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Welding and testing of PE geomembranes

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ABSTRACT: NIL, the Dutch Welding Institute coordinated a research project which was carried out by some twenty parties. The project was aimed at optimization of welding procedures for different PE (poly ethylene) geomembranes. Different welding windows were applied using HD (high density) PE, LLD (linear low density) PE and VLD (very low density) PE materials. The short term behaviour of the welds were tested using shear, peel and impact tests and the long term behaviour was tested using constant load tests at 60 or 90 °C in an aqueous solution. The mechanical behaviour of a number of PE geomembranes was studied in more detail to quantify the stress relaxation in the geomembranes and to investigate the failure behaviour under service conditions.

1 INTRODUCTION

The Dutch Welding Institute together with some twenty parties (a.o. the Dutch Government, Test Institutes, PE and Geomembrane manufacturers, installers, etc.) carried out a research project on PE geomembranes. Up till now, geomembranes for landfill and civil applications were made of HDPE and PVC based on insight in the long term behaviour of those materials. The importance of the long term behaviour of welds and the question if the current flexible PE materials (modified HDPE, LLDPE and VLDPE) can be used for this application as well were the starting points of this research.

The objectives of the research were:
* to obtain reliable weld properties;
* to design procedures to quantify the applicability of new materials;
* to correlate the quality of the weld with inspection and testing procedures;
* to elaborate guidelines for geomembranes concerning lifetime.

2 SITUATION IN THE NETHERLANDS

The protocols for the application of plastic geomembranes are very comprehensive in the Netherlands [1]. Requirements are given for dimensional quantities (thickness, width), for chemical degradation (thermal stability, UV stability, chemical resistance), for physical degradation (environmental stress cracking, leaching, permeation), for processing (folding and welding) and for mechanical properties (puncture, tearing strength). A summary of the tests prescribed in the Netherlands is presented in table 1.

Table 1 Prescribed tests on PE geomembranes in the Netherlands

Standard	Description
DIN 16726; NEN 3056	Dimensions
NEN 7116	Amount of carbon black
ASTM-D 3895	Thermal stability (OIT)
non	Conditioning at 100 °C (water/air)
KIWA BRL 519	Leaching of plasticizers
ISO 62	Exposure to mixtures
NEN 3056	(Micro)biological degradation
KIWA BRL 546	UV resistance
DIN 16726	Shrinkage
ASTM D1693-70	Environmental stress cracking (ESC)
ISO 899	Creep for 2000 hrs
DIN 16726	Slit pressure strength
DIN 53361	Folding resistance
DIN 16726	Puncture resistance (falling ball)
ISO 527	Tensile strength
DIN 53363; NEN 3056	Tearing strength
DIN 53448	Tensile impact strength
DIN 53357	Peel strength

Each requirement determines a specific aspect in relation to the behaviour of the PE geomembranes in service. To evaluate welding windows and flexible PE geomembranes, a number of the requirements does not need further research.

Although an insufficient dispersion of carbon black in the polymeric matrix is thought to cause preliminary failure of PE geomembranes [2], this project started with well-processed PE materials. The PE materials used fulfilled the requirements on carbon black, on thermal stability, on conditioning at 100 °C, on leaching of plasticizers and on UV resistance. Most of these requirements are related to additives used in the PE. For example, the OIT (oxygen induction time test) and the UV (ultra-violet radiation test) are fulfilled due to the presence of stabilizers.
The more important degradation processes, which are related to the polymer morphology and not to the presence of stabilizers, were studied in this project.

Degradation by swelling, which will only occur in the presence of high concentrations of aliphatic, aromatic and/or chlorinated hydrocarbons, is thought to be of minor importance. The same holds for permeations of chemicals through the geomembrane.

When the deterioration of the PE geomembrane due to thermal degradation, leaching of plasticizers and UV degradation can be neglected, the short term behaviour of the geomembrane is determined by the puncture resistance, the shrinkage, the impact strength, the tearing strength and the peel strength of the welds.
The long-term behaviour of geomembranes is then dominated by the resistance of the PE material and the weld to crack initiation and to slow crack growth.

This project is concentrated on the short and long term behaviour of welds and on the long term behaviour of the PE materials.
The crack initiation and the slow crack growth are thought to dominate the lifetime of geomembranes and geomembrane welds.

