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Mechanical strength evaluation of geomembrane welds - welding factors

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ABSTRACT: Peel tests and shear tests were carried out on welds performed on five types of geomembrane, respectively HDPE and bituminous. We show that for a given chemical family and a given type of welding, the welding factor varies according to the constitution of the membrane (physio-chemical characteristics, thickness, type of reinforcement). The welding factor should thus be considered differently depending on whether personnel/welders are being qualified for a certification, or specifications are being drawn up for a project. This confirms that the question of evaluating weld quality has not yet been completely settled, although it has already been the subject of debate in the past.

1 INTRODUCTION

In terms of mechanical strength, what defines a good weld? This very old question has been studied by numerous specialists (Peggs et al 1994, Rollin et al 1991, Haxo et al 1990). It is a crucial and recurrent one, since for a given project, for 10,000 m^2 of geomembrane installed, there are approximately between 1000 and 2500 meters of welds. The quality of the membrane itself doesn't usually pose a problem, since it is an industrial product generally subjected to quality controls according to ISO standards. However, the same does not apply to the quality of welds performed on sites in conditions which are sometimes quite difficult.

The test methods used, and for the most part standardized, on an international level – usually peel tensile tests and shear tensile tests – have changed very little. Analysis of their results, for example the welding factor, remains difficult.

This problem becomes acute when one considers the human aspects of the problem. When the quality of a weld is evaluated, it is often the welder himself who is judged, usually due to problems detected during site inspections and welder certification (the French ASQUAL certification procedure). For welds on HDPE and bituminous membranes, doubt has been shed on the relevance of the certification requirements with respect to the type of geomembrane concerned. It was in this context that the French Geomembrane Committee (CFG) launched this study.

The objective of the study was thus to verify if under optimum welding conditions, (welders with recognized competence welding in a workshop), for a given generic chemical family of geomembrane, respectively HDPE and bituminous, one could observe significant variations of the tensile strengths of the welds according to the intrinsic characteristics of the geomembrane, e.g. polymer density grade, thickness, and mass per unit area of reinforcement.

2 STUDY DESCRIPTION

The study consisted in having performed by certified welders and under optimum technical conditions, extrusion and fusion welds on five types of HDPE, and fusion welds on five types of bituminous membranes chosen from the products encountered most often on the market (tables 1 and 2).

2.1 *Physio-chemical characteristics of the geomembranes*

Table 1. characteristics of the HDPE geomembranes

	Unit	Gmb 1	Gmb 2	Gmb 3	Gmb 4	Gmb 5
Density		0.945	0.940		0.944	0.941
Carbon black content	%	> 2	> 2		2.1	2.26
Degree of crystallinity	%	65	68	62	61	61
Thickness	mm	2	2	2	2	2
Production method		calan-dering	calan-dering	blow forming	calan-dering	blow forming

Table 2. characteristics of the bituminous geomembranes

	Unit	Gmb A	Gmb B	Gmb C	Gmb D	Gmb E
Chemi-cal nature		SBS polymer bitumen	SBS polymer bitumen	oxidized bitumen	oxidized bitumen	oxidized bitumen
Thick-ness	mm	3	4	3	4	5.5
MUA	g/m²	160	225	160	225	340

MUA: mass per unit area of reinforcement (non-woven needled geotextile)

2.2 *Weld and test performance conditions*

2.2.1 *HDPE*

The double welds were performed with a heated wedge machine (CONCORD, WEGENER) and an extruder (MUNCH) for the extrusion welds. They were performed in a workshop at a temperature of 12°C on a concrete support. Each welder performed 5 m of double welding and 2 m of extrusion on each of the 5 geomembranes. The welds were carried out at a temperature ranging from 380°C to 440°C at speeds from 1.4 to 2 mm/min. The welders were in charge of defining all the welding parameters. The double welds were 2x15 mm wide. Inspection tests were carried out on site with a shop dynamometer, and the entire operation was supervised by a representative of the laboratories.

2.2.2 *Bituminous*

These welds were performed with partial fusion using a propane blowtorch over a width of 150 to 200 mm, followed by manual roller-pressing.

