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Experimental study of the interaction between geomembrane and gravel in terms of shear and puncturing

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ABSTRACT: The aim of this study is to investigate the behavior of geomembrane-gravel interfaces both in terms of resistance to shear and resistance to puncturing. Different geomembranes are submitted to puncture tests and direct shear tests in contact with the same specific gravel. The aspect of the geomembrane after shear testing is also considered as part of the result. Results obtained illustrate the significant interface behavior differences according to the thickness and type of the geomembrane and the moisture of the interface, with or without protective geotextile. Considering a 30 mm or a 50 mm displacement for the calculations generally leads to the same shear characteristics. Puncture resistance of geomembranes are shown to be highly variable from one type of geomembrane to another. Interesting data concerning shear-damage of the geomembranes are also given and compared with results obtained performing the gravel puncturing test, showing that solicitations are definitely different.

1 INTRODUCTION

Geomembranes are often placed in contact with granular material, such as gravel or ballast. This is notably the case when the geomembrane is placed under or over a layer of such materials to constitute a specific complex. In such cases, and mainly on slopes, the geomembrane is submitted to shear stress and to puncturing both during installation and service life.

Very little is known about the behavior of geomembrane-gravel interfaces. A test campaign has thus been conducted by the Cemagref in order to investigate the behavior of different types of geomembrane submitted to gravel puncture and shear stress.

This paper aims at presenting the result of this test campaign. The different tested geosynthetics and testing methods will be presented. Results obtained will then be detailed allowing comparison of the different interfaces behavior. A discussion on the material and test methods follows.

2 MATERIALS AND METHODS

2.1 *Materials*

Fourteen different geomembrane lining systems (GLS) have been tested. Twelve were composed of a single geomembrane and two were composed of a geomembrane protected by a geotextile.

Table 1 presents the fourteen geosynthetics concerned by this study. The product designation makes explicit reference to the polymer from which the geomembrane is made or to the type of geotextile. The product designation makes implicit reference to the thickness or to the mass per unit area of the geosynthetic. The thickness and mass per unit area are producer's values.

The twelve geomembranes were made of five different materials (bitumen, PVC, HPDE, PP, EPDM). They varied in thickness. These smooth geomembranes are commonly used and available in Europe. Bitumen3 and Bitumen4 were similar products coming from two different producers. PVC geomembranes were translucent geomembranes mainly used in tunnels applications but having the same properties as more widely used PVC geomembranes.

The two geotextiles were non-woven needle punched geotextiles, only differing in thickness. They have been designed to work as protection layers. These geotextiles were associated with the thinner PVC geomembrane for testing.

Table 1. Geosynthetics tested.

Product designation	Thickness or mass per unit area
HDPE1	1.5 mm
HDPE2	2 mm
PVC1	1.5 mm
PVC2	2 mm
PP1	1.5 mm
PP2	2 mm
EPDM1	1.14 mm
EPDM2	1.5 mm
Bitumen1	3.9 mm
Bitumen2	4.8 mm
Bitumen3	5.6 mm
Bitumen4	5.6 mm
NW-NP1	300 g/m²
NW-NP2	700 g/m²

2.2 *Methods*

2.2.1 *Gravel puncturing tests*

Gravel puncturing tests were performed according to the NF P 84-510 standard (AFNOR, 2002) which purpose is to assess the puncture resistance of a GLS in contact with a layer of aggregates, by determining the maximum load at which the geomembrane keeps its watertighness.

The test consists in submitting a GLS laying on a steel plate to puncturing by gravel under a pre-set normal load. Load is applied moving a 90 mm in diameter pressure-foot at a rate of 2 mm/min (Fig. 1). Varying the pre-set load allows finding the minimum load leading to puncture. The puncture is detected turning upside down the GLS and aggregates complex and submitting the down face of the geomembrane to an air pressure of 20 kPa during 30 minutes, with water on top as shown on Figure 1.

The granular material specified by the standard is a 10/20 mm crushed quarry gravel without elements narrower than 8 mm. Pieces of gravel have no sharp angles. The layer of gravel on the geomembrane is about 50 mm in height.

The result of the test is the nominal effort for puncturing (NEP) of the GLS. It is the maximum load exerted during the test at which the number of leaks on 10 specimens tested at the same pre-set load does not differ from one of the conditions below:

- no leak,
- one leak,
- two leaks distributed on one or two test specimens,
- three leaks distributed on three test specimens.

