Experimental analyses on cellular polymers in different forms for geotechnical applications

Analyses expérimentales de polymères cellulaires sous différentes formes pour des applications géotechniques

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ABSTRACT: Cellular polymers represent an important category among the polymeric materials. Nowadays they experience large applications in different areas (packaging, building, sport, road safety). There is already a widespread geotechnical use of these materials, e.g. for settlements reduction or soil strengthening, especially for existing structures. However, a need of a deeper mechanical properties study is required. Oedometric and triaxial laboratory tests have already been carried out on polyurethane samples obtained from ready-to-be-used slabs (RTBU samples). However, because of a will of polyurethane foam injection inside the soil, an ad-hoc-prepared foam needs to be prepared and its mechanical properties to be investigated. This paper is therefore aimed to analyse the geotechnical behaviour of the ad-hoc-prepared foam (by testing AHP samples), studying the influence of several factors on the applicability, and comparing the results with the failure tests conducted on RTBU samples.

RÉSUMÉ : Les polymères cellulaires représentent une catégorie importante parmi les matériaux polymères. De nos jours, ils connaissent de grandes applications dans différents domaines (emballage, bâtiment, sport, sécurité routière). Il existe déjà une utilisation géotechnique généralisée de ces matériaux, par exemple pour la réduction des établissements ou le renforcement des sols, en particulier pour les structures existantes. Cependant, un besoin d'une étude des propriétés mécaniques plus profonde est nécessaire. Des essais oedométriques et triaxiaux ont déjà été réalisés sur des échantillons de polyuréthane obtenus à partir de plaques prêtes à être testées (éprouvettes RTBU). Cependant, en raison d'une volonté d'injection de mousse de polyuréthane à l'intérieur du sol, une mousse ad hoc-préparée doit être préparée et ses propriétés mécaniques à étudier. Cet article vise donc à analyser le comportement géotechnique de la mousse préparée ad hoc (en testant les éprouvettes AHP), à étudier l'influence de plusieurs facteurs sur l'applicabilité et à comparer les résultats avec les essais triaxiaux effectués sur des éprouvettes RTBU.

KEYWORDS: Cellular polymers, physical-mechanical properties, oedometric and triaxial tests, geotechnical behaviour

1 INTRODUCTION.

In recent years many unexpected seismic events have occurred, especially in Italy. There is therefore a concrete need of a seismic retrofitting of the existing structures. It would be desirable to find solutions causing the minor modification to the structures. Innovative systems are going to be thought in University of Parma. Thanks to the partnership with B.A.S.F., a campaign finalised to the study of polyurethane foam has been started. However, before starting with the real evaluation of the mitigation capacity, a good geotechnical and mechanical characterisation is required. First, oedometric and triaxial tests have been conducted on samples obtained from ready-to-be-used polyurethane slabs (Montrasio and Gatto 2016). In order to investigate the effects of injected polyurethane, new experimental laboratory tests have been carried out on samples obtained from an ad-hoc-prepared polyurethane foam suitably realised from its main components. For this purpose, first the correct ratio which guarantees the workability of the foam has to be chosen.

2 MATERIALS

"Cellular solids" are materials composed of a set of cells, or spaces containing gas delimited by edges and, possibly, solid faces. Generally it is, therefore, a two-phase systems. The major property of this material type is their density which is always smaller, sometimes even two orders of magnitude, compared with that of the solid that forms the structure. However, this is not enough to speak of cellular polymers as it is also important that the cells are properly identified and demarcated.

Polyurethanes (PU) in general are polymers in which there are many urethane groups (NHCOO) obtained from the synthesis of molecules containing different isocyanate groups and molecules containing different hydroxyl groups. For the realization of the most suitable mixture for the application, it is good practice to add the catalysts, i.e. substances necessary for the realization of the foams that allow to adjust the speed of growth, a very important aspect because only with a specific rate of reaction it is possible to trap the right amount of gas within the mass and obtain complete reticulation of the polymer. In particular, some catalysts can be employed to accelerate the reaction between polyol and isocyanate (catalysis gel), others to optimize the interaction between isocyanate and water that leads to the formation of the expanding gas, etc.

