CRREL
REPORT 76-22

Evaluation of MESL membrane – puncture, stiffness, temperature, solvents

CRREL Report 76-22

Evaluation of MESL membrane – puncture, stiffness, temperature, solvents

John M. Sayward

June 1976

Prepared for
DIRECTORATE OF MILITARY CONSTRUCTION
OFFICE, CHIEF OF ENGINEERS
By
CORPS OF ENGINEERS, U S ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE

For conversion of U S /British customary units of measurement to SI metric units consult ASTM Standard E380, Metric Practice Guide, *published by the American Society for Testing and Materials, 1916 Race St , Philadelphia, Pa 19103*

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS
BEFORE COMPLETING FORM

1 REPORT NUMBER
CRREL Report 76-22

2 GOVT ACCESSION NO

3 RECIPIENT'S CATALOG NUMBER

4 TITLE *(and Subtitle)*
EVALUATION OF MESL MEMBRANE – PUNCTURE, STIFFNESS, TEMPERATURE, SOLVENTS

5 TYPE OF REPORT & PERIOD COVERED

6 PERFORMING ORG REPORT NUMBER

7 AUTHOR*(s)*
John M Sayward

8 CONTRACT OR GRANT NUMBER*(s)*

9 PERFORMING ORGANIZATION NAME AND ADDRESS
U S Army Cold Regions Research and Engineering Laboratory
Hanover, New Hampshire 03755

10 PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
DA Project 4A162121A894
Task 01, Work Unit 018

11 CONTROLLING OFFICE NAME AND ADDRESS
Directorate of Military Construction
Office, Chief of Engineers, Washington, D C 20314

12 REPORT DATE
June 1976

13 NUMBER OF PAGES
65

14 MONITORING AGENCY NAME & ADDRESS*(if different from Controlling Office)*

15 SECURITY CLASS *(of this report)*
Unclassified

15a DECLASSIFICATION/DOWNGRADING SCHEDULE

16 DISTRIBUTION STATEMENT *(of this Report)*
Approved for public release, distribution unlimited

17 DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

18 SUPPLEMENTARY NOTES

19 KEY WORDS *(Continue on reverse side if necessary and identify by block number)*
Cold effect
Membranes
MESL (membrane-enveloped soil layer)
Non-woven fabric (plastic)
Plastics film
Polyethylene
Polypropylene
Puncture
Stiffness
Solvent action

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

Several membrane materials used or considered for MESL (membrane-enveloped soil layer) utilization of poor soils in road construction have been tested for cold effect on puncture and stiffness PE (polyethylene) film was also tested for solvent soak effects A simple blunt needle apparatus was devised for puncture testing For plastic films (mainly PE), both puncture resistance and stiffness increase at low temperature (0°F, -18°C) For non-woven, spunbonded fabrics these properties are little affected by cold For both non-wovens and PE film, puncture and bending strengths increase linearly with weight or thickness The slope is steeper for the non-wovens, which generally are stronger on a per unit weight basis PE film soaked in a hydrocarbon solvent swelled approximately 17% and lost about 30-40% of

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

20 (cont'd)

its puncture strength These effects are apparently reversible upon drying Consideration has been given to sealing and patching requirements and to the drying of sealant liquids when adhering film to film Also considered have been possible slippage related to the reported low angle of friction of plastic films in soil and the possibility of lamination for improved membrane properties

PREFACE

This report was prepared by John M Sayward, Research Chemist, of the Earth Sciences Branch, Research Division, U S Army Cold Regions Research and Engineering Laboratory It was funded by DA Project 4A162121A894, *Engineering in Cold Environments*, Task 01, *Winter Mobility Assurance and Denial*, Work Unit 018, *Expedient MESL Roads in Winter Environments* The work described in this report was done while the author was in the Northern Engineering Research Branch, Experimental Engineering Division, of USA CRREL in 1972-1973

This report was technically reviewed by North Smith and Kevin Carey, of USA CRREL Acknowledgement is made of the interest and assistance of N Smith, W F Quinn, A F Wuori, K A Linell and R Plump in early discussion and of SP J Karalius in the use of his adhesion results

CONTENTS

ILLUSTRATIONS

TABLES

EVALUATION OF MESL MEMBRANE – PUNCTURE, STIFFNESS, TEMPERATURE, SOLVENTS

by

John M Sayward

INTRODUCTION

Soils without excessive fine materials are best for construction of roads, airports, and railroads, because when these soils are properly compacted they will maintain their strength over a wide range of moisture contents In many areas such soils are increasingly scarce Soils with excessive fine materials (silty or clayey) are often more available, but these lose bearing strength when too wet or too dry In areas of seasonal frost, such soils are also subject to frost action, with disruptive heaving in winter and loss of strength when water drawn from below during freezing melts to produce an excessive water content

The idea of protecting poor soil from moisture or frost action by means of an impermeable membrane seems to have originated several decades ago Proksch[18] states that in 1930 the Bavarian Highway Department started a 15-m test section near Deggendorf, Germany, using prefabricated asphalt membranes He says that in 1936 Casagrande suggested the use of prefabricated bitumen-coated jute for two test sections in the same area (on Federal Highway No 11) In 1955 a 30-m envelope-type membrane of 85/40 O A (oxidized asphalt) was placed in a frost-active area of State Highway No 2165 near Amberg, Germany (Proksch's diagram indicates a membrane on the top and sloping sides but not on the bottom, which rested on a 2-in sand cushion) Proksch indicates that the success of the Amberg test led to another 30-m test section installed in 1968 on Federal Highway No 2 near Hof, Germany This membrane was laid on silty sand, and it utilized a complete envelope of asphalt (8 mm thick), bottom as well as top From nuclear moisture observations over three years, the membrane was concluded to be watertight Again, in 1968 an asphalt membrane was used to protect from moisture a 5½-in insulating layer of expanded clay on county road K-10 near Hannover, Germany

In a 1953 review on the subject, Benson[5] indicates that the idea of using asphalt membranes under pavements was suggested even before 1930, by Prevost Hubbard (then Chief Chemist) and Bernard Gray (later President), of the American Asphalt Institute To some extent, the technique relates to practices used to control seepage in ponds, canals, dams and levees Some of the test sections Benson describes were single membranes (capillary cut-offs) and some were complete envelopes He recommends catalytically blown asphalt, as pavement grade asphalt is too soft when warm and too brittle when cold He cites tests as follows

1930 – Four tests near Eau Claire, Wisconsin (capillary cut-off)
1935 – Test near Ventura, California (capillary cut-off)
1945-6 – Tests at U S Army Engineers Waterways Experiment Station (USAE WES), Vicksburg, Mississippi – soil mattress and sub-grade moisture protection for runways (complete envelope, with a prefabricated bitumen surface)

1947 – Installations on Gulf Freeway, Houston, Texas (complete envelope, methods elaborated by van London in discussion following Benson's paper[5], see also Harris[10])

1947 – Similar installations at Paris, Texas

1949 – Trials in Maine (complete envelope, 2 in tar and aggregate)

The asphalt membranes installed in the Houston Freeway in 1947 and performance since were reviewed by Harris[10] in 1963 They were used on 104 abutment fills The method has been adopted there as standard for all fills except those of very low plastic properties Coverage of 1 gal/yd^2 of grade OA-55 oil asphalt has been found sufficient

An early enveloping of highway base with asphalt in Alberta, Canada, was discussed by Pinchbeck[17] in 1954 He relates the development of soil envelopment to the availability of specially modified asphalt for pond linings, etc Just north of Calgary where Highway No 2 crosses Parson's Slough, 2000 ft of the top 3 ft of gravel base was enveloped in ½ in of catalytic asphalt (2 gal/yd^2) spread in six passes over the bottom and sides, with asphalt concrete on top

The use of asphalt membranes with expansive soils on interstate highways in Colorado, starting in 1967, has been discussed by Merton and Brakey[15] It has been said[4] that membrane methods have also been used in Wyoming (joint report with Colorado, L W Elsperman, Bureau of Reclamation, Denver)

An early trial of plastic film enclosure of soil for a road base was conducted at Purdue University by Bell and Yoder[3] in about 1953 Complete envelopes were made using plastic film [~ 4-mil PE (polyethylene) bottom and sides, 8-mil PVC (polyvinyl chloride) top] Joints were sealed with adhesive (unspecified), although it was considered that heat sealing could be adapted to field needs Tests indicated the PVC to be more resistant to puncture than PE, but the availability of PVC in only 10-ft widths was a handicap at the time of testing

Through recent contacts with Charles Staff[29] of Staff Industries (active in the pond lining field), it is learned that the Purdue test was not altogether successful, due to poor performance of the PE-to-vinyl adhesive when the whole test area was under water the next spring Staff did indicate that, in another report, Yoder had shown the basic soundness of such an envelope in resisting moisture penetration under the influence of frost cycles For pond lining, Staff prefers vinyl, Butyl or CPE (chlorinated polyethylene), since PE will not pass the Bureau of Reclamation puncture test (film laid on ¾ – 1½-in crushed rock and subjected to slowly increasing hydrostatic pressure) Vinyl goes to 50 psi but PE fails at below 5 psi Staff says that the Bureau recommends 10-mil vinyl for ponds, but he prefers 20 or 30 mil, which he says is more widely used According to literature from Staff Industries, vinyl is now available in widths of 4 to 61 ft

If the Purdue test were to be done now, Staff would recommend vinyl rather than PE because the cost of vinyl has decreased to nearer that of PE, and it is more puncture-resistant, more readily heat sealed and more weather-resistant He has available an adhesive for vinyl, applicable by squeeze bottle or by machine, which can join sheets in seconds and develop 50% of full strength within 5 min, the solvent is evidently able to diffuse through the film Staff indicated that heat sealing of PE would have the disadvantage of weakening the film adjacent to the seal He also intimated that high frequency sealing is a possibility

For some years, USAE WES has been conducting tests and field trials of membrane-enveloped soil layer (MESL) for expedient roads in temperate areas The initial work is reported by Burns and Barber[6] It involved enclosing a "poor" soil, bottom and sides with polyethylene (PE) film and top with a polypropylene (PP) non-woven fabric impregnated with asphalt emulsion, which was sprinkled with sand to give a temporary, trafficable surface Josephs and Webster[11] have prepared a manual on this method for field use Further trials at WES have been reported by Burns, Brabston and Grau[7] and by Josephs et al [12] Strength tests of asphalt slab reinforced with PP non-woven fabric for pavements have been reported by Gagle and Draper[9]

The WES method may be described briefly as follows The fine-grained soil is excavated and stockpiled for re-use, its moisture content being adjusted if necessary to 2 to 3% below the optimum moisture content for the specified compaction (a possible difficulty in moist climates) The subgrade is prepared with a grader and compacted While not initially specified, asphalt emulsion (CRS-2, a medium viscosity, cationic, rapid-setting type, approximately 65% solids) is sprayed on the subgrade, which helps to hold the PE film in place if there is any wind and serves as assurance against leaks if the membrane is cut or torn during placement After the PE film has been placed on the prepared subgrade, the excavated soil is replaced and compacted to the desired density and moisture content Asphalt emulsion is sprayed on the surface and the PP non-woven membrane is installed Seams between sheets of both PE and PP are sealed with asphalt, which also is applied (at 0 3 gal/yd^2) to the whole top membrane A final light sprinkling of sand blots up any excess asphalt The PP non-woven with asphalt and sand provides a tough trafficable surface suitable for temporary use

Interest in the MESL construction technique has extended to possible use in cold climates, where is should permit the use of frost-susceptible soils by protecting them from moisture that causes frost heaving Cooperating with USAE WES on cold regions aspects, USA CRREL has undertaken several trials in Alaska, by Smith and Pazsint[27], Smith and Karalius[28], and Schaefer[26] Recently Quinn[19] et al have discussed the possibilities of MESL application in frost areas, and have conducted laboratory tests of freezing and other properties of three typical soils (plastic clay, sandy silt, lean clay) proposed for USA CRREL field trials of MESL where frost heave can be a problem (Some of these tests were begun in the fall of 1973, others in 1974 Similar tests will be done in special facilities where several short road sections can be subjected to artificial frost cycles year-round under controlled conditions)

As developed by WES, MESL was designed for temporary roads in warm climates More recently interest in MESL has broadened to application with more permanent roads and airports (and conceivably railroads) and to use in cold areas to forestall frost heaving while allowing use of poor, frost-susceptible soils In these cases, as for earlier asphalt membrane envelopes, there would be a conventional pavement or other wearing surface placed on top of the MESL layer This might allow a wider choice of membrane materials, with possible advantages in procedures and costs

Sale et al [24] give a brief review of the development of MESL methods in road and airfield construction Included is citation of British developments in Burma in WW II, where bituminous-impregnated jute membrane worked well until the jute decayed Also cited is a WES demonstration at about the same time of a "soil mattress" of bituminous-encapsulated clay to support truck traffic for several months Sale et al summarize MESL work at WES The results provide encouragement for high expectations and increasing use of MESL for both expedient and permanent construction

This report, a part of USA CRREL's contribution, is an effort to seek and evaluate alternative membranes and sealant materials Since proposed areas of use include cold regions, the effect of low temperatures is a consideration both in handling and in service To be of interest in this investigation, a membrane material must not only have suitable properties and be easy to apply, but must also be commercially available in wide widths and in large quantities at low cost Accordingly, much emphasis remains on PE film, which is cheap, available in various thicknesses and in widths up to 40 ft and is usable in the cold Protected by a surface pavement, it would not be vulnerable to puncture and tear hazards which had been experienced in the PP asphalt expedient road surfacing during snow removal operations[28] However, consideration is being given to various non-woven fabrics, which, to be made impervious, require asphalt or other sealant, or lamination with a waterproof film

Results of an information search for encapsulating materials have been drawn upon herein but may be given in more detail in another report[25] Reported here are experimental evaluations of solvent-soaked PE film and of several materials as to puncture strength and flexibility and the effect of temperature and thickness. Simple methods were devised for these tests. In tests for solvent effect, samples were weighed and measured before and after soaking. The puncture test involved measuring the force of penetration with a blunt needle. Though less sophisticated than the ASTM (American Society for Testing and Materials) "dart test" (D-1709-67), this is considered to simulate more nearly the action of sharp soil grains. The flexibility test was simply a measurement of the pull required to bend a sample 45°.

