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The mechanical properties of the expandable polyurethane resin based on its volumetric expansion nature

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Abstract. The expandable polyurethane resin is an innovative material used in the field of soil stabilization and foundation restoration. The injection technology using the expandable polyurethane resin is an effective way that raises the foundations rapidly, strengthening the soil beneath. Nevertheless, different technical aspects have not been studied yet, which might affect the lifting and stabilization process, such as the density of the resin formed in the massive of the injected soils. The density of the resin formed in the massive of the injected soils during the injection process is varied due to the expansion nature of the resin when mixed proportionally controlled by the amount of the injected resin, the injection pressure, the injection temperature, and other factors. Obviously, the differences in resin densities lead to a variation of the resin mechanical properties; consequently, it affects the desired lifting and strengthening results gained. The article demonstrates the results of a laboratory experiment that has been conducted to investigate the mechanical properties of an expandable polyurethane resin consists of two components based on its volumetric expansion ratios controlled by the amount of the injectable resin. The density of the resin gained for each expansion ratio has been obtained and given in this article. The stress-strain diagrams of the resin for various densities and expanding ratios are incorporated. The results were interpreted, and the strength-density relationship of the resin has been established and introduced.

1. Introduction

The expandable polyurethane resin is an expansive material consists of two-liquid components which can be injected into the soil massive using a hydraulic system. Component A represents a polyol, while component B is mainly isocyanates. However, each component contains additives in its composition according to the manufacturers of the material [1–10]. When the resin is injected into the soil massive under high pressure, it expands and propagates in the hydrofracturing mode, leading to compact the surrounding soil, altering its properties. Thus, it leads to strengthening the injected soil, increasing its bearing capacity, besides the rapid lifting of the foundations gained through the propagation and expansion process of the resin [1–3, 11, 12].

The main uses of the expandable polyurethane resin are foundation lifting and soil compaction. However, it is also used for extruding the undesired water from the soil cavities and as injectable barriers to control the groundwater level [1, 2, 15, 16, 3, 4, 6–8, 11, 13, 14].

This resin is capable of expanding up to 30 times its original volume in non-restricted volumes due to the chemical reaction of the mixing components. When the resin is injected into the soil massive, it forms in various densities based on its mixing amount when combined in volumetrically established proportions. Several factors affect the actual density formed in the injected soil's massive, such as the amount of the injected resin, the injection pressure, the injection temperature, and the type of the injected soil itself. The exothermic reaction between its components produces the expansion process of the resin [1, 17, 18].

During the injection process, the volumetric expansion of its mixture occurs due to the chemical reaction between the resin's components, which produces a large amount of carbon dioxide, leading to form a porous structure. The water is required to fulfill the production of carbon dioxide as it reacts with the isocyanates

group. In the absence of water, a chemically inert swelling agent with a low boiling point is used, which is a vaporized consuming part of the polymerization heat [1–3, 10, 19–21].

The resin mixture changes from a liquid to the solid-state and hardens in the soil massive within several seconds. The reaction time, which depends on the amount of the injected resin and the catalysts used, is influenced by the mixing temperature of the components and the controlled injection pressure in the hydraulic system. In practice, controlling the mixing temperature, lead to speed up or slow down the reaction time, while, the injection pressure lead to ease the flow of the material in the soil massive [1–3].

The low viscosity and liquidity of the resin ensure easy penetration into any soil type, when hardened, compact the surrounded soils, and displacing water without a negative impact on the structure and the stability of the injected resin properties [1–3].

2. Methods and Materials

2.1. The aim of the experiment

A laboratory experiment was conducted to investigate the strength-density relationship of an expandable polyurethane resin consists of two components for various densities, formed based on its volumetric expansion nature controlled by the amount of the injectable resin. Resin samples of different densities have been prepared based on the injected weight of the resin, considering its volumetric expansion, determined the density, and the stress-strain state of the resin using the uniaxial compression test. Thereby the relationship between the strength characteristics and the density of the resin formed according to prespecified volumetric expansion ratios was established. The investigated resin in the experiment is called (MC-Montan Injekt LE) produced by the company MC-Baucheime.

2.2. Samples preparation

Seven PVC cylindrical tubes with a special valve were used to model the resin samples of various densities in the laboratory environment. The valves were pre-welded to each tube to prevent the resin's overflowing during the injection process, as shown in Fig. 1. The volumes of the tubes used are constant, as given in Table 1.

Table 1. The dimensions of the tubes used.

Tube length	900 mm
Inner tube diameter	42 mm
Tube volume	1246898.124 mm^3

Figure 1. The injection process during the laboratory investigations.