Thus, in fact, the NEP is not the load for which there is no hole on the ten specimens but the minimum load for which the number and distribution of hole are statistically significant of the resistance to puncturing of the GLS. A zero-hole criterion from tests on a limited number of small specimens had been thought not to be realistic.

The NEP is comprised between 0 and 30 kN expressed as a multiple of 5 kN, for loads higher than 10 N and as a multiple of 2.5 N under.

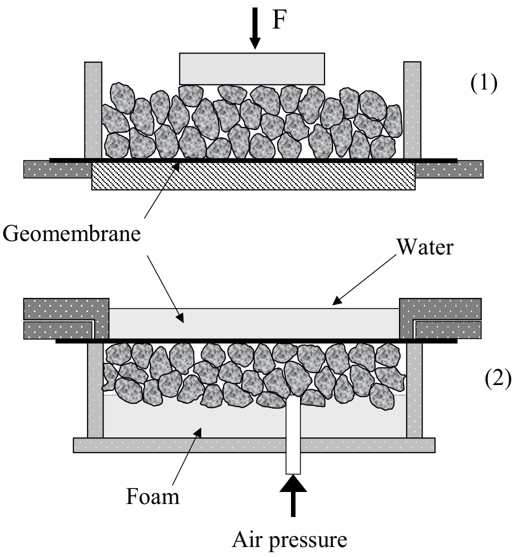

Figure 1. Test configuration during (1) puncturing and (2) hole detection phases of the gravel puncturing test.

2.2.2 *Direct shear tests*

Shear tests were performed according to the NF P 84-505 standard (AFNOR, 93) using a large shear box 300 × 300 mm in dimensions. The box displacement speed was 1 mm/minute. For each GLS, 4 specimens were tested under 10, 25, 40 and 60 kPa normal stresses.

Tests were performed in dry conditions first on each GLS. Then, tests were performed in wet conditions only on the thicker geomembrane of each type. These were performed hydrating the gravel prior to its placement on the GLS in such a way that no excess water remained on top of the geomembrane during the test.

The granular material used was not a standard sand as required by the French standard but the gravel used for the gravel puncturing test and described in the previous section, laid in a 12.5 cm thick layer.

To avoid important slippage and elongation, specimens of PVC, PP and EPDM geomembranes were glued on the support. This was not necessary for HDPE and bituminous geomembranes.

Tests with geotextiles were performed in such a way that the geotextile-geomembrane interface was submitted to shear. The geotextile was fixed to the upper half box, filled with the gravel, while the geomembrane was fixed to the lower half box.

Shear test curves were examined considering both the NF P 84-505 standard and prEN ISO 12957-1 draft standard (AFNOR, 98). Indeed, cohesion and friction angles were calculated from maximum shear strength respectively reached before a 50 mm shear displacement and before a 30 mm shear displacement i.e. 10% of the shear length.

As the prEN ISO 12957-1 test method was only a draft when the test campaign began the French standard was considered as the reference standard.

2.3 *Comments on the test methods*

Consideration shall be given to the fact that stress applied on the geomembrane is really different from the shear test to the gravel puncturing test. Indeed, the gravel used is the same but in the first case, the maximum stress value applied is 60 kPa whereas in the second case, the maximum stress applied by the 90 mm in diameter pressure-foot on the 50 mm thick gravel layer is 1700 kPa.

For both shear and puncture tests, the bituminous geomembranes were tested the sandy face in contact with the gravel. Other geomembranes exhibit quite no difference of surface between the two faces. Their face exposed to gravel was chosen arbitrarily.

3 RESULTS

Results are presented with explicit reference to the geosynthetic concerned. In the case of the geotextile-PVC geomembrane complex, results are presented with the only reference to the geotextile concerned.

3.1 *Gravel puncturing tests*

Test results are presented in Figure 2. Due to insufficient quantity of material, tests on Bitumen3 were not satisfactorily achieved and, thus, results are not presented.

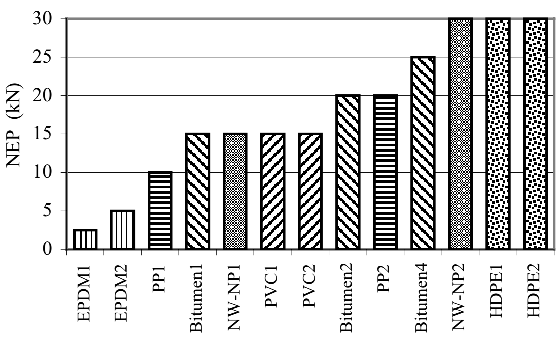

Figure 2. Gravel puncturing test results for the different GLS.