The puncture test here was initially developed to evaluate the effect on PE film of solvents such as gasoline or kerosene, since the use of PE film for the upper MESL membrane beneath a permanent pavement could entail exposure to such solvents when used in "cut-back" asphalts. Exposure to solvents might also occur in patching, since cut-back may be used for quick, cold-weather patching, or in case of a fuel spill penetrating the pavement.

Mention should be made of exploratory tests for puncturability of plastic film made more recently by Ricard[23]. In these, three Griffolyn membranes (2, 3 and 4-ply PE with nylon web between) were placed on 2½ in. of compacted sandy gravel in a 6-in.-diam mold. Silt was compacted on top in five 1-in. layers at optimum water content and wet density about 124 lb/ft^3. The membrane was then removed, to be clamped at the bottom of a 5-in.-diam. cylinder in which a 12-in. head of water was maintained. The 2-ply pieces tested developed leaks of 0.006 to 0.0075 $\text{g cm}^{-2}\,\text{sec}^{-1}$. The 3-ply had leaks of 0.00002 to 0.028. None of three tests on 4-ply developed leaks. This test was developed to simulate field conditions for MESL and was deemed practical. It somewhat resembles the Bureau of Reclamation puncture test (see above and reference[29]).

The tests reported here were carried out at RT (room temperature, approximately 70°F or 21°C) and at about 0°F (−18°C), with a few additional values for flexibility of PP non-woven fabric at 20°F (−7°C).

The tests were done in 1972-73 and are recorded in USA CRREL Laboratory Notebook 6012, p. 18-80, 102-105.

EXPERIMENTAL

Materials

The materials tested here represent both continuous films (PE film, PE film with laminated nylon web reinforcement, and Butyl rubber) and pervious, non-woven fabrics (PP, PE, polyester, and nylon), the latter requiring asphalt or other sealant treatment. It is not implied that other materials are not available or not of interest, but these were the specimens obtained from manufacturers as the result of telephone or mail inquiries. Sample characteristics and sources are listed in Table I.

PE film is a commercial material commonly used for moisture barriers, construction shelters, shipment wrapping, etc. It tears quite readily, especially in the lighter gages, when the tear starts from a cut or puncture, and it can stretch fairly readily. It remains quite flexible in the cold and has a low brittle point, −50° or −70°C (−59° or −94°F)[20,30], as has become evident in balloon use in the cold upper atmosphere[20]. PE's poor weatherability can be improved by additives, it is considered quite resistant to biological attack[21].

The duPont deNemours Company produces three varieties of non-woven fabrics: Tyvek, Reemay and Typar. These are "spun bonded" (thermally fused at junctions, spaghetti-like random arrays of continuous filaments). Tyvek is made of PE (low density), Reemay of polyester, and Typar of PP. Tyvek and Reemay are relatively smooth on both sides and are used for paper, apparel, filters, etc. The numbered Typars are also smooth on both sides, but one which is unnumbered (from WES, used in MESL tests) is rough with loose, unbonded fibers on one side – presumably to enhance asphalt absorption (it resembles Typar 3401). Suggested uses of Typar are packaging, tarpaulins, furniture coverings, filters, carpet backing, as well as roof and bridge decking and highway membrane underlying pavement overlays (for which it is combined with asphalt, e.g. for crack stopping). In some grades of Reemay (e.g. 2034, 2033) the filaments are relatively straight, in others, (e.g. 2431, 2470, and perhaps 2440) they are crimped, giving more body to the fabric. A waffle (or "woven fabric") effect is embossed on 2254, 2431, 2440 and 2470. Only these somewhat heavier specimens were tested of the 14 samples furnished.

According to Mr. R. J. Bennett[4], of Phillips Petroleum Co., the Phillips PP non-woven product, Petromat, was originally developed for bridge decking. On bridges and also on Portland cement concrete pavements, an overlay of Petromat impregnated with asphalt plus an asphalt cement concrete wearing surface protects the concrete from road salt, which may otherwise attack the concrete and corrode reinforcing bars, with consequent breakage of the pavements and weakening of the bridge structure. Petromat has also been used to prevent telegraphing of cracks in concrete when repaving, as well as for pond linings.

Quite probably Petromat was an outcome of non-woven fabric development in textiles. It is made of 3-denier (21 μm or 0.84 mil) filaments (see Appendix for explanation of "denier"). These are chopped into perhaps 6-in. lengths and laid down randomly on a light scrim of parallel polyester strands and punched with blunt needles at intervals to entangle them. (DuPont's Typar is similar, except that its filaments are not chopped, both Typar and Petromat are spun-bonded.) The sheet is partially fused to bond the structure by passing one or both sides over a heated roller. Petromat is black, presumably containing carbon black for better weather resistance. It somewhat resembles tar paper but is much lighter in weight and is, of course, porous. It was apparently the preferred material in the WES tests of MESL for expedient roads, where Petromat's asphalt absorption capacity (about three times its weight) and strength were both important when used without a surface pavement (only a thin coat of sand).

Polypropylene in bulk or film form normally becomes quite brittle at low temperatures. It may have a brittle point of −4°F (−20°C) or higher[21] depending on sample or source, but this can be lowered by plasticizers. In some cases it has been found usable to temperatures as low as −80°C (−112°F)[30]. The stretching of the filaments during extrusion or processing[4] and the very fine filamentous forms may produce partial orientation and improved strength and cold properties in the non-woven form. As stated above, Petromat filaments are less than 1 mil thick. By micrometer measurement, individual filaments were found to be 1 mil or less for Petromat, and 1 to 1.5 mil for Typar. Petromat is said[4] to have been used successfully at temperatures as low as −40°C (−40°F).

Cerex (manufactured by the Monsanto Chemical Co.) is a spun-bonded (non-woven) fabric made of nylon 66 which is self-bonded by a "catalytic" process not involving either a thermal fusion or an adhesive. It is said to be stronger to tear, burst and heat than any other commercial non-woven fabric. It is used for reinforcing textiles and apparel, labels, filters and parachutes. All the non-woven or spun-bonded fabrics are remarkable for their strength and flexibility.

Griffolyn (manufactured by the Griffolyn Co.) is built up of two or more layers of 2-mil PE film interlaminated with multifilament nylon strands (not twisted or woven) in a ¼–½-in. grid. An adhesive bonding agent, which bonds the layers, can be seen to be tacky upon dissection. Tiny air pockets are visible along the strands, particularly where folded. Its construction makes Griffolyn very resistant to tear propagation, even from a cut or puncture. While typically black, Griffolyn may be clear, white or green; some black samples had white as an inner layer or on one side. Griffolyn is used primarily as a light, strong covering for bulk shipment wrapping, construction shelters, temporary buildings, greenhouses, etc. (The 4-ply Griffolyn found use in Vietnam for dust control on landing pads.) Although not named in the report, it was Griffolyn that was used in the

Table I Materials data

Type	Material[a]	Color[j]	Source[b]	Designation[c]	Thickness[d] (Mil)	Sp. gr.	Max. Size Wdth x Lgth (ft)	Weight lb/Mft^2	Weight oz/yd^2	Cost[k] (¢/ft^2)	Remarks
I	PE	black	Monsanto(P&E	constr.	(4.0) 4.0-7.5	0.93	40 roll	19	2.8	2.1	From stock
II	PE	clear	Monsanto(P&E)	constr.	(6.0) 4.0-6.0	.93	40 roll	29	4.2	2.4	From stock
III	PE	clear	Mobil Chem.	fertil. bag	(7.0) 6.5-7.0	.93	40 roll	34	4.8	(2.8)	Rec'd 1969
IV$_1$[h]	PE/nylon web	cc 2	Griffolyn Co.	55-2(2 ply)	4.4-4.8/8.2-8.7	.95	600 x 900[f]	26	3.7	4.5	Rec'd 9/18/72 nbk, p. 27
		bb 1		55-1(2 ply)	4.0-4.4/8.0-8.7	.95	600 x 900	26	3.7	4.5	
		dd 1		65-1(2 ply)[i]	4.8-5.0/9.0-9.5	.95	600 x 900	32	4.6	6.5	
IV$_2$[h]		bbb 2		85-2(3 ply)	-/10-12	.95	600 x 900	38	5.5	8.5	Rec'd 11/24/72,nbk,p. 56
		bww 1		85-1(3 ply)	-/9.5-11.5	.95	600 x 900	38	5.5	8.5	
		bwb 3		85-3(3 ply)[g]	-/9-11	.95	600 x 900	38	5.5	8.5	
IV$_3$[h]		bb 2		65-2(2 ply)[i]	6/8-9	.95	600 x 900	32	4.6	6.5	Rec'd 2/13/73,nbk,p. 65
		bcb 4		85-4(2 ply)	-/12	.95	600 x 900	38	5.5	8.5	
		bbbb 1		105-1(4 ply)	-/15-18	.95	600 x 900	62	8.9	12.5	
V	PE nw	white	duPont	Tyvek 1056	(6) 4.5-7.0(5.8)	.93	10 x 9000	11.1	1.6	1.35	Rec'd 11/16/72,nbk,p. 48
				1053	(6) 4.5-6.5(5.5)	.93	10 x 9000	11.1	1.6	1.35	
				1073	(8) 6.3-8.0(7.2)	.93	10 x 6600	15.3	2.2	1.85	
				1079	(10) 7.5-10.5(9.0)	.93	10 x 6000	17.4	2.5	2.15	
				1085	(10) 7.5-9.5(8.5)	.93	10 x 5700	18.8	2.7	2.60	
VI	Polyester nw	white	duPont	Reemay2024	10-12 (11)	1.37 ?	4.8 roll	~15	2.2	2.3	Rec'd 11/16/72,nbk,p. 49
				2033	13.5-16.5(15)	1.37 ?	4.9 roll	~20	2.9	3.8	
				2254	18-23(20.5)	1.37 ?	not mfd	~23	3.3	not mfd	
				2431	12-16(14)	1.37 ?	4.8 roll	~16	2.3	2.85	
				2440	16.7-18(17.4)	1.37 ?	3.8 roll	~20	2.8	2.9	
				2470	23.5-27(25.2)	1.37 ?	4.9 roll	~46	6.6	6.2	
VII	PP nw	gray	duPont	Typar 3201	7.5-12.0(9.5)	.90	15.7 roll	13.9	2.0	2.23	Rec'd 11/16/72,nbk,p. 48 -smooth both sides
		black		3301	9.0-14.0(11)	.90	15.7 roll	20.9	3.0	3.33	
		gray		3351	(13)10.3-14.2(11.4)	.90	15.7 roll	24.4	3.5	3.89	
		khaki	duPont via WES	--	10.5-16.3(15.1)	.90	15.7 roll	29.0	4.2	4.45	Rec'd via WES 9/72, nbk, p. 26

Table I (Cont'd)

Type	Material[a]	Color[j]	Source[b]	Designation[c]	Thickness[d] (Mil)	Sp gr	Max Size Wdth x Lgth (ft)	Weight		Cost[k] ($¢/ft^2$)	Remarks
								$\frac{lb}{Mft^2}$	$\frac{oz}{yd^2}$		
VIII	PP nw	black	Phillips	Petromat	13 0-20 2	0 90	12 5(15 5)30	1 0	4 5	5 1	From Alaska 1972,nbk p 12
IX	Nylon nw	white	Monsanto	Cerex 1 0	(5 1)3 8-5 7 4 7	1 14	9 8 roll	7 7	1 1	1 45	
				2 0	(9 4) 9-14 11 0			14 5	2 1	2 9	Rec'd 1/29/73,nbk,p 64
				3 0	(13 2)9 5-12 10 9			20 8	3 0	4 33	
X	Butylrubber	black	Hodgman[e]	nylon reinf(32)	28 5-29 0(29)		large[f]	210 5	30	20	Rec'd 11/17/72,nbk,p 48
		"	Goodyear[e]	unreinf (60)	67-68 5 (68)		spliced	411	59	42	

NOTES a) PE = polyethylene
PP = polypropylene
nw = non-woven (spun-bonded) fabric

b) Sources (P&E) - CRREL Plant & Equipment via GSA, probably manufactured by Monsanto
Monsanto - 800 N Lindbergh Blv , St Louis, MO 63166
Mobil Chemical Co Films Dept (?) Macedon, NY 14502
Griffolyn Co , Inc , P O Box 33248, Houston, Texas 77033
E I duPont de Nemours & Co Inc , Textile Fibers Dept , 1007 Market St , Wilmington, Del 19898
Phillips Petroleum Co , Chemical Dept , Plastics Div , Bartesville, Okla 74003
Hodgman Rubber Co , Revere St , Canton, Mass 02021
Goodyear Tire & Rubber Co , P O Box 301, New Bedford, Mass 02741 See note (e)

c) Designation Construction grade
Fertilizer (ammonium nitrate) bag
Trade name and number (no after dash represents sample no and identifies ply colors for Griffolyn (note j)

d) Thickness (nominal or specified), as measured by micrometer - for Griffolyn between web/on web, ("average")
e) Butyl is manufactured by Enjay Chemical Co , Elastomers Dept , P O Box 201, Florham Park, N J , who sent samples
f) Large sheets spliced at factory Griffolyn heat-sealed, Butyl adhesive-sealed
g) This sample of Griffolyn sent as #105 but proved to be 3 ply, i e #85
h) Griffolyn three separate shipments Difficult to get between web thickness on multiple-ply, as webs staggered
i) Griffolyn 65 is "copolymer"
j) Griffolyn color (by plies) c - clear, b - black, d - dull black, w - white, nos are sample nos (note c)
k) Costs PE film quoted by local supplier, Mar 1974, others by mfr as of Mar/Apr 1974, except Butyl, 1972

recent MESL test in Alaska by Schaefer[26] It handled satisfactorily during construction Moisture contents have remained constant, observations are continuing (1975)

The Butyl rubber materials (manufactured by Enjay Chemical Co) are quite thick and therefore heavy and very durable Butyl is highly weather resistant and impervious, as well as puncture resistant and usable at low temperatures Regardless of fabrication width, Butyl sheets can be sealed in factory or field (using a rubber cement or mastic) to obtain continuous coverage hundreds of feet wide Their chief use is for pond and canal linings, e g for potable water, waste water treatment and irrigation systems Roof decking membrane is another use