The resin was injected into each tube using a particular injection pistol according to the mixing ratio (2:1) of both A and B components, respectively. Extraneous external pressure was not used to ensure resin supply to the tubes. That is, the injection process was carried out through the pressure arising as a result of a chemical reaction during the expansion of the composite components, which is a natural property of the material used.

The resin was introduced into each tube according to a sequential decrease in the weight of its components, which led to forming different densities samples by occupying the full fixed volume of the tube, due to volume expansion of the substances.

After the formation of the resin in the tubes, the resin remained in the tubes to fulfill the hardening process, allowing the resin to gain its maximum mechanical properties. Further, each tube was cut to five cylindrical samples of approximate fixed sizes (Diameter = 4.25 cm, Length = 10 cm).

The prespecified resin expansion ratios and the mixing weights of its components are given in Table 2.

Table 2. The resin expansion ratios and the mixing weights of its components used.

The expansion ratios of the resin	Number of samples tested	The total amount of resin used, Gramm	Amount of component A, Gramm	Amount of component B, Gramm	Reaction time, Seconds
3	5	416	277	139	4
4	5	312	208	104	4
6	5	208	139	69	5
8	5	156	104	52	6
10	5	125	83	42	8
12.5	3	100	67	33	12
15	5	84	56	28	29

The reaction time of the injected resin increases in direct proportion to the weight of the components used; however, this relationship is nonlinear, as shown in Fig. 2. The volumetric expansion of the injected resin decreases in direct proportion to its weight; however, this dependence is also non-linear, as shown in Fig. 3.

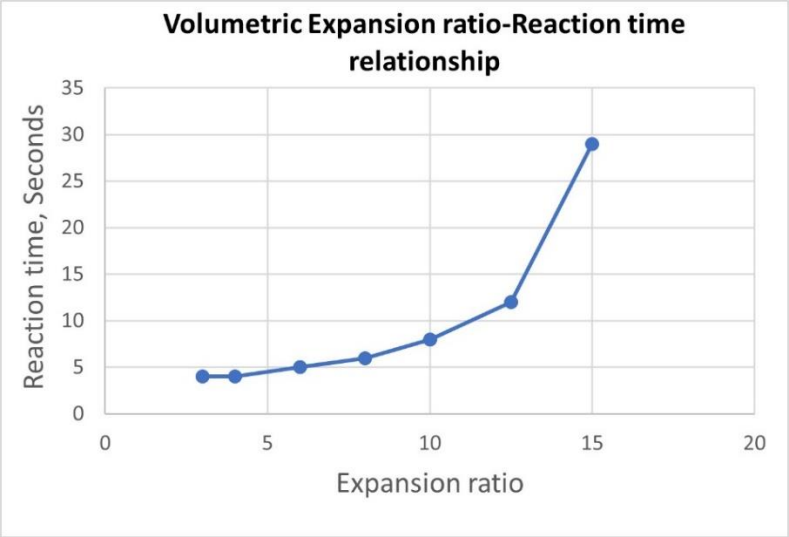

Figure 2. The relationship between the chemical reaction time and the volumetric expansion ratio.

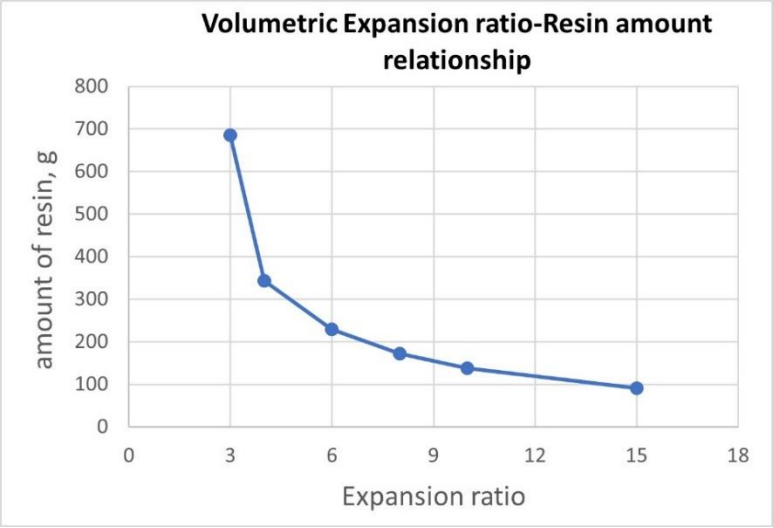

Figure 3. The relationship between the resin's amount used and its expansion ratio.

2.3. Determination of the resin densities

The density of the resin in the liquid state is equal to 1.1 g/cm^3. However, the density of the resin changes due to its expansion properties, and the amount of the injected resin plays a significant role in its resulting density. For a constant volume, the injection of a different amount of resin leads to the formation of different densities compared to its initial density in the liquid state.

