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Improvement of the strength of soils which comprises granular pumice by injection of cement under low pressure

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Abstract. In this study, improvement of granular pumice soils strength by injection method in Nevşehir City (Turkey) was investigated. In the first phase of the study, the geotechnical properties of granular pumice soils were investigated. The specific density, dry unit weight and water absorption value increased with the decrease of grain size. Thus, it can be seen that the bearing capacity of pumice varies depending on the grain size. In the second level, changes in strength of unconfined compression of injected pumice samples were analysed. The samples taken from the field were prepared to 35, 65 and 85% density, relatively. Pressure of 100 kPa and water/cement ratio of 1.0 was applied to these test samples and the samples were allowed to be cured for a period of 7 and 28 days. The results of the study showed that injected pumice soil reached its maximum strength value with 35% relative density and reached its minimum value with 85% relative density. At the end of 28 days curing period, injected pumice soils prepared with 85% relative density have an equivalent strength to C8 concrete class, and grouted pumice soils prepared with 35% relative density have an equivalent strength to C12 concrete class.

1. Introduction

Pumice is found as a granular and clast material in nature. Granular pumice deposits exist in many parts of the world and Turkey. This type of soils is formed as a result of a series of volcanic explosions. The pumice material which spread wide are, spread larger areas by the way of the winds and the rivers. In our age, pumice deposits exist mainly as deep sand layers in river valleys and flood plains, but are also found as coarse gravel deposits in hilly areas. Interest in these materials stems from the softness of the grains compared to more usual sands, the low densities and the high void ratios [1].

The pumice deposits are characterized by the vesicular nature of their particles. Each particle contains a dense network of fine holes, some of which may be interconnected and open to the surface, while others may be entirely isolated inside the particles [2]. While Figure 1 shows a pumice particle, Figure 2 presents a schematic representation of pumice particles [3].

For natural soils, it is easy to estimate void rate with traditional method. Specific density of soil is calculated, and so, it is determined how much space it occupies. Because of its vesicular structure, pumice does not behave like former. Its vesicular structure composes of internal and external voids [4]. This issue makes the calculation of void rate and porosity more difficult. Pumice soils present differences from silica

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Figure 1. Voids within a pumice clast.

Figure 2. Schematic representation of pumice particles.

sands as physical and engineering characteristics when regarded by the geotechnical point of view. These differences are low grain strength, high friction angle grain, void ratio and compressibility. At stresses greater than a few hundred kPa, the stress-strain-strength behaviour of these soils is determined by particle crushing. Grains of pumice sand may be readily crushed on a ground by fingernail pressure. With the exception of calcareous and carbonate sands, grain crushing in geotechnical engineering usually occurs only at high stresses. Particle crushing leads to changes in density and a reduction in the shear strength components due to dilatancy [5]. The granular pumice that spreads over a wide area by the volcanic activity outside the volcanic region creates the soil from the soils which are now residential areas. Pumice soils cause many problems in their area. Regarding the problems that pumice sand cause, it has been encountered soils, which was formerly pumice, in some large geotechnical projects in volcanic region in New Zealand. Liquefaction of these types of sands has been observed during the Edgecumbe earthquake at 1987 [6]. The slope failures have occurred due to the low-density of pumice under the conditions of water in the Tukuyu, region of Tanzania [7]. Big problems had been occurred as a result of landslides in the vicinity of granular deposits of pumice in and around Nepal [4]. Researchers investigated that how much water is in the gaps of pumice and problems caused by them, in terms of slope stability and stabilization in the event of rainfall. As the result of studies, it was discovered that the presence of inter- and intra-particles voids within the pumice is unusual geotechnical materials and they have distinctive behaviours. Improving of geotechnical properties of soils by injection method can be considered as an alternative solution. Injection is a method frequently used in the solution of the problems encountered in geotechnical engineering. Soil injection is used for decreasing permeability of soil, increasing the shear strength and decreasing the deformation of soil. Soil injection is applied by giving the soil mixture to the gaps of soil with pressure, so the gaps in the soil are filled [8]. Permeation injection is probably the oldest and most commonly used injection method in geotechnical engineering [9]. In this injection method, water or air between soil and rock surfaces is replaced by suspension consisting of liquid injection material. The process is designed to prevent the hydraulic fracturing of rock formation and swelling of soil according to the selected pressure. Although many of the injection projects are different and original, most of the permeation injection is done to increase the strength of the formation and reduce or stop the flow of underground water formation [10]. The geotechnical properties of granular pumice soils (sands) were investigated in this study. To increase the bearing capacity of the soil, samples taken from the field were prepared to 35, 65 and 85% density, relatively. Pressure of 100 kPa and water/cement ratio of 1.0 was applied to this test samples and the samples were allowed to cure for a period of 7 to 28 days. Unconfined compression strength of injected pumice samples was analysed. The samples were taken from three different fields of Nevsehir City center in which granular pumice soils exist (Figure 3). The investigated area and soil profile are given in Figure 4. The working area has been located in an urban area and granular pumice layers can be observed in the excavation area of the current construction, as seen in Figure 5, and also most of the construction foundations were settled on this layer.

