Geosynthetic Institute
475 Kedron Avenue
Folsom, PA 19033-1208 USA
TEL (610) 522-8440
FAX (610) 522-8441

GSI White Paper #27

"The *Intimate Contact* Issue of Field Placed Geomembranes with respect to Wave (or Wrinkle) Management"

by

Robert M. Koerner, Ph.D., P.E., NAE
Director Emeritus – Geosynthetic Institute
Professor Emeritus – Drexel University
610-522-8440
robert.koerner@coe.drexel.edu

George R. Koerner, Ph.D., P.E., CQA
Director – Geosynthetic Institute
610-522-8440
gkoerner@dca.net

(GSI Members, please note that there is also a fifty-five slide power point presentation accompanying this white paper. If interested, please advise.)

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“The *Intimate Contact* Issue of Field Placed Geomembranes with Respect to Wave (or Winkle) Management”

Abstract

GSI either directly or through its on-line servicing of the Techline (gmatech@ifai.com) receives many questions as to deployment of geomembranes and, more specifically (to the topic of this white paper), the fate of waves (or wrinkles) in geomembranes when they are backfilled and entombed by the overlying soil materials. We generally respond by scanning various published papers but now feel it is time to summarize the relevant information in the form of a GSI White Paper (#27) which is posted on our website and available to everyone at

www.geosynthetic-institute.org/whitepaper.htm.

After a brief overview and background of the situation, we describe a major laboratory study which was the dissertation of Dr. Te-Yang Soong and is very revealing in this regard. The major findings of that study being (i) that waves as small as 14 mm in height do not flatten out upon the application of normal pressure, (ii) that the waves actually collapse forming relatively sharp folds, and (iii) that residual stresses at the folds can be as high as 22% of yield where they are most accentuated. As a result of a national survey of state regulatory agencies, the implications of entombed waves are then addressed followed by five methods for achieving “intimate contact” of the installed and backfilled geomembranes to their subgrade. A summary and recommendation section is also presented.

1.0 Overview and Background

It is clear that the concept of a *composite liner*, i.e., a geomembrane placed over compacted clay liner (GM/CCL) or geosynthetic clay liner (GM/GCL), in the minds of regulators (and designer's as well) is to achieve a flat geomembrane completely over the substrate whatever it may be. That said, it is intuitive that waves or wrinkles will compromise this situation as the photographs of Figure 1 attest. The generally voiced concerns over burying or entombing these waves are the following:

- Leakage flow through geomembrane holes into the open space beneath the wave
- Possible shortened life due to tensile stress concentrations in the folded geomembranes
- Mini-dam impediment to leachate flow along the upper surface of the geomembrane
- Distortion of the underlying CCL or GCL due to uneven stresses created by the wave

Fig. 1 – Waves in exposed geomembranes (GSI photos).

The above said, it is well known that the waves are caused by elevated temperatures (in comparison to the geomembrane temperatures at placement and seaming) and are fundamentally related to the type of geomembrane resin as well as its stiffness and thickness. Table 1 presents coefficients of thermal expansion/contraction for common geosynthetic resins. The table is followed by a numeric example illustrating the amount of expansion movement caused by a temperature increase of 30°C which is a typical field situation. The calculation is performed for HDPE, LLDPE and PVC geomembranes.

Table 1 – Coefficients of Thermal Expansion/Contraction (various references)

Polymer Type	Thermal Linear Expansivity ($\times 10^{-5}$ /°C)
Polyethylene	
high density	11-13
medium density	14-16
low density	10-12
very low density	15-25
Polypropylene	5-9
Polyvinyl chloride	
unplasticized	5-10
35% plasticizer	7-25
Polyamide	
nylon 6	7-9
nylon 66	7-9
Polystyrene	3-7
Polyester	5-9

Example: What is the expansion of a 5 m long sheet of geomembrane due to a 30°C increase in temperature. Use the table for HDPE, LLDPE and PVC values.

Basic Equation:

$$\Delta L = (\Delta T)(L)(\alpha)$$

where

ΔL = expansion or contraction (+ or -)
ΔT = change in temperature (+ or -)
L = distance between waves
α = coefficient of thermal expansion/contraction