After the preparation, the obtained samples were divided into seven groups according to the values of their density obtained by their prespecified volumetric expansion ratios, as shown in Fig. 4.

Figure 4. The prepared resin's samples of different densities.

The actual density of each obtained sample was determined according to the following formula:

$$\rho = m / V$$

where ρ is the density of the sample, m is the measured weight of the sample, V is the sample's volume.

In this manner, the average density was calculated for each expansion ratio, as shown in the Table 3. The weight measurement process of each sample is shown in Fig. 5.

Table 3. The values of the average density of the resin and expansion coefficients obtained.

The resin's expansion ratios	The actual resin's density obtained, g/cm^3
3	0.349
4	0.255
6	0.184
8	0.128
10	0.088
12.5	0.066
15	0.056

Figure 5. The weight measurement process of each obtained sample.

2.4. Samples testing using the uniaxial compression test

At this step, samples were tested using the uniaxial compression test under a laboratory environment, as shown in Fig. 6, to determine the mechanical properties of the resin for each obtained density. The test has been conducted at x % deformation (yield strain %).

Figure 6. Some of the resin samples during the uniaxial compression tests. (a) The sample during the compression test; (b) The sample at the end of the compression process; (c) The sample after the release of the uniaxial forces

It was observed that the resin has fully returned to its initial state after the release of the uniaxial force.

According to [22–26], The expandable polyurethane resins have three stages of stress-strain response when subjected to the unconfined compression test. The first stage is the so-called initial linear elastic phase leading to the yield strength followed by a post-yield protracted plateau of either (elastic or plastic) based on the type of the solid foam and a final sharp rise, which called densification.

Moreover, Gibson [26] has revealed that there are three different kinds of the stress-strain curve of solid foam under compressive loading: elastomeric foam, elastic-plastic foam, and elastic-brittle foam as shown in Fig. 7. Polyurethane foams have an elongated stress-strain plateau after yield, making them different from the standard behavior of solid materials, which generally do not.

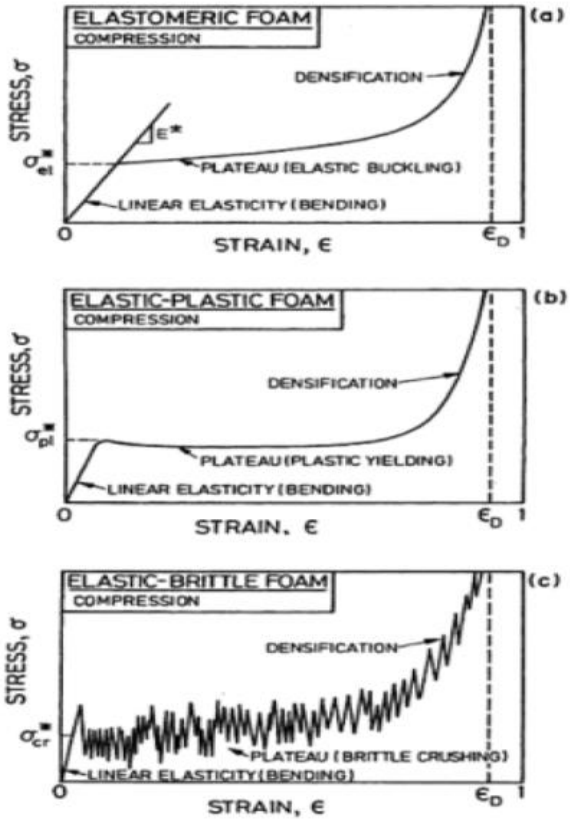

Figure 7. The patterns of the stress-strain state of polyurethane foams under compression loading, according to Gibson [26].

Furthermore, the failure point differs at which noticed in standard deformed solid materials. At the densification part of the polyurethane foams, the cellular structure "cells" of the foam are subjected to so-called "localization deformation" due to the nature of the material [22–26].

3. Results and Discussion

The stress-strain state of the investigated resin, according to its expansion ratios are obtained, as shown in Fig. 8−13.