2.1 Previous experimental analyses on RTBU samples

Figure 1. RTBU samples for oedometric and triaxial tests

Oedometric and triaxial tests have already been carried out on samples obtained from the ready-to-be-used (RTBU) polyurethane slab (Figure 1). In particular, the rigid polyurethane foam (ELASTOPOR) and extruded polystyrene foam (STYRODUR) slabs have been analysed. ELASTOPOR is a closed-cell polyurethane rigid foam used in a wide range of thermal insulation applications due to its excellent insulation properties; STYRODUR is the only one approved for insulation in seismically active areas. In order to investigate the density influence on polyurethane mechanical behaviour, slabs at two different densities have been considered (see Table 1).

Table 1. Properties of the employed materials.

Type	BASF code	Density (kg/m^3)	Acronym
Polyurethane rigid foam	ELASTOPOR® H1131/91/0	35.65	PUR 35
	ELASTOPOR®H1221/109/8	40.74	PUR 40
Extruded Polistyrene Foam	STYRODUR 3035CS	33	XPS B
	STYRODUR 4000CS	35	XPS A

Figure 2 shows the oedometric tests results. It can be noticed that the different density for the same material affects only the first part of the results until the yielding stress; after that there is a coincidence of the two curves. Although none of the specimens had been subjected to a previous stress history, all the results show an "apparent pressure of pre-consolidation" that increases with the material density; this pressure is approximately 60 kPa for lower density materials, i.e. XPS B and PUR 35 and about 100 kPa for XPS A and PUR 40. In general, however, a more rigid compressive behaviour is experienced by STYRODUR.

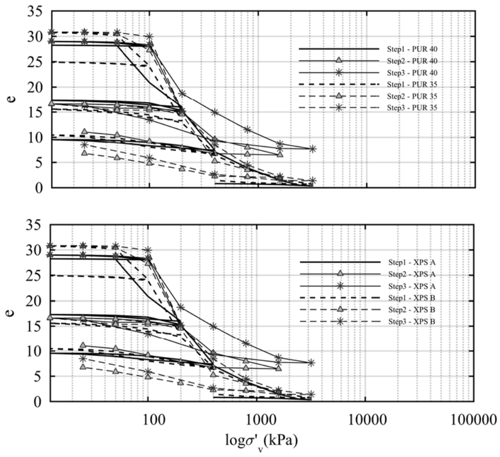


Figure 2. Oedometric test results on RTBU samples.

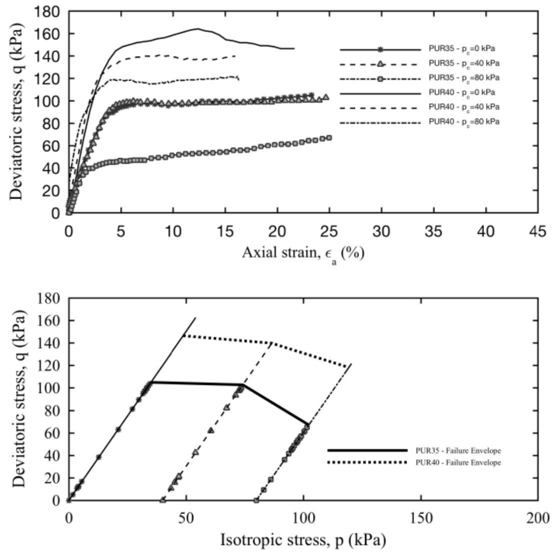


Figure 3. Failure envelop for slab-obtained samples.

Analysing the triaxial tests results on PUR - RTBU samples (Figure 3) it is clear that the failure envelope for the lower-density ELASTOPOR (the so-called "PUR35") has deviatoric failure stress of about thirty-five-per-cent less in the first two cell pressures and more than seventy-per-cent at 80 kPa cell pressure. This is mainly justified with the deterioration of PUR 35 subjected to cell pressure bigger than 60 kPa, while PUR40 will experience a decay in the failure envelope for pressures bigger than 100 kPa, as evident from oedometric tests.