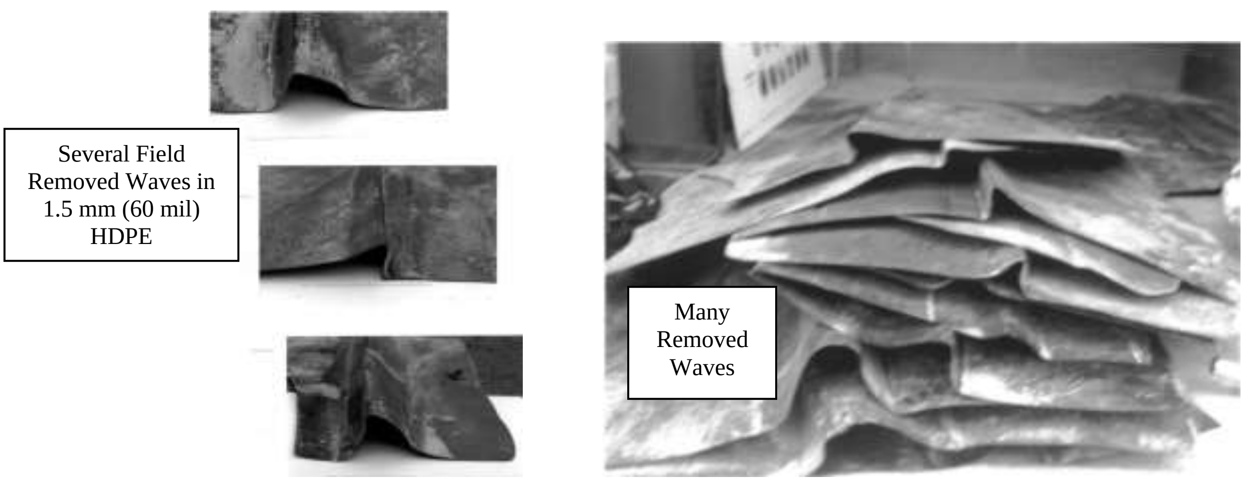
Solutions:

Ex.	ΔT	L	α	ΔL (expansion)	
	(deg. C)	(m)	(/°C)	(m)	(mm)
HDPE	30	5.0	15×10^{-5}	0.022	22
LLDPE	30	5.0	11×10^{-5}	0.016	16
PVC	30	5.0	16×10^{-5}	0.024	24

Note: Due to stiffness effects, the HDPE and LLDPE geomembranes result in a single large wave, while the PVC geomembrane results in numerous small waves.

Figure 2a shows such waves (beneath a overlying white protection geotextile) being backfilled by the gravel of a landfill's leachate collection layer. These waves are indeed entombed by the backfilled materials and (as will be seen) retain their distorted shape even after exhuming as the photographs of Figure 2b indicate.

(a) Waves being entombed during backfilling



(b) Entombed waves remaining after excavation

Fig. 2 – Various field cases of poor wave management practice (GSI photos).

It should be mentioned that waves in geomembranes on side slopes generally accumulate downslope due to day-to-night thermal cycling such that a final large wave often occurs at the toe of the slope. Furthermore, such waves are often filled with water making the repair through multiple geosynthetic layers extremely difficult.

2.0 A Major Laboratory Wave Study

The concern over the fate of entombed and backfilled waves prompted a laboratory study sponsored by the U.S. Environmental Protection Agency which formed the dissertation topic of Dr. Te-Yang Soong*. The study was conducted in both a large wooden box (1.8 × 1.0 × 1.0 m) and in small steel boxes (0.3 × 0.3 × 0.3 m). The large wooden box shown in Figure 3 had a 0.5 m wide plexiglass window behind which the geomembrane waves were positioned. An air bag capable of 20 kPa pressure was used for normal pressure to observe the actual distortion of the as-placed wave in the geomembrane over time. It is important to note that the ends of the geomembrane were short of the box width on both sides by 150 mm. Thus the geomembrane wave was free to move horizontally as pressure was applied at the surface if it was inclined to do so.