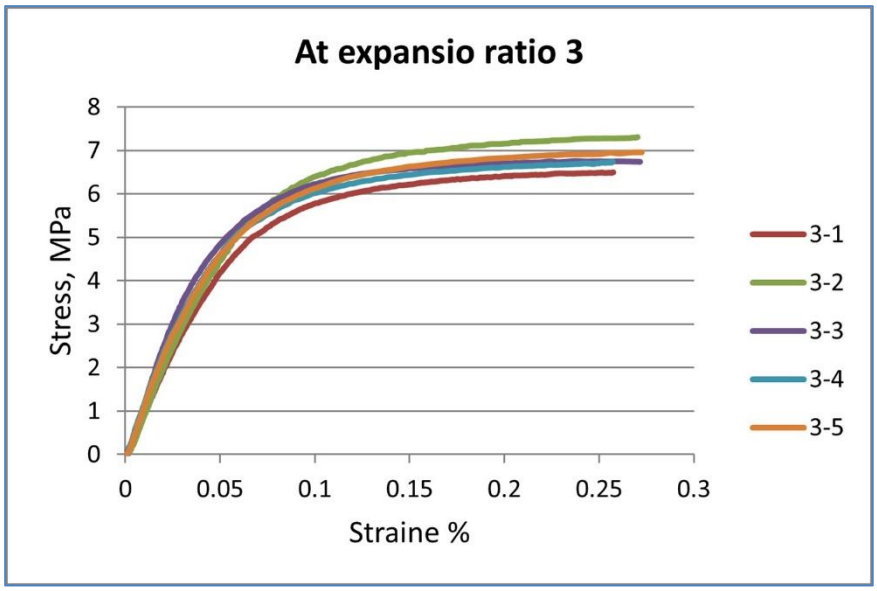

Figure 8. The stress-strain state of the resin at volumetric expansion ratio 3.

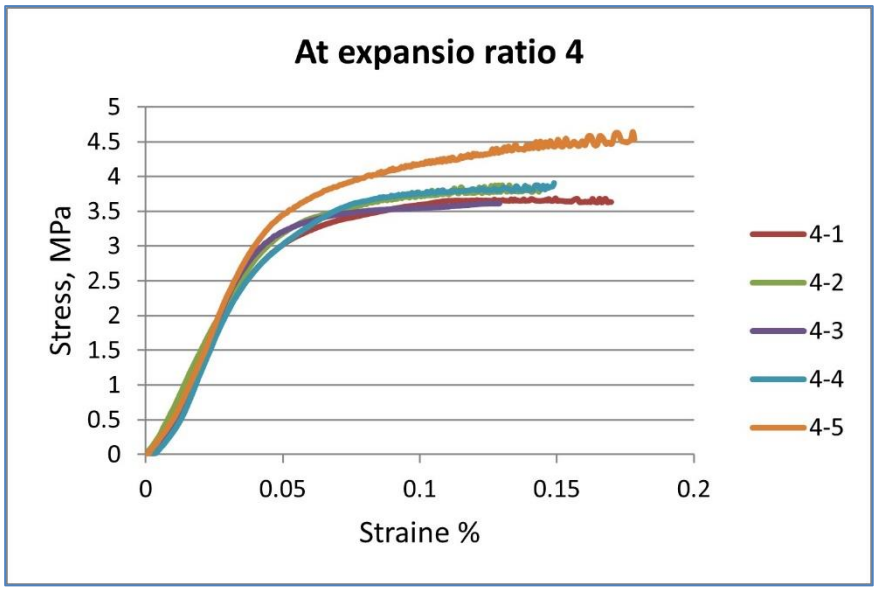

Figure 9. The stress-strain state of the resin at volumetric expansion ratio 4.

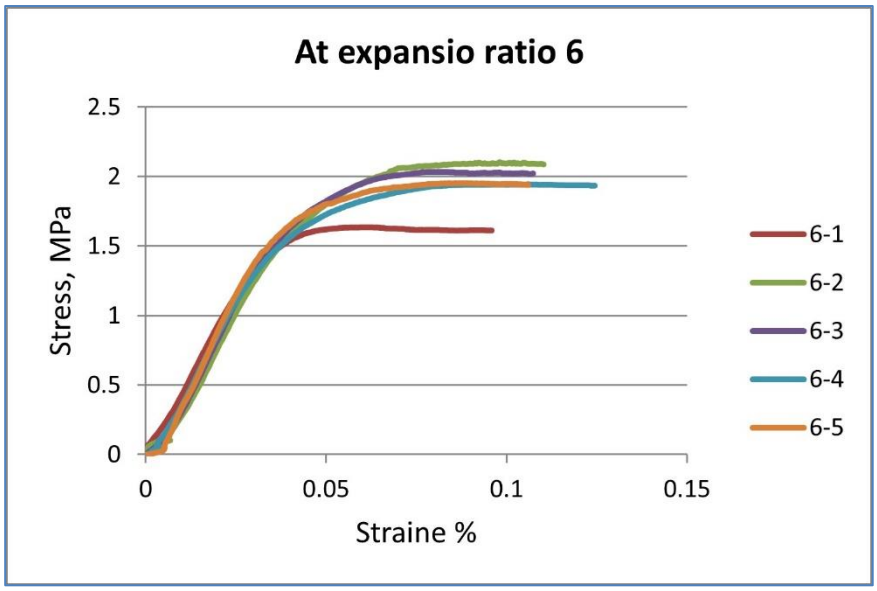

Figure 10. The stress-strain state of the resin at volumetric expansion ratio 6.