3 EXPERIMENTAL PART

3.1 Materials

PE materials can be divided in HDPE and LDPE grades on basis of the polymerisation process. The division of the raw materials without additives is on basis of density as follows:

HDPE (high density)	> 946	$kg.m^{-3}$
LDPE (low density)	< 930	$kg.m^{-3}$

Although due to another polymarisation process the structures of the recent developed categories of low density PE differ from the original LDPE, the density of those categories is:

LLDPE (linear low)	916-930	$kg.m^{-3}$
VLDPE (very low)	900-915	$kg.m^{-3}$

Two HDPE grades were studied (coded: HDPE1[1)], HDPE2), LLDPE (coded: LLDPE) and VLDPE (coded VLDPE). The basic properties of the PE materials studied are presented in table 2.

Table 2 Basic properties of the PE materials used

Code	Density ($kg.m^{-3}$)	MFI[2)] ($g.min^{-1}$)	Carbon black (%)
HDPE1[1)]	0.939	1.64	2.2
HDPE2	0.951	0.80	2.8
LLDPE	0.930	2.90	2.2
VLDPE	0.916	5.61	1.3

1) Notice that the HDPE1 is problably not a HDPE material according to the division given in this section. However, it is assigned as HDPE by the supplier.
2) condition 190/5.

3.2 Tests

DSC

The melting temperatures and the melting enthalpies were obtained by differential scanning calorimetry (DSC). The measurements were performed on a Perkin Elmer DSC7 in nitrogen atmosphere with a heating rate of 10 $°C.min^{-1}$.

DMTA

DMTA stands for dynamic mechanical thermal analysis. The test strips (40x14x2 mm) were subjected to a cyclic deformation (0.1 %; 1 Hz). The temperature was increases during the measurement with 1 $°C.min^{-1}$. The temperature interval studied was -50 to 120 °C.

The "torsion head" of Polymer Laboratories was used in this study for the DMTA measurements.

Tensile strength

The tensile strength of the PE materials and the welds were measured on a Zwick UTM 1455 tensile machine according to ISO 527-3 using a test speed of 100 for HDPE, LLDPE and VLDPE. The test specimens (type 1B) were punched from the (welded) geomembranes.

Tensile impact strength

A Zwick 5101 impact tester with a 500 kpcm (49 J) pendulum was used for the tensile impact test according to DIN 53448. The test specimens were the same as used for the tensile tests.

Peel strength

Peel tests were performed to evaluate the quality of the welds. Peel strength was recorded according to DIN 53357 using the Zwick UTM 1455 and a test speed of 100 $mm.min^{-1}$.

Constant load strength

The long term stability of the welds was studied using constant load tests according to DVS 2203-Teil 4. The specimens were exposed to a 2 % Rhodacal DS10 solution in tap water. The temperature was 90 °C for HDPE1 and HDPE2 and 60 °C for LLDPE and VLDPE. The load applied was approximately 40 % of the tensile strength at the corresponding temperature. The specimens were the same as for the tensile strength measurements.

Craze initiation stress

The threshold value for craze initiation was studied in order to quantify the threshold level for crack initiation. A craze is a crack with stress carrying polymer fibrils and is the predecessor of a crack [3]. Surface crazes have a length of the order of magnitude of 10-100 µm and a width of 1-10 µm. A tapered test strip (thickness, 2 mm; width varying from 10 to 20 mm; length, 120 mm) was used for the craze initiation experiments. The strip was subjected to a constant load in a frame which was enclosed by glass windows. The stress gradient was used to determine the craze initiation stress as a function of the loading time. Surface craze were observed with a light microscope (magnification x50-100) in oblique light [4].

During the craze initiation measurements at 23 °C, the PE geomembranes were exposed to an aqueous solution of IGEPAL (10 % IGEPAL CO630).

Stress relaxation

Stress relaxation measurements were performed at 23 °C using home-built tensile testers in order to quantify the long term stress in a deformed geomembrane. Rectangular test strips (150x20x2 mm) were strained at 2,5; 5 and 10 %. The stress was recorded automatically using a calibrated loadcell and a data acquisition system.

3.3 Welding

Although some extrusion welding was studied as well, here only the results on the wedge welding are presented.

The averaged welding conditions are summarized in table 3. The welding temperatures for LLDPE were higher than for the other materials. Therefore the conditions for the LLDPE material are mentioned separately.

Table 3 Averaged welding conditions

Material	Temperature (°C)	Speed ($m.min^{-1}$)	Force (kgf)
HDPE1,HDPE2,	342 ± 2	1.2	35 ± 10
VLDPE	422 ± 5	2.4	79 ± 20
	485 ± 15	3.1	125 ± 25
LLDPE	395 ± 5	1.2	30 ± 8
	475 ± 10	2.4	67 ± 13
	517 ± 7	3.1	128 ± 15

27 conditions (3 temperatures; 3 welding speeds; 3 pressure forces) were applied for the 4 PE materials under study. The results of only two welding conditions are presented in this paper, namely the most extreme ones. On the one hand the weld, which is produced using the lowest temperature, the highest speed and the lowest pressure force (coded ATX) and on the other hand the weld, which is produced using the highest temperature, the lowest speed and the highest pressure force (coded CRZ).