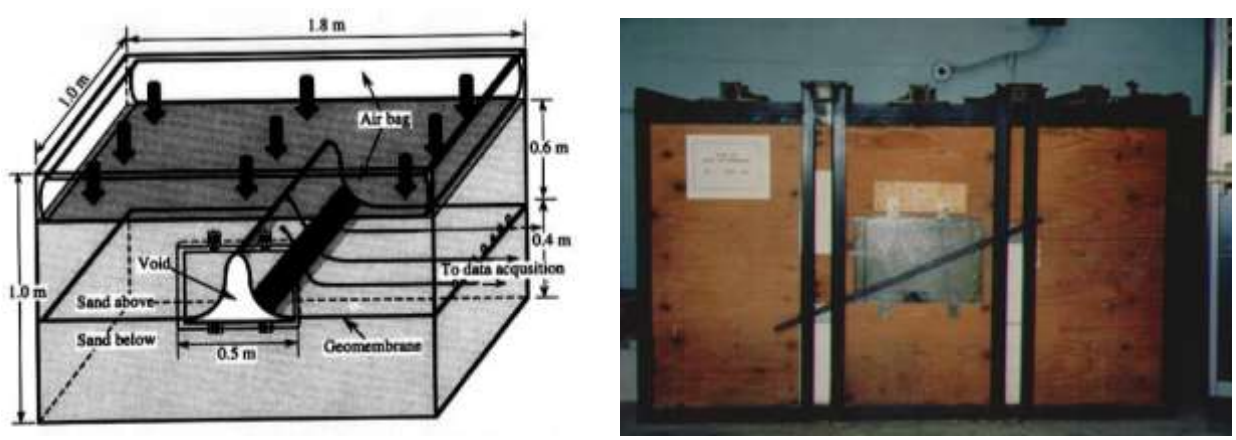
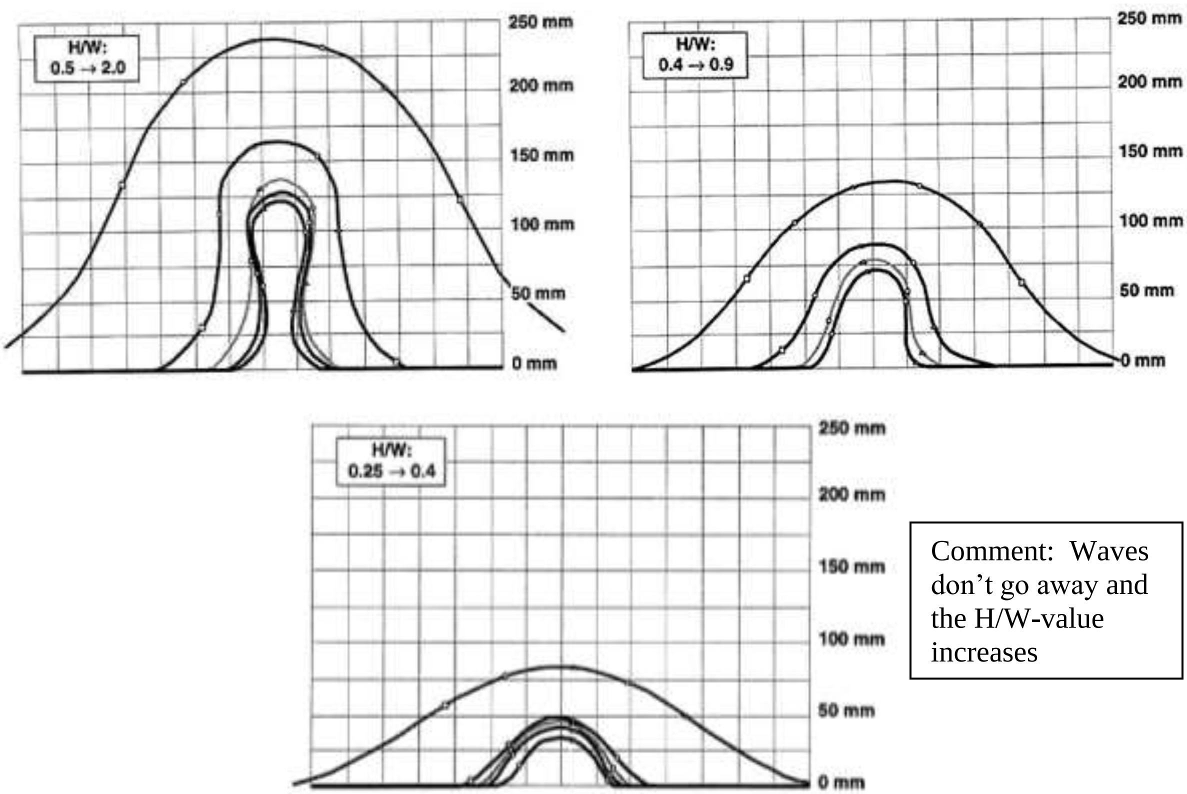


Fig. 3 – Large wooden box wave test setup.

*Soong, T.-Y. and Koerner, R. M. (1998), "Laboratory Study of High Density Polyethylene Waves," Proc. 6th IGS Conf., Atlanta, IFAI Publ., pp. 301-306.
*Soong, T.-Y. and Koerner, R. M. (1999), "Behavior of Waves in High Density Polyethylene," Jour. Geotextiles and Geomembranes, Vol. 17, No. 2, pp. 80-104.

The results of three waves (large, medium and small) are shown in Figure 4.



Comment: Waves don’t go away and the H/W-value increases

Fig. 4 – Visual observations of large, medium and small waves under increasing pressure.

Individual markers were placed on the edges of the waves adjacent to the plexiglass window so that the same points could be observed in their movements (notice the small circles on Figure 4 sketches). In all cases, the as-placed wave decreased in its void space under the applied pressure with the top moving down and the two sides collapsing inward. In terms of a wave height-to-width ratio, the following occurred;

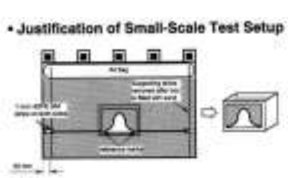
- large wave, H/W ratio went from 0.5 to 2.0,
- medium wave, H/W ratio went from 0.4 to 0.9, and
- small wave, H/W ratio went from 0.25 to 0.4.