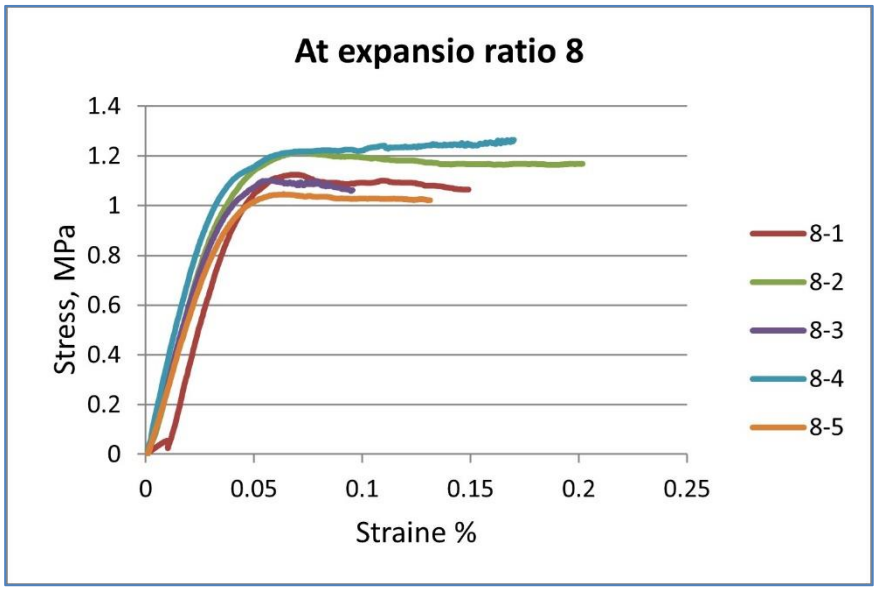

Figure 11. The stress-strain state of the resin at volumetric expansion ratio 8.

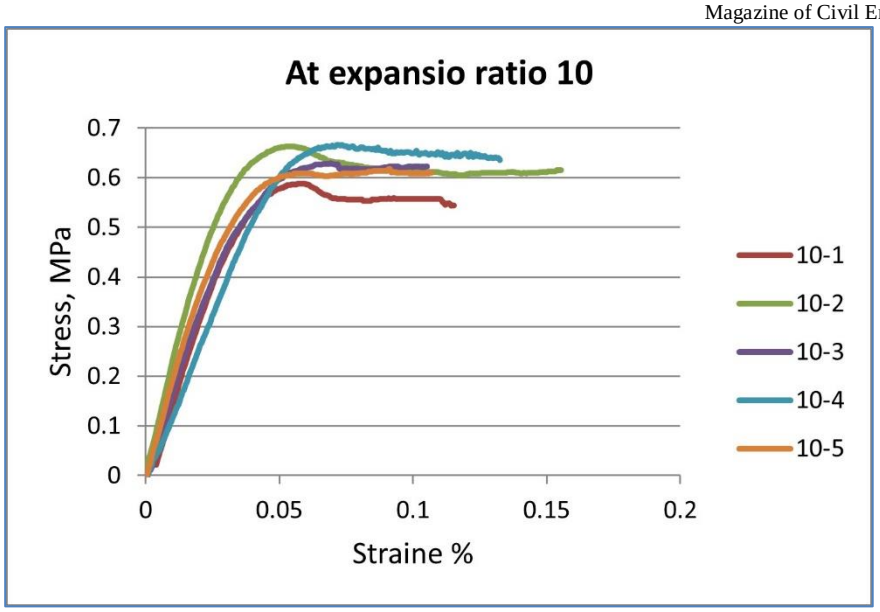

Figure 12. The stress-strain state of the resin at volumetric expansion ratio 10.