2. Experimental study

In the experimental study, the sieve analysis, specific density, determination of dry unit weight and determination of water absorption ratio, sink-float test in water, mercury porosimeter, SEM analysis, chemical analysis and permeability tests were conducted to determine the geotechnical properties of pumice.

Figure 3. Area under investigation.

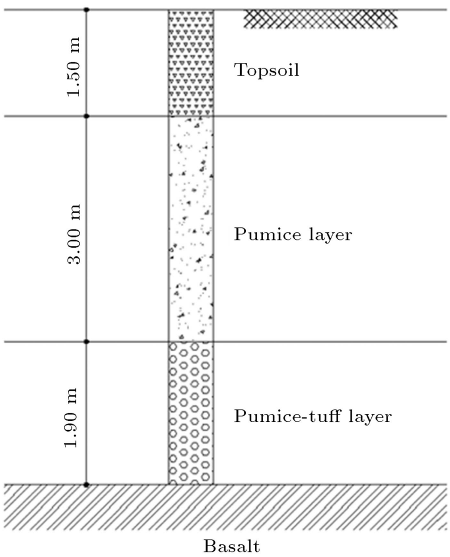

Figure 4. Soil profile for working area 1.

In addition, a study was conducted to improve the properties of the strength of pumice. Cement injection technique has been used as a method of improvement. The aim is to improve the engineering properties of pumice with low-pressure cement injection. Some of these studies were conducted in the laboratories of the Civil Engineering Department of Selcuk University Engineering Faculty while the others were carried out in different institutions.

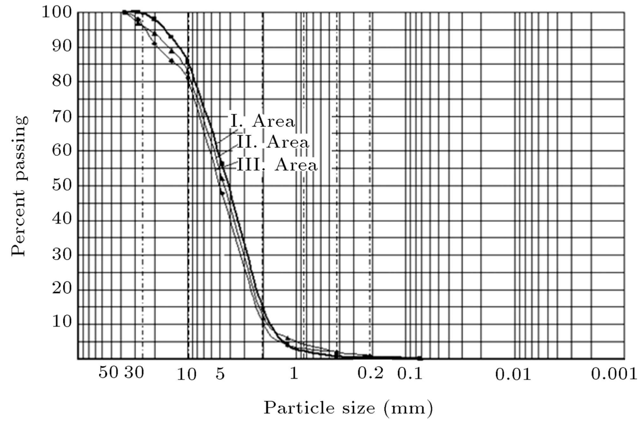

Figure 6. Particle-size distribution curve for granular pumice samples.

2.1. Determining of the geotechnical properties of pumice soil (sand)

2.1.1. Sieve analysis

The sieve analysis was made as shown in ASTM C136-06 [12] to determine the particle-size distribution. The results of sieve analysis, performed on three study areas, were given in Figure 6. Regarding the average values of the granulometric curves, 44% and 56% gravel-sized pumice and sand-sized pumice rate were obtained, respectively; $D_{60} = 5.2$, $D_{30} = 2.8$, $D_{10} = 1.7$, $C_u = 3.06$ and $C_c = 0.89$ were also obtained. According to these values, the pumice soil takes place in SP classification in Unified Soil Classification System.

2.1.2. Determination of specific density

The specific density tests were carried out in three different ways. Firstly, a simple displacement technique was used. The material whose dry weight was known, was poured into a measuring cylinder containing water, and the rise in water level was measured. It was expected that this procedure would minimize the entry of water into the internal voids of the particles. Secondly, a calibrated pycnometer was used without using any vacuum or air extraction method. It was found that these two methods gave virtually identical results. The specific gravity obtained with this method

Figure 5. Working area 1-2.

Table 1. Specific density values obtained for different pumice sizes by using or not using vacuum extraction.

Particle size (mm)	Direct value without vacuum extraction (G_D)	Standard value using vacuum extraction (G_S)
9.51 - 19	0.91	1.82
4.76 - 9.51	0.99	1.84
2 - 4.76	1.50	1.87
1 - 2.00	1.75	1.91
0.5 - 1.00	1.87	1.96

was named "direct" or "displacement" (G_D). Thirdly, measurements were made using the standard procedure with a pycnometer and vacuum extraction of air, which is called ASTM 854-10 [13] standard procedure. The values obtained by this method are the "standard" values (G_S) given in Table 1.