Most importantly the collapse of the waves did not shift the horizontal ends of the geomembranes toward the wooden box walls at all, i.e., the geomembrane ends remained fixed in their original position. *This observation completely contradicts the often-heard notion that applied pressure tends to flatten the entombed waves.* This simply does not occur since the increasing applied normal pressure also increases the friction on the top and bottom horizontal ends of the geomembrane holding them fixed in position even for these smooth HDPE sheets. More troubling is that the reshaped wave has now tended to contort into much sharper bends suggesting high stress concentrations.

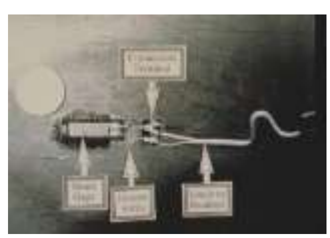
Having these visual findings, emphasis shifted to small steel boxes in which normal pressures up to 1,100 kPa could safely be applied, see Figure 5a. Furthermore, foil strain gages were bonded on six locations of each of the waves and the assembly was then placed in an environmental chamber as shown in Figure 5b. The experimental design for these boxes consisted of 1000 hour tests with varying;

- normal stresses; from 180 to 1100 kPa,
- original wave heights; from 14 to 80 mm,
- geomembrane thicknesses, from 1.0 to 2.5 mm, and
- testing temperatures; from 23 to 55°C

These results are shown visually and numerically in Figures 6 a-d, respectively.



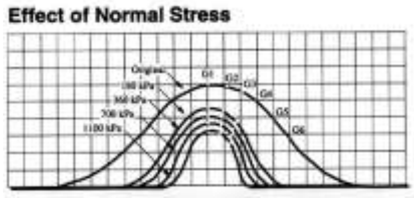
As pressure increases horizontal portions of GM remains fixed in position. Pressure above and below holds the GM ends stationary.



(a) Logic and photo small box tests

(b) Strain gauge and environmental chamber

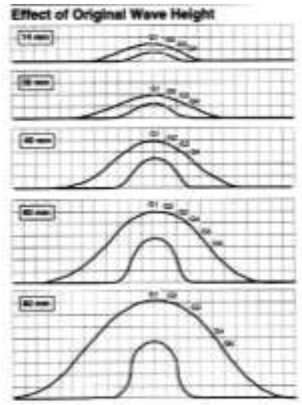
Fig. 5 – Small “strong” box tests and environmental chamber.



Effect of Normal Stress

Normal Stress (kPa)	Final Wave Ht. (mm)	Final H/W Ratio	Max. Strain (%)	Location
0 (original)	60	0.33	+1.7	Crest
180	47	0.47	+1.8	Crest
360	42	0.51	+2.0	Crest
700	38	0.58	+3.0	Upper
1,100	34	0.62	+3.2	Upper

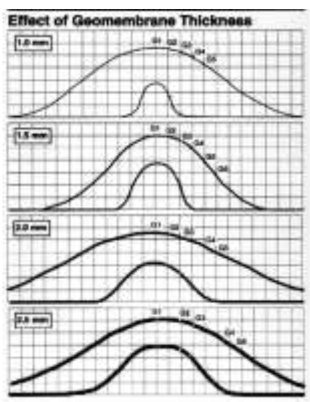
(a) Effect of normal stress



Effect of Original Wave Height

Original Ht. (kPa)	Original H/W Ratio	Final Ht. (mm)	Final H/W Ratio	Max. Strain (%)	Location
14	0.17	8	0.14	+0.2	-
20	0.15	12	0.18	+1.2	Base
40	0.27	25	0.38	+2.4	Base
60	0.33	38	0.58	+3.0	Upper
80	0.33	47	0.65	+3.4	Upper

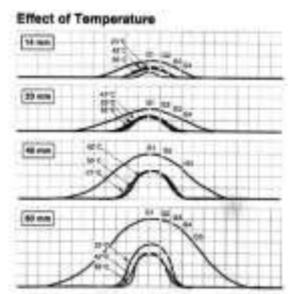
(b) Effect of original wave height



Effect of GM Thickness

GM thickness (mm)	Original H/W Ratio	Final Ht. (mm)	Final H/W Ratio	Max. Strain (%)	Location
1.0	0.24	27	0.52	+2.5	Base
1.5	0.33	38	0.58	+3.0	Upper
2.0	0.18	33	0.34	+3.1	Base
2.5	0.21	38	0.32	+3.3	Upper