2.2 *Realization of polyurethane foam for injections*

Ad-hoc-prepared (AHP) samples have been prepared mixing the two main chemical components which constitutes the polyurethane foam: isocyanate and polyol, both of them provided by B.A.S.F. In particular, the employed materials have been **Iso PMDI92140** and **ELASTOPOR H/2000/16 mod**, both previously chemically corrected by means of catalysers in order to have suitable foam cream and hardening time, compatible with the practical times required for the injections. The polyurethane foam to be injected has been realised mixing isocyanate and polyol by means of a drill provided of a helix on the drill bit (see Figure 4). The component ratio has been chosen according to a workability criterion, so that the mixture was suitable to the application.

Figure 4. Phases of ad-hoc foam realisation in laboratory

It is noticed that a factor which influences the injections is the mixing time, as well as the mixing velocity, both of them increasing the reaction rapidity start at their increase. Moreover, more is the quantity of polyol in the component ratio, earlier the expansion reaction will start. The components have been separately weighed, taking care of leaving the polyol for only few seconds in the plastic cup before mixing it with isocyanate. The expansion reaction lasts about dozen minutes, after that a rigid polyurethane foam can be observed inside the cup. Two component ratio have been analysed: **R12** (Ratio 1:2 polyol/isocyanate) and **R115** (Ratio 1:1.5 polyol/isocyanate). Overall, 40 grams of material has been employed for each cup.
Actually, the R115 ratio was not really suitable to the laboratory employment of the foam for injection since the bigger quantity of polyol fastens the reaction starting time. Nevertheless, thinking of a possible large scale application of the foam, in which larger instruments could overcome such technological problems, mechanical properties of R115 polyurethane foams are investigated as well.

3 LABORATORY TESTING

Triaxial tests have been performed on polyurethane samples obtained trimming the hardened foam inside the plastic cup, after the expansion reaction. Since the polyurethane foam expands following a conic pattern inside the cup, there was a lack of uniformity in the samples obtained trimming the rigid foam with 70mm-samplers and cylindrical samples were impossible to be obtained (Figure 5.a).

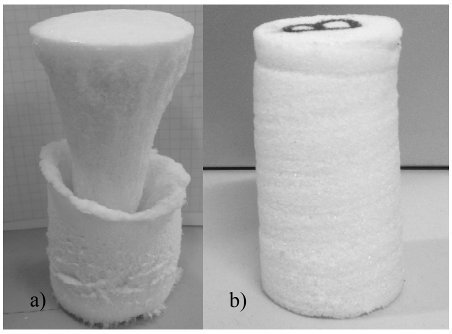


Figure 5. Polyurethane sample obtained from ad-hoc prepared foam.

The maximum cylinder inscribed in this conic form was therefore a 38mm sample (Figure 5.b).

R12 and R115 samples have been created and triaxial tests have been performed. Initially, all the samples have been subjected to three different cell pressures : 0 kPa, 40 kPa and 80 kPa. In a second moment, R12 samples have been consolidated to bigger cell pressures up to 200 kPa in order to widely study the failure behaviour of this ratio foam. A press velocity of 0.5 mm/min has been employed in all tests and undrained triaxial tests were performed, as water is unable to flow under the polyurethane samples. The failure condition is characterised by the achievement of 15%-axial strain. A comparison between R12 and R115 failure condition is provided. Moreover, the influence of the external humidity conditions on the mechanical behaviour has been evaluated. Finally, a comparison between the previous triaxial tests on samples obtained from slabs is provided.

3.1 *Component ratio influence to failure properties*

R12 and R115 samples have been conducted to failure conditions after the first consolidation phase to cell pressures of 0, 40 and 80 kPa (See Figure 6).