Many plastics are vulnerable to sunlight, which brings on deterioration, brittleness and cracking, particularly in the polyolefins (PE and PP) The presence of carbon black makes black grades more sunlight resistant and preferable where exposure is likely Other additives designed to absorb deleterious radiation are also used this is the case with Cerex (which is not as susceptible as PE or PP) Butyl is inherently more resistant to light and also ozone than most plastics and rubbers All of the materials tested here are believed to be quite resistant to soil burial and biological attack (by molds, fungi, bacteria) It should be borne in mind that plastics properties and weatherability may vary with source, processing and formulation *

For the solvent tests, gasoline was obtained from the USA CRREL Plant and Equipment stock It was supplied by Agway, Inc and had a pink-orange color The kerosene had a straw color, and was obtained from the USA CRREL Soils Lab (original source not known)

Apparatus

Solvent soak Covered glass petri dishes of 4-in diameter and ½-in depth served for soaking the 2-in square specimens of PE film Samples were measured with a ruler marked in $\frac{1}{32}$ in (readable to $\frac{1}{64}$ in) and thickness with a micrometer marked in 0 001 in (readable to 0 0002 in)

Puncture test In MESL, the lower membrane is substantially protected by burial and the upper membrane by asphalt and sand and perhaps by a pavement The chief hazard of puncture is then from sharp grains of sand or aggregate, as when relatively small grain points and slight relative movement are likely Prick or abrasion hazards may also exist during handling, e g when the membrane is rolled or dragged to position it Thus, ASTM test D-1709-67 (the "dart test") was deemed less suitable, as it involves puncture or bursting by a 1 5-in -diam hemisphere It also requires special apparatus not readily available

Therefore, a puncture test was devised using a blunt needle and Chatillon spring gages The blunt needle was the back end of a laboratory dissecting needle removed from its wooden handle Its flat blunt end was measured by micrometer as about 0 0027-in (0 0686 mm) in diameter, corresponding to 0 00367 cm^2 in area Thus, for each 1000-g loading there was 273 5 kg/cm^2 or 263 5 atmospheres (3880 psi) pressure at the tip The needle was mounted on the rod (push end) of the Chatillon gage by an improvised plastic adapter The Chatillon gages had 0-500, 0-1000 and 0-5000 g capacity and each had a sliding disk which indicated maximum load reached In the early tests, i e those on the black PE film and the solvent soak test, the test sample was hand-held over the end of a wooden spool having a ⅜-in (9 5 mm) hole

Later, a more convenient yet simple apparatus was devised to hold the film sample with uniform and reproducible pressure (see Fig 1) With this apparatus, the sample was held on the lower spool (⅜ in I D) by a second spool reamed to ¾ in I D To insure uniform, planar contact, the upper spool was pivoted crosswise in a wooden arm which was universally pivoted at one end, and weighted at the other A pointer and index scale assisted in aligning the spools, so that the needle, when

---

*References 30, 21 and 16 are of general usefulness concerning cold and weather effects and general information on plastics

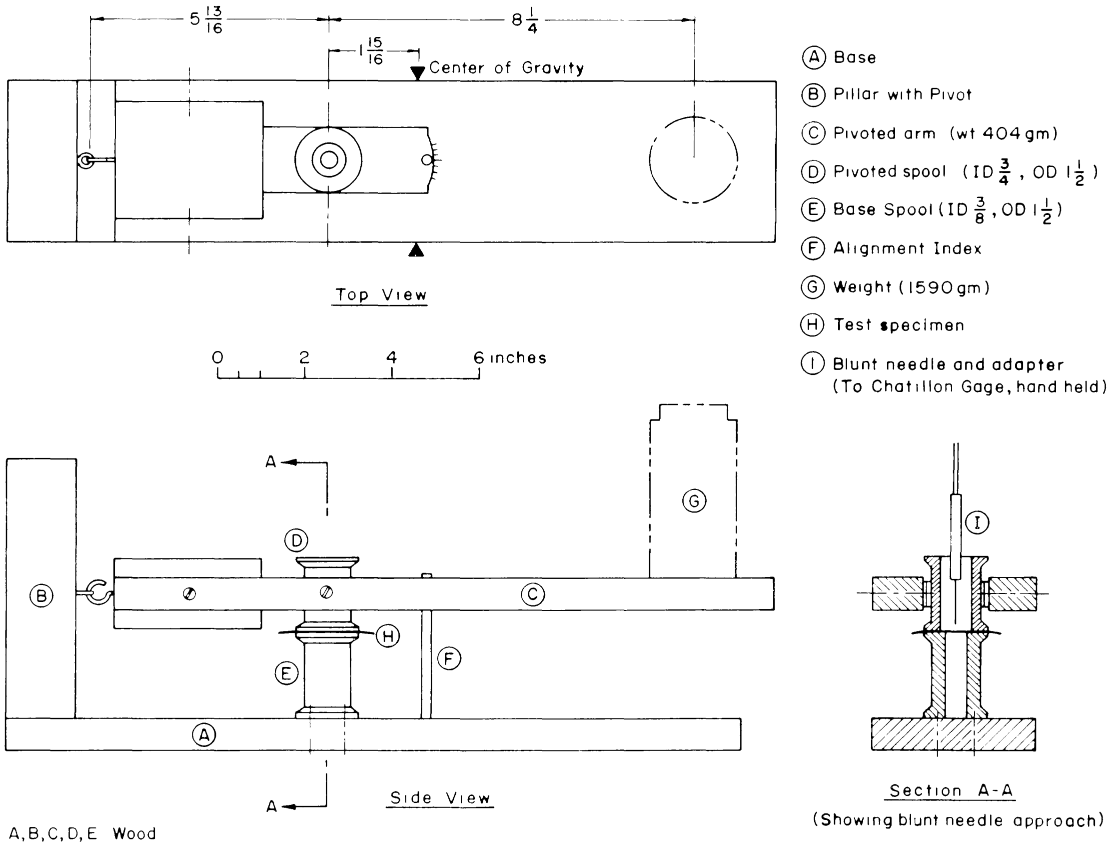

Figure 1 Puncture tester

centered in the upper spool, was over the lower spool hole. Shock upon puncture was absorbed by a plastic plug in the base or by the improved needle holder striking the top of the lower spool. Consideration of weights, moment arms and upper spool area showed the sample holding pressure to be 485 g/cm^2 (0.47 atmosphere or 6.9 psi).

Also, a better holder for the needle was made of Teflon, with an adapter to accommodate the larger rod on the 5-kg Chatillon gage. These adapters also made possible the use of ⅛-in. and ⅜-in. flat cylindrical puncture tips if desired.

Bending test. The bending test apparatus was very simple. A specimen sheet of known length was placed on the edge of the bench and held with a wooden block, so that 5 cm protruded. A paper guide fastened to one end of the block served to delineate a 45° angle to horizontal. By using the hook (pull) end of a Chatillon gage, the force required to bend the sheet up to approximately a 45° angle was measured. Here the smallest Chatillon gage (0-50 g) was sufficient, as this did not have an indicating disk the maximum reading was noted while pulling. As samples actually bent in a curve, the 45° point had to be roughly estimated. Since the gage hook overlapped the sheet about 2 cm, the actual moment arm of applied force was about 3 cm.

Procedure

Solvent soak. Samples of the black PE film were cut with a sharp knife and straight edge into 2-in. squares, with an accuracy believed near ± 0.01 in. Their width was measured at about ⅓ and ⅔ of total width each way, the four values (which varied but little) were then "eyeball" averaged. Thickness was checked at several points to obtain a representative value. Within the pieces used initially , thickness proved quite uniform at about 4 mil Later, variations of 3 5 to 7 mil were found in other areas of the same black PE sheet, some thicker pieces were also given the soak test

The pieces were immersed in gasoline or kerosene 3-5 mm deep, several to a dish, and left covered for 0 5 to 3 hours (or even up to 16 days) until measured As shown in Table II, the samples were usually measured wet

Cold tests When puncture and flexibility tests were to be done in the cold, the specimens were stored in a coldroom at the chosen temperature either overnight or for several days The testing apparatus was conditioned for several hours to assure its being at the test temperature

Puncture test For a puncture test, the hand-held Chatillon gage with the blunt needle on the push end was brought into contact with the sample membrane held over the $^3\!/_8$-in hole in the spool and pressure was applied at a moderate rate, such that puncture generally occurred within 1 or 2 sec (The effect of rate is discussed below) Several replicate punctures were made on each sample In the earlier experiments the film was hand-held on the spool However, the apparatus of Figure 1, devised to hold the sample more uniformly and reproducibly, was used in most of the tests

Bending test For the bending test, the free part of the sample was engaged by the hook at the pull end of the smallest (50-g) Chatillon gage and the sheet bent up to about a 45° angle Friction in this small gage caused results to vary, and a representative maximum of the flexing load was noted from among several trials for each specimen The tests were done face up and face down, usually on two or more samples, at each temperature (Face-up and face-down tests are desirable because in some cases the manufacturing process or being on a roll may cause dissymmetry between the two sides) The orientation perpendicular to the sample bending axis was also noted where distinguishable (The machine direction (MD) is parallel to length as a long band comes from the machine, while transverse direction (TD) is perpendicular to this Properties are apt to differ in the two directions, owing to structural orientation, built-in stress from process tension, or from being on a roll) As the samples varied in length along the bend, the recorded loads were normalized to "load/dm", (g/10 cm)

Statistical treatment Variability of the test sample thickness and, in the case of the non-wovens, observable variation in mat density of the fibers, as well as test procedure variations, made replicate tests necessary and statistical treatment desirable In the puncture test, generally 5 to 10 punctures were made on each sample, i e within a 1 or 2 in ^{2} area, and in many cases a number of replicate specimens were tested Results were segregated by thickness as determined by micrometer For stiffness, there was a face-up and a face-down datum for each specimen tested, and usually two or more replicate specimens The face-up and -down data were handled separately and together

The mean value and σ, the standard deviation from the mean, were computed by standard methods for each group of replicates The value of σ as a ± on the mean value indicates the band within which the true value will lie 68% of the time The values of $\pm\ \sigma$ are shown with all data herein

When there are groups of results done on different but similar specimens, the mean and σ may be better known The latter is not calculated, however, by simply lumping all the results together, each set of replicates in the group may have its own mean So, to determine the group σ, the variances (σ^2) for each replicate set are pooled, using the formula for pooled variance [8] In this way, an overall σ for all the specimens for a given type and condition may be found This is applied to the overall mean of the group, i e it indicates the precision of the group mean The values σ_p in the Tables are such pooled values

On the bar graphs, Figures 2, 3 and 4, the $\pm\ \sigma$ uncertainty bands show their use in distinguishing significant and non-significant differences, e g between RT and 0°F or soaked and not soaked Where bands overlap, (i e when means differ by $< 2\sigma$), they are deemed not different, if bands do not overlap, the means do differ (at the 68% level) If one used $\pm\ 2\sigma$, means must differ by 4σ for the differences to be significant at the 95% level

Table II Solvent swelling of PE film

Sample		Exposure(a)		Width(c)			Thickness(d)			
no	solv	soak (hr)	dry(b) (hr)	initial (in)	after (in)	Δ%(e)	initial (mil)	after (mil)	Δ%(e)	Remarks
I Thickness 3 9-4 5 mils										
1	gas	1	0	2 00	2 10	5	4 0	4 0+	tr	Blot dry, curls sl
	"	1+2 3	0		2 13	6 5				Wet, same after blot dry
	"	3 3	16		2 00	0		4 0-	-tr	Re-dried
	"	3 3	48		2 016	0 8		4 0	0	Re-dried
4	"	23	0	2 00	2 13	6 5	4 0	(5 0)(f)	25(f)	Wet
	"	23+24	0		2 12	6		4 0	0	Wet(b)
	"	380	0		2 11	5 5		4 0	0	Wet
5	"	23	0	2 00	2 13	6 5	4 0	3 9	-2 5	Wet
	"	23+24	0		2 12	6-		4 0-	-tr	Wet(b)
	"	380	0		2 12	6-		3 9	-2 5	Wet
6	"	23	0	2 00	2 14	7	4 0	3 9	-2 5	Wet-dry 1 min , curls
	"	23+24	0		2 12-	6-		3 9	-2 5	Wet(b)
	"	380	0		2 12-	6-		3 8-4 0	(-2 5)	Wet
3	ker	1	0	2 00	2 09	4 5	4 0	4 0+	tr	Blot dry, no curl
	"	1+2 3	0		2 10	5				Wet, same after blot dry
	"	3 3	16		2 00	0		4 0-	-tr	Re-dried
	"	3 3	48		2 008	0 4		4 0	0	Re-dried
7	"	23	0	2 00	2 07	3 5	4 0	4 4	10	Wet
	"	23+24	0		2 09	4 5		4 2	5	Wet(b)
	"	380	0		2 10	5 0		4 3-4 4	9	Wet
8	Ker	23	0	2 00	2 10	5 0	4 0	4 0	0	Wet
	"	23+24	0		2 09	4 5		4 3	8	Wet(b)
	"	380	0		2 08	4 0		4 2-4 3	(6)	Wet

Table II (cont'd) Solvent swelling of PE film

Sample no		Exposure[(a)] solv soak (hr)	Exposure[(a)] dry[(b)] (hr)	Width[(c)] initial (in)	Width[(c)] after (in)	Width[(c)] Δ%[(e)]	Thickness[(d)] initial (mil)	Thickness[(d)] after (mil)	Thickness[(d)] Δ%[(e)]	Remarks
9	ker	23	0	2.00	2.08	4.0	4.0	4.2	5	Wet-dry 1 min, no curl
	"	23+24	0		2.09	4.5		4.3	8	Wet(b)
	"	380	0		2.08	4.0		4.3-4.5	(11)	Wet
0'''	gas	0.5	0	1.995	2.086	4.6	4.0	4.05	1.2(d)	Wet
1'''	"	0.7	0	1.99	2.093	5.2	4.05	4.2	3.8(d)	Wet
3'''	ker	0.6	0	2.00	2.055	2.8	3.9	4.1	5.1(d)	Wet
2'''	"	0.7	0	2.00	2.062	3.1	4.05	4.1	1.2(d)	Wet
II Thickress 4.9-6.5 mils										
4"	gas	0.8	0	2.00	2.093	4.6	5.55	5.85	5.4(d)	Wet
5"	"	1.0	0	2.00	2.093	4.6	5.45	5.65	3.7(d)	Wet
2"	ker	0.9	0	2.00	2.047	2.4	5.45	5.65	3.7(d)	Wet
3"	"	1.1	0	2.00	2.055	2.8	5.5	5.6	1.8(d)	Wet
III Thickness 7.0-7.5 mils										
0'	gas.	1.2	0	2.00	2.093	4.6	7.1	7.33	3.2(d)	Wet
1'	"	1.3	0	2.00	2.093	4.6	7.1	7.33	3.2(d)	Wet
2'	ker	1.2	0	2.00	2.047	2.4	7.1	7.1	0 (d)	Wet
3'	"	1.4	0	2.00	2.047	2.4	7.2	7.45	3.5(d)	Wet

(a) Solvents gasoline, kerosene

(b) Except where shown "dry", "re-dried" or "blot dry", measurements were made wet, fresh from soak. (For Nos. 4-9 at 23+24 hrs., puncture tests (Table III) made first)

(c) Width is eyeball average of four values at 1/3 and 2/3 points each way.