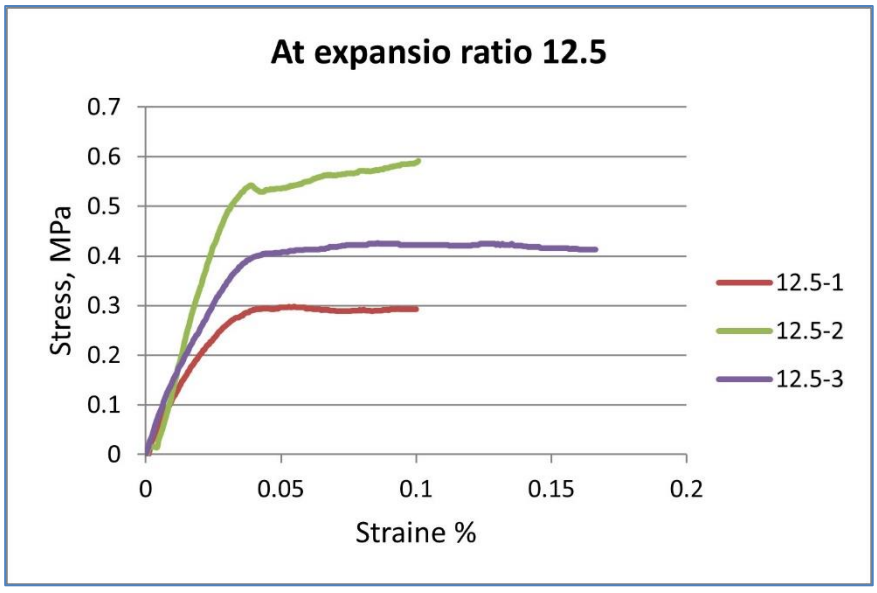

Figure 13. The stress-strain state of the resin at volumetric expansion ratio 12.5.

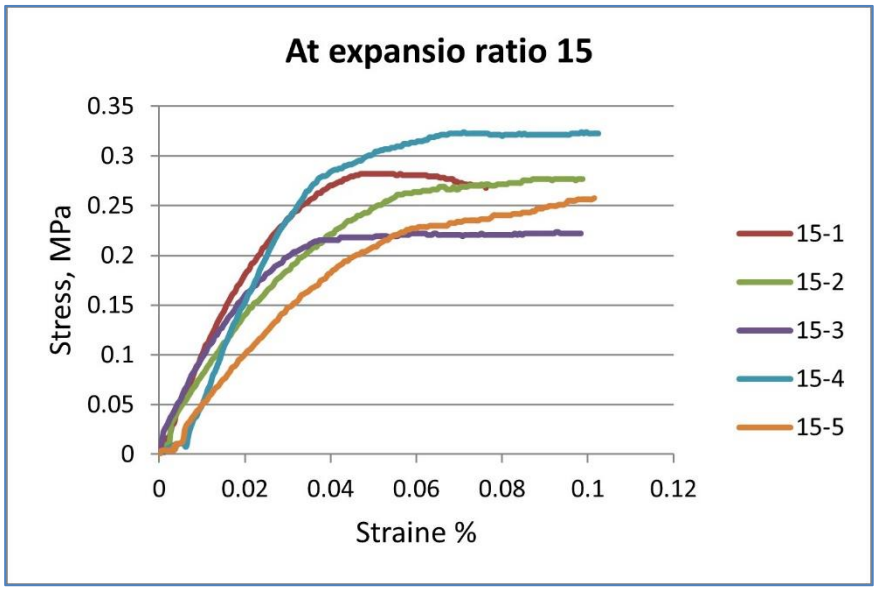

Figure 14. The stress-strain state of the resin at volumetric expansion ratio 15.

From the above, the obtained laboratory results are consistent with stress-strain state patterns categorized by Gibson [26], as shown in Fig. 7-a. Thus, the stress-strain state of the investigated resin seems to behave likely as an elastomeric foam under compression. This behavior of the material justifies the reverse of the expandable resin to its initial state after the release of the uniaxial compressive forces, as observed during the unconfined compression test of the investigated samples. The deformation of the samples (the buckling) shown in the Fig. 6-b is similar to the buckling elastic and not a shear failure. It occurs due to the nature of the closed-cell structure of PU foam under compression (filled by air, which is compressed and reverses to its original state unless reaching the densification).

Focusing on Fig. 8−14, the yield strain % of the investigated samples mostly ranged between 4−4.5 % based on the density of the samples tested except for the expansion ratio (3) where the yield strain % elongated up to approximately 6 %.

The resin under compression behaved linearly until reaching its yield strength, followed by the protracted plateau where the deformation (elastic buckling) occurred. The compression process in this investigation is limited to the linear part reaching the yield strength and the plateau part of the stress-strain state.

The elastic modulus has been calculated at a strain, which equals 50 % of the yield strain % of each sample using the following formula:

$$E = \frac{\sigma}{\varepsilon}$$

where: E is the elastic modulus; σ is the stress at the yield starin%; ε is the yield starin%.

A verification process of Young's modulus prediction values has been carried out through computing the regression between two points at the linear part of the stress-strain state. Further, according to [24, 26], the slope of the stress-strain curve in the elastic phase characterizes Young's modulus of the polyurethane foam. The three ways used for predicting the elastic modulus have mostly shown similar results.