The exact NEP of both HDPE geomembranes were not measurable due to apparatus limits. HDPE geomembranes real NEP are in fact higher than 30 kPa that is the apparatus limit. But the fact is that damages observed on these geomembranes seem to indicate that the NEP is just over the apparatus limit.

NEP of geomembranes made of EPDM, bitumen and PP are a function of the thickness of the geomembrane.

For highest loads, bituminous, PP and HDPE geomembranes exhibited imprints or indentation, that is to say thickness reduction under contact points. The magnitude of this reduction depends on the type of geomembrane. In the case of the bituminous geomembranes, pieces of gravel were embedded in the geomembranes after the test for high loads.

The thickness of the PVC geomembrane does not seem to have an effect on the resistance to gravel puncturing. Nevertheless, differences on individual specimen were observed between the two geomembranes. It tends to show that there is a little difference of resistance that the test cannot show due to the fact that results are given every 5 kPa. PVC2 should have a slightly higher resistance to puncturing than PVC1. For these geomembranes, localised puncture was due to cracks across the membrane under gravel contact point. This kind of observation was possible because these geomembranes were translucent. For other geomembranes this observation was not possible due to their opaqueness.

The geotextile NW-NP2 has a real effect in protecting the PVC geomembrane contrarily to NW-NP1 that does not seem to reduce the risk of puncture for the PVC geomembrane.

Independently of the thickness, it is possible to range the different type of geomembrane according to their NEP. HDPE geomembranes exhibit the highest resistance to puncturing whereas EPDM geomembranes exhibit the lowest ones. In between, bituminous, PVC and PP geomembranes vary in resistance according to their thickness.

3.2 *Direct shear tests*

Results are presented in table 2 and table 3. Friction angles and cohesion are given for both criteria of the NF P 84-505 and the prEN ISO 12957-1 standards, even if the NF P 84-505 standard does not require the cohesion.

Table 2. Dry condition direct shear tests results.

Criterion	NF standard Cohesion (kPa)	Friction angle (°)	PrEN standard Cohesion (kPa)	Friction angle (°)
Bitumen1	11	48	9	48
Bitumen2	7	49	8	47
Bitumen3	10	41	9	41
Bitumen4	15	42	9	44
EPDM1	13	34	12	35
EPDM2	7	41	7	41
HDPE1	-7	46	-5	42
HDPE2	2	31	2	31
PP1	1	37	2	36
PP2	2	39	2	39
PVC1	6	42	5	42
PVC2	7	49	6	50
NW-NP1	-3	36	-2	32
NW-NP2	0	26	-1	26

Table 3. Wet condition direct shear tests results.

Criterion	NF standard Cohesion (kPa)	Friction angle (°)	PrEN standard Cohesion (kPa)	Friction angle (°)
Bitumen3	13	37	13	38
EPDM2	4	30	4	30
HDPE2	2	31	2	31
PP2	2	33	2	33
PVC2	-1	46	0	44

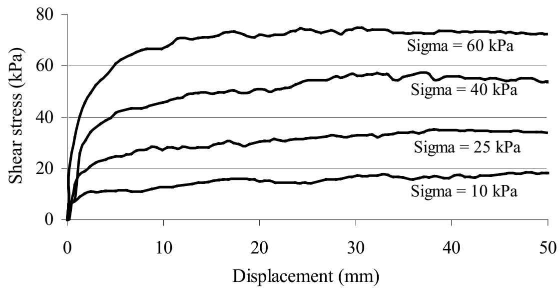

Figure 3. Direct shear tests curves on PVC2.

Figure 3 gives, as an example, the curves obtained with PVC2. Curves obtained for the other geomembranes of this study were similar in shape to these ones.

Friction angles vary from 29° to 49° that is smaller than the internal friction angle of the gravel used. Cohesion values range from 15 kPa down to – 7 kPa. The reason for presenting negative values of cohesion is discussed later.