2.1.3. Determination of dry unit weight

The dry unit weight of pumice was determined according to the procedure ASTM C 29 [14]. The results of dry unit weight for specific gravity, porosity and void ratio for pumice samples prepared with different diameters are given in Table 2.

2.1.4. Determination of water absorption ratio

The water absorption ratio of pumice was determined according to the procedure in ASTM C 127-88 [15]. The results of water absorption ratios for different pumice diameters are given in Table 3.

2.1.5. Sink-float test in water

Due to their low gravity weight, the granular pumices may float on water. The sink of pumice particles stems from the intrusion of water into the pores. The relation between time and dry unit weight during the test, which is performed on different pumice samples, is given in Figure 7.

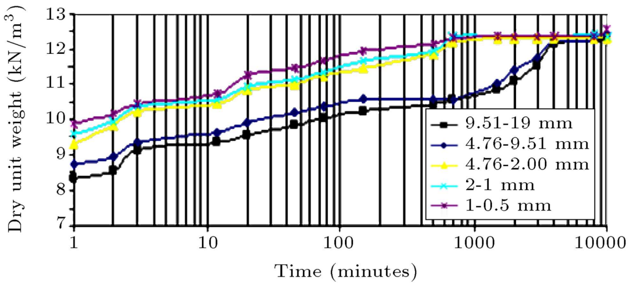

Figure 7. Sink of pumice particles at time for different grain size fractions.

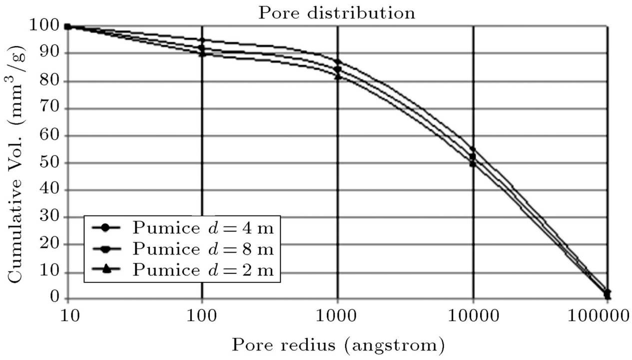

Figure 8. Mercury penetration curve.

2.1.6. Mercury porosimetry experiment

In mercury porosimetry experiment, a particular pressure (P) of mercury entering the pores in the volume (V) is measured. In this experiment, the aim was to determine the size of the pores. This experiment consists of two steps; purifying a material from air, and then coating it with mercury, applying it to high pressure. Three different diameters of pumice particles (8 mm, 4 mm and 2 mm) were tested. The pore distribution curve is given in Figure 8.

2.1.7. SEM (Scanning Electron Microscopy) analysis

The pumice samples taken from the different working areas were analyzed with EDX and WDX detectors

Table 2. The results of dry unit weight, specific gravity, porosity and void ratio for pumice samples prepared with different diameters.

Sieve diameter (mm)	Dry unit weight (kN/m^3)	Specific gravity (standard procedure)	n	e
9.51 - 19	8.35	1.82	0.53	1.14
4.76 - 9.51	8.75	1.84	0.51	1.06
2 - 4.76	9.30	1.87	0.49	0.97
1 - 2.00	9.58	1.91	0.48	0.95
0.5 - 1.00	9.88	1.96	0.48	0.94

Table 3. The results of water absorption ratios for different pumice diameters.

Sieve diameter (mm)	9.51 - 19	4.76 -9.51	2 - 4.76	1 - 2.00	0.5 - 1.00
Water absorption (%)	22.70	28.90	35.60	43.20	52.10

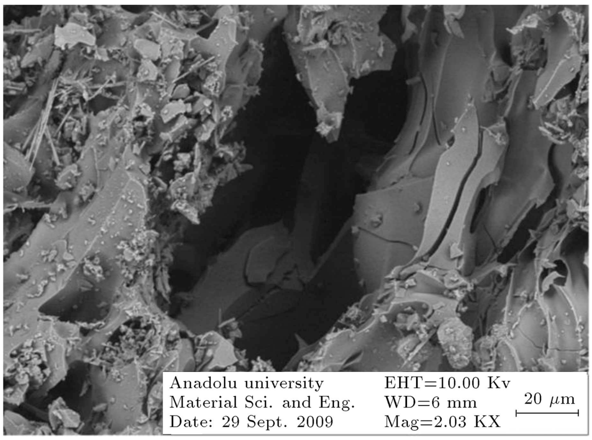

Figure 9. SEM photograph of pumice, taken with Zeiss 50 VP, which has diameter of 6 mm taken from working area 2.

Table 4. Chemical analysis of Nevşehir pumice.