2.2.3 *Test methods*

The tests on the welds and the classification of the failure modes were performed according to French standards NF P 84-502.1 (shear testing) and NF P 84-502.2 (peel testing). The test specimens had a dumbbell shape with a central width of 25 mm and a width in the grips of 50 mm. The distance between grips was 135 mm for the HDPE and 200 mm for the bituminous membrane, and the pulling speed was 50 mm/min.

The tests were carried out by the APAVE and CETE-LRPC Lyon laboratories, which are accredited by COFRAC (the French Accreditation Committee) to perform mechanical tests on geomembranes and their welds.

To calculate the welding factor $F_S = R_{max}/R$ it is necessary to have a good idea of the tensile strength R of the membrane (yield strength for the HDPE membrane or the maximum tensile strength for the bituminous membranes). This tensile strength R was measured on specimens taken from two points, one very close to the weld (as required by the French standard), and the other distant from it. These specimens were taken in the same direction as those taken for the weld tests. R_{max} is the maximum tensile strength of the weld.

3 TEST RESULTS AND ANALYSIS

Tables 3 and 4 show the the results. Each test result is an average calculated from 5 specimens. The codes L1, L2 and S1, S2, S3, and S4 respectively refer to the 2 laboratories and the 4 welders.

One can observe good homogeneity of results between laboratories and welders for the same geomembrane.

3.1 HDPE

3.1.1 *Strength and strain yield of the membrane*

Certain materials showed heterogeneity of the yield strength between the distant zone and the zone close to the welds.

This has a direct influence on the calculated welding factor. It is therefore wise to comply with the standard and to measure this tensile strength close to the tested weld (which can multiply the number of tensile tests).

We can distinguish two families of materials:

- the first one, (Gmb 1 and 3), with a deformation at the yield point of the order of 11 % and a yield strength between 40 and 45 N/mm,
- the second one (Gmb 2, 4 and 5) with a deformation at the yield point between 12 and 12.5 % and a yield strength between 36 and 39 N/mm.

These two families will be respectively referred to as "stiff" and "flexible" in the rest of this paper (however these terms have no value in the classification of HDPE geomembranes).

3.1.2 *Welding factors for double fusion welds*

For the shear test, F_S is between 88 % and 100 %. Therefore the criterion presently used (90 %) seems well-suited to all of the products tested.

For the peel test, F_S is between 62 and 90 %, with the following distribution:

- 62 to 65 % for the "stiff" geomembranes (Gmb 1 and 3)
- 68 to 90 % for the "flexible" geomembranes (Gmb 2, 4, 5)

The failure appears at the edge of the weld, with the deformation of the material increasing along with the "flexibility" of the membrane (ductile failure mode). The required threshold of 70 % does not appear appropriate for the "stiff" membranes.

3.1.3 *Welding factors for extrusion welds*

For the shear test, F_S is between 90 and 98 %. The criterion presently used (90 %) therefore appears appropriate for all the products given. The low values (78 and 84 %) were clearly attributed to problems caused by excessive grinding during the weld preparation phase.