The results were interpreted, determining the yield compressive strength, ultimate compressive strengths, and the modulus of elasticity of the resin according to its predetermined densities. The average yield, ultimate compressive strength, and the modulus of elasticity of the investigated resin for each obtained density are shown in Table 4.

Table 4. The average ultimate compressive strength and the elastic modulus of investigated resin under compression for each density obtained.

The resin's expansion ratios	The actual resin's density obtained, g/cm^3	The yield compressive strength, MPa	The ultimate compressive strength, MPa	The modulus of elasticity, MPa
3	0.349	5.145	6.756	104
4	0.255	2.886	3.943	73
6	0.184	1.597	1.933	44
8	0.128	1.020	1.150	30
10	0.088	0.558	0.636	18
12.5	0.066	0.407	0.447	14
15	0.056	0.236	0.275	9

The relationships between the density and the compressive strength of the resin, in addition to the relationship between the density and the modulus of elasticity under compression, are established and shown in Fig. 15, 16.

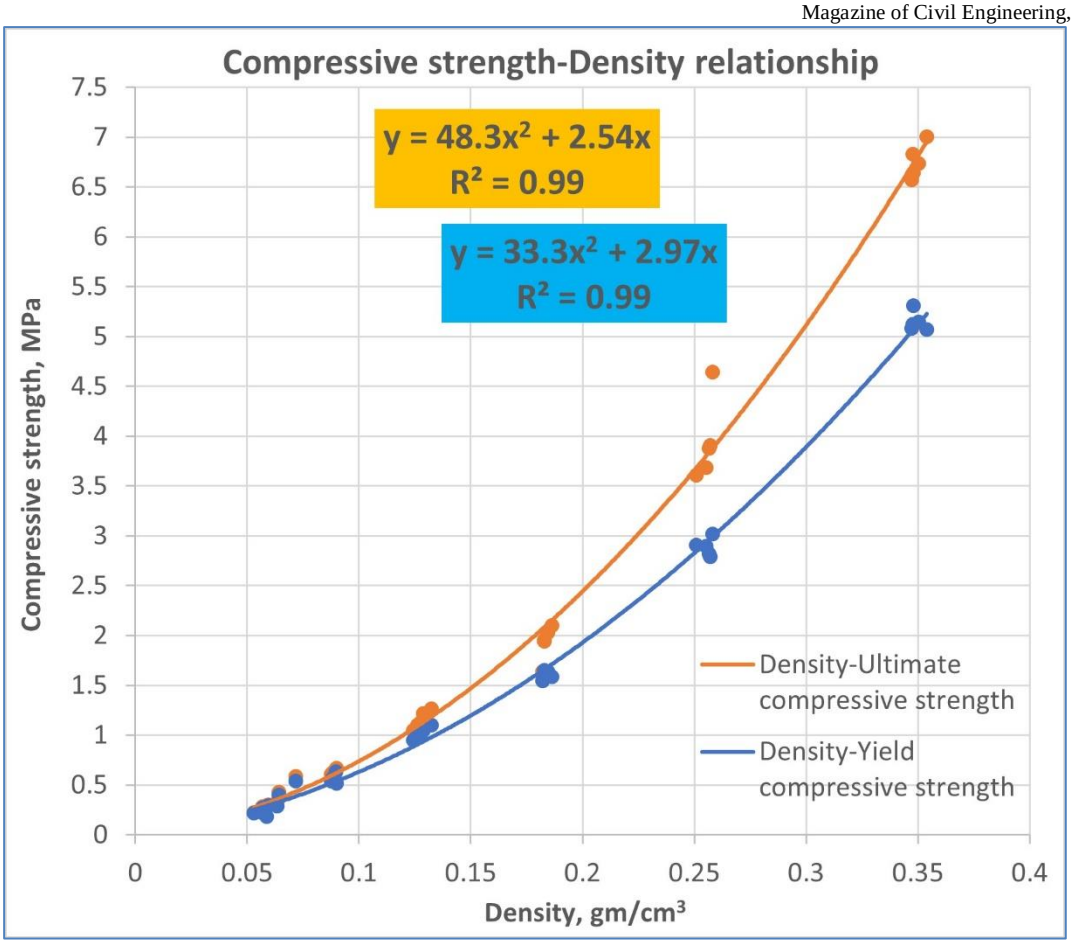

Figure 15. The relationship between the resin's density and its compressive strength obtained under compression.