(c) Effect of geomembrane thickness



Effect of Temperature

Original Ht. / H/W Ratio	Temp. (°C)	Final Ht. (mm)	Final H/W Ratio	Max. Strain (%)	Location
14/0.17	23	8	0.14	+0.2	-
	42	10	0.19	+0.8	-
	55	8	0.23	+1.3	Base
20/0.18	23	12	0.18	+1.2	Base
	42	14	0.21	+1.6	Base
	55	18	0.30	+2.1	Base
40/0.27	23	25	0.36	+2.4	Upper
	42	35	0.42	+3.2	Base
	55	25	0.46	+2.1	Crest
60/0.33	23	39	0.58	+3.0	Crest
	42	30	0.52	+4.8	Base
	55	28	0.55	+4.9	Base

(d) Effect of Testing temperature

Fig. 6 – Variables evaluated in small steel box tests.
(See Soong, et al. 1998, 1999 for details)

Finally, the effect of distorted waves on geomembrane stresses were evaluated using data from the strain gage readings and is shown in Table 2. The data was taken after 10,000 hours for each of the four sets of variables mentioned. Here is seen that waves as small as 14 mm in height did not flatten and furthermore that residual stresses were always present. As a percentage of yield stress of the geomembrane they were as high as 22% for the 60 mm geomembrane at 42°C. Such implications are not very encouraging to say the least!

Table 2 – Residual Stress after 10,000 hours in HDPE geomembrane waves

Experimental Variables and Conditions		Residual Stress (kPa)	Residual Stress (% of yield)
Normal Stress	180 kPa	1200	7.9
	360 kPa	1300	8.8
	700 kPa	2000	13.2
	1100 kPa	2100	13.8
Original Height of Wave	14 mm	130	0.8
	20 mm	740	4.9
	40 mm	1500	9.5
	60 mm	2000	13.2
	80 mm	2300	14.9
Thickness of Geomembrane	1.0 mm	1600	10.3
	1.5 mm	2000	13.2
	2.0 mm	1600	10.6
	2.5 mm	1800	11.5
Testing Temperature	23°C	130	0.8
	14 mm - 42°C	250	2.1
	55°C	440	4.5
	23°C	740	4.9
	20 mm - 42°C	850	7.3
	55°C	750	8.0
	23°C	1500	9.5
	40 mm - 42°C	1600	13.7
	55°C	690	7.4
	23°C	2000	13.2
	60 mm - 42°C	2600	22.0
	55°C	1600	17.5

3.0 Implications of Entombed Waves

It is important to note that the U.S. EPA in promulgating its original RCRA landfill regulations in the 1980's fully recognized that for the concept of a composite liner to function optimally the geomembrane had to fully reside on the underlying compacted clay liner. They called it *intimate contact* between the two materials. (The German BAM regulations are equally descriptive in that it translates into *press-fit*). Subsequently, individual states in the USA became landfill permit grantors and developed their individual regulations. A recent survey of these regulations is given in Table 3. Here it can be seen that it is very clear that full contact of the geomembrane to the underlying material is either the intent or actually required for achieving *intimate contact* in composite liners.

Table 3 – Survey of State Regulations on the Wave Issue

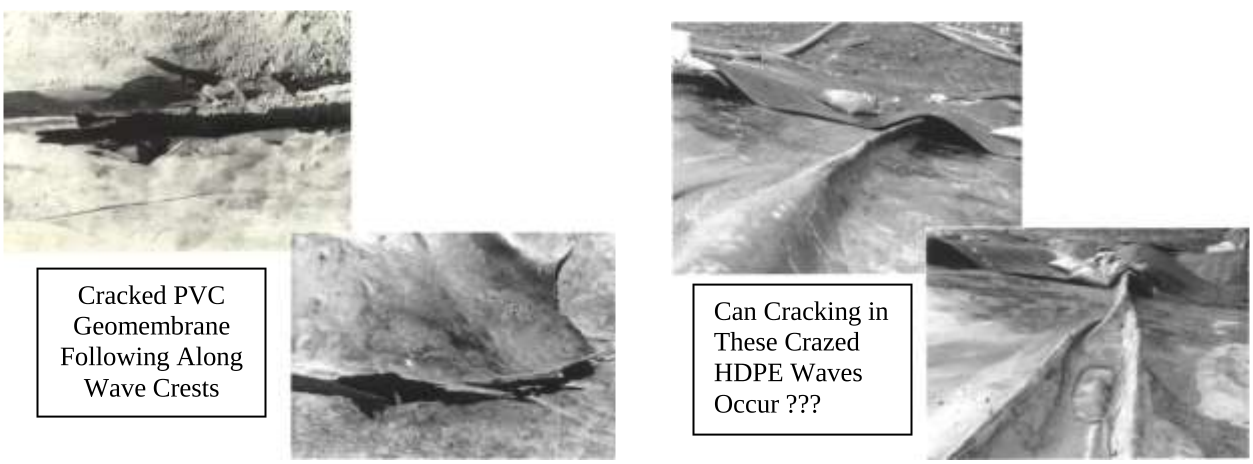
<u>"Direct and Uniform Contact"</u> AK, AL, AZ, CO, GA, IA, KS, LA, MT, NC, ND, NE, NJ, NV, OK, PA, SC, SD, TX, UT, VA, VT, WI	23	(50%)
<u>"Intimate Contact"</u> HI, ID, MO, MS, NH, OR	6	(13%)
<u>"Directly Overlying"</u> CA, FL, IL, MD, MI	5	(11%)
<u>"Minimize (or Prevent) Wave Occurrence"</u> MN, TN, WA, WY	4	(9%)
<u>"Directly Overlain and in Contact"</u> NY, RI	2	(4%)
<u>Others</u> • "uniform and complete" – KY • "proper slack" – DE • "installed on top of" – WV • "inspected by qualified CQA" – ME • "acceptable to director" – OH • "acceptable to manufacturer" - CT	6	(13%)
	46	(100%)

