.

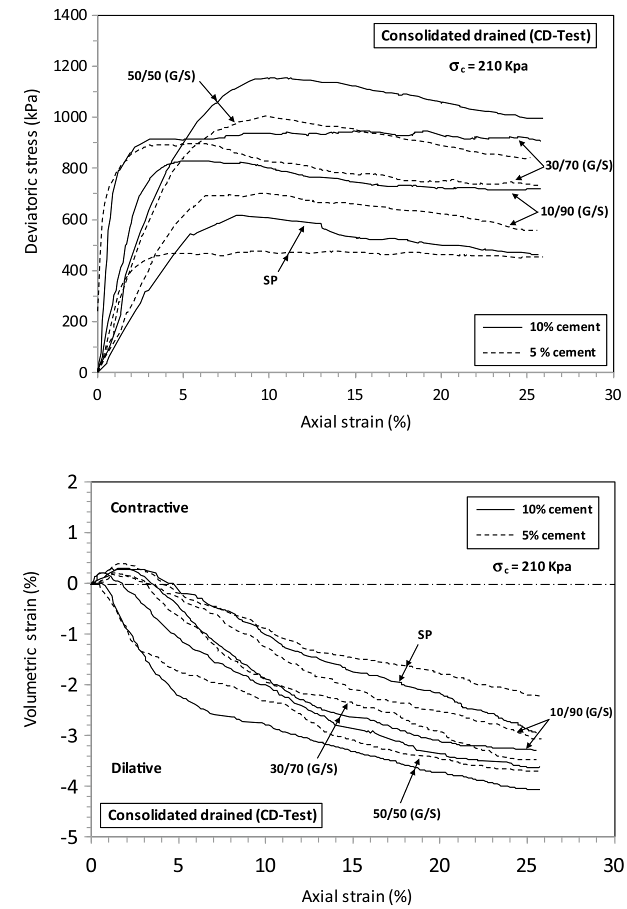

Fig. 7 CD triaxial shear test results for 5 and 7% cement stabilized SP and CG–SP blends

3. Direct shear test indicated that the best amount of crushed glass is 30% for use in sandy soils and does not affect the soil resistance parameters c and ϕ increases more crushed glass.
4. Addition 50% crushed glass to sandy soil stabilized by 10% cement increases unconfined compressive strength (q_u) 3.4 times. However, if in this combination the amount cement is replaced with 3% of cement, the amount of q_u will increase 4.3 times.

In conclusion, the range of properties obtained by cement stabilized CG–SP blends offer the designer a versatility to utilize different properties of CG and SP to potentially optimize on several design parameters such as percentages of CG or PC, CG grain size, etc. or even in different fill areas of the same site. This versatility can increase the beneficial use of CG and SP as fill materials, road bed, embankments and general for engineering applications.

Abbreviations

φ: friction angle; σ'_c: effective confining pressure; $\gamma_{d,max}$: maximum dry densities; c: cohesion; q: deviatoric stress; q_u: unconfined compressive strength; R^2: coefficient of variation; w_{opt}: optimum moisture content.

Acknowledgements

The authors sincerely appreciate Mr. Haghshenas for giving the laboratory data for doing this research project. Also, the last author especially thanks Mrs. Parvin Alian for financial and intellectual support during this Project.

Authors contributions

Sina Salamatpoor has contributed on conception and design of the study, as well as acquisition, analysis and/or interpretation of data; Siavash Salamatpoor has drafted and revised the manuscript. Both authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Received: 23 October 2016 Accepted: 31 March 2017
Published online: 28 April 2017

References

1. Tam VWY, Tam CM (2006) A review on the viable technology for construction waste recycling. J Resour Conserv Recycl 47(3):209–221
2. Arulrajah A, Piratheepan J, Aatheesan T, Bo MW (2011) Geotechnical properties of recycled crushed brick in pavement applications. J Mater Civ Eng 23(10):1444–1452
3. Arabani M, Sharafi H, Habibi MR, Haghshenas E (2012) Laboratory evaluation of cement stabilized crushed glass–sand blends. Electron J Geotech Eng 17:1777–1792
4. Austroads (2009) Guide to pavement technology. Recycle Mater. Part 4E. Publication No. AGPT04E/09, New South Wales
5. Wartman J, Grubb DG, Nasim ASM (2004) Select engineering characteristics of crushed glass. J Mater Civ Eng 16(6):526–535
6. Younus Ali MM, Newman G, Arulrajah A, Disfani MM (2011) Application of recycled glass-crushed rock blends in road pavements. Aust Geomech 46(1):113–122
7. Landris TL, Lee Jr (2007) Recycled glass and dredged materials. US Army Corps Eng Eng Res Dev Cent report no. ERDC TNDOER T8 Mississippi
8. Dupas J, Pecker A (1979) Static and dynamic properties of sand–cement. J Geotech Eng 105(3):419–436
9. Kukko H (2000) Stabilization of clay with inorganic by-products. J Mater Civ Eng 12(4):307–309
10. Wartman J, Grubb DG, Strenk P (2004) Engineering properties of crushed glass soil blends. In: Yegian MK, Kavazanjian E (eds) Geotechnical engineering for transportation projects. pp 732–739
11. Grubb DG, Davis A, Sands SC, Carnivale M, Wartman J, Gallagher PM, Yigang L (2006) Laboratory evaluation of crushed glass–dredged material blends. J Geotech Geoenviron Eng 132(5):562–576
12. Jafarian Y, Ghorbani A, Salamatpoor S, Salamatpoor S (2013) Monotonic triaxial experiments to evaluate steady-state and liquefaction susceptibility of Babolsar sand. J Zhejiang Univ SCIENCE (A) 4(10):739–750
13. Salamatpoor S, Salamatpoor S (2014) Evaluation of Babolsar sand behaviour by using static triaxial tests and comparison with case history. Open J Civ Eng 4:181–197
14. American society for testing and materials (ASTM) (2000) Standard test methods for laboratory compaction characteristics of soil using standard effort. ASTM D698-00
15. American society for testing and materials (ASTM) (2004) Standard test method for direct shear test of soils under consolidated drained conditions. ASTM D3080-04
16. Disfani MM, Arulrajah A, Bo MW, Hankour R (2011) Recycled crushed glass in road work applications. Waste Manag 31:2341–2351
17. BSI (1990) Methods of test for soils for civil engineering purposes. Shear strength tests (total stress), part 7. British Standards Institution, pp 1377–1387
18. American society for testing and materials (ASTM) (2006) Standard test method for unconfined compressive strength of cohesive soil. ASTM D2166-06
19. Lade PV, Duncan JM (1973) Cubical triaxial tests on cohesionless soil. J Soil Mech Found Div 99:793–812
20. Cosentino PJ, Kalajian E, Shieh CS, Heck HH (1995) Developing specifications for waste glass and waste-to-energy bottom ash as highway fill materials (waste glass). Florida Institute of Technology Report, Florida Department of Transportation, report no. FL/DOT/RMC/06650-7754