(d) Thickness less accurate in last six sets (0''', 4", 0' etc.), due to poor uniformity, values shown are rough averages.

(e) Δ% = change as % of initial.

(f) Possibly in error, as other 4 mil in gas did not increase, although thicker specimens did.

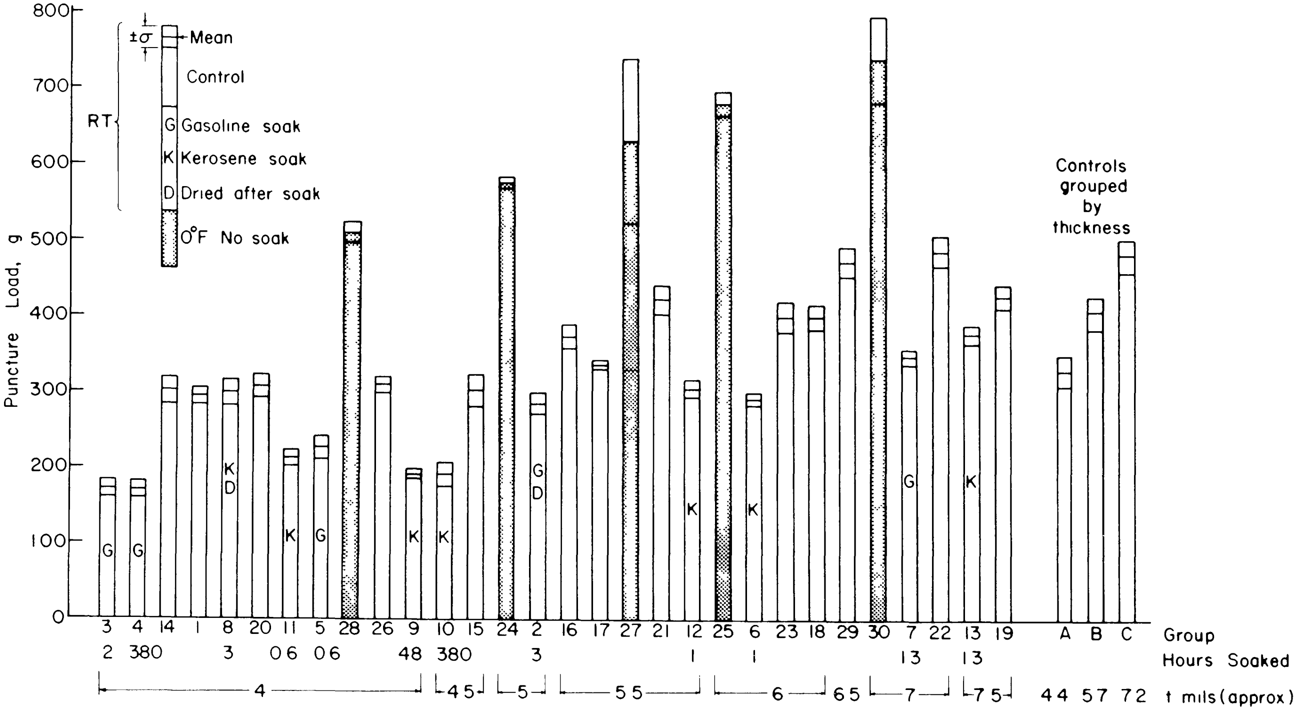

Figure 2 Puncture strength of PE film, effects of solvent soak and temperature

Results

Solvent soak Solvent soak tests were done only on the black PE film, in view of possible use of solvent cut-back asphalt with such film in a MESL test in Alaska The data for swelling in gasoline and in kerosene appear in Table II Related puncture tests appear in Table IIIA and in detail in Appendix Table AIA

Puncture tests The puncture data are summarized in Table III and recorded in detail in Appendix Table AI There are many replicates on the black PE film at RT, which were done to prove out the puncture test method and also to explore the effect of the considerable thickness variations in this material These results have been combined into master groups of three thickness ranges (details in Table IIIA)

A 3 9-4 8 mil, about 4 35
B 4 9-6 5 mil, about 5 70
C 7 0-7 5 mil, about 7 25

These are used in Table IIIA as the control bases for assessing solvent soak effects and in Table IIIB as the bases for assessing cold effects on the PE film For graphical comparison, the puncture test results are shown in bar graphs in Figures 2 and 3 The bars are arranged in order of increasing film thickness and identified with the groups in Tables III and AI Further graphical display of puncture results appears in Figures 5, 6 and 7, where for each temperature the data are plotted against fabric weight (oz/yd^2), and against thickness for the film types – see **DISCUSSION** section

Bending tests The data for bending tests of temperature effect are shown concisely in Table IV and in detail in Appendix Table AII Here the number of replicates is not as great as for puncture, and the test itself is inherently less precise The group means indicate that the temperature effect is essentially the same for face-up or face-down or combined Therefore, only the mean load for each condition (combined face-up and face-down values) is shown in Table IV

Where known or guessable, the orientation of the bend to MD or TD is recorded, since properties may be directional Tests were not usually made in both directions on the same material, since the object was primarily to assess the stiffening at lower temperature In the case of Typar some results are recorded for both orientations (see **DISCUSSION** section)

Graphical presentation of the bending test results is made in Figure 4 The bars are identified with the data in Tables IV and AIII The bending data are also plotted, for each temperature, against fabric weight (oz/yd^2) in Figure 8 and, for the film types, against thickness in Figure 9

DISCUSSION

PE solvent soak and swelling

Swelling of PE film in hydrocarbon solvents is evident from the test data (Table II) Gasoline and kerosene both caused lateral increases within an hour up to 4 5-7% and 2 8-5% respectively, depending on time and sample thickness Swelling was quite rapid, occurring mostly within an hour or so, with little change beyond the first day Thickness generally increased as well, although some tests with gasoline seemed to indicate slight decrease in thickness Kerosene seemed to cause more increase in thickness than gasoline (in contrast to the effect on width) Difficulties in measurement, due to softness and variable thickness of the original film may be involved A better method of measuring and more replicates would be desirable

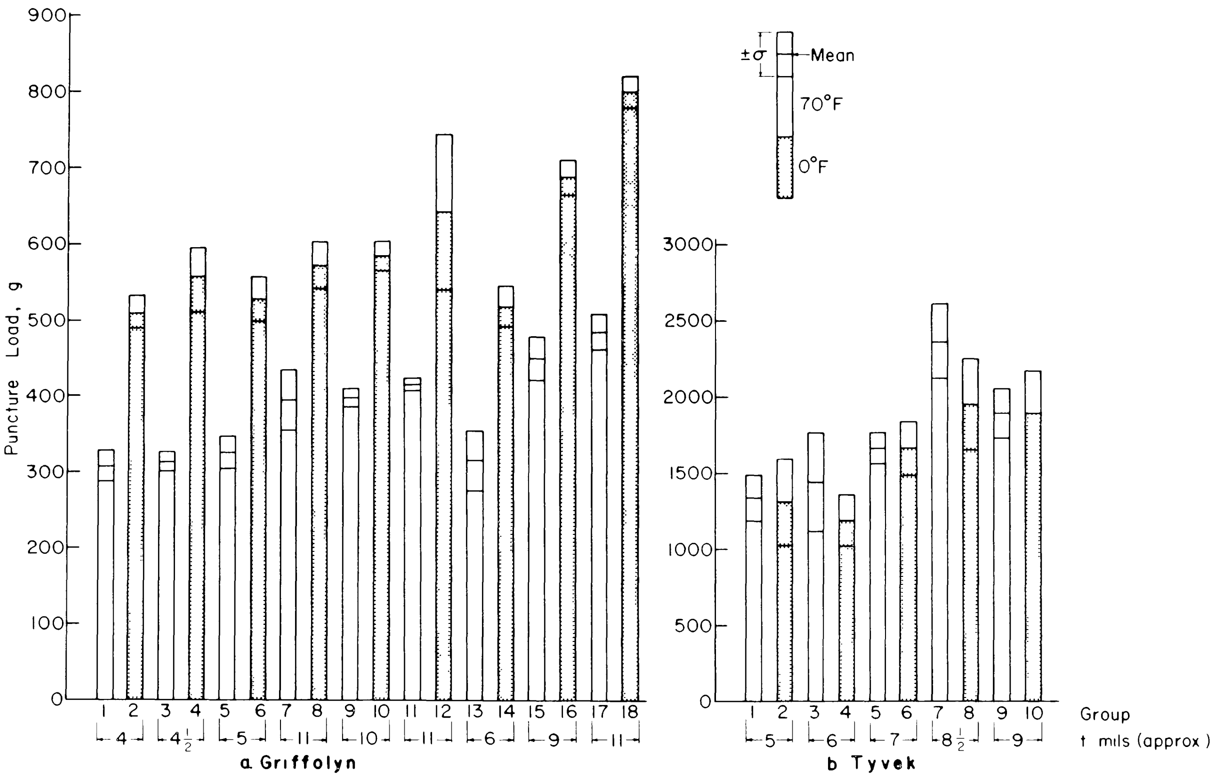

Figure 3 Puncture strength vs temperature for various membrane materials a) nylon-web laminated PE film, b) PE non-woven fabric (Tyrek), c) polyester (Reemay), d) PP (Typar), e) PP (Petromat), f) nylon (Cerex) sheet, g) Butyl rubber (32 mil, reinforced, 60 mil unreinforced)

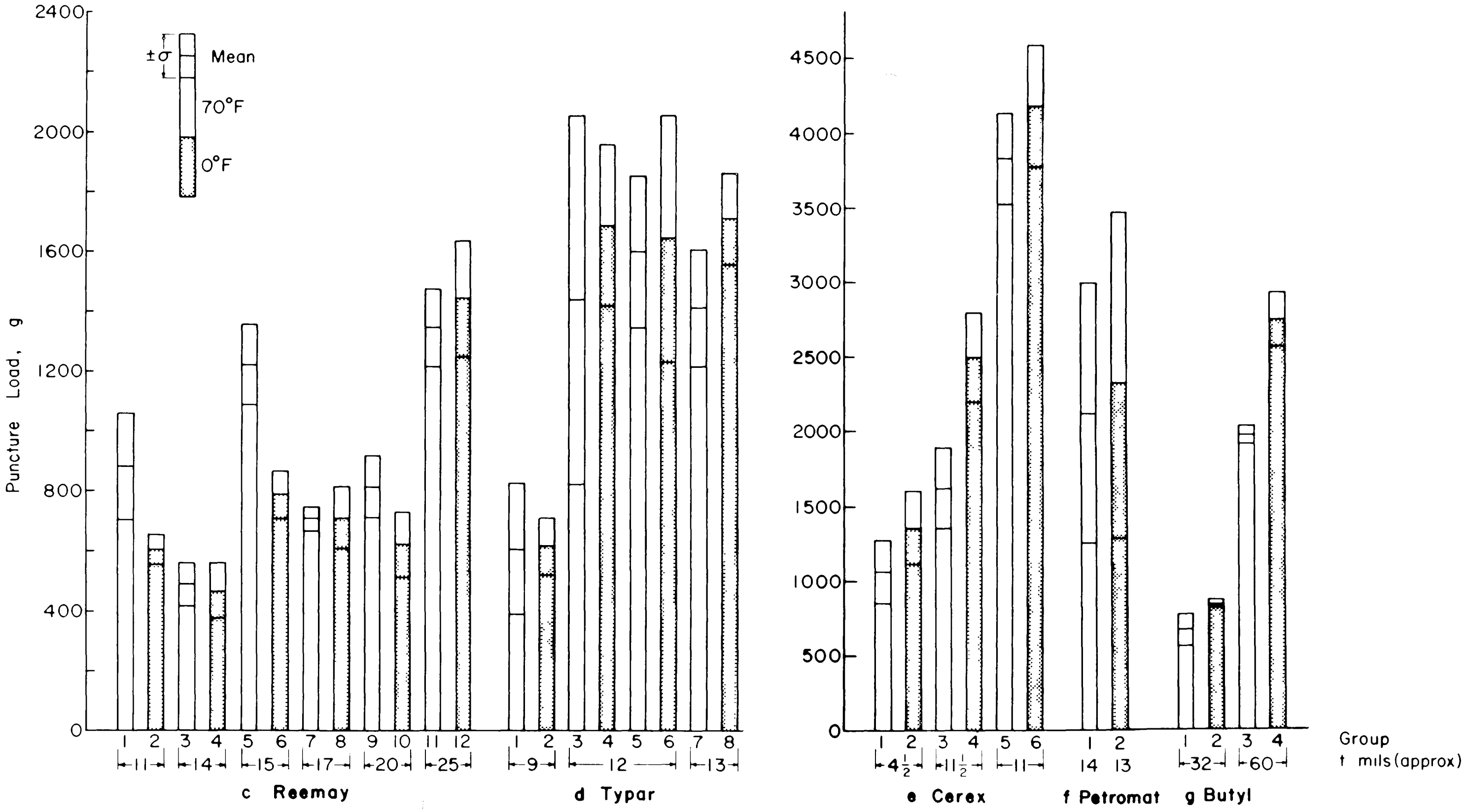

Figure 3 (cont'd)