3.2.1 *Preliminary comments*

EPDM1, PP1 and PVC1 specimens were observed to be partly unglued after the test at the highest normal stress at least. The curves obtained when this phenomenon occurred had unexpected shapes. The shear resistance exhibited a sudden and rapid decrease for a displacement less than 20 mm what is different from the behavior shown in Figure 3. This abnormal behavior affected sensibly the results. It also explains the fact that PVC1 and EPDM1 have respectively smaller friction angles than PVC2 and EPDM2.

Results obtained for these materials were therefore not extensively exploited in this study due to lack of confidence. That is also the reason why wet condition tests were not performed on these products.

The fact that the only thinner geomembranes underwent this ungluing is unexplained.

3.2.2 *Comparison of the shear resistance of the different interfaces*

Shear stress resistances are compared in Figure 4. For clarity purpose, this figure only gives the results on one thickness of each GLS tested in dry conditions, using the French standard criterion. Such a presentation allows comparing obtained shear resistance values of the various GLS at the different normal stresses. It also allows comparing the increase of shear resistance versus the normal stress for each GLS without drawing regression lines. The reason for not presenting the shear test results in Mohr-Coulomb graphs will be discussed later.

It clearly appears that on the 0-60 kPa normal stress range, bituminous geomembrane-gravel and PVC geomembrane-gravel interfaces are the strongest while the others geomembrane-gravel interfaces are more or less equivalent. The geotextile-PVC geomembrane is the weakest interface.

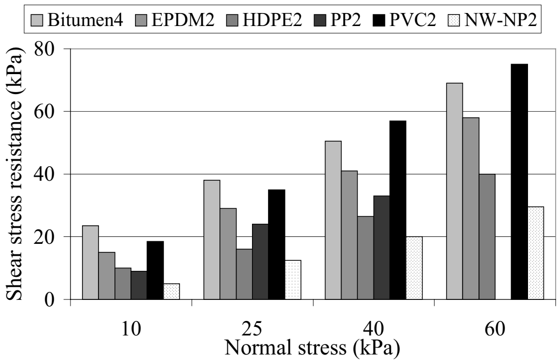

Figure 4. Shear resistance of dry interfaces.

3.2.3 *Comparison of results obtained from both criteria*

The curves in Figure 3 show that the maximum shear resistance is reached before a displacement of 30 mm. As a consequence, cohesion and friction angles calculated from the 30 mm limit and from the 50 mm limit are the same. The same reason explains why for almost all the interfaces tested, dry or wet, the two criteria lead to comparable values.

This is not the case for the only NW-NP1. Indeed, the shear resistance still increases after a displacement of 30 mm.

Cohesion values are systematically smaller with the prEN ISO 12957-1 standard.

3.2.4 *Comparison between dry and wet tests*
Considering the friction angle, EPDM geomembranes seem to be the most affected by the wetting of the interface. Comparison based on the cohesion indicates that the PVC-gravel is the only interface significantly affected. It appears that EPDM and PVC geomembrane-gravel interfaces are weaker when wetted: the shear resistance reductions at a 60 kPa normal stress are respectively of 34 % and 20 %. Other geomembrane-gravel interfaces are not affected, mainly bituminous and HDPE geomembranes-gravel interfaces.

3.2.5 *Influence of the thickness of the geomembrane*
Considering the preliminary comments presented in section 3.2.1, it appears that comparison between the shear resistance of interface of the gravel with different thickness of a geosynthetic is possible for the only bituminous-gravel interface and the geotextile-PVC geomembrane interface.

For the bituminous geomembranes, the shear resistance of the interface with gravel is higher for thinner geomembranes. This is unexplained.

The influence of the thickness of the geotextile is presented in the next section.

3.2.6 *Influence of the geotextile*
The PVC geomembrane-gravel interface has a higher friction angle than the geotextile-PVC interface as well as a higher cohesion. Moreover, the friction angle decreases with the thickness of the geotextile.

Thus, protecting the PVC geomembrane with a geotextile introduces a weaker interface. This reduction depends on the geotextile thickness.

3.2.7 *Damage*
Damages observed on specimens after testing were of different nature: stretching, scratches, indentations or puncturing.

HDPE1, PVC1 and PVC2 were punctured after the test, for at least the highest stress level.

For the PVC geomembrane, punctures were in fact cracks across the geomembrane under the gravel contact points. The PVC geomembrane tested in association with the geotextiles exhibited no damage.

The damage of the PP geomembranes was rather high: residual local stretching deformations were observed. Bituminous geomembranes exhibited indentation proportional in depth to the normal stress.