Upon numerous discussions with regulators around the world (Germany, United Kingdom, Canada, South Africa, United States, etc.) the concerns over entombed geomembrane waves are the following;

- they violate both the word and intent of the large majority of regulations,
- any leakage through the geomembrane wave has a relatively large void area beneath it for flow to occur; hence increased leakage is possible
- such waves imped surface flow thereby creating mini-dams, and

- they create stress concentrations and could possibly decrease the geomembrane's lifetime.

It is this last point which the authors have as their major concern. GSI has researched and published the half-lifetime of covered HDPE geomembranes as being approximately 450 years at 20°C temperature.* In that study the geomembrane was placed in a completely flat orientation over the subgrade. Had a folded and flattened wave been evaluated, as shown in Figure 2b, this lifetime would most likely have been compromised. Figure 7 shows exhumed PVC and HDPE geomembranes which had flattened waves in which the high stress concentrations at the apex of the fold was precisely where cracking occurred in the PVC and crazing in the HDPE. Clearly their lifetimes were shortened in comparison to the same geomembranes lying flat without waves.



(a) Cracking of PVC geomembranes (b) Crazing of HDPE geomembranes

Fig. 7 – Exhumed geomembrane waves which exhibited premature problems (GSI Photos).

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*See Designing With Geosynthetics, 6th Ed. (2012), Xlibris Publishing Co., Table 5.12, Page 564.

4.0 Achieving "Intimate Contact"

There have been several formalized attempts at achieving intimate contact of a geomembrane to its subgrade prior to backfilling. At the outset please recognize that none are easy to accomplish nor are they inexpensive. Five different methods will be described.

4.1 Push/Accumulate/Cut/Seam – As awkward as this description appears it is rather straightforward and commonly practiced. As shown in Figure 8, a lift of backfill soil is pushed forward using a bulldozer as the ever increasingly height of geosynthetic layers of geosynthetics advance ahead of it. Eventually the wave consisting of these layers grow so large that the backfilling process cannot continue. At this point, the installer's personnel cut the geosynthetic waves along their crests (all of them since there will often be multiple layers), fold over the excess material and then seam them as follows;

- geomembranes are extrusion fillet welded to one another,
- geonets are overlapped to one another and tied using plastic electrical ties,
- geotextiles are overlapped to one another and heat tacked, and
- GCL's are simply overlapped on one another.

After inspection and/or testing of each layer, soil backfilling can resume until the next set of waves becomes unwieldy and the process is then repeated.

Fig. 8 – Push/Accumulate/Cut/Seam method to achieve intimate contact (compl. B. Smith).

4.2 <u>Flat Sheet Between Fixing Berms</u> – This method, developed by Rolf Schicketanz of Aachen, Germany uses a just-placed roll of geomembrane with no waves and “fixes” one end with its cushioning geotextile and stone, see Figure 9a, while pulling the opposite end tight. A similar geotextile and stone fixing berm is then placed at the other end resulting in a tight (unwaved) geomembrane panel; see Figure 9b. It is a slow, labor intensive method which must be done with utmost care so that stones do not get beneath the geomembrane or between the geomembrane and the geotextile.

(a) Nearside fixing berm (b) Farside fixing berm

Fig. 9 – Fixing berm method of installing flat geomembranes with no waves (compl. R. Schicketanz).