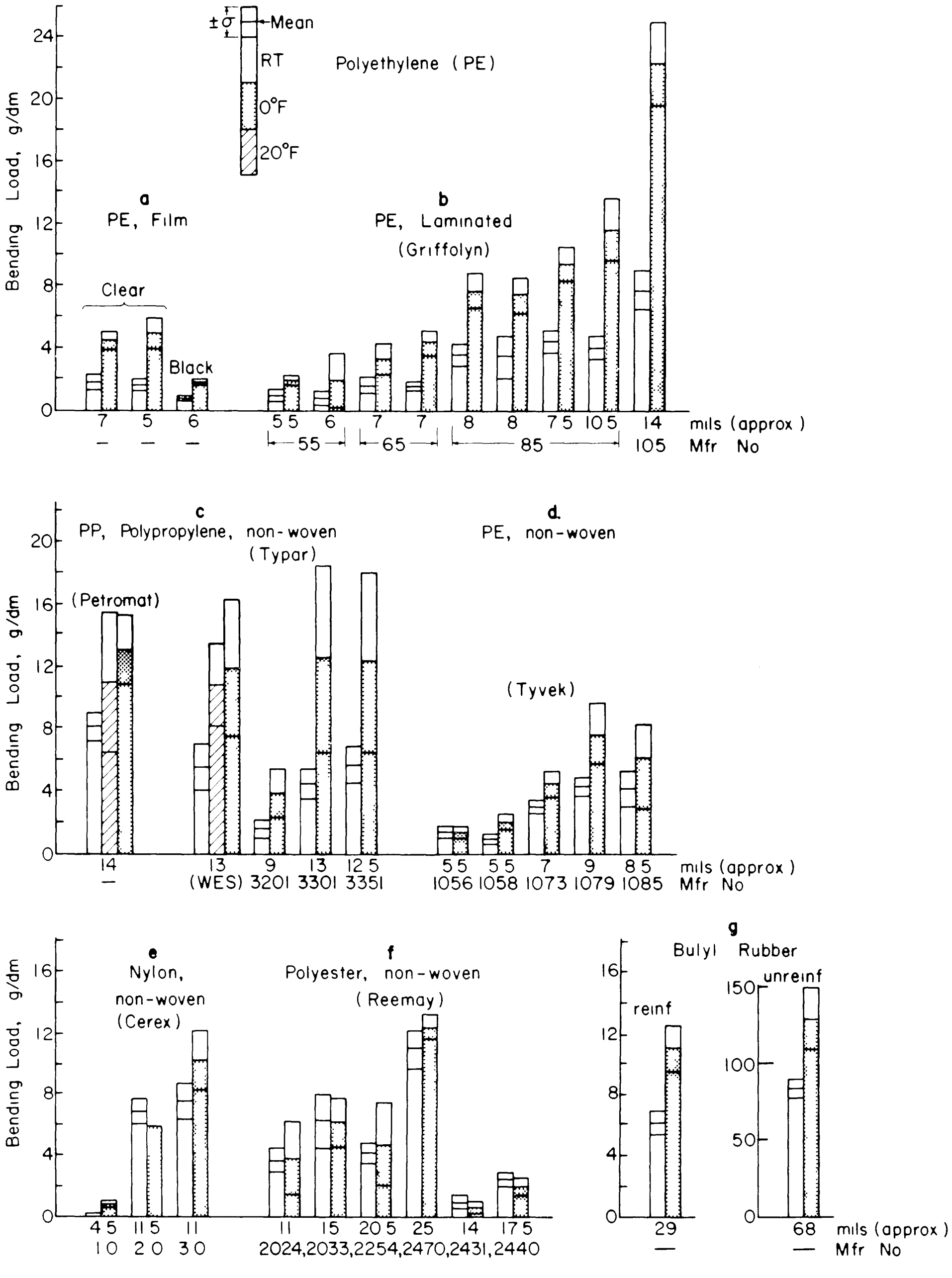

Figure 4 Bending load and temperature for various membrane materials

Table IIIa Puncture strength of solvent-soaked PE film

Treatment				Nbk.	Piece	No of		Puncture Load (g)		
Group	Solvent	Soak (hr)	Dry (hr)	p.	no	Pieces	Punctures	Mean	±σ	% of control
A	3.9-4 8 mils control A					16	102	309	21	100
2	gasol.	3	48	35	1	1	5	286	13	93
3		24	-	35	4,5,6	3	15	172	11	56
4		380	-	39	4,5,6	3	15	173	11	56
5		0 6	-	40	0''',1'''	2	20	227	15	73
8	keros	3	48	35	3	3	5	299	6	97
9		24	-	35	7,8,9	3	15	197	6	64
10		380	-	40	7,8,9	3	15	192	15	62
11		0 6	-	40	2''',3'''	2	20	214	10	69
B	4 9-6 5 mils Control B					15	116	408	24	100
6	gasol.	0 9	-	40	4",5"	2	20	293	8	72
12	keros	1 0	-	40,41	2",3"	2	20	306	11	75
C	7 0-7 5 mils Control C					5	46	482	22	100
7	gasol	1 2	-	41	0',1'	2	20	348	10	72
13	keros	1 4	-	41	2',3'	2	20	378	12	78

Controls are combined results from Table AIA

	mils	nbk p	Piece no	Groups
A	3 9-4.8	35,36 41,48	2,0,B,K,E,L P,J,A,G 4''',5''',6''',a',c'	1,4,15 20,26
B	4 9-6 5	36,37 41,42	D,H,I,C,A',B', 0",1",6",7",8",9",10",11"	16,17,18 21
C	7 0-7 5	37,41	C',4',4',6',5'	19,22

Table IIIb Puncture strength and temperature

Sample		Temp	Thickness	Nbk	Piece	No of		Puncture load (g)		
Group	Desig	°F	(mil)	p	no	Pieces	Punctures	Mean	±σ	% of RT control
	Black PE Film									
A		RT	3 9-4 8		A	16	102	309	21	100
B			4.9-6 5		B	15	116	408	24	100
C			7 0-7 5		C	5	46	482	22	100
28		0	4 2±	46	b	1	5	510	14	165
27			5 4±	46	a,b,c	3	15	630	108	154
	Clear PE Film									
23		RT	5 8±	48	d,e	2	12	400	21	-
24		0	4 7±	46	a	1	6	576	7	186
25			5 8±	46	b,c	2	10	680	16	167(170)
	Clear PE Film (bag)									
29		RT	7 0±	53	1,4	2	13	473	19	
30		0	7.0±	56	2,3	2	14	779	57	162(165)
	Griffolyn									
1	55-1	RT	4 2/8 4	47,53,54	-	3	19	308	20	
2		0		47	-	1	5	509	22	165
3	55-2	RT	4 6/8 4	47,53,54	-	3	18	314	12	
4		0		47	-	1	5	556	38	177
5	65-1	RT	4 9/9.2	47,53,54	-	3	17	325	21	
6		0		47	-	1	9	527	29	162
13	65-2	RT	6/8 5	68	A,B,C	3	30	316	39	
14		0		70	D,E,F	3	28	518	27	164
7	85-1	RT	-/10.5	56	-	1	6	395	40	
8		0		56	-	1	6	572	31	145

Table IIIb (cont'd)

Sample Group	Sample Desig	Temp. °F	Thickness (mil)	Nbk p	Piece no	No of Pieces	No of Punctures	Puncture load (g) Mean	Puncture load (g) ±σ	Puncture load (g) % of RT control
9	85-2	RT	-/11	56	-	1	6	416	8	
10		0		56	-	1	6	642	102	154
11	85-3	RT	9/11	56	-	1	6	398	12	
12		0		56	-	1	6	584	19	147
15	85-4	RT	9/12	68	A,B,C	3	30	450	29	
16		0		70	D,E,F	3	30	688	23	153
17	105-4	RT	11/17	68	A,B,C	3	30	506	23	
18		0		70	D,E,F	3	30	800	21	158
	Tyvek									
1	1058	RT	4 5-6 5	52	-	1	6	1335	155	
2		0		51	-	1	6	1308	285	98
3	1056	RT	4 5-7 0	52	-	1	6	1442	327	
4		0		51	-	1	6	1192	171	83
5	1073	RT	6 3-8 0	52	-	1	6	1672	95	
6		0		51	-	1	6	1670	183	100
7	1085	RT	7 5-9 5	52	-	1	7	2377	245	
8		0		51	-	1	6	1958	301	83
9	1079	RT	7 5-10 5	53	-	1	6	1897	165	
10		0		51	-	1	6	1958	273	103
	Reemay									
1	2024	RT	10-12	53	-	1	6	882	178	
2		0		52	-	1	6	605	49	69
3	2431	RT	12-16	53	-	1	6	490	73	
4		0		52	-	1	6	468	94	96
5	2033	RT	13 5-16 5	53	-	1	6	1225	133	
6		0		52	-	1	6	790	80	65
7	2440	RT	16 7-18 0	53	-	1	6	708	41	
8		0		52	-	1	6	712	103	100

Table IIIb (cont'd)

Sample		Temp	Thickness	Nbk	Piece	No of		Puncture load (g)		
Group	Desig	°F	(mil)	p	no	Pieces	Punctures	Mean	±σ	% of RT control
9	2254	RT	18-23	53	-	1	6	818	104	
10		0		52	-	1	6	622	110	76
11	2470	RT	23 5-27	53	-	1	6	1348	129	
12		0		52	-	1	6	1443	194	107
	Typar									
1	3201	RT	7 5-11	53	-	1	6	650	220	
2		0		51	-	1	6	255	94	39
3	3301	RT	10-14	53	-	1	6	1438	613	
4		0		51	-	1	6	1681	276	117
5	3351	RT	10 3-14 2	53	-	1	6	1597	253	
6		0		51	-	1	6	1642	413	103
7	(WES)	RT	11-15	48	3,4,8	3	20	1412	196	
8		0		52	2,7	2	13	1711	154	121
	Cerex									
1	1 0	RT	3 8-5 3	67	d,b	2	20	530	105	
2		0		69	a,c	2	20	676	120	128
3	2 0	RT	9-14	68	d,b	2	20	808	133	
4		0		69	a,c	2	20	1244	149	154
5	3 0	RT	10-12	68	d,b	2	20	1912	153	
6		0		69	a,c	2	20	2086	204	109
	Butyl Rubber									
1	reinf	RT	29	48,53	-	1	11	670	125	
2		0		52	-	1	6	845	30	126
3	unre	RT	68	48,53	-	1	12	1973	60	
4		0		52	-	1	6	2750	180	139
	Petromat									
1	(Alaska)	RT	12-16	47,52	1,10,13,15	4	29	2125	873	
2		0		51	2,11	2	13	2332	1042	109

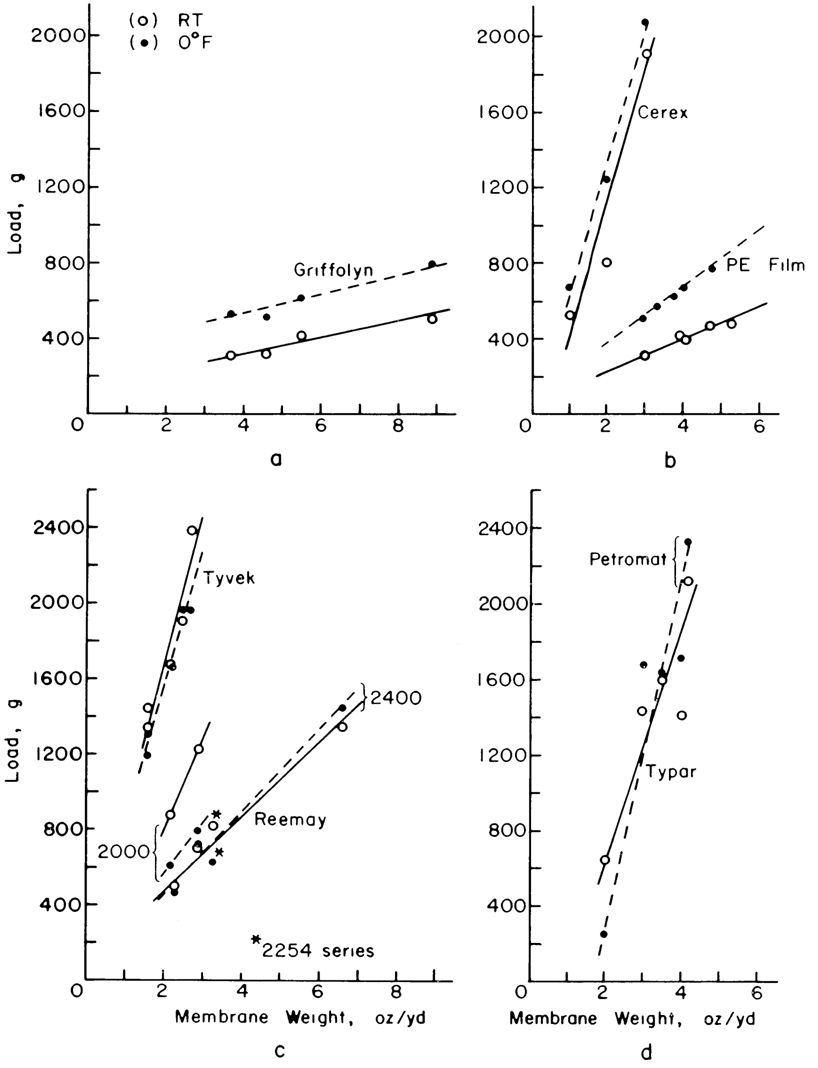

Figure 5 Puncture load vs membrane weight at room temperature and 0°F for Griffolyn, Cerex, PE film, Tyvek, Reemay, Typar and Petromat

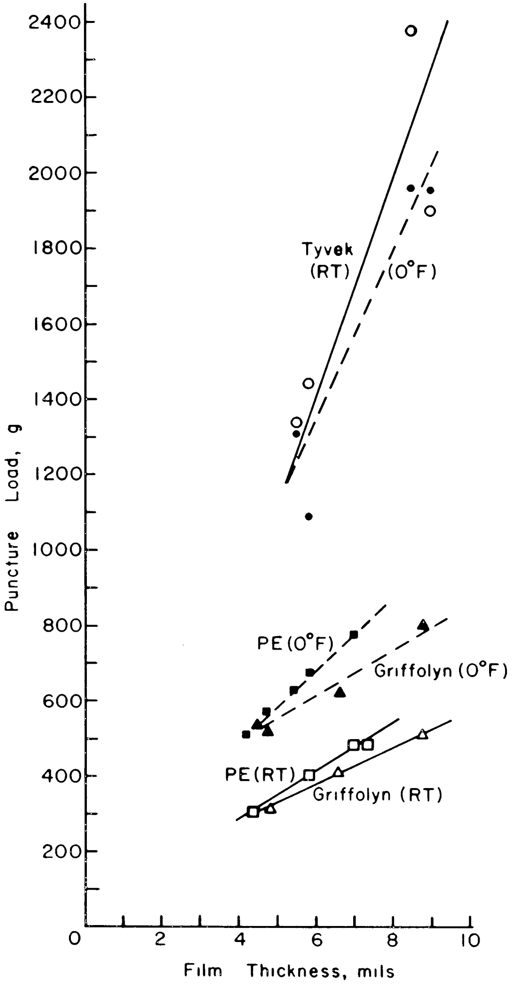

Figure 6 Puncture load vs thickness at room temperature and 0°F for Tyvek, PE film, and Griffolyn