Fe_2O_3	Al_2O_3	CaO	MgO	Na_2O	K_2O	MgO	SiO_2
3.10	14.90	2.90	0.08	4.10	2.75	0.08	68.50

Oxford model and Scanning Electron Microscopy of Zeiss SUPRA 50 VP model in Anatolian University to observe the internal voids inside the samples. The results of analyse is given in Figure 9.

2.1.8. Chemical analysis on pumice

There are two kinds of pumice: acidic pumice and basic pumice. Acidic pumice is the most common pumice type in the world. The most important component in pumice sample is SiO_2 and the percent of SiO_2 changes between 60-70 in acidic pumice [11]. The Chemical analysis was performed to determine the ratio of %SiO_2 in pumice. The chemical analysis of pumice was given in Table 4.

2.2. Permeability test on pumice

The constant head permeability test was carried out in accordance with ASTM D2434-68 [16]. Granular pumice samples were used in the tests. Granular pumice was placed into a limpid cylinder, with the diameter (D) of 15.20 cm and height (L) of 15.20 cm, similar to the relative density of the nature; to prevent the passing of pumice particles, a filter was made above and below the mold. The water that came from the reservoir through a constant water level was collected 1000 cc burette. The amount of water collected in 15, 30, and 45 second was read and recorded, so k (permeability coefficient) was calculated from Darcy's law (Eq. (1)). The figure of the permeability test was given in Figure 10.

$$k = \frac{VL}{AHt}\ (\text{cm/s}), \tag{1}$$

where V is the volume of water collected, L is the length of the specimen, A is the area of cross section of the soil specimen, t is the duration of water collection, and H is the hydraulic water height on the soil sample.

Figure 10. Permeability test on pumice soil.

At the end of the test, average rate of the permeability of granular pumice was found to be 1.44 cm/s. This value changes depending on the particle diameter and relative density of granular pumice in nature. Marks et al. [6] found a permeability value (k) of 0.08-0.4 cm/s within the range about the dynamic properties of pumice in their study.

2.3. Permeation injection test on pumice

Permeation injection is a low-pressure form of cement injection that involves grout injection into voids, fissures and cavities in soil or rock formations in order to improve their properties, specifically to reduce their permeability, to increase their strength and durability, or to decrease their deformability [17].

In this injection technique, injection of low-viscosity material is permeated to the gaps of soil with lower pressures, thus it does not make any changes in the structure of soil. The material injected into the soil hardens over time and thus it modifies the mechanical and hydrological characteristics of the soil. Because the aim is filling the gaps in the soil, injection material is selected as regarding to the particle size [18].

Low-pressure permeation injection is an effective method for increasing the strength and reducing the permeability of coarse-medium-sized soils with low initial stiffness. The most common granular injection material is cement. Pulverized pozzolanic material or clay, and their mixtures with cement are also used. The cement can be used only or with other materials and it can be used as micro cement also. Particle size of cement is eligible to enter the interparticle voids of coarse sand and coarser soils. The water-cement ratio varies from 0.5 to 1.0. Penetration of micro cement to the interparticle voids of fine grained sandy soils has been possible in recent years. Sand-cement, clay-cement mixtures can be injected into the coarse-grained soils.

In this study, using the low-pressure cement injection to improve the resistance of pumice soils is intended. For this purpose, changes of unconfined compression strength of injected granular pumice soils were investigated in the laboratory study. Particle-size distribution curve for granular pumice and experimental setup is given in Figures 11 and 12, respectively.

In this study, a suitable material was selected according to the granulometry of soil in the nature. Regarding to the average values of the granulometric curves, they are 44% and 56% for gravel-sized pumice and sand-sized pumice, respectively.

The laboratory experiments were conducted on

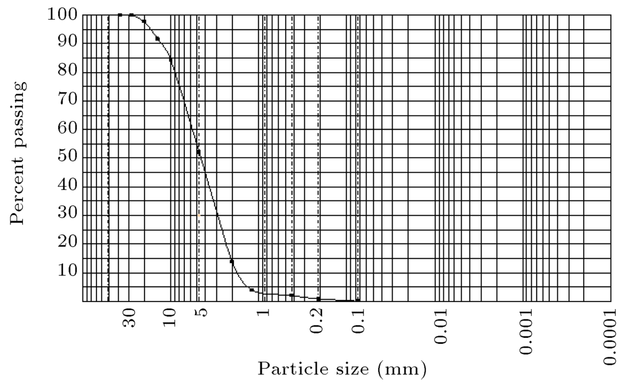

Figure 11. Granulometric curve of pumice type tested.

