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Stress relaxation of smooth HDPE geomembranes

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Abstract. The stress relaxation behavior of the HDPE part is dependent on formulated density and melt flow index. Since 1990, the multi-axial tension test has been regularly used to assess the ability of geomembranes to undergo out-of-plane deformations as in cases of rising gas bubbles or differential settlements. This multiaxial deformation is simulated in ASTM D5617 Standard Test Method for Multi-Axial Tension Test for Geosynthetics, at a constant rate of 6.9 kPa/min. While such a rate appears reasonable for index properties of most geomembrane types, semi-crystalline geomembranes like high density polyethylene (HDPE) might be better represented at much slower rates. This experimental study was undertaken to investigate this possibility. Using eight sequentially slower pressurization rates from the default value down to 0.000157 kPa/min the strength values were not markedly changed (yield was unchanged and break increased slightly). However, the elongation values changed considerably (yield increased by 200% and break increased by 400%). Thus, it is felt that the field performance of HDPE geomembranes can best be simulated by conducting the multi-axial test at very slow pressurization rates. While such rates are not practical in the context of an index test method the authors feel that some type of commentary to this effect could well be included in the respective test method standards.

1 Background and Introduction

From the very first uses of geomembranes they were characterized, in part, by their tensile strength and elongation in an in-plane stress state using various test specimen configurations, e.g., dog bone, narrow strips, grab or wide-width. By the 1980's, however, it was recognized that a different testing orientation was sometimes required. While each of these cases are the result of rising gases impinging on the geomembrane in a landfill cover or in a liquid filled reservoir, the opposite direction, i.e., downward deformation, arises for geomembranes placed on yielding soil foundations or settling waste masses as in landfill covers. Of course, such situations place the geomembrane in out-of-plane axisymmetric tension state. It will be called a multi-axial tension state herein.

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Early forms of the multi-axial tension test have been noted in the literature in a variety of forms. Frobel (1981) at the U.S. Bureau of Reclamation and Laine, et al. (1989) of the Southwest Research Institute used large pressure vessels with geomembranes on different types of subgrade (sand, gravel, cones and pyramids, etc.) in the form a large scale puncture test. Steffen (1984), in a similar type of apparatus, gradually removed the subgrade support soil thereby generating large scale out-of-plane tension in the geomembrane. Subsequently, he used the pressure vessel with no support soil beneath the geomembrane in the first reported multi-axial tension test. Steffen analyzed a number of different polymeric geomembranes. Van Zanten (1986) has also reported on the test illustrating the behavior of a number of geomembrane types. Subsequently, Hoekstra (1987, 88, 89) evaluated a series of bituminous geomembranes and presented some of the requisite theory. STUVA (1988) further refined the experimental apparatus which ended the early period of this type of testing.

This research in the 1980's was analyzed and extended by Koerner, et al. (1990) which established a theory to convert the measured values of pressure and deflection into stress and strain, hence the desired values of strength and elongation at break could be identified. It also set as a default pressurization rate a value of 6.9 kPa/min (1.0 psi/min) which, as will be seen, is unfortunate for semi-crystalline geomembranes and high-density polyethylene (HDPE) in particular. HPDE is about 50% crystalline whereas other thermoplastic geomembranes are 0 to 5% and are therefore called noncrystalline. The formalized testing protocol was first made available as GRI-GM4 (1989) and subsequently adopted as ASTM D5716 in 2004. A difference, however, is that the ASTM procedure changed the incremental pressurization rate from 6.9 kPa/min to 20 mm/min in a continuous fashion.

The data generated by the multi-axial tension test is pressure-versus-center point deflection that can be plotted and used directly. However, to obtain stress-versus-strain (which is more desirable), certain assumptions must be made. The original analysis by Koerner, et al. (1990), has been modified by Merry, et al. (1993, 1995). Both are based on the assumption that the deflected shape is being deformed as a portion of a sphere (small deformations) or ellipse (large deformations) with gradually moving center point along the centerline axis.

2 The multi-axial tension test

Koerner et al. (1990) used a steel pressure vessel of 600 mm diameter. A geomembrane test specimen was firmly fixed and sealed between its base and cover plate. Water pressure from above deformed the geomembrane into the air space of the empty vessel. Center point deflection was measured along with the applied pressure. Geomembrane break was readily evidenced by an abrupt pressure drop and an abrupt audible sound. It should be noted that the test is currently performed using air beneath the geomembrane which is consequently inflated upward, and in a readily observable orientation.