Table IV. Bending strength and temperature

Sample	Temp (°F)	Thickness (mil)	Nbk p.	Piece no.	Bend ⊥ to dir*	No. of pieces	Mean load g/dm	±σ	Factor of RT load
PE Film									
black	RT	4.0-4 5	60	a',c'	T	2	0 84	0 1	
	0			a',c'		2	1 90	0 2	2 3
PE Film									
clear	RT	5 5-6 5	60	d,e	T	2	1 7	0 4	
	0			d,e		2	5.0	1.0	2 9
PE Film (Bag)									
clear	RT	~7	60,63	A'4,1,B'3,2	T	4	1 75	0 5	
	0		60	A4,1,B3,2		4	4 38	0 6	2 5
Griffolyn									
55-1	RT	4.2/6 9	30	-	M ?	1	1 00	0 4	
	0		33			1	2 00	0 3	2 0
55-2	RT	4 6/7 0	29		M ?	1	0 85	0 5	
	0		33			1	2 0	1 8	2 4
65-1	RT	5 1/9 2	29		M ?	1	1 65	0 5	
	0		33			1	3 30	1 0	2 0
85-1	RT	(5 1)/10 5	60		M ?	2	3 55	0 7	
	0		63			2	7 70	1 1	2 2
85-2	RT	(5 1)/11	60,63		M ?	2	3 45	1 4	
	0		60			2	7 42	1 2	2 2
85-3	RT	5 1/10	60,63		M ?	2	4 38	0 7	
	0		60				9 35	1 1	2 1

---

*M = MD = machine direction
T = TD = transverse direction

Table IV (cont'd)

Sample	Temp. (°F)	Thickness (mil)	Nbk p	Piece no	Bend ⊥ to dir *	No of pieces	Mean load g/dm	±σ	Factor of RT load
Butyl Rubber (From Enjay)									
reinf	RT	29	60	-	?	1	6.2	0.8	
	0		60	-		1	11.1	1.6	1.8
unreinf.	RT	67-68	60	-	?	1	84.4	6.3	
	0		60	-		1	130.6	19.6	1.6
Cerex									
1.0 oz	RT	3.3-5.3	66	d,b	M	2	0.18	0.0	
	0			a,c		2	0.83	0.2	4.6
2.0 oz	RT	9-14	66	d,b	M	2	6.9	0.8	
	0			a,c		2	5.9	0	.9
3.0 oz	RT	10-2	66	d,b	M	2	7.50	1.2	
	0			a,c		2	10.28	2.0	1.4
Petromat (Alaska)									
	RT	13-19	22,61	1,5,1,10,13,15	T	6	8.14	0.9	
	20		21	3,4,7,8	T	4	10.95	4.5	1.35
	0		21,22,61	2,6,1,10,13,15	T	6	13.01	2.2	1.6
Typar									
3201-2 oz	RT	7.5-11	60,63	A',B'	M,T	2	1.62	0.6	
tan	0		60	A,B		2	3.88	1.6	2.4
3301-3 oz	RT	10-14	60,63	A',B'	M,T	2	4.58	0.9	
black	0		60	A,B		2	12.5	5.9	2.7
3351-3.5 oz	RT	10.3-14.2	61,63	A',B'	M,T	2	5.7	1.2	
gray	0		61	A,B		2	12.32	5.8	2.2
Typar	(WES)								
	RT	10.5-15.5	29,61	3,4,8,10	M,T	6	5.6	1.5	
	20		32	1,58		3	10.8	2.6	1.9
	0		32,61	2,3,4,6,7,8,9		7	11.9	4.6	2.1

	Molecular wt	Boiling range (°C)
Gasoline "average"	114	70°-200°
pentane to undecane	72-156	
C_5H_{12} $C_{11}H_{24}$		
Kerosene "average"	184	175°-275°
decane to hexadecane	142-226	
$C_{10}H_{22}$ $C_{16}H_{34}$		

Structurally, polyethylene polymer is made up of -$(CH_2$-$CH_2)$- chains which are comparable in form and hence compatible with the solvent molecules. Accordingly, interpenetration and swelling are to be expected. The smaller molecules of gasoline may penetrate the polymer structure more readily than kerosene but perhaps swell it in a different mode and to a lesser volume. The lower molecular weight, boiling point and viscosity would also allow the more rapid drying of gasoline-soaked PE. The tendency to curl concave upwards while drying is due to contraction as solvent escapes faster from the exposed upper surface.

The swelling process of PE with kerosene and gasoline is reversible, for after 16 or 48 hours of air drying, the dimensions return essentially to the initial values (Table II). As discussed below, puncture strength also is regained upon drying.

Very often the width of the sample changes slightly more in one direction than in the other. This is not evident in Table II, where the width shown is the average of two measurements in each direction, but can be seen from the following:

Sample	Solvent	Soaked (hr)	Width, after soak (in.)
1	Gasoline	1 + 2 3	$2\frac{7}{64} \times 2\frac{5}{64}$
3	Kerosene	1 + 2 3	$2\frac{5}{64} \times 2\frac{8}{64}$

Such differences from the initial 2- × 2-in. squares are likely due to some difference in sheet structure between the MD and TD, i.e. due to the geometry of construction and/or the force in the direction of processing and winding, influencing the spacing or alignment of polymer chains and branches. Such differences are typical of paper, textiles and plastics made in long, continuous sheets. Strength properties may also be directional. While they would not show up in the puncture tests described herein, such effects could influence bending tests.

PE solvent soak and puncture

Soaking in gasoline or kerosene not only causes swelling but is also detrimental to the strength of PE film. This is clearly evident in Table IIIa and Figure 2. While the present tests were of puncture strength, there can be no question but that such solvents decrease tear and tensile strength, for puncture really involves both of these properties.

It appears that the puncture strength of PE is reduced to about 75% of original within about an hour of soaking. Within 24 hours the decrease is to about 60%, with little further change in 16 days.

Following a three-hour soak, the samples regained much of their original puncture strength when they were dried for 48 hours. Although the soak-and-dry value appears to be less (92%) for gasoline than for kerosene (97%), these differences are not significant when the ±σ values are applied to each datum: gasoline 286 ± 13 g, kerosene 299 ± 6 g, control 309 ± 21 g.

Table VI Film puncture rate effect

Sample	*mils*	*No of tests*	*Load (g)*		*σ*	*Rate*
			Range	*avg*		
		a PE (black) at RT (nbk p 37)				
A′	5 3-5 7	5	330-345	337	6	Normal
		5	325-375	354		Slow
		5	395-420	409		Fast
		5	470-510	485		Very fast
		5	330-420	363		Very slow
B′	6 0-6 5	11	365-425	400	17	Normal
		2	360-380	370		Very slow
		2	480-490	485		Very fast
		b Griffolyn at 0°F (nbk p 47)				
65-1	4 9	9	480-570	527	29	Normal
		1		490		Very slow
		1		560		Fast
55-2	4 6	5	530-620	556	38	Normal
		1		500		Very slow
		1		540		Fast
55-1	4 2	5	490-535	509	22	Normal
		1		420		Very slow
		2	560-570	565		Fast

The apparent regain of puncture strength on drying may be encouraging for the use of solvent-based adhesives in MESL, provided that the solvent can indeed diffuse sufficiently from the membrane before any great puncture or other stress occurs The topic of adhesion is further discussed below (see *General considerations – Sealing and patching*)

Film puncture rate effect

The rate of application of load could be a factor in puncture tests This was qualitatively explored in a few cases, shown in Table VI The results in Table VI tend to suggest higher loads for faster rates and lower loads for slower rates, particularly for the PE at room temperature The results on Griffolyn at 0°C are less consistent, perhaps because these tests were so limited in number and variability is so great Higher loads at higher application rates are quite typical in strength tests In the case of film like PE, this is easily explained, since such film stretches readily Consequently, in a slow test it becomes thinner and hence more susceptible to puncture, in a fast test it doesn't have time to stretch as much Failure load thus being a function of time indicates that plastic deformation is involved

Bending orientation

Orientation of the test bend to machine or transverse direction (MD or TD) has been recorded in Tables IV and AII All bending tests were usually in the same direction for a given material Although bending load *per se* would likely depend on direction, the stiffening action of cold (i e load ratio for 0°F/RT values), would probably be equally manifest in both MD and TD directions

Direction was not identified on samples received but in most cases it was interpretable from appearance In the case of Typar, bending tests were made in both directions In Table AII, individual values are shown for Typar 3201, 3301, 3351 in both MD and TD and face up and face down, and also the combined MD and TD values are given Combined up and down values with MD and TD segregated are shown in Table VII For the WES sample of Typar, from which the majority of the specimens tested came, segregated as well as combined MD and TD values are shown in Table AII Both sets are reproduced in Table VII

Table VII Typar bending and fabric orientation

Sample	*Direction to bend*	*Temp (°F)*	*No of tests**	*Bending load, g/dm up and down mean*	*Factor of RT load†*
3201	MD	RT	2	1.65	
		0	2	4.95	3.0
	TD	RT	2	1.6	
		0	2	2.8	1.8
	MD & TD	RT	4	1.62	
		0	4	3.87	2.4
3301	MD	RT	2	3.95	
		0	2	11.95	3.0
	TD	RT	2	5.2	
		0	2	13.05	2.5
	MD & TD	RT	4	4.58	
		0	4	12.50	2.7
3351	MD	RT	2	5.6	
		0	2	12.85	2.3
	TD	RT	2	5.8	
		0	2	11.8	2.0
	MD & TD	RT	4	5.7	
		0	4	12.32	2.2
WES	MD	RT	4	6.58	
		20	2	12.85	1.95
		0	6	13.26	2.0
	TD	RT	8	5.12	
		20	4	9.72	1.9
		0	8	10.90	2.1
	MD & TD	RT	12	5.6	
		20	6	10.8	1.9
		0	14	11.9	2.1

* Combined face up and down
† Load at 0° F/Load at RT)

The Typar 3201, 3301 and 3351 data do seem to show a difference between MD and TD, i.e. factors for 0°F/RT values differ. This difference is not believed meaningful, however, considering the variability of this test and considering that only one test was made at each orientation. This conclusion seems borne out by the WES sample. Here the factors 20°F/RT and 0°F/RT are nearly identical for MD and TD and combined MD and TD. This supports the validity of conclusions based on only one direction for other materials.

Comparative tables and graphs

To facilitate comparisons, pertinent data have been taken from the more cumbersome Tables III and IV and set out in Table VIII for PE and in Table IX for the other materials. Tables VIII and IX show simply the puncture and bending load results for RT and 0°F, averaged for each material and type or thickness. Thicknesses shown are representative, i.e. they show the midpoint of the range of actual measurements by micrometer. The fabric weights (oz/yd^2) are the manufacturers' values (except as noted). Apparent density* is also shown in Table IX, where Part B shows for comparison a new and more fluffy non-woven polyester recently received (see Section on E2B below).

The effects of weight (oz/yd^2) and thickness, as well as temperature, are plotted in Figures 5-9 from the data of Tables VIII and IX. Reemay, Typar and Cerex are not plotted vs thickness for lack of a systematic relationship, i.e. apparent density (degree of compactness) varies, so that thickness does not relate to strength. Butyl is not plotted, as there were no variants in thickness.

---

* Calculated from (oz/yd^2) (1/mil) 1.337 = g/cm^3

Table VIII Load, thickness, weight and test data for PE film

Temp (°F)	PE film Color	PE film Group	Thickness[a] approx (mil)	Thickness[a] range (mil)	Thickness[a] %	Weight[a] ($\frac{oz}{yd^2}$)	Weight[a] (%)	No of tests	Test result[c] load	Test result[c] σ	Test result[c] %
A. Puncture											
RT	black	A	4.35	3.9-4.8	100	3.0	100	102	209	21	100
		B	5.70	4.9-6.5	132	3.95	132	116	408	24	132
		C	7.25	7.0-7.5	164	5.05	168	46	482	22	156
	clear	23	6.0	5.5-6.5	138	4.15	138	12	400	21	130
		29	6.7	6.4-7.0	154	4.65	155	13	473	19	153
0	black	28	4.15	4.0-4.3	100	2.95	100	5	510	14	100
		27	5.45	4.2-6.7[b]	131	3.75	127	15	630	108[a]	124
	clear	24	4.75	4.5-5.0	114	3.3	112	6	576	7	113
		25	5.75	5.5-6.0	139	4.0	136	10	680	16	133
		30	6.85	6.6-7.1	165	4.75	161	14	779	57	153
B. Bending											
RT	black		4.25	4.0-4.5	100	2.95	100	4	0.84	0.1	100
	clear		6.0	5.5-6.5	141	4.15	141	4	1.7	0.4	203
			7.0	7.0±	165	4.85	164	8	1.75	0.5	208
0	black		4.25	4.0-4.5	100	2.95	100	4	1.90	0.2	100
	clear		6.0	5.5-6.5	141	4.15	141	4	5.0	1.0	264
			7.0	7.0±	165	4.85	164	8	4.38	0.6	231

a) 0°F and RT values for thickness and weight differ for puncture but not for bending because many more pieces were tested for puncture at RT than at 0°F.

b) Large variability owing to wide thickness range.

c) Load· g for Part A, g/dm for Part B.