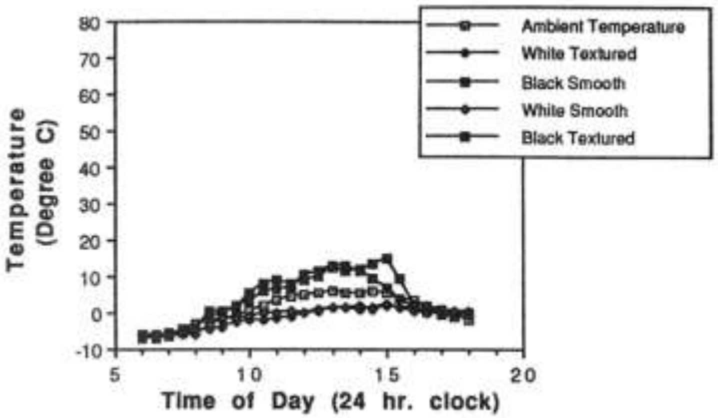
4.3 White (Rather than Black) Geosynthetics – White surfaced geomembranes, either coextended or laminated, as well as white geotextiles are both useful in minimizing waves. The mechanism involved comes strictly from temperature reduction of the exposed surface. George Koerner* has performed such a field study comparing temperature (hence) wave height formation versus geomembrane temperature for white and black, smooth and textured, HDPE sheets. Each sheet was 5 m square placed in a checkerboard configuration with five thermocouples on each sheet for average temperature measurements, see Figure 10a. Readings were taken for one-year with the seasonal results contrasted to ambient temperature as shown in Figure 11. Since wave height is linearly related to temperature these results reflect the situation under consideration. Here is seen a sizeable reduction in temperature for the white versus black geomembranes particularly in the summer. This, of course, is directly reflected in lower wave heights as seen in Figure 11b. It was also noted that there is little difference between smooth and textured sheet in this regard.

*Koerner, G. R. and Koerner, R. M. (1995), "Temperature, Behavior of Field Deployed HDPE Geomembranes," Proc. Geosynthetics '95 Proc., IFAI, Roseville, MN, pp. 921-937.

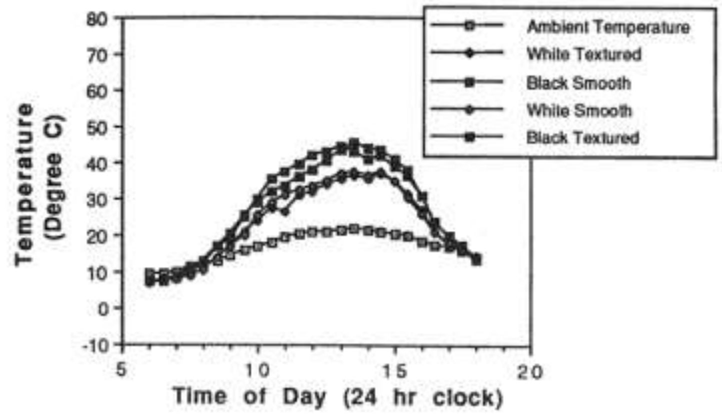
(a) Field temperature study
(Koerner and Koerner, 1995)

(b) Co-extrusion white surfaced sheet
(compl. GSE Lining Technology LLC)

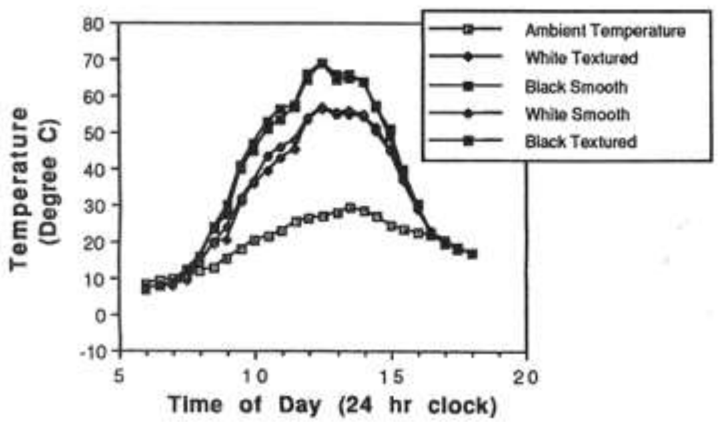
Fig. 10 – Examples of white surfaced geomembranes to reduce temperature, hence wave heights.



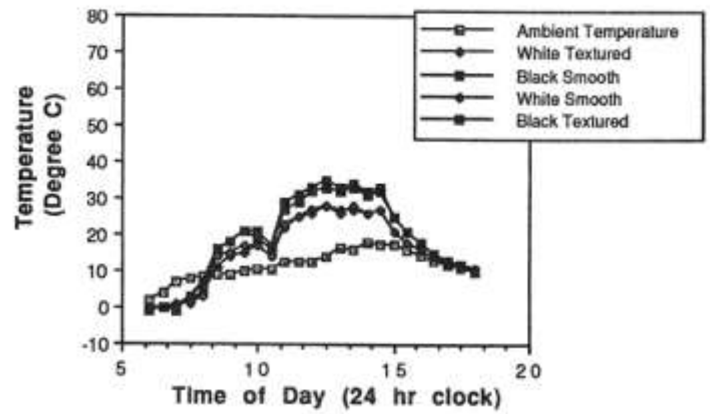
(a) Winter Results



(b) Spring Results



(c) Summer Results



(d) Fall Results

Fig. 11 – Results of temperature investigation of exposed geomembranes; Koerner and Koerner 1995).