Table 3. Results of tensile tests on HDPE geomembranes and welds

			Unit	Gmb1 L2S2	Gmb1 L1S1	Gmb3 L2S2	Gmb3 L1S1	Gmb4 L2S2	Gmb4 L1S1	Gmb2 L2S3	Gmb5 L1S3	Requir. ***
Tensile characteristics of the membrane												
Deformation at yield point (zone distant from weld)			%	11.1	11.1	10.9	10.9	12.7	12.7	12.1	12	
Yield strength R_O (zone distant from weld)			N/mm	45.3	41.5	40.8	40.2	37.6	34.2	38.7	39.3	
Yield strength R_1 (close to the extrusion)			N/mm			37.7	39.7	36.5	36	37	39.1	
Yield strength R_2 (close to the double weld)			N/mm	42.3	42.3	35.7	39.8	37.3	34.3	38.6		
fusion	shear	Max strength	N/mm	44.9	41.6	35.8	38.4	35.4	34	34.5	38.6	
double		F_S (R_0)*	%	99	100	88	96	94	99	89	99	
weld		F_S (R_2)*	%		98	100	97	95	99	89	96	
		Failure **		D	D	D	D	D	D	D	D	D
	peel	Max strength	N/mm	27.9	26.8	26.8	27.1	30.5	30.7	31.2	29.3	
	(external	F_S (R_0)*	%	64	65	66	67	81	90	80	75	70
	seam)	F_S (R_2)*	%		63	75	68	82	89	81	73	70
		Failure **		D	D	D	D	D	D	D	D	D
	peel	Max strength	N/mm	30.1	26.2	28.1	27.2	31.4	29.6	32.3	27.6	
	(internal	F_S (R_0)*	%	66	63	69	68	83	87	83	70	70
	seam)	F_S (R_2)*	%		62	79	68	84	86	84	68	70
		Failure **		D	D	D	D	D	D	D	D	D
extrusion	shear	Max strength	N/mm	43.8	32.2	37.8	36.2	37.1	32.1	36	33.1	
single		F_S (R_0)*	%	97	78	93	90	98	94	93	84	90
weld		F_S (R_1)*	%			100	91	101	89	97	85	90
		Failure **		D	D	D	D	D	D	D	D	D
	peel	Max strength	N/mm	22	20.2	25.2	22.2	24.6	22.1	28.2	18	
	(external)	F_S (R_0)*		49	49	62	55	65	65	73	46	60
		F_S (R_1)*				67	56	67	61	76	46	60
		Failure **		D	D	A+D	A+D	A+D	D	D	A+D	D

* e.g. $F_S(R_O)$: welding factor calculated with respect to yield strength R_0

** Failure mode evaluated as per standards NFP 84 502-1/2; for example A: adhesive mode; D: tearing of the membrane next to the weld; A+D: initial adhesive mode (A) then tearing (D) of the membrane next to the weld

***previous ASQUAL requirements for welder certification.

3.2 Results on bituminous membrane

Table 4. Bituminous membranes - Results of tensile tests on geomembranes and welds

	unit	polymer bitumen		oxidized bitumen			requir. *
		Gmb A	Gmb B	Gmb C	Gmb D	Gmb E	
		L1 S4	L1 S4	L2 S4	L2 S4	L2 S4	
Weld width	mm	160	165	211	185	192	150 / 200 **
Membrane tensile strength	kN/m	19.3	25.9	14.5	19.0	32.8	
Weld shear strength	kN/m	19.7	23.1	11.2	12.9	17.2	
Shear welding factor	%	100	89	77	68	52	80
Failure mode ***		A + D	A + D	A	A	A	/
Weld peel strength	kN/m	5.1	6.0	0.7	0.6	0.5	
Peel welding factor	%	26	23	5	3	1	/
Failure mode ***		A	A	A	A	A	/

* Requirements: same origin as Table 3 - ** for polymer bitumen and oxidized bitumen respectively - *** see table 3

For the peel test, F_S is between 49 and 73 %, with the following distribution:

- 55 to 67 % for the "stiff" geomembranes (Gmb 1 and 3)
- 65 to 75 % for the "flexible" geomembranes (Gmb 2 and 4).

The smaller values of 46 % (Gmb 5) and of 49 % (Gmb 1) due to excessive grinding of the weld and a partial adhesive failure mode, have not been taken into account.

The failure occurs most often on the edge of the weld. In the case of Gmb 1 and 2, it is a brittle type (very low or no deformation). One can also observe a few partial adhesive failure modes (Gmb 3 and 4).

The two "chemical" families are clearly distinct from each other with respect to the strength of their welds. The polymer bitumen membranes have higher weld strengths due to an elastic rheological behavior of their binder, whereas the behavior of the oxidized bitumen binders is essentially plastic.

3.2.1 *Peel testing*

The peel strengths for the polymer bitumen membrane are 7 to 10 times higher than those of the oxidized bitumens. This peel strength is essentially given by the characteristics of the bituminous binder located at the interface between the two membranes. Therefore there is very little correlation between the peel strength and the tensile strength of the membrane itself, its thickness and the mass per unit area of reinforcement.