Table IX Other load, thickness, weight and test data

Part A

Material		Thickness[a] (mil)	Weight[b] (oz/yd^2)	Apparent density[c] (g/cm^3)	Load			
					Puncture[d] (g)		Bending[d] (g/dm)	
					RT	0°F	RT	0°F
PE Film - See Table VIII								
Griffolyn[c]	55	4 4	3 7	1 12	310	532	9	2 0
	65	4 8	4 6	1 27	320	522	1 65	3 85
	85	6.6(?)	5 5	1 12	415	621	3 85	9 05
	105	8.8(?)	8 9	1 35	506	800	7 7	22 3
Tyvek	1056	5 8	1 6	37	1440	1190	1 4	1 4
	1058	5 5	1 6	39	1335	1310	1 0	2 1
	1073	7 2	2 2	41	1670	1670	2 0	4 5
	1079	9 0	2 5	37	1895	1960	4 25	7 7
	1085	8 5	2 7	42	2375	1960	4 15	6 1
Reemay	2024	11	2 2	27	880	605	3 7	3 85
	2033	15	2 9	26	1225	790	6 3	6 2
	2254	20 5	3 3	22	818	620	4 2	4 8
	2431	14	2 3	22	490	470	1 0	0 7
	2440	17 4	2 9	22	710	710	2 5	2 0
	2470	25 2	6 6	35	1350	1445	11 05	12 5
Typar	3201	9 5	2 0	.28	650	255	1 6	3 9
	3301	11.0	3 0	36	1440	1680	4 6	12 5
	3351	11 4	3 5	41	1595	1640	5 5	12 3
	(WES)	15 1	4 0	35	1410	1710	5 5	11 9
Petromat	PG	19.0	4 2	30	2125	2330	8 15	13 0
Cerex	1 0	4 7	1 0	28	530	675	0 2	0 85
	2 0	11 0	2 0	24	810	1245	6 9	5 9
	3 0	10 9	3 0	37	1910	2085	7 5	10 3
Butyl	reinf	29	30	1 38	670	845	6 2	11 1
	unreinf	68	59	1 17	1975	2750	84	131

Table IX (cont'd) Other load, thickness, weight and test data

Part B

Material		Thickness (mil)			Weight$^{(b)}$ (mfr.) (oz/yd^2)	Weight$^{(b)}$ (meas.) (oz/yd^2)	Apparent Density$^{(c)}$ (mfr) (g/cm^3)			Apparent Density$^{(c)}$ (meas) (g/cm^3)		
		i	ii	iii			i	ii	iii	i	ii	iii
$^{(e)}$E2B	200	105	50	43	5 9	7.4	0.08	0.16	0.18	0.09	0.20	0.23
	300	118	55	46	8 8	9.8	0.10	0.21	0.26	0.11	0.23	0.28
	400	145	90	52	11 8	12.0	0.11	0.18	0.30	0.11	0.18	0.32
	600	179	119	91	17.6	22.1	0.13	0.20	0.26	0.16	0.25	0.33
$^{(e)}$Petromat	PG	25	21	17	4.2	4.5	0.22	0.27	0.33	0.25	0.30	0.37

(a) Mil values are measured, either midpoint of range or average of a number of values. For Griffolyn, measured between webs for 2-ply, estimated for 3- and 4-ply.

(b) (Oz/yd^2) are manufacturers' values, except calculated from thickness for PE film, determined by weighing for Reemay, and Butyl. For E2B and Petromat, values measured by weighing (135-575 $in.^2$ pieces) are also given in Part B.

(c) Apparent density calculated: $\frac{oz/yd^2}{mil} \times 1.337 = g/cm^3$

(d) Puncture and bending loads taken from Tables III and IV; those for Griffolyn are averages of the several samples.

(e) The values for E2B (see text) and Petromat PG (paving grade) in Part B are based on measurements with micrometer in (i) visual (loose) contact, (ii) moderately firm contact (somewhat free to slide), (iii) from (clicker knob) tight contact (not free to slide). As point-to-point variations occur in both, values shown are "representative". For (oz/yd^2) both manufacturers' and measured values are given, with density values based on each.

Puncture and temperature

The puncture strength of plastics would be expected to be greater at lower temperatures, since plastics in general get harder, stiffer, and tougher at low temperatures. This is plainly evident with the true films, PE and Griffolyn, in the graphs of Figures 5, 6 and 7 and also in the bar graphs of Figures 2 and 3. Table IIIB indicates that puncture strengths at 0°F were 115-185% of RT values for PE, 150-175% for Griffolyn, 139% for Butyl and 126% for reinforced Butyl.

The non-woven fabrics show little of the expected increase in puncture strength when cold in either Figures 2, 3, 5 and 6, or Table IIIB. In fact, a slight decrease of strength in the cold seems to occur in some cases. As tests on the non-wovens did not have as many replicates and had great variability, these results are not very significant. Application of ± σ to each mean shows that the bands overlap heavily for most of the non-wovens (note the bar graphs). Only four of the 18 non-wovens show a significant difference between RT and 0°F. Three of these (Reemay 2024, 2023, 2254) all show *lower* puncture strength values at 0°F, only Cerex 2.0 shows a statistically significant increase. Such results on the non-woven, spun-bonded membranes may come about because the non-wovens are not continuous sheets but random matting of fine filaments. Variations in mat density are obvious when they are held to light. These variations would affect puncture loads and scatter of results.

Only Tyvek is fairly densified (more fused and less pervious, resembling paper, for which it is often used). The other non-wovens are all relatively loose, open structures which might be used as filters or as stiffening for other fabrics. Thus, the thin, blunt puncture needle may pass partly between filaments in these materials, resulting in lower load and more scatter.

Although plastics generally become stronger and tougher at lower temperature, some may become more brittle, and all become stiffer and less extensible. This may mean that filaments of non-wovens exposed to low temperatures break more easily under the needle or, lacking stretch, may snap aside as the needle bears on them, allowing puncture at lower loads with more scatter. Such behavior may not necessarily mean that the use of non-wovens for MESL membranes with asphalt sealer would be unsatisfactory in the cold, however.

Bending and temperature

Stiffness of plastics is also expected to be greater at lower temperature. In Figures 4, 8 and 9 this is clearly evident for the true films, PE and Griffolyn, and also for Butyl. As for the non-wovens, Typar and Petromat (and to a lesser degree Tyvek) exhibit some increase in stiffness with cold (shown by the factor of RT load in Table IV). However, the results seem erratic and the tests are limited in number and high in varability. The ± σ range is large in proportion to load (bar height, Fig. 4) in most bending tests, often with overlap of 0°F and RT ranges.

The bending graphs, Figures 8 and 9, seem to indicate only small differences between 0°F and RT at small thicknesses, but more prominent differences at greater thicknesses. This may result because at small thicknesses the bending load is so small (compared to the sensitivity of the gage) that differences due to temperature hardly show and the observed values may be misleading. At greater thicknesses, the cold effect becomes more evident, however, due to the stiffening action of cold temperature which produces a more rigid molecular structure. Because tension and compression of lower and upper surfaces occur in bending, cold stiffening produces a relatively greater effect in a thick sheet than in a thin sheet. This would be particularly evident in a true film, but it also would show in a non-woven fabric that was somewhat fused. A completely non-fused non-woven (such as E2B) might not stiffen as much with cold and thickness, as its individual random filaments would be more able to adapt to new configurations upon bending.

The ability of non-woven fabrics to remain relatively flexible even at low temperatures should be a plus factor for their use in construction under cold as well as normal conditions. It should facilitate handling and also enable the membrane to resist stress and soil shifting.

Test result vs thickness and weight

The strength of plastic film is expected to vary with thickness The relatively large number of puncture tests on PE film and the variations in its thickness permit assessment of such a relation This is evident in Figures 2 and 3, where the bars are arranged by increasing film thickness, and their heights increase correspondingly, for RT or for 0°F It is shown also in Table VIII, giving the results for groups of different thicknesses at RT and at 0°F Here thickness, weight/unit area and load are also expressed as percentages of the thinnest films Similarity of the percentage figures suggests a linear relationship, as is also indicated in Figure 7 Similar plots for PE puncture appear along with graphs for the other materials against membrane weight in Figure 5 and, for some, against thickness in Figure 6 These results are approximate, since the thicknesses are not closely defined The PE plots exhibit steeper slopes for 0°F than for the RT data This suggests that toughening at lower temperatures is more significant for thicker film However, the 0°F and RT slopes do not differ for Griffolyn (a PE laminate)

As might be expected, the plots in Figures 5-9 also show an essentially linear relation of puncture or bending resistance to membrane weight and thickness for all the other materials Two separate lines apply for Reemay for the 2000 series (which are straight fibers) and for the 2400 series (which are crimped) The nature of the 2254 is unspecified Just why straight fibers should give greater strength is not immediately clear

The plots also show that the true film materials exhibit lower slopes, with a less marked increase of puncture strength with weight (oz/yd^2) than for the non-wovens Presumably this reflects the increasing chance of the blunt needle encountering individual filaments in a thicker, heavier non-woven material, plus the known greater strength of materials in filament than in bulk or film form, and the greater tear-vulnerability of plastic films vs non-wovens (a puncture being in this sense a tear)

It will be noted in Tables VIII and IX and Figures 5-9 that the values for PE film and Griffolyn are quite similar at the lesser thicknesses or weights, as might be expected For increasing thickness or weights (oz/yd^2), however, values increase more for PE than for Griffolyn in puncture, and more for Griffolyn in bending This must reflect the influence of the reinforcing web in Griffolyn on bending, but not on puncture, whereas the web does contribute to the (oz/yd^2) values Further, an assembly of thin PE films, laminated with elastomeric adhesive, may well be more susceptible to stretch-weakening and puncture than an equivalent single thickness

The plots in Figure 5 and 8 show much steeper puncture and bending slopes for the non-wovens than for the films, as well as greater strengths than film at a given (oz/yd^2) This may seem surprising, considering that the films are continuous, impermeable sheets and the non-wovens are random assemblies of discrete filaments However, the filament diameters are small compared to that of the blunt needle, and as thickness, weight and packing density increase, the needle cannot as readily penetrate Further, films like PE are known for poor tear strength and easy puncture, while the general rule that materials are stronger in fiber than in bulk or film form gives the non-wovens an advantage As to bending, the more open structure of non-wovens, particularly if partially fused at the surface, gives them, to some extent, a sandwich panel or "trussed" effect, which would stiffen the sheets more at greater thicknesses and apparently also at low temperatures

General considerations

Bulkiness of non-wovens The calculated apparent density shown in Table IX is an inverse indication of the relative bulk (or "fluffiness") of the material Both are factors of interest in non-wovens if the permeable, open structure is to be used for MESL or other water barriers Fluffiness or low density should relate to the ability to absorb and hold asphalt or other sealer

Of the non-wovens tested, Table IX shows that the bulk figure is highest (density lowest) for Reemay and next for Cerex, neither of which has so far been produced for road construction use Reemay, a polyester, might also merit consideration, since its cost is comparable with the cost of the PP non-wovens, Typar and Petromat (Although, next to PE, PP is usually the cheapest plastic, one industry source suggests that the PP non-woven sold for road construction goes for a higher price than similar materials for other uses) Cerex may not be a good candidate for MESL, its manufacturer suggests, because of the slight tendency for nylon to absorb water reversibly, with consequent swelling and shrinking and possible strain on an asphalt binder

New polyester non-woven, E2B Monsanto Chemical Co , the manufacturer of Cerex, now is promoting a new non-woven, E2B It is a polyester (density 1 38 g/cm^3) which softens at 460°F and melts at 500°F This they hope might be useful for MESL and other road construction use It is presently produced in France and has been used in Canada since 1972 Monsanto intends to produce it in the USA by 1976 It can be made in widths up to 17 4 ft, which is wider than the 15 5 ft maximum width for Petromat and Typar So far the main uses of E2B have been

1) Engineering – chemical filters, reinforcement of road bases, crack prevention beneath pavement overlays, and lining for waterways, subsurface drainage, and thaw erosion control
2) Shoe construction (adhesive carrier)
3) Reinforcing or backing for vinyl sheet goods and plastic flooring
4) Furniture blankets (cushions)
5) Wall covering

According to Monsanto, the road base use of E2B (with already hundreds of miles installed) is made without asphalt, the E2B serving as a filter blanket and reinforcing layer over compressible soils, allowing passage of water while retaining fines down to 60 μm and thereby preserving the load-bearing ability of good gravel placed on top of mucky soil It has been used successfully, e g by paper companies in Maine, for inexpensive tote roads built with 8-15 in of gravel laid on E2B placed directly on forest or bog soil and able to carry 20-ton axle loads Scott Paper Co used E2B in June 1974 at Greenvile, Maine, where it was trafficked only four days after construction, and the U S Forest Service has used it around pilings and for bank restraint Such uses of E2B may be of value in arctic conditions and for military construction

Samples of E2B received in January 1974 have weights of 200, 300, 400 and 600 g/m^2 (5 9, 8 8, 11 8, 17 6 oz/yd^2), 150 and perhaps 100 g/m^2 (4 4 and 3 0 oz/yd^2) are also made The material is relatively loose and fluffy, the heavier sample somewhat resembling a heavy blanket It is distinctly bulkier than Petromat and Typar

Some data for weight and for thickness with different degrees of micrometer contact and the corresponding apparent densities are recorded in Table IXB, for E2B and, for comparison, Petromat is also included E2B is fluffier than Petromat (or even Reemay), as shown by the apparent density figures based on visual (approximation of loose) contact With tighter contact this factor indicates that E2B is bulkier than most of the others in Table IX Even with the tightest contact, E2B is fluffier than many, including Petromat and Typar in most instances

E2B is said by the manufacturer to be made of continuous filaments laid down randomly and extensively interlocked in the thickness direction by heavy needle-punching The filaments are 5 8-8 5 denier, with a density of 1 38 g/cm^3 for polyester, this denier corresponds to 24 6-29 8 μm or 0 9-1 17 mil Micrometer measurement of some E2B fibers confirmed this, indicating a thickness of 0 6-1 0 mil (15 3-25 4 μm), or a denier of 2 3-6 3 Their diameter is, then, comparable with Petromat filaments (0 84 mil, 21 μm), but the much lower density of PP makes them only 3 denier This density difference should, other things being equal, make Petromat fluffier and less dense than E2B That it is not must reflect more compression plus partial fusion E2B is apparently not fused at all and this makes it springier This characteristic could be of value for the laminated film/non-woven combination membrane proposed in the following section Such springiness might help avoid abrasion or puncture damage

Puncture and bending tests of E2B were not made, as it arrived when the Chatillon spring gages were not available Qualitatively, it is judged that its flexibility would be no problem Puncture resistance of E2B alone would probably be low, due to its low fiber packing density and non-fusion