NB The short term and long term mechanical properties found for these welds will not be the optimum results which can be obtained, because it is thought that the extreme welding conditions applied here will yield the poorest welds.

4 RESULTS

4.1 Welds

4.1.1 Tensile strength

The results of the tensile tests on the welds of the PE materials studied are mentioned in table 4 for the two welding conditions.

The strength, which is defined as the stress at failure, shows the largest difference for the two welding conditions for the HDPE1 material. The larger reduction in the strain at failure is observed for the HDPE2 material. The LLDPE and the VLDPE also show a significant difference in the strain at failure for the two conditions considered.

Table 4 Strength and strain at failure for two welding conditions (ATX and CRZ)

Material	Strength (MPa)		Strain (mm)	
	ATX	CRZ	ATX	CRZ
HDPE1	14.5	13.6	122	111
HDPE2	16.6	17.1	143	78
LLDPE	12.1	11.6	216	154
VLDPE	10.1	10.2	210	163
	± 0.3	± 0.3	± 10	± 20

4.1.2 Peel strength

The results of the peel strength tests on the welds of the PE materials studied are given in table 5 for the two welding conditions.

The peel strength shows the largest difference for the two welding conditions for the HDPE1 material. The reason for this difference is the quality of the weld. The HDPE1 material was not welded properly under the ATX condition, it was just sticked.

Table 5 Peel strength for two welding conditions (ATX and CRZ)

Material	Peel strength (N)	
	ATX	CRZ
HDPE1	1000 ± 202	1506 ± 158
HDPE2	1580 ± 91	1419 ± 18
LLDPE	1108 ± 42	1069 ± 12
VLDPE	879 ± 6	882 ± 16

The reduction in the peel strength between the conditions ATX and CRZ is related to changes in the morphology of the PE materials which are introduced during the welding process.

4.1.3 Constant Load

The constant load experiments were performed under constant relative stress levels. The results of those measurements are presented in table 6.

Notice that the welds of the VLDPE and the LLDPE materials do not fail within 1000 hours at 60 °C.

The HDPE materials failed within 1000 hours, but at 90 °C.

The welding at higher temperature, longer welding time and under higher pressure (CRZ condition) seems detrimental for the HDPE materials.

Table 6 Time to failure under constant load for two welding conditions (ATX and CRZ)

Material	Temperature (°C)	Time to failure (hrs)	
		ATX	CRZ
HDPE1	90	47 ± 11	28 ± 9
HDPE2	90	116 ± 27	67 ± 61
LLDPE	60	> 1000	> 1000
VLDPE	60	> 1000	> 1000

4.1.4 Tensile impact strength

The results of the tensile strength tests on the welds of the PE materials studied are given in table 7 for the two welding conditions.

The tensile impact strength shows the largest difference for the two welding conditions for the HDPE materials.

Table 7 Tensile impact strength for two welding conditions (ATX and CRZ)

Material	Tensile impact strength ($kJ.m^{-2}$)	
	ATX	CRZ
HDPE1	1212 ± 286	784 ± 78
HDPE2	778 ± 138	338 ± 245
LLDPE	1497 ± 110	1124 ± 473
VLDPE	1550 ± 300	1162 ± 535

The reduction in the tensile impact strength between the conditions ATX and CRZ is related to changes in the morphology of the PE materials which are introduced during the welding process.

4.2 PE properties

4.2.1 DSC

The DSC measurements provide information on the crystallinity and on the melting temperatures. The melting enthalpy is proportional to the degree of crystallinity and the melting temperature is related to the size and shape of the crystallites.

From table 8, it is concluded that the melting temperatures of the PE materials under study are very close. The sequence for the melting enthalpy reads:

HDPE > LLDPE > VLDPE

Table 8 Melting temperature and melting enthalpy for the PE materials studied

Material	Melting temperature (°C)	Melting enthalpy ($J.g^{-1}$)
HDPE1	124	135
HDPE2	123	156
LLDPE	120	116
VLDPE	124	91

4.2.2 DMTA

The shear modulus is determined for 4 PE materials. The results of the DMTA measurements are presented in figure 1.