The EPDM geomembrane exhibited the best behavior: no residual deformation was observed either than surface defects.

For the bituminous geomembranes, pieces of gravel were slightly encrusted in the geomembrane for high stress levels. For the lowest stresses, the geomembrane exhibited indentations.

HDPE1 and HDPE2 exhibited shallow scratches, even for low confining stresses. For HDPE1, the piercing occurred for a 60-kPa stress for which the shear resistance appeared to be slightly higher than the one obtained for HDPE2. It is assumed that the gravel was 'anchored' in the geomembrane what would explain both cohesion and friction angles values for HDPE1. Indeed, a high shear resistance obtained for the 60 kPa normal stress tends to modify the linear regression in such a way that the friction angle is increased and the cohesion decreased, explaining the negative cohesion for HDPE1. Considering the only 10, 25 and 40 kPa normal stress test results leads to a friction angle of 38° a cohesion of –2 kPa and according to the French standard instead of 46° and –7 kPa also considering the 60-kPa normal stress result.

4 DISCUSSION

4.1 *Gravel puncturing tests*

Geomembranes exhibit different behaviors and resistance when exposed to gravel puncturing on a rigid support. The gap between EPDM geomembranes and HDPE geomembranes is very important. For some products, the thickness has a real influence, whereas for others it is little or undetectable.

Gravel puncturing on a rigid support lead to localized compressive stresses on the geomembrane. There is no bending or direct tensile stress, neither than cutting by sharp elements during this test. Results obtained in this study, and mainly comparison between the different geomembranes, are related to these specific testing conditions and may not be used when other solicitations are encountered.

Analyzing the punctured zone and the mode of piercing of the different geomembranes may give indications about the characteristic governing it.

In the case of bituminous geomembranes, the piercing is the result of an increasing indentation in the material. (see Fig. 5) The increase of the NEP for increasing thickness of bituminous geomembranes is due to an increase of contact surface between the gravel and the geomembrane. Indeed, as a piece of gravel gets in the geomembrane, the contact surface increases, and thus the resistance to penetration increases. As a consequence, a thicker bituminous geomembrane will have a higher NEP. But the NEP should also depend on characteristics linked to the penetrability of the bitumen. This has not been addressed here.

Figure 5. Bituminous geomembrane specimen after the gravel puncturing test.

Interpretation of mode the mode of piercing of the other geomembranes is difficult to carry. Nevertheless, there are obvious similarities between the aspect of geomembrane specimens in the punctured zone and in the rupture zone after uni-axial tensile test. Cracks in the PVC are the best example. From visual inspection, it seems that the localized compressive stress induces an indirect tensile stress in these homogeneous polymeric membranes. 'Indirect tensile stress' has the same meaning as for rock testing. The mode of piercing during gravel puncture test should thus depend on the type of geomembrane.

This aspect based comparison seems to be confirmed by the results presented in Figure 6 giving the NEP as a function of the uni-axial tensile test results on PVC1, EPDM1, HDPE1 and PP1. The results of these tests performed on a narrow dumbbell specimen according to the NFP84-501 standard (AFNOR 92) are not presented in this paper.

As puncturing is a rupture of the material, the NEP is compared in Figure 6 to the resistance at rupture during tensile test for PVC, PP, and EPDM geomembranes. For the HDPE geomembrane, the result considered is the resistance at yield. The gravel puncturing test should rather be considered as a constant stress-rate test than as a constant strain rate test, such as the standardized tensile test, which justifies considering the characteristics at yield instead of the characteristics at rupture. The figure indicates that there is a linear correlation between the two tests for homogeneous geomembranes.

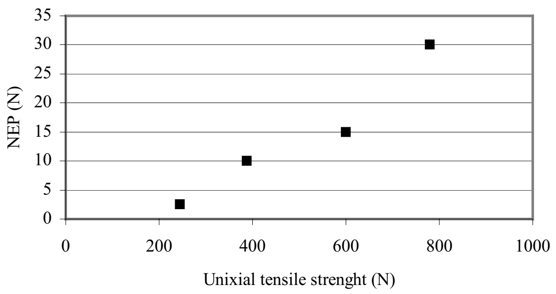

Figure 6. Comparison between tensile test and gravel puncturing test results for homogeneous geomembranes.