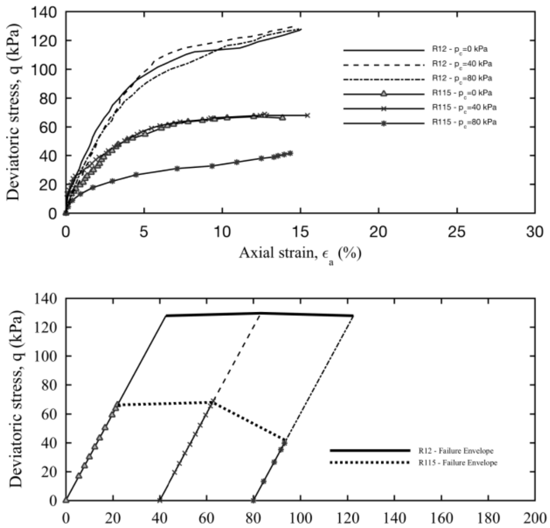
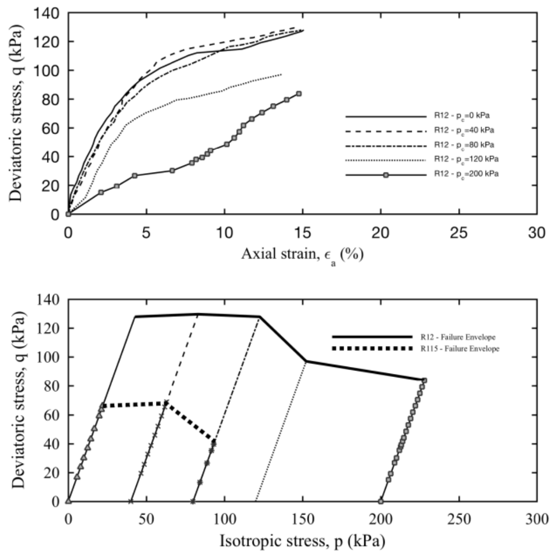


Figure 6. Influence of the component ratio on the mechanical behavior

It can be observed that a greater isocyanate amount in R12 mixture improves the failure characteristics of the foam. Moreover it is noticeable that the failure deviatoric stress is steady and the cell pressures is essentially irrelevant to the failure conditions in R12 case, while R115 samples experiences a fall in properties after 80kPa – cell pressure. In order to see until which cell pressure the R12 failure behaviour keep steady, triaxial tests have been carried out at 120 and 200 kPa cell pressure. (See Figure 7). It is clear a decay in R12 failure envelope for cell pressures greater than 80 kPa. In the follows, further studies are shown on only the R12 samples because of their better properties with just a little difference in isocyanate content. Moreover, Figure 7 shows that the R12 failure envelop is shifted in both the p- and q- directions, since just a slight more quantity of isocyanate determines either a higher failure deviatoric stress and a bigger isotropic stress from which there is the decay in the failure envelope. This is really interesting, since the main difference between the two mixture is the isocyanate quantity, (24 g in R115 samples and 26 g in R12 samples, together with a polyol quantity reduction from 16 g in R115 samples to 13 g in R12 samples), and in particular a slight component quantity difference determines an important difference in



resistance and compressibility terms.

Figure 7. Influence of the initial cell pressure on R12 samples.

3.2 *External humidity condition influence*

Since the examined foam is destined to be injected inside the soil, the water presence is a common situation. That's the reason why the external humidity influence on the R12-samples mechanical properties has been investigated. In particular, two R12 samples previously immerged in water for a weekhave been subjected to 0 and 40 kPa cell pressure, before going to failure; a sample wetted for a month, instead, has been consolidated until 80 kPa cell.

Results and comparisons with the dry samples are shown in Figure 8. Generally, the material is proved to be quite waterproof, since the mechanical behaviour is almost the same.

4 COMPARISON WITH PREVIOUS EXPERIMENTAL RESULTS ON SLAB SAMPLES

Figure 9 shows a comparison between the experimental results obtained in failure condition for slab-PUR40 samples and R12 samples. It is evident a greater cell pressure susceptibility for PUR40 samples since there is a thirthy-per-cent decrease in the failure deviatoric stress increasing the cell pressure from 0 to 80 kPa, differently to R12 samples, in which there is a quite steady response in this cell pressure, as previously investigated.