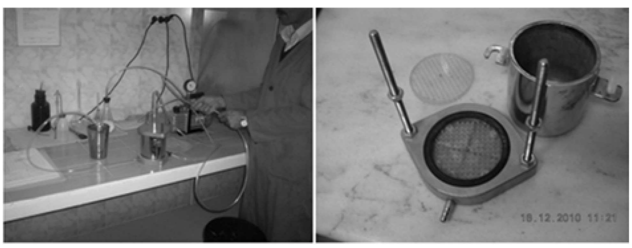

Figure 12. Cement injection test apparatus for pumice soil.

the soil samples which replaced in molds with 35, 65 and 85% density, relatively. The samples were dried at 105°C in the oven. Calculation of the required relative densities was obtained using the equation for relative density:

$$D_r = \frac{\gamma_d - \gamma_{d\min}}{\gamma_{d\max} - \gamma_{d\min}} \times \frac{\gamma_{d\max}}{\gamma_d}, \tag{2}$$

where γ_d is the necessary dry unit weight of the soil sample, and $\gamma_{d\max}$ and $\gamma_{d\min}$ are calculated with the studied soil granulometric curve according to ASTM D-4253 [19] and ASTM D-4254 [20] standards (Table 2), respectively. The weight (W) of the requiring material quantity is calculated according to:

$$W = \frac{V.\gamma_{d\max}.\gamma_{d\min}}{\gamma_{d\max} - D_r.(\gamma_{d\max} - \gamma_{d\min})}, \tag{3}$$

in which V is the volume of the mold in which the sample is placed. By substituting the required relative density (D_r) values, used in the tests, into Eq. (3), the necessary dry unit weight (γ_d) values are calculated.

For the experiment, minimum and maximum dry densities of the samples were found. Since the volume of mold and required density of the specimen are known, relative density were calculated as 35%, 65% and 85% for required sample weight. The sample with calculated weight was poured into the mold with the aid of funnel, and the samples were then placed into the molds through skewers.

Each layer of pumice sample was compacted by rubber hammer not to crush. The cement used in the experiments was an ordinary Portland cement (code CEM2-42.5-R), which was produced by Turkish Nuh Cement Factory. Because of its easy availability and its lasting strength, this particular type of cement was selected. The chemical and physical properties of the cement used in the experimental study are presented in Table 5.

Injection mortar consisted of water and cement ($w/c = 1$) was injected into the molds with the diameter of 10.16 cm and height of 11.25 cm. The injection mortar was composed of 800 gr water and cement mixture for each sample (400 gr water, 400 gr cement). The mortar was injected into pumice soil with the help of vacuum pump at 760 mm/Hg (100 kPa) inverse pressure. For observing the pressure, a manometer was put on the compressor to see the pressure. A filter was placed at the top and bottom parts of the sample to prevent the flow of material. After the injection, the samples were removed from the molds after 1 day hardening period and cured in water at 21°C, over 7 and 28 days curing periods (Figure 13).

At the end of the curing period, the samples were subjected to unconfined compression tests to determine their unconfined compressive strength. The change

Table 5. (PÇ 42.5 R)physical and chemical properties of cement.

Chemical properties	%	Physical properties	
SiO_2	21.35	Specific density, gr/cm^3	3.15
Al_2O_3	4.14	Freezing time, start (Vicat minutes)	182
Fe_2O_3	3.79	Freezing time, end (Vicat minutes)	264
CaO	62.74	Volume stability, Le Chatelier (mm)	2
MgO	1.11	Specific surface, Blaine (cm^2/g)	3504
SO_3	2.57	Passing 50 μ%	92
Undissolvable solids	0.73	Passing 45 μ%	89
Heat loss	1.98	Passing 37 μ%	85
Free lime	0.95	Passing 30 μ%	77
Chloride	0.0087	2 day pressure resistance (MPa)	27.5
Lime standard (LSF)	99.20	7 day pressure resistance (MPa)	46.8
Hydraulic Module (H.M.)	2.25	28 day pressure resistance (MPa)	60.1
Silicate Module (S.M.)	2.46		
Ton module (Al_2O_3/Fe_2O_3)	1.11		
C_3S	61.00		
C_2S	12.57		
C_3A	4.55		
C_4AF	11.81		

Figure 13. a) Pumice soil applied injection in the molt. b) Samples cured in water and room temperature at 7 and 28 days curing periods.

Table 6. Relative density, injection pressure and injection ratio of w/c used in the test.

Relative density (%)	Injection pressure (kPa)	Water/cement ratio
35	100	1.0/1.0
65	100	1.0/1.0
85	100	1.0/1.0

of unconfined compression strength was investigated according to their relative density. Relative density, injection pressure and mixture ratio of w/c were given in Table 6.