Koerner et al. (1990) evaluated a number of testing variables including various types and thicknesses of geomembranes. Those selected were as follows:

- 1.0 mm thick high density nonreinforced polyethylene (HDPE)
- 0.53 mm thick nonreinforced linear low-density polyethylene (LLDPE)
- 0.51 mm thick nonreinforced polyvinyl chloride (PVC)
- 0.91 mm thick scrim reinforced chlorosulponated polyethylene (CSPE-R)

The response curves of these four geomembranes in terms of stress versus strain is shown in Figure 1. (Conversion of pressure and deflection into stress and strain used Equations 1, 2 and 3.) In Figure 1 it is seen that the noncrystalline and nonreinforced geomembranes (LLDPE and PVC) performed excellently in their strain at break (aka, elongation) out to values from 75 to 100%. In contrast, the scrim reinforced CSPE-R and highly crystallinity HDPE geomembranes failed at much lower strains at break of 12 to 30%, respectively. Also, note that their strengths are much higher, but that is felt to be of much less importance than elongation in the field applications mentioned previously.

While the low elongation at break for the scrim reinforced CSPE-R geomembrane is understandable (the scrim is generally made from very strong and high modulus woven polyester or nylon yarns), the poor elongation at break for the nonreinforced HDPE is much less so. Most importantly, this relatively low elongation value for HDPE (in comparison to other noncrystalline and unreinforced geomembranes) has had the effect of general disuse of the material for out-of-plane deformation scenarios in the field. That said, to evaluate all geomembranes alike and at the same pressurization raters and then compare them as shown on Figure 1 may be misrepresentative and, in the case of a crystalline resin, might be somewhat unfortunate. In this regard, it is possible that by using a pressure rate considerably less than the default values in the test method standards the response (particularly elongation at break) might be higher. This paper has as its single purpose the evaluation of lower-and-lower pressure rates when testing HDPE geomembranes per the standards mentioned earlier so as to evaluate the material's performance in this regard.

3 Description of tests and the results

The geomembrane specimens used for testing in this study were from a 1.0 mm nominal thickness smooth HDPE geomembrane made by the blown film process. The material is characterized by the properties of Table 1 and conforms to the GRI-GM13 specification.

The pressure vessel used in this study was 610 mm in diameter as shown in the test setup of Figure 2. Air pressure was held incrementally constant which inflated the test specimen upward. Its center point and upward movement was tracked by laser while air pressure was maintained by a regulated compressor and controlled manually with two pressure gauge readings to the nearest 0.7 kPa.

The initial test was at a pressurization rate of 6.9 kPa/min. It resulted in a yield of 15.6 MPa at 13.5% elongation and a break of 15.6 MPa at 17.4% elongation; see Table 2. Thus, yield was essentially followed immediately by break as is conventionally seen for HDPE in testing per GRI-GM4 and ASTM D5617. As indicated in Table 2 this initial test was followed by seven additional tests at gradually slower pressurization rates down to 0.000157 kPa/min (i.e., 6.9 kPa/month). This is 44,000 times slower than the default value. See Figure 3 for a progression of photographs between yield and break for the slowest pressurization rate. The results of the stress-versus-strain responses for all eight tests are shown collectively in Figure 4. Here can be seen that the initially short stress-vs-strain curve at fast pressurization rates is gradually lowered and lengthened with sequentially applied slower pressurization rates. The specific data of yield and break from which these eight curves were obtained are summarized in Table 2. This strength and elongation data, when plotted as in Figure 5, is felt to be quite revealing. The following four items can be deduced in this regard:

- Yield strength is relatively unaffected by slower pressurization rates.
- Beak strength is marginally increased by slow pressurization rates by approximately 25%.
- Yield elongation is increased by slow pressurization rates by approximately 200%.
- Break elongation is significantly increased by slower pressurization rates by over 400%.

It should be mentioned in light of the above findings that these are single-point test results. The entire study took ten years to conclude with the slowest pressure rate test lasting over four years.