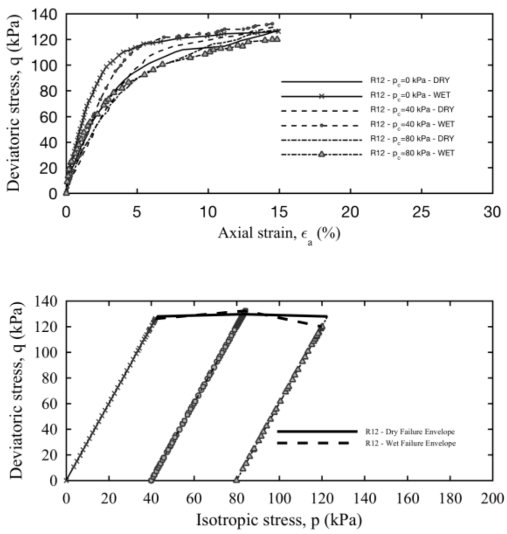


Figure 8. Influence of humidity condition on mechanical behaviour

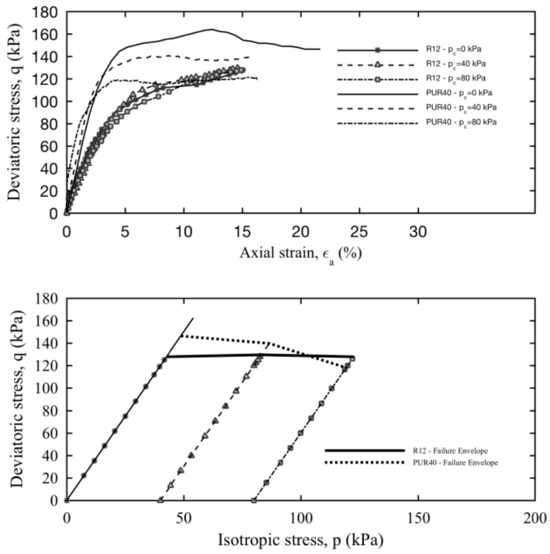


Figure 9. Comparison between triaxial tests on RTBU and AHP polyurethane foam samples

5 CONCLUSION

A preliminary study finalised to the realisation of a specific polyurethane foam to inject inside the soil for attenuation purposes has been carried out. Two main polyol/isocyanate ratio cases have been considered: R115 (ratio 1:1,5) and R12 (1:2), employing generally 40 grams of mixture. In both cases, low velocity and mixing time are more suitable to the practical aim. From the hardened foam produced inside plastic cups, samples to be tested in triaxial tests have been realised and the biggest dimension sampler compatible with the conic "expansion pattern" inside the plastic cup has been of 38mm diameter.

Triaxial tests have therefore been conducted on both R115 and R12 samples. The main evidences are summarised as follows:

1. A slightly larger isocyanate quantity determines significantly better failure mechanical properties since R12 samples shows greater failure deviatoric stresses values and a steadier behaviour with respect to the cell pressure. A constant failure envelope is experimented up to 80 kPa cell pressure for R12 samples, while R115 samples experiences an important deterioration in the mechanical properties in the same pressure range;
2. External humidity condition is experimentally demonstrated to be quite not conditioning the mechanical properties since the failure envelope of R12 samples previously immerged in water for a week or a month presents the same failure characteristics to the corresponding dry samples consolidated with the same cell pressure.
3. Comparison with previous experimental tests conducted on samples obtained from pre- prepared polyurethane slabs with similar density characteristics shows quite similar properties with the laboratory created foam, even if the slab are a bit more stiffer and resistant but the foam demonstrates a more steady behaviour with the cell pressure;
4. Component ratio can be further studied in order to obtain a bigger cell pressure range in which the failure behaviour of polyurethane foam can be described with Tresca's criterion.
5. Further analyses will investigate the influence of maturation time on the mechanical characteristics.

6 REFERENCES

Frigerio G. 1998. Introduzione ai polimeri cellulari. *XX convegno- Scuola "Mario Farina" su I Polimeri Espansi"*.AIM.

Gibson L. J. and Ashby M. F. 1999. Cellular Solids: Structure and Properties. *Cambridge University Press*.

Landrock A. H. 1995. Handbook of Plastic Foams – Types, Properties, Manufacture and Applications. *Noyes Publications*. Park Ridge, New Jersey, U.S.A.

Montrasio L. and Gatto M.P.A. 2016. Experimental analyses on cellular polymers for geotechnical applications. *VI ITALIAN CONFERENCE OF RESEARCHERS IN GEOTECHNICAL ENGINEERING (CNRIG) – Geotechnical Engineering in Multidisciplinary Research: from Microscale to Regional Scale*. Bologna, Italy.

Negussey D. and Jahanandish M. 1993. Comparison of some engineering properties of expanded polystyrene with those of soils. *Transportation Research Board*.

Wirpsza Z. 1993. Polyurethanes: chemistry, technology and applications. *Ellis Horwood*.