3. Test results and discussion

Pumice soil was prepared as samples has 35, 65 and 85% density rate, relatively. These samples were prepared for each relative density as three unit, injection pressure of 100 kPa, and water/cement ratio of 1.0/1.0 was applied to these test samples, which were allowed to be cured for a period of 7 and 28 days. At the end of the curing period, the samples were subjected to unconfined compression tests to determine their unconfined compressive strength. Crest was made at the top and the bottoms of the samples to obtain plain surface, and the samples are loaded rate of 0.85 mm/s. Stress-strain curves of samples were given in Figure 14 with 35% relative density, in Figure 15 with 65% relative density and in Figure 16 with 85% relative density at 7 and 28 days curing periods.

3.1. Evaluation of results

3.1.1. Evaluation of geotechnical properties

The specific density was determined with a calibrated pycnometer in two different ways; without any vacuum extraction (G_D= direct value) and by vacuum extraction (G_S=standard value). Substantial difference between these two values is observed. In addition, as the particle size decreases, the specific gravity increases for each of these two values. The results show similar characteristics with the results of the study of Wesley's [3] on New Zealand pumice. In this study, the specific gravity values increase also with decreasing particle size. The results of dry unit weight are consistent with the literature. As the particle size decreased, the volume value of dry unit weight increased. Esposito and Guadagno [4] calculated the dry unit weight of pumice samples with 16 mm, 8 mm, 4 mm, 2 mm and 0.85 mm diameters. While the dry unit weight of 16 mm pumice was obtained as

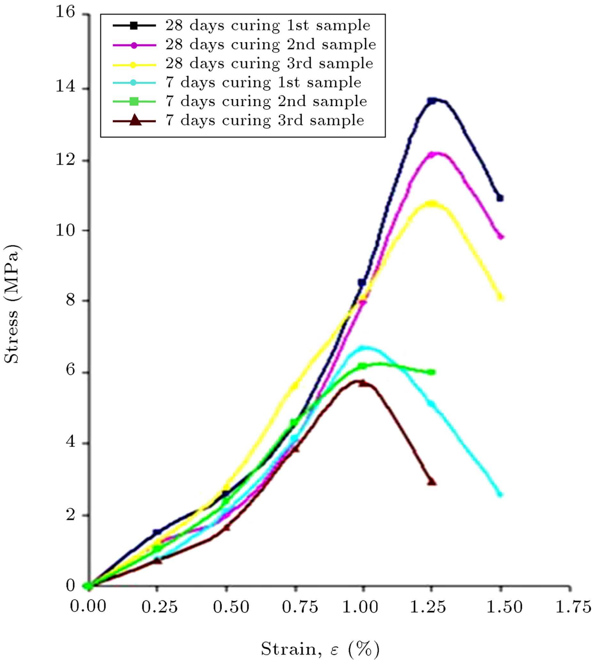

Figure 14. Unconfined compression experiment ($D_r = \%35$).

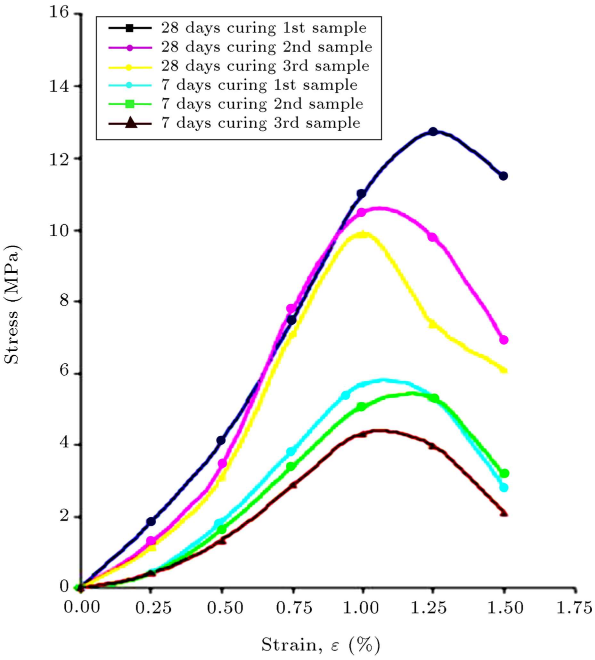

Figure 15. Unconfined compression experiment ($D_r = \%65$).

6.1 kN/m^3, the dry unit weight of 0.85 mm pumice was determined as 7.5 kN/m^3 from the experiments.

For water absorption rates, as the particle size decreased, the value of water absorption increased. Esposito and Guadagno [4] found that the water absorption value as 67% for 16 mm diameter pumice and 70% for 0.85 mm diameter pumice. This difference is related with the structure of pumice.