4 Summary and recommendations

This study has focused on evaluating a single variable in the conducting of the multi-axial tension test for geomembranes, and for HDPE in particular. That variable is the pressurization rate at which the test specimen is subjected to in an out-of-plane tension mode. The test method originally used 6.9 kPa/min per GRI-GM4 and subsequently 20 mm/min per ASTM D5617. Both values are felt to be relatively rapid and yet have served the industry quite well as index test values for manufacturing quality control and assurance as well as for specification values. When it comes to predicting field performance or comparing different types of geomembranes, however, a bias can occur and it was long felt by the authors that such a bias occurred when evaluating semi-crystalline geomembranes. The suggested reason being that those geomembranes made from semi-crystalline resins cannot respond to rapidly applied pressurization rates so as to allow for stress relaxation to occur. Thus, the objective of this study was to use successively slower strain rates to observe the material's response insofar as multi-axial tensile strength and elongation is concerned. Since the geomembrane being evaluated is HDPE both yield and break of the test specimens are involved and not merely the break response as with other types of noncrystalline geomembranes.

Beginning with the first test at the default value of 6.9 kPa/min, seven subsequent tests as slow as 0.000157 kPa/min (44,000 times slower) were performed. In viewing the eight separate test responses it was seen that (i) strength at yield remained constant, (ii) strength at break increased about 25%, (iii) elongation at yield increased about 200%, (iv) elongation at break increased about 400%. Thus, it appears as though the elongation at break is the most sensitive parameter to the pressurization rate. That said, the curves do appear to becoming asymptotic to the x-axis suggesting that a limit may have been reached.

As with most studies of an experimental nature other question arise, primarily the questionable response of other (noncrystalline) geomembranes to extremely low pressurization rates. Still other questions have to do with the role of geomembrane thickness, behavior of textured or structured sheet, use of volume-controlled pressurization at a constant or incremental rate, and the effect of cold and hot temperature on the response curves. It appears that extensions of this study can be made with the understanding that such tests take considerable time. The above questions being unanswered at this time, there is no recommendation to change the index test method default values but only to recognize that in practice, the performance of semi-crystalline geomembranes may be considerably different than test results indicate in this multi-axial mode of deformation. The authors feel that a note to this effect is justified to be placed in the existing test method standards.

We sincerely thank all of our sponsoring organizations. The current GSI member organizations and their contact members are on the institute's website at www.geosynthetic-institute.org.

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Table 1 – Physical and Mechanical Properties of the HDPE Geomembrane Used in this Study

Property	ASTM Test	Value
thickness	D5199	1.50 mm
specific gravity	D792	0.941 g/cc*
carbon black content	D4218	2.64%
carbon black distribution	D5596	Category 1
melt flow index	D1238	0.17 g/10 min.
tensile yield strength (dogbone)	D6693 (MD) (XMD)	23.6 kN/m 22.9 kN/m
tensile yield elongation (dogbone)	D6693 (MD) (XMD)	14.2% 13.8%
tensile strength (dogbone)	D6693 (MD) (XMD)	46.1 kN/m 43.8 kN/m
tensile elongation (dogbone)	D6693 (MD) (XMD)	840% 810%
tear strength	D1004 (MD) (XMD)	190 N 192 N
pin puncture	D4833	483 N
CBR puncture	D6241	3.12 kN
Stress Crack Resistance (SP-NCTL)	D5397 Appendix	300 hours
Standard OIT by DSC	D8117	122 minutes
High Pressure OIT by DSC	D5885	402 minutes
Oven Aging 85°C 90 days % retained standard OIT	D5721	65%
UV resistance after 1,600 light hours % retained high pressure OIT	D7238	55%

*Note 0.940 g/cc is the threshold between HDPE and LLDPE per ASTM D883

Table 2 – ASTM D5617 Multi-Axial Tension Test Summary Data on 1.5 mm Smooth HDPE

Test No.	Pressure Rate (kPa/min)	Strength		Elongation	
		Yield (MPa)	Break (MPa)	Yield (%)	Break (%)
1	6.9	15.6	15.6	13.5	17.4
2	3.45	15.5	17.6	19.6	37.5
3	0.69	15.2	21.0	24.8	57.1
4	0.115	14.2	18.8	30.7	62.1
5	0.00957	14.6	19.1	34.7	63.8
6	0.00478	14.2	20.4	30.7	70.0
7	0.000683	15.2	22.9	40.0	81.4
8	0.000157	14.0	19.1	33.0	72.4