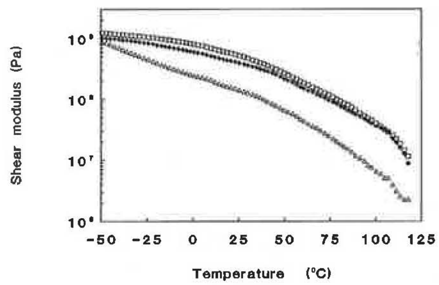

Fig. 1 Shear modulus versus temperature for PE materials □: HDPE1; +: HDPE2; ▵: VLDPE.

Starting from -50 °C, the difference between the HDPE materials and the VLDPE material increases with increasing temperature. The ratio in modulus between the HDPE materials and the VLDPE material studied is already a factor of 2-3 at 0 °C and at 75 °C even a factor of 4-5.

The strong decrease in modulus at about 120 °C is related to melting of crystallites.

4.2.3 Craze-initiation

The results of the craze initiation measurements are shown in figure 2. The craze initiation measurements were difficult because of the surface roughness of the geomembranes studied. Therefore, no reliable craze initiation could be found at short loading times.

The craze initiation was performed on test strips which were exposed to an aqueous IGEPAL solution. The threshold value for craze-initiation at 23 °C in the IGEPAL solution is about 2 MPa for the PE materials studied.

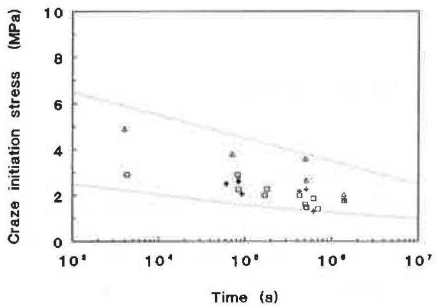

Fig. 2 Craze initiation stress versus time at 23 °C. □: HDPE1; +: HDPE2; ▵: VLDPE.

4.2.4 Stress relaxation

Soil deformations and temperature changes are thought to cause stresses in a geomembane. The size of the deformations are expected to be about 2 % for the bottom geomembrane and about 5 % for the upper geomembrane when the geomembranes are applied correctly.

In order to determine the long term tensile stress in a PE geomembrane, stress relaxation measurements were applied. In figure 3, the relative stress is shown versus the loading time. The relative stress is defined as the actual stress divided by the stress after a loading time of 100 s.

The stress relaxation is during the first hours faster for the HDPE materials than for the VLDPE materials. After this period, the relative stress relaxation rate is almost identical for all PE materials studied, namely 5% per unit on a logarithmic time scale.

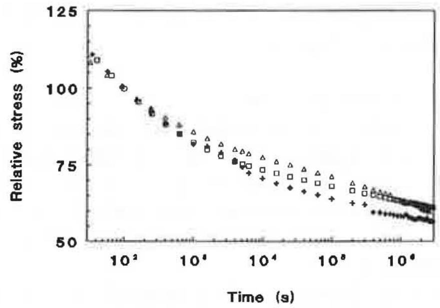

Fig. 3 Relative stress versus loading time for an applied deformation of 5 % at 23 °C.
□: HDPE1; +: HDPE2; ▵: VLDPE.

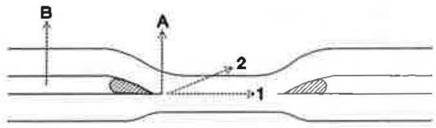

Fig. 4 Schematic illustration of the weld. The arrows represent the different fracture surfaces found and the striped areas the expelled material.

5 DISCUSSIONS

5.1 Welds

5.1.1 Weld strength

The welding condition ATX (lowest temperature, fastest speed and lowest pressure) yields better results where it concerns the constant load tests, the tensile impact strength and the strain at failure than the welding condition CRZ (highest temperature, slowest speed and highest pressure). These observations can be explained in terms of less changes in the morphology of the geomembrane material in the weld under the ATX condition.

The conclusion, whether the welding condition ATX results in better properties than the welding condition CRZ, can however not be drawn without considering the failure process. Furthermore, one should keep in mind that two extreme welding conditions are presented here.
When the failure process is considered, four different fracture surfaces can be defined. The position of those surfaces is shown schematically in figure 4.

Mode 1: Failure in the bond line due to insufficient heat and polymer transfer;
Mode 2: Failure in the heated zone due to polymer degradation;
Mode A: Failure at the weld boundary;
Mode B: Failure in the geomembrane.

Mode 1 failures are observed for welds in the HDPE1 produced under ATX conditions. Mode 1 failures normally show a lower peel strength (see table 5). In order to prevent mode 1 failures to occur under service conditions, it is recommended to perform tests to quantify the peel strength of the weld.