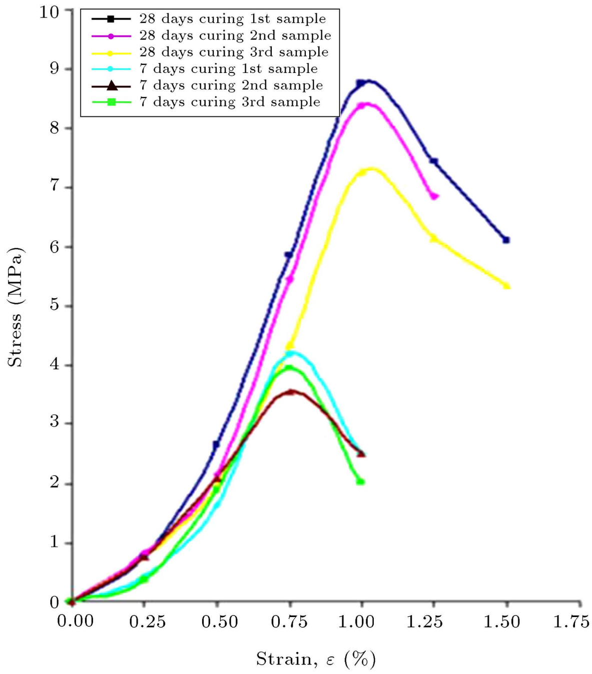

Figure 16. Unconfined compression experiment ($D_r = \%85$).

In Figure 6, different diameters in sink-float test are given for the change in dry unit weight of pumice. As can be seen in Figure 6, the voids of different size pumices were filled with water at the end of 10000 minutes (a period of approximately 1 week), and the dry unit weight increased 1.2-1.4 times.

As shown in the mercury penetration curve of Figure 7, the average values were nearly 10.000 angstrom. 80% of the pores had a radius which was larger than 2000 angstrom.

The SEM analysis was carried out on the size of d=6 mm pumice. As can be seen from Figure 8, there are pores on the surface of pumice. This structure is similar with the internal structure of pumice that Esposito and Guadagno [4] and Sparks [21] also investigated.

The results of the chemical analysis are consistent with the literature, by the geochemical analyses of Başpınar and Gündüz [22] on Nevsehir pumice.

3.1.2. Evaluation of injection experiment results

The average unconfined compression strength of injected pumice soils, which were prepared with three different relative densities (35%, 65% and 85%) and cured over 7 and 28 days, are given in Table 7 and Figure 17.

The highest unconfined compression strength value is 13.56 MPa and this value was obtained from the sample which was prepared as 35% relative density rate and cured over 28 days. This value is approximately equal to the value of C12 concrete class.

As can be seen from the results, unconfined

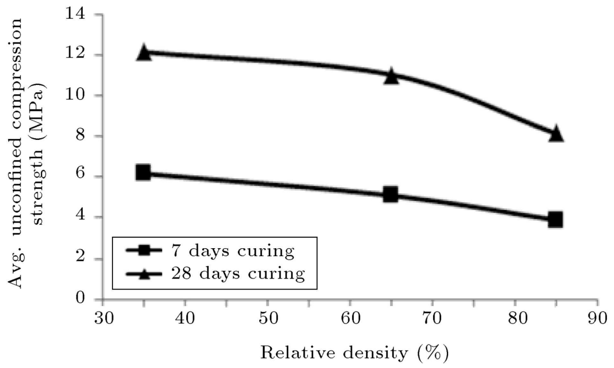

Figure 17. Changing of the average unconfined compression strength of 7 and 28 days cured samples depending on relative density.

Table 7. The average values of unconfined compression strength of 7 and 28 day cured samples.

	Unconfined compression strength (MPa)					
D_r (%)	**7-day-cured specimens**			**28-day-cured specimens**		
	min.	**max**	**avg.**	**min**	**max**	**avg.**
35	5.711	6.661	6.171	10.731	13.568	12.129
65	4.317	5.674	5.093	9.868	12.705	11.019
85	3.552	4.193	3.897	7.277	8.757	8.140

compression strength depends on curing time and relative density. Figures 14-16 show the stress-strain relationship of unconfined compression test samples.

Whereas the effect of curing time on the unconfined compression strength was investigated using the ratio q_{u28}/q_{u7}, the compression strength of the samples cured over 28 days was twice stronger than the compression strength of the samples cured over only 7 days.

At the end of 7 and 28 days of curing, the unconfined compression strength of prepared samples in three different relative densities with 35%, 65% and 85% and with 1.0 w/c ratio by applying 100 kPa injection pressure was obtained stress-strain graphs parallel to each other. The samples were cured for 7 days have 35% relative density cracked at 1.00% strain, while samples cured for 28 days have 35% relative density cracked at 1.25% strain. Similarly, 7 and 28 day cured samples have 65% relative density cracked with 1.00% deformation, 7 day cured samples have 85% relative density cracked with 0.75% deformation, and 28 day cured samples have 85% relative density cracked with 1.00% deformation.