4.4 Temporary Tent Moving Over Placement Area – On several occasions installers have used a temporary tent over the geomembrane placement and backfilling area. This can cover a single unrolled panel, as in Figure 12a, or over a much larger area as in Figure 12b. Obviously, ultraviolet light is avoided and temperatures can be somewhat reduced but backfilling under these conditions is difficult and must be done with great care. Additionally, the tent itself must be secured sufficiently so as to avoid wind uplift and subsequent damage.

(a) Single roll panel size (b) Multiple roll panel size

Fig. 12 – Temporary tent moving over placement area (compl. R. Schicketanz).

4.5 Working With Nature – It can be easily observed that the waves shown in Figure 1 are at their height in the noonday sun or shortly thereafter. Furthermore, they dissipate rapidly as the temperature decreases and ultraviolet light is avoided during the night. This can be seen in Figure 13 and is common to all sites. It then begs-the-question as to requiring that backfilling should be limited to night work extending only into the early morning hours. In this regard it is simply *working with nature*.

That said, there are distinct disadvantages to night work in that temporary lights must be provided, worker efficiency is compromised, worker safety must be assured, and the work schedule for all involved (installer, contractor, inspector, regulator and others) must be coordinated and this is often unwieldy to accomplish.

Fig. 13 – Working with nature to achieve wave-free geomembranes (GSI photos).

5.0 Summary and Recommendations

This rather lengthy white paper is framed around a topic called by many as "wave (or wrinkle) management" of field deployed and backfilled geomembranes. It is prompted because the composite action of a geomembrane over a low permeability soil (CCL, GCL, other) is optimized when the geomembrane is flat with no entombed waves or wrinkles. From a regulatory perspective it is necessary to achieve *intimate contact* or equivalent wording.

To examine the technical aspects of the situation, a major laboratory study was conducted indicating that waves as small as 14 mm in height when backfilled and entombed simply do not flatten. In fact, the larger waves squash under applied normal pressure and can form sharp bends. The residual stresses in the topmost 180° bend of the flattened waves were measured to be as high as 22% of yield strength for HDPE. Exhumed folded waves have even cracked or crazed along these 180° folded waves (recall Figure 7).

Other implications of entombed folded waves are increased area of seepage when holes are in the geomembrane wave, distortion of the subgrade (particularly CCL's) due to uneven ground pressure (the pressure is zero beneath the wave) and an interrupted flow surface on the top of the geomembrane due to the waves and their random orientation.

This summary leads to the recommendation that waves should not exist during backfilling in order that *intimate contact* is achieved. To do so, however, is not easy or inexpensive. The white paper offered five methods so as to avoid entombed waves. Table 4 provides summary comments in this regard.

Table 4 – Methods for Achieving "Intimate Contact"

Method	Advantages	Disadvantages
4.1 push/accumulate/cut/seam	quick and cheap	extrusion welds; inspection
4.2 fixing berms or piles	helps greatly	slow and expensive
4.3 white sheet or white geotextile	quick and easy	smaller waves still present
4.4 temporary tent	helps somewhat	low productivity; high cost
4.5 backfill during night or in morning	working with nature	limits productivity; safety

In closing, it appears to the authors that the necessary coordination in facilitating a no-wave strategy is between the geosynthetics installer working in tandem with the earthwork contractor. They must closely facilitate any strategy listed in Table 4 so as to obtain the desired result. Furthermore, all strategies will cost more (even much more) than simply burying and entombing the waves during backfilling as has often been done in the past.

Critically important in construction bidding is specifically what is stated, or not stated, about the situation in pre-bid documents. If no waves are allowed to be backfilled and entombed in the project permit, the installer/contractor team must be aware of the situation before bidding since increased installation costs are significant. At a German/USA joint workshop[*] is was estimated that both the fixing berm method and the temporary tent method were approximately ten-times the installation cost of not being concerned about entombed waves. Thus, at the heart of a transition to a no-entombed wave strategy is a regulatory requirement followed by an unequivocal statement in the construction quality assurance document for the field inspectors to follow. In the end, however, a "no wave" strategy will result in a greatly improved environmentally safe and secure liner system.

*Corbet, S. P. and Peters, M. (1996), "First Germany/USA Geomembrane Workshop," Geotextiles and Geomembranes, Vol. 14, No. 12, pp. 647-726.