Mode 2 failures are found when degradation occurred during the welding process.

The other materials studied showed mode A and mode B failures as expected for welded geomembranes.

5.1.2 Long term behaviour

The interpretation of the constant load experiments in the 2 % Rhodacal DS10 solution at higher temperatures for a long term prediction is difficult, because the acceleration factors are unknown. The proposal of Koerner that the time to failure of a HDPE material should exceed 100 hours at 50 °C in an aqueous IGEPAL solution is probably based on the assumption that the failure process, i.e. slow crack growth, is increased by a factor of 10 per 20 °C and that the surfactant IGEPAL causes an increase by an additional factor of 10.

A HDPE geomembrane, which is used at 10 °C (about the temperature experienced by a geomembrane), will than have a lifetime of at least 10^5 hours (about 11 years).

Using the same starting points, a HDPE material, which withstands a constant load for 10 hours at 90 °C in an aqueous surfactant solution will have a predicted lifetime of at least 200 years at 10 °C.
It should however be noticed that the acceleration factor due to the surfactant will decrease with increasing temperature. Nevertheless, the times to failure found for the HDPE welds studied here seem to guarantee a long lifetime under service conditions.

For LLDPE and the VLDPE welds, the lifetime seems to guarantee a long lifetime under service conditions. One should however be careful because the effect of the surfactant on the acceleration of the slow crack growth will be decreased for the corresponding PE materials.

5.2 PE materials

In the previous section the lifetime of a PE material was predicted using the results of the constant load tests. Unfortunately, the prediction method applied has to be verified. For HDPE materials, the verification was performed using burst tests at different temperatures on pipes. For LLDPE and VLDPE, those test can not be performed. As a consequence, some other tests were performed in order to evaluate the need for verification.

From the DMTA and DSC results (sections 4.2.1 and 4.2.2), it is concluded that the VLDPE material has a lower modulus than the HDPE materials studied in the temperature range from 10 to 90 °C. Thus it is impossible to test those materials at high stress levels and at high temperatures. Therefore, the constant load tests on these materials were performed at 60 °C.

When an optimum welding condition is used, a weld is obtained which shows plastic deformation in a tensile, a tensile impact and a peel test. The long term failure behaviour will then be dominated by the initiation of crazes and cracks and by the slow crack growth. No crack growth will occur provided that there is no crack initiation. The threshold level for craze initiation is thought to be the threshold level for crack initiation and crack growth as well.

From the craze initiation experiments, it is concluded that the threshold level for craze initiation is about 2 MPa for all PE materials studied. The threshold level for craze initiation for a welded geomembrane will be lower due to the stress concentration factor at the welded zone.
The threshold level for craze initiation will then be exceeded in the constant load test performed. The load level applied in the constant load tests was about 40% of the yield stress at the corresponding temperature.

The stress relaxation measurements were performed to verify the actual long term stress in the geomembrane. For a strain level of 5% in the geomembrane, the stress level is about

5-6 MPa for the HDPE materials studied;
2.5-3 MPa for the VLDPE material studied
after 1 week and about

4.5-5.5 MPa for the HDPE materials studied;
2.3-2.7 MPa for the VLDPE material studied
after 1 year at 23 °C.

When the PE geomembrane is thus subjected to a strain level of 5%, craze initiation will occur in all PE materials studied. Experiments, in which the slow crack growth is quantified, are recommended then.

6 PRELIMINARY CONCLUSIONS

The conclusions drawn here are based on the results presented on the two extreme welding conditions. The final conclusions on all welding conditions studied will be published later.

The two welding conditions presented here resulted in a decrease of mechanical properties (e.g. impact strength, time to failure under a constant load) due to the geometry of the weld and due to changes in the morphology induced by welding.

Although the differences in mechanical properties are moderate for the two welding conditions considered, some trends are noticed.

Higher temperature, slower welding speed and higher pressure during welding resulted in a decreasing tensile impact strength and a decreasing time to failure under constant load for the HDPE materials.

Too low welding temperatures together with high welding speed resulted in insufficient bonding, which can be easily quantified by peel tests.

The welded LLDPE and the welded VLDPE materials studied showed high values for the tensile impact strength and the time to failure under a constant load. No slow crack growth was observed up till 1000 hours at 60 °C in an aqueous surfactant solution.

From the stress relaxation and craze initiation measurements, it is concluded that craze initiation will occur in welded geomembranes which experience a strain level about 2% or larger.

7 ACKNOWLEDGEMENT

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