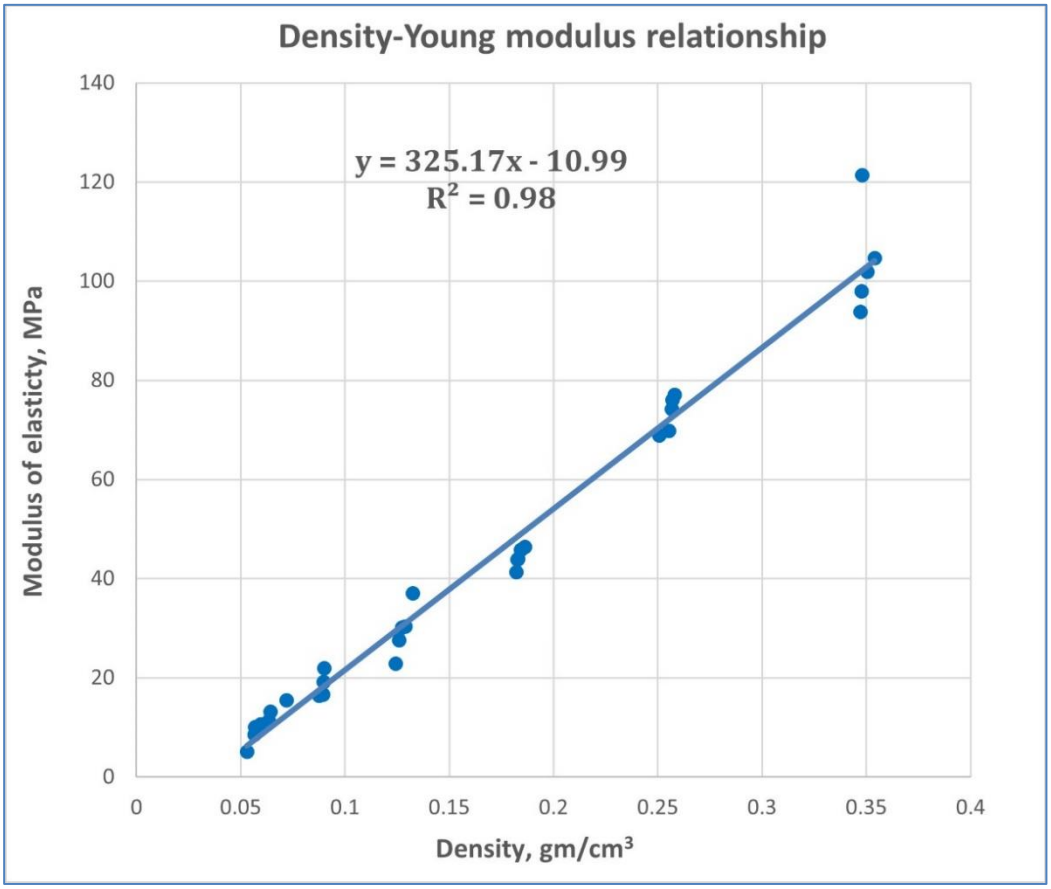

Figure 16. The relationship between the resin's density and its elastic modulus obtained under compression.

The obtained results prove that the investigated resin can be formed in various densities according to the amount of the injected resin, allowing a high spectrum of the mechanical properties in the soil massive (E = 5−121 MPa, ultimate compressive strength = 0.2−7 MPa), respectively, at prespecified expansion ratios ranges (3−15 times). Consequently, this resin is considered a high strength elastic injected material compared to various injection materials used in the field of soil stabilization, taking into account the rapid lifting and strengthening processes, and the full control over desired results. Also, the high fluidity allows the resin to propagate in different types of soils according to their specifications.

Furthermore, the actual propagation of the resin and its density formed in the massive of the injected soils (in a homogeneous injection environment) depends mainly on the amount of the injected resin and the properties of the injected soil.

The obtained relationships play an essential role in the theoretical and practical applications of the injection process when applying the injection technology using an expandable polyurethane resin for the soil strengthening and foundation lifting process.

4. Conclusion

1. The mechanical properties of the expandable polyurethane resin of various densities based on its volumetric expansion have been obtained, determined its strength-density and young modulus-density relationships under compression within density ranges (0.053−0.354 gm/cm^3) and volumetric expansion ratios (3-15) respectively, controlled by the amount of injectable resin. These relationships allow the prediction of the mechanical properties and the expansion volume of the injected resin through its density formed in the soil massive.

2. The obtained relationships prove the dependency of the resin's mechanical characteristics on its density based on its expansion nature controlled by its injected amount in a homogeneous injection environment. However, the actual density of the expandable resin formed in the massive of the injected soils is affected by other factors such as the injection pressure, the injection temperature, and the specification of the injected soil itself.

3. The high spectrum of the mechanical properties of the investigated resin, which depends on its expansion nature controlled volumetrically by its injected amount, leads to high control over the lifting process and gain the desired soil strengthening results, especially that the injection process is carried out in "shots" using the injection pistol.

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