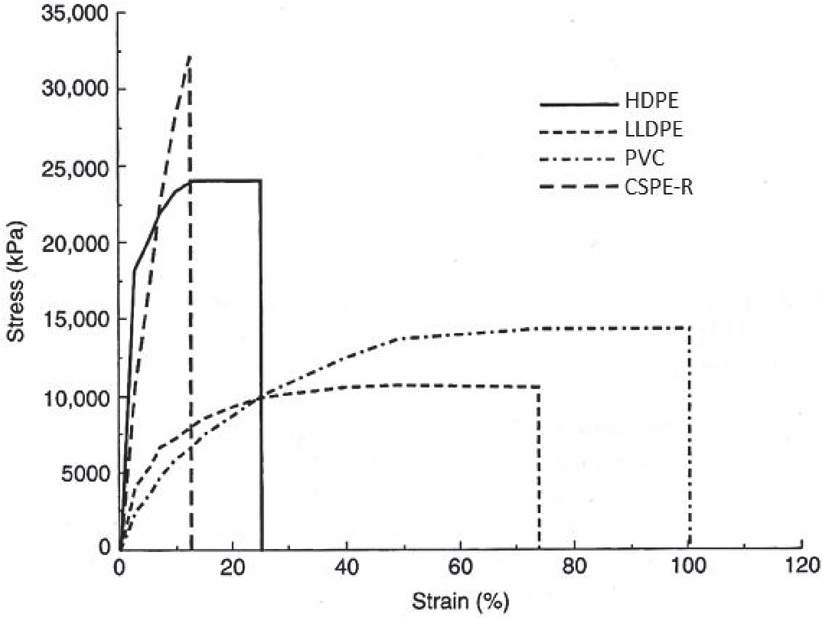


Figure 1. Stress-versus-strain response curves of various types of geomembranes under multi-axial hydrostatic pressure (Koerner, et al., 1990).

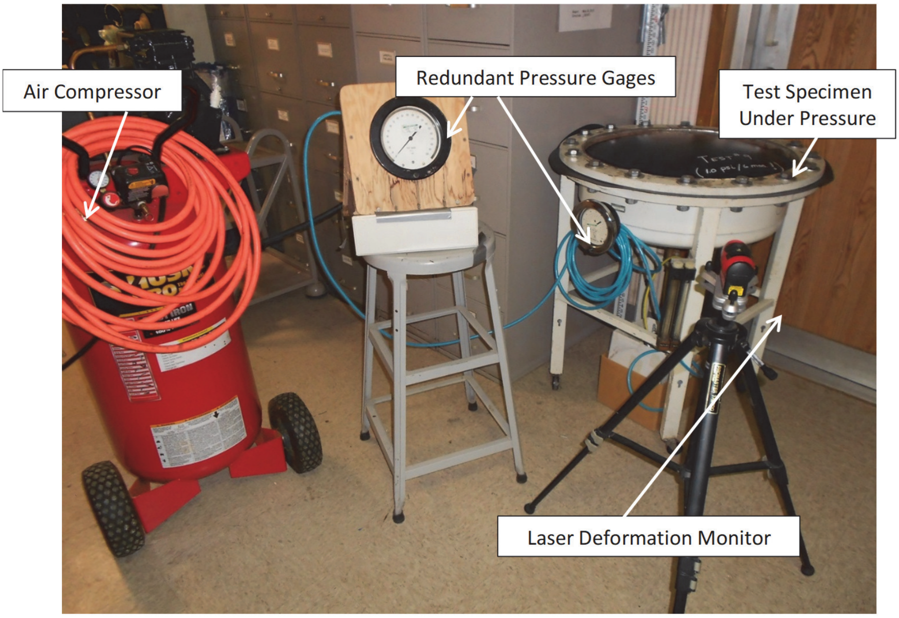


Figure 2. Test setup for multiaxial tension testing of geomembranes at extremely low pressurization rates.