But, due to the testing method limits and accuracy, the NEP is not a precise value. An exact correlation between both tests may not be obtained. For instance, the fact that the two PVC geomembranes have the same NEP value shows the limit of the correlation. Indeed, as the tensile strength is proportional to the geomembrane thickness we should have obtain, if there were a precise correlation, two different NEP values for the two PVC geomembranes.

Nevertheless, this correlation can be discussed. Tensile properties are often considered as governing puncture resistance of geomembranes laying on a soft support (Giroud et al. 1995). But, in our case, the support is rigid and flat. There is thus no tensile solicitation during the gravel puncturing test, as it is the case in common and real puncturing contexts. But, it appears from our results that tensile properties may also be important for the puncture resistance of geomembranes laying on a rigid support.

This cannot apply to bituminous geomembranes as their tensile strength resistance mainly depends on the geotextile(s) characteristics, whereas the resistance to puncturing depends on the characteristics of both bitumen and geotextile.

Concerning the geotextile protection efficiency, it is assumed that the increase of NEP is due to the increase of contact surface provided by the thicker geotextile. Indeed, the geotextile increases the area concerned by a piece of gravel leading to a reduction of the local stress. Attention should be paid to the fact that the results concerning the geotextiles should not be generalised to the protection of other kinds of geomembrane. These results and conclusion concern the PVC geomembrane only.

Considering the mode of piercing, and the indirect tensile stress, a test consisting in submitting a geomembrane laid on a rigid plate to puncturing by a probe could reproduce the solicitations of the gravel puncturing test and thus the solicitations by gravel on a geomembrane laying on a rigid support. The current draft standard method WI189066 (CEN 2001) could be appropriate for this purpose. Indeed, this test specifies an index test method to determine the pyramid puncture resistance of a geosynthetic placed on a rigid support.

4.2 *Direct shear tests*

Direct shear curves were examined considering both the NF P84-505 and prEN 12957-1 standard criteria. This does not mean that the tests were performed according to the European draft method. Moreover, the European draft standard imposes to take into account the internal shear resistance of the gravel to calculate a friction ratio. This was not considered in this study mainly aiming at comparing different interfaces with the same apparatus and gravel.

It is important to underline that observation of the specimen after testing is essential to evaluate the validity of the test results. Mainly, surface defects, local ungluing of the specimen or its puncturing may explain unexpected curves leading to low or high shear resistance values. Moreover, ungluing of the specimen makes possible the damage of some specimen, such as local stretching observed on the PP geomembrane. In the case of the HDPE1, the observations allowed invalidating the 60-kPa data.

Different reasons may explain the negative cohesion values obtained for the geotextiles. They can be due to apparatus limits: it is possible that the stresses applied for these shear tests are too low for this kind of equipment for the cohesion determination to be satisfactory. These negative values may also be due to the inadequacy of the approach used to characterise the behavior of the gravel-geotextile interface. Whatever the reason, the cohesion values are small and may be considered equalling zero.

Confronted to the negative cohesion values, we should certainly have not give it or have modified the linear regression so that the cohesion be zero prior calculating a friction angle. But, this would have hid the importance of surface defects on the shear resistance. Moreover, such a decision would be based on the consideration that the behavior of a geosynthetic-gravel interface submitted to shear stress can be represented by a line in a Mohr-Coulomb graph, and thus characterised by a set of cohesion and friction angle. This has been shown not to be always correct (Giroud et al. 1993).

In the case of geomembrane-gravel interfaces the inadequacy of this simple approach is mainly due to the fact that the interface between the 'hard' gravel and the 'soft' geomembrane is modified when increasing the normal stress. The surface aspect of the geomembrane, and thus its shear properties, is different for a low normal stress than for a high normal stress. In the case of bituminous geomembranes encrustation of gravel that only occurs for high confining stresses has a great influence on the geomembrane-gravel interface shear resistance. Piece of gravel are anchored in the geomembrane and the interface is no more a flat surface. On the other side, for a very low confining stress there is almost no shear resistance as the geomembrane is smooth and as there is no interaction between the gravel and the geomembrane

This hypothesis is confirmed by the fact that the resistance of this interface is not reduced when wet.

This interface changing argument is obvious for bituminous geomembranes but it may be extended to other types of geomembranes for which indentations can be considered as a sign of the modification of the interface. The effect of the penetration of gravel in the geomembrane may explain that the friction angles and cohesion values obtained in this study are rather high compared to other soil-geomembrane interfaces ones (Briançon 2001).