The deformation of a concrete sample, which was subjected to axial pressure, is 2.00% at the time of cracking and this value is independent of the concrete class. Injected granular samples did not behave like a concrete and they can be considered as an intermediate material between soil and concrete [23].

Since the voids in the injected pumice soils, having 35% relative density, are completely filled with cement mortar, test samples behave like a concrete. But, since the cement mortar cannot enter the interparticle voids of the pumice at 85% relative density, the particle crushing determines the stress-strain behaviour of the material, thus the crashing of the sample can be observed at lower deformations and at lower stresses.

In direct proportion to the time, an increase was observed between the unconfined compression strength of 7 and 28 day cured samples at different relative densities. Mutman and Kavak [24] have reached similar results about the improvement of granular soils by low pressure injection. Researchers sieved sand/gravel mixture samples from 4.76 mm, 8 mm, 2 mm, 1 mm and 0.425 mm sieves and mixed the particles retained on these sieves and obtained SP gradation. The strength of 7 day cured samples increased from 4.14 MPa to 7.79 Mpa at the end of 28 days curing when $D_r = 25\%$, 1.0 w/c ratio and $p = 100$ kPa, and it was observed that this value decreased with the increase of relative density.

In our study, the strength of injected pumice soil increased with decreasing relative density. The injected pumice soils reached their maximum strength value when $D_r = 35\%$, and reached their minimum strength value when $D_r = 85\%$. Özgan et al. [25] found similar results for various soil samples with sand/gravel ratio 30/70, 40/60 and 20/80 by using Microcem 900 H type cement. By the result of their study, one is determined that for 28 days the highest pressure strength value is 11.8 MPa for soil samples with sand and gravel ratio is 20/80 when $D_r = 35\%$, and the lowest pressure strength value is 10.5 MPa for soil samples with sand and gravel ratio is 20/80 when $D_r = 70\%$.

Cement injection changed structure of pumice soils significantly. The 1000 times magnified photograph was taken under a microscope to be able to see the porous pumice and cement injected pumice in accordance with standards ASTM C295 [26].

4. Results

As a result of assessing the studies performed, granular pumice soils have an important role in geotechnical materials. Their behaviours are different due to the presence of pores in grains and link between pores. Some of pores in grain may constitute the internal voids like meshes while others were placed on the surface. Comparing with average soil, this can cause differences in the physical and volumetrical parameters as well as in the behaviour of the soils.

The results showed that whereas the grain size of the pumice decreases, the specific density, dry unit weight and water absorption value increase. Thus, it can be seen that the bearing capacity of pumice varies depending on the grain size.

The penetration of water into the particle pores significantly modifies the weight-volume relationship and results in an increase in the weight of the particles. Thus, the slope stability can be an important problem for this type of soil. Therefore, cement injection has considerably changed the structure of pumice. Microscopic results showed that the cement injection is successful for pumice soils. While the relative density of pumice soil decreased, the strength of the pumice increased. Injected pumice soil reached its maximum strength value with 35% relative density and reached its minimum value with 85% relative density.

For a 28 day curing period, injected pumice soils prepared with 85% relative density exhibit an equivalent strength to C8 concrete class, while grouted pumice soils prepared with 35% relative density exhibit an equivalent strength to C12 concrete class. The absence of clay in pumice, which is similar to the sand used in concrete as granulometric, has been effective for obtaining this pressure. It is clear that pumice soils can reach a very high bearing capacity with the injection of cement.

As the voids in the injected pumice soils, having 35% relative density, are completely filled with cement mortar, test samples behave similar to the concrete. As the cement mortar cannot enter the interparticle voids of the pumice at 85% relative density, the particle crushing determines the stress-strain behaviour of the material, thus the crashing of the sample can be observed at lower deformations and stresses.

When the stress-strain relationship of the samples, cured over 28 days and prepared with different relative densities, was under investigation, the crushing usually occurred in the range of 1%-1.25% deformation rate and, thus, it was concluded that the structure of pumice has a more important role in the crushing than the amount of cement.

For normal concrete, the maximum strain is around 0.002 independent of the concrete strength. For a %35 relative density, the strain of the samples cured for 28 days was observed to be equal to C12 concrete, which had an approximately 1.25% deformation rate.

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The data used in this paper is taken from the PhD thesis of Ali Sinan Soğancı entitled "Determination of the geotechnical properties of the pumice type soils in Nevsehir region in terms of load-bearing capacity and settlement and their stabilization" [27].

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Biographies

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