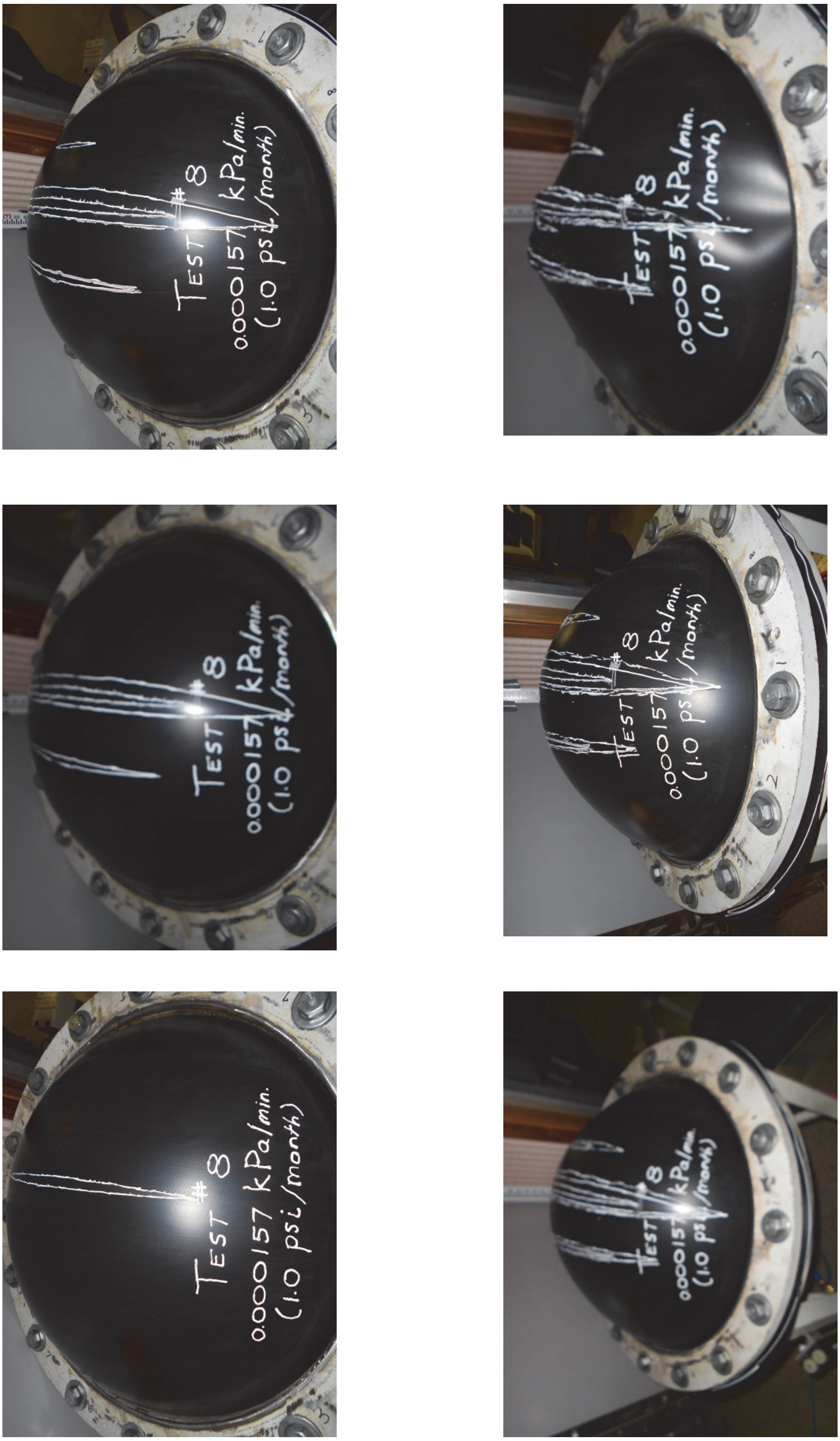


Figure 3. Progression of Test #8 photographs at slowest pressurization rate through various yield stages until break.