3.2.2 *Shear testing*

The strength of the polymer bitumen welds is also greater, but with equal thickness and reinforcement, the difference is brought down to only 60-70%. The membrane's physical constitution affects the shear strength, and for each of the two chemical families one notes a regular increase in the weld strength according to the strength of the membrane itself. Since the weld shear strength increases more slowly than the sheet's tensile strength, the calculated welding factor undergoes a regular decrease that has no direct relationship with the intrinsic qualities of the welder and the weld.

It therefore appears that the unique requirement of 80% used for the shear welding factor for all types of bituminous membranes to qualify a weld and a welder is not suited to oxidized bituminous membranes, since in the present case no weld would be acceptable although the welder performed correctly. Since this welding factor cannot be lowered, which would create the risk of accepting poor welds and poor welders in the case of polymer bitumens, it is therefore recommended that specifications differentiate according to chemical family (see section 4.2).

4 SUGGESTIONS FOR REQUIREMENTS

4.1 *HDPE Geomembrane*

It appears that the peel test for "stiff" materials is a destructive test for the material itself and not only for its welds. Indeed, during this test, one of the two geomembranes undergoes a very aggressive 180° bend that does not represent normal usage conditions. Therefore the use of the present criteria does not allow distinction between a mechanical weakening of the membrane caused by the test method and damage due to the welding. Upon first analysis, one is tempted to refrain from changing the specifications (70 %), since the welds carried out with the "flexible" product family conform. This could rapidly lead to the elimination of the so-called "stiff" products in the future, but for certain applications these products offer useful characteristics (for example, chemical inertia), due to their micromorphology (high crystallinity).

The following suggestions were made to the French Geomembrane Committee regarding the acceptance criteria for HDPE geomembrane welds:

- keep the two types of destructive tests (peel and shear) for all types of products. Indeed, only the peel tests allow to identify with certainty the welds which have an adhesive type failure mode, which is abnormal, whereas the shear test allows to detect damage of the membrane at the edge of the weld during its performance, which can affect its proper functioning in the structure,
- keep the 90 % welding factors for shear testing on all types of weld,
- keep the 60 % welding factor for peel testing on extrusion welds,
- lower the welding factor from 70 to 65 % for peel testing on each of the seams of double fusion welds,
- refuse failure modes of the "adhesive" type, even partial ones, whatever the type of weld, for welder certification. However, tolerances for a partial adhesive failure mode could be defined for site-performed welds.

It should be noted that the welding factor requirements defined for membranes with a thickness of 2 mm and less may not be relevant for thicker membranes.

4.2 *Bituminous geomembranes*

The peel characteristics of the welds are essentially linked to the consistence and cohesion characteristics of the membrane binder itself and not to the conditions of weld performance. This is therefore not a good test to evaluate the competence of a welder, even if it is still an interesting element of information.

Note: binder is the compound of oxidized bitumen (or polymer bitumen) with mineral filler.

The shear characteristics of the weld are also strongly influenced by the cohesion of the binder and therefore dependent on the chemical nature of the latter, even if the differences between polymer bitumen and oxidized bitumen are less significant than with peel characteristics. It is therefore necessary to adopt a different requirement threshold for each chemical family. For an oxidized bitumen membrane, the weld strengths increase much more slowly than those of the polymer bitumen membrane in a similar series with an increasing value of thicknesses and strength of reinforcements. For this reason we suggest that the specifications take into account minimum shear strengths rather than welding factors. This differs with synthetic membranes, since the welding factor for bituminous products gives no information regarding possible deteriorating quality of the membrane during welding and thus does not allow to evaluate the performance of a welder.

The thresholds proposed for the certification of a welder are 16 kN/m for a polymer bitumen-based membrane and 12 kN/m for an oxidized bitumen-based membrane. These values can be decreased for worksite inspection requirements (e.g. 20 %).

5. CONCLUSION

For a given chemical family, for example HDPE, specifying a welding factor may not determine the performance of a welder, since poorly suited test methods (peel test) can alter the membrane material characteristics. Therefore it is necessary to consider the specific testing behavior of certain products within the family. In the case of bituminous membranes, it is recommended to define specifications adapted to the chemical and physical nature of each group of membranes.

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