The indentation depending on the hardness of the material, this characteristic may govern the geomembrane-gravel shear resistance. PVC and EPDM geomembrane-gravel interfaces exhibit significant cohesion values whereas PP and HDPE geomembrane-gravel interfaces have no real cohesion what tends to confirm the influence of the hardness. The fact that the shear resistance reduction due to the geotextile increases with the thickness of the geotextile is also an argument in favour of this idea. Indeed, the geotextile reduces the indentation of each piece of gravel on the geomembrane by increasing the contact surface proportionally to its thickness.

Of course, geomembrane hardness may not be sufficient to interpret shear resistance of different geomembrane-gravel interfaces. The fact that HDPE geomembrane-gravel interfaces are not sensitive to wetting whereas PVC and EPDM geomembrane-gravel ones are shows that there are other parameters to consider. These are certainly related to physical properties of polymer surface properties. This should be investigated by further research.

The approach presented here to discuss shear test result differences should not be confused with the approach used in the previous section on gravel puncturing tests as the magnitude of the penetration of the gravel into the geomembrane is really different form one test to the other. In one case, it's a shallow phenomenon, under low loads, whereas in the other it's a deep phenomenon where the geomembrane is led to piercing under high loads. In one case, the characteristic to be correlated with the test result is the hardness whereas in the other it as been shown to be tensile strength.

It has been shown that the cohesion calculated takes into account the behavior of the changing interface over a range of normal stresses. The cohesion is thus not a real cohesion but an 'apparent cohesion' depending on the range of normal stress used for the test. A set of cohesion and friction angle is thus not appropriate to describe the changing interface justifying why the results of this study are not presented using Mohr-Coulomb graphs.

However, the practical interest of shear tests is often to compare the resistance of two interfaces at a given stress. Thus, friction angles and cohesion are only useful to calculate shear resistance over the stress range of interest for the designer. But, considering the only shear resistance data prevents the designer from questions related to the meaning of cohesion for this kind of interfaces.

Beyond the technical and scientific interest of the determination and meaning of the cohesion, it must be underlined that considering the simplistic cohesion-friction angle description of the interface can lead to misleading conclusions. For instance, results given strictly according to the French standard would put it at a disadvantage on geomembranes exhibiting a high cohesion, as this characteristic is not considered by the standard.

4.3 *Damage during the tests*

Shear test damage was observed after a gravel displacement on the geomembrane of 50 mm that is rather important compared to service life displacement. Nevertheless, it is realistic compared to conditions of installation of gravel layers. These data are thus of great interest.

HDPE geomembranes appeared to be sensitive to this shear damage unlike EPDM what is in opposition with the gravel puncturing test results. Moreover, normal stress during shear stress is small compared to the normal stress applied during puncture test. This shows that damaging solicitation are really different from one test to the other and that results given by the gravel puncture test should be counterbalance by observations made during shear tests when considering the risk of puncturing.

Shear damage obtained during the shear test is interesting to appreciate the behavior of geomembranes when submitted to gravel installation damage. But, during the shear test, some of the geomembranes are glued on the rigid support. This clearly influences the damage of the geomembrane. On site, as geomembranes are not glued and may move, shear damage may be more important than was observed after the test. A more appropriate test, allowing testing of every kind of geomembrane in the same conditions should be developed.

5 CONCLUSION

Conclusions concerning the behavior of different interfaces in term of shear resistance and resistance to puncturing can be drawn from this study. It has been shown that, with the specific gravel used, bituminous and PVC geomembranes exhibit the highest shear resistance. It has also been shown that HDPE geomembranes on a rigid support exhibit the highest gravel puncture resistance but may be sensitive to shear damage. The efficiency of geotextiles in protecting a PVC geomembrane as well as its influence on the shear resistance of the interface has been addressed.

Concerning the test methods, this study has highlighted the importance of examining tested specimen after shear resistance tests with the aim of identifying local ungluing or damage of the specimen that can modify significantly the test results. The study also showed the interest of using the shear test for another purpose than the only shear resistance as it gives complementary information to classical puncture tests related to installation damage.

The discussion underlined the complexity of shear behavior of gravel-geomembrane interfaces. This behavior seems to be mainly governed by the hardness of the geomembrane and a set of cohesion and friction angle does not appropriately describe it. It has been also suggested that the resistance to puncture by gravel of a geomembrane laying on a rigid support depends on the tensile properties of the geomembrane. These points should be addressed.

6 AKNOWLEDGEMENT

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