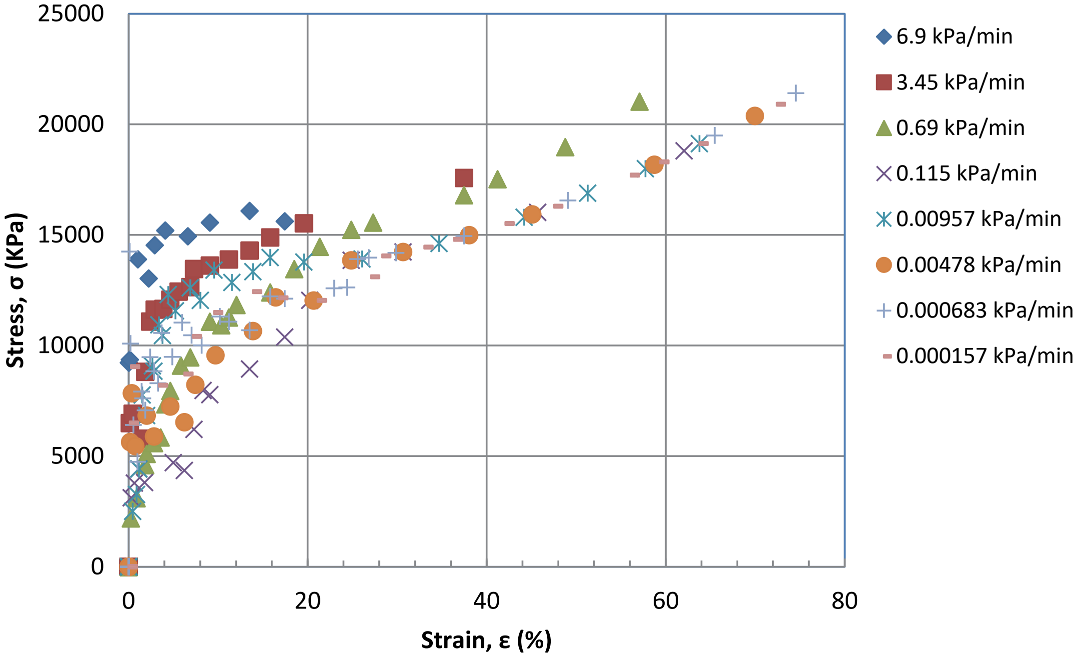
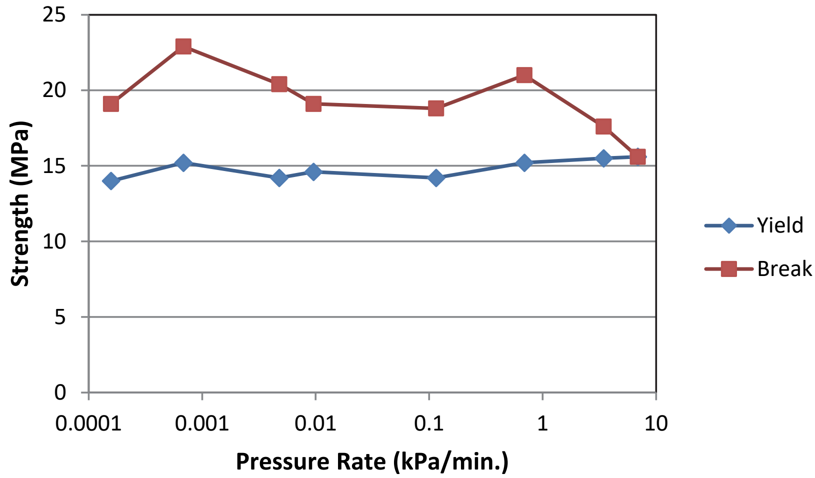


Figure 4. Stress-versus-strain behavior for eight multi-axial tension tests at gradually slower pressurization rates.



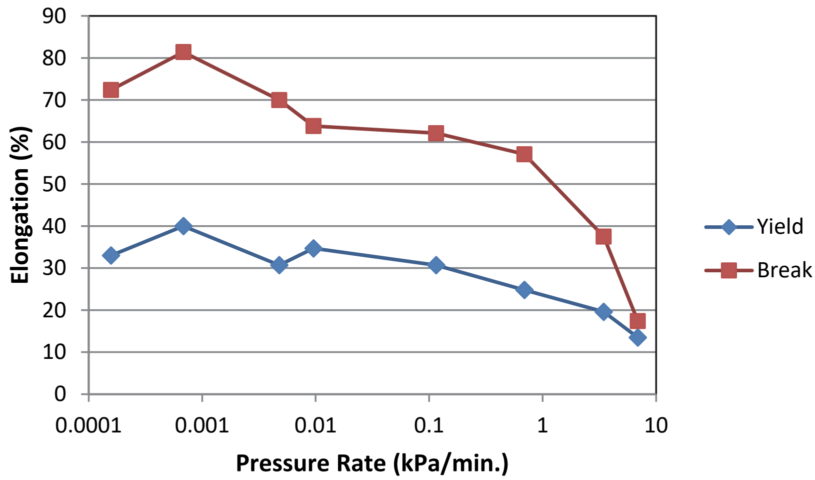


Figure 5a & b. Summary strength and elongation results for eight tests at yield and break as a function of pressurization rate.