Monsanto indicates that they have furnished a 100-yd roll of 6 oz/yd^2 E2B to the USAE Waterways Experiment Station for MESL trial (The 4 5 oz/yd^2 material would have been prefered and more comparable to the PP non-wovens used for MESL but was not available) There is some concern lest the greater bulk and fluffiness of E2B require too much asphalt for saturation, increasing the cost of application The E2B itself cost 10¢/oz, or 45¢/yd^2 or 5¢/ft^2 in the 4 5 oz/yd^2 grade in early 1974 (in early 1975, prices were 8 4 - 19 4¢/ft^2 depending on weight) Thus, it is comparable in price with Petromet and a bit more expensive than Typar (Table I)

Film/non-woven lamination Non-woven, spun-bonded materials have virtues of light weight, durability, toughness, strength, tear resistance, and flexibility even at low temperatures, but alone they are highly porous Plastic films, on the other hand, are generally highly impermeable to moisture and have usable strength properties, but they are more subject to puncture and tear So, one might consider the possibility, for MESL or other purposes, of combining the film and non-woven materials by laminating one or more sheets of each to one or more sheets of the other If two films were used, it would help to overcome the very slight leakage that may occur through the occasional tiny pinholes which are acknowledged to exist in plastic film Such an advantage is gained in Griffolyn, having two or more layers of PE film On the other hand, placing non-woven on one or both outside surfaces might offer advantages in durability, protecting the system from puncture and increasing the angle of friction to soil (see below)

The properties of the non-woven and the film plastics seem to make them amenable to lamination, either by application of adhesive (as in Griffolyn) or by controlled partial fusion during production operations Manufacturers have indicated that this should be feasible, and one indicates that it has been tried in the past on a limited scale[4] The preferred film for lamination with non-wovens might be PVC (polyvinyl chloride), which has superior properties, weather resistance and puncture strength Polyethylene, or a combination of PVC and PE, might also be of interest (e g in possible heat sealing of PE without damaging the higher-temperature melting PVC or PP non-woven component)

The use of a film/non-woven laminate should eliminate the need for any general asphalt application in MESL construction, although it or other suitable adhesive would still be needed to join sheets together in the field Since PE is notably difficult to adhere, alternate films may merit consideration It has been indicated that PVC, with its better properties, is now considered more competitive with PE because its price is now not as much higher Another possible material for a laminate is CPE (chlorinated PE), which is often used for pond linings

The idea of heat-sealing the membrane when PE is involved is considered in *Sealing and patching* below This might be the more feasible if PE were laminated to a non-woven or another film having a higher melting point

Angle of friction of film in soil Another point to consider in using plastic film for the upper membrane of MESL is its angle of friction in soil If a relatively thin, say 2-in , pavement is placed directly on a smooth plastic upper membrane, what will be the effect of a hard-braking truck or airplane? The pavement may tend to slide and buckle The possibility of this seems real in light of some experience with pond liners and some angle of friction measurements in Germany[2] The latter showed the angle of friction of smooth plastic to soil is about $\frac{1}{3}$ lower than for soil to soil, and is lower when the soil is wet

The German study also indicated that the angle of friction of plastic films is lower for gravel than for sand. Although the authors expressed surprise at this, it may relate to the greater angularity of most natural sands, whereas gravels are generally smooth. Thus, the sand may have more bite or grip on the plastic. However, a sharp sand might be more likely to eventually puncture a plastic film. Thus, it might be necessary to have sufficient thickness of sand and/or pavement above the membrane to eliminate, by inertia and by stress spreading, the tendency for sliding at the plastic surface. Or, combining film and non-woven by lamination might also help to overcome sliding by having the rough laminate of non-woven on one or both sides outside the smooth film, thus increasing the angle of friction.

Sealing and patching. A problem in MESL applications is the sealing of adjacent strips and patches. Adequate patching techniques are needed for instrumentation, for core sampling or for damage repairs. If the angle of friction is not unduly lowered, a finite layer of unbonded sand (perhaps ½ or 1 in. thick) above the membrane would allow cutting the pavement on a diameter larger than a core-hole or injured area without damaging surrounding membrane. After back-filling the hole, an overlapping patch might be applied, with asphalt or other suitable adhesive.

Some effort was made to learn of adhesives suitable for MESL applications and for patching, particularly where PE film may be involved. Asphalt emulsion apparently works for sealing the PP non-woven to itself and has been satisfactory so far for sealing PE film. Adhesion to the inert surface of PE generally is not good unless modified by slight sintering, partial oxidation, or radiation treatment to enable adhesives to take hold. However, such processes add expense and typically must be factory-applied on the whole sheet, whereas for MESL only narrow strips at edges and ends (or patches) are needed.

A survey of a few dozen manufacturers seemed to indicate that most had no recommendations for adhering raw PE film in the field. A few firms sent samples, which included hot melt, solvent-based or emulsion type adhesives. Tests of these were made by J. A. Karalius. Descriptions of them appear in Table X, assembled from information in his USA CRREL Technical Note of May 1974,[13] from which Figure 10 is reproduced to summarize the results.

Hot melt adhesives cure instantly upon cooling; there is no problem of escape of solvent or water. Instant cure also occurs with heat sealing, a method applicable to thermoplastic films in general and particularly to PE film. However, as Staff[29] suggests, heat sealing tends to weaken the film next to the seal. The difficulty of heat sealing in the field and obtaining the critical temperature control needed has seemed to preclude this method from use onsite, although it is feasible in factory conditions. The same adjacent weakening effect is likely in using hot melt adhesives, which generally require temperatures higher than the melting range of polyethylene, 109°-125°C (230°-257°F) for low density PE, and 130°-135°C (266°-275°F) for high density PE. So, hot melts as well as heat sealing may be impractical for field use.

The reactive or catalyzed, two-part type of adhesive (such as polyester, epoxy, urethane, phenolic, etc.) also avoids the problem of liquid escape in curing. Staff[29] has mentioned a squeeze bottle or "sewing machine fashion" applicable adhesive (presumably of this type and available from Union Carbide), which is apparently successful for adhering PVC strips in the field, as for pond linings. However, none of the adhesives tested by Karalius were of this type (which may not develop good adhesion to PE). High frequency sealing is another possible method with instantaneous cure, but this, too, may not be field-adaptable.

For curing of either solvent or emulsion type adhesives, the solvent or water must escape. For a pervious non-woven fabric this seems not to be a problem, but with two film layers it would be. PE and most plastic films are quite impermeable to water (vapor or liquid) and generally fairly impermeable to solvents. Staff[29] suggests that solvent-based adhesives can be used with PE film, for

Table X Adhesives for PE (J A Karalius)[13]

Name	Mfr & loca	Base	Type	Liquid	% Solids	(°F) Appl T	Cure or tacky time (min)	Usage (gal/yd^2)	Cost (¢/lb)	(¢/yd^2)	
Mystery X Plastic	Husky Oil Co Cody, WY	asphalt rubber asbestos	solvent	naphtha	79	RT	slight				works wet
Deck #4	"	asphalt rubber	hot melt	-	100	350-375	0	0 66			black, soft
AC 85/100	"	asphalt	hot melt	-	100	285-350	0				black
AC 2-1/2	"	asphalt	hot melt	-	100	260-325	0				black, v soft
Flash Patch	Park, Inc Cleveland, OH	asphalt elastomer	tape (press sens)	-	100	RT -65-180°	∞			43	black, works damp, max 8" wide 1/8" thick
Bostik 8601	USM Corp Middleton, MA	?	emulsion	water	65-69	RT	(15) to sev hrs				white
Bostik 7514	"	synth resin	solvent	?	45	RT	15-20				amber color, 6 mos shelf life at RT
Milastic 15J56B	J G Milligan & Co Milwaukee, WI	synth rubber	solvent	(non-flam)	20	RT	$\frac{1}{4}$ - 10				Recom for PE
Scotch grip 4693 Industrial Adhesive	3M Co St Paul, MN	elastomer	solvent	?	?	RT	(1)-60				clear
Bondmaster K218-DLA	Bondmaster Div Nat Starch & Chem Corp NY, NY	synth rubber	solvent	naphtha	28	RT	2-30+	0 02-0 03			clear
M&M 7317	Moore & Munger Stamford, CT	oletac (amorph PP)	hot melt	-	100	350-375	0				good for PF?
Essex 52-512 hot melt	BFC Div , Essex Chem Corp , Sayreville, NJ	chem mod homopolymer	hot melt	-	100	300-350	0		43		lt brown, tacky, good for PE?
CRS-2	Peckham Material Corp Athens, NY	asphalt	emulsion	water	(63+)	RT-140	short (15)	0 3	5	14	black
Polybutene											
Gilsonite											viscous not promising
RTV (silicone)											

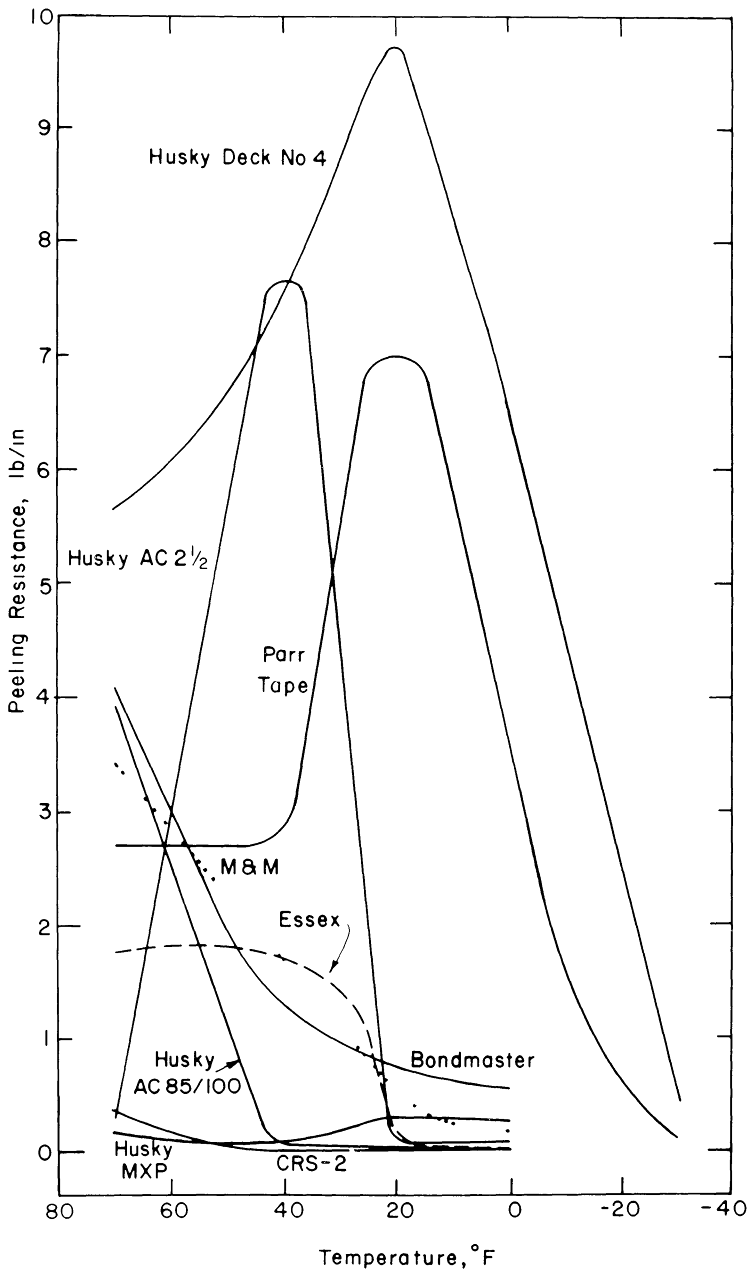

Figure 10 Tests of adhesives on PE – T-peel test at 10 in /min (from reference 13 – see Table X for adhesives identity)

such solvents can slowly diffuse through the film However, a 6 to 12-in overlap seam assembled promptly after coating might be slow to dry During this time, stress should be limited, as the film may be vulnerable due to the temporary 30-40% loss of strength upon solvent soak reported above Perhaps this transient weakness could be tolerated, with care and avoidance of undue or premature stress, but it would delay completion of construction or use of the pavement Meanwhile, however, overburden pressure would tend to prevent the mutual curling away of the films noted by Karalius[1,3]

Problems of dispersing liquid loss and solvent softening may also be mitigated by assembly "open time " This may be a redeeming factor for solvent or water dispersed adhesives – their application, as with many glues, requires an "open time" before assembly of the joint During this period the adhesive becomes tacky as solvent or water escapes by evaporation, as well as by diffusion into the substrate if permeable Thus, N Smith comments that, before assembly of MESL in the field, asphalt emulsion is allowed to coagulate (turning from brown-black to black as water is lost and asphalt droplets coalesce) and becomes tacky In his Alaska field test[27], where CRS-2 asphalt emulsion was mopped on at 16°-21°C (60°-70°F), this took about one hour, at two hours it still remained tacky CRS-2 emulsion is normally hot sprayed at about 60°C (140°F) and it becomes tacky and "sets" much sooner With suitable equipment available, this was done in Smith's later test[28] in Alaska, evolving clouds of vapor

Karalius has stated that in his lab tests he usually allowed about 15 min assembly time for solvent or emulsion type adhesives, in which time the emulsion type developed a typical change in appearance due to coalescence As Table X summarizes, manufacturers suggest periods varying from a few seconds to a half hour, or even up to several hours, open time for emulsion or solvent type adhesives, assembly should, of course, be made before tack is lost The hot melt types naturally cure instantly on cooling In the case of emulsions, particularly CRS-2, Karalius says that he judged open time primarily by the change in color and development of tack That he found CRS-2 considerably poorer than the other adhesives tested might be due to inadequate escape of water, although it might also be because the asphalt of CRS-2 remains quite soft and tacky at room temperature

Moisture transmission through PE film Transmission of moisture through film, as from asphalt emulsion sealed seams, is now considered Vapor transmission through a film is given[22] by

$$Q = P\,(At/d)\,\Delta p$$

where Q = g, or cm^3, of vapor transmitted
$P = Qd/(At\Delta p)$, the permeability (usually independent of thickness)
A = area
t = time
Δp = partial pressure difference of vapor across the membrane
d = membrane thickness

Various units may be used in this equation For water through low density PE the following are given

$$P = 1\ 25\ \frac{\text{g} \times \text{mil}}{100\ \text{in}^2 \times 24\ \text{hrs} \times 44\ \text{mm Hg}} \qquad \text{(Ref 16)}$$

or

$$P = 0\ 118 \times 10^{-10}\ \frac{\text{g} \times \text{cm}}{\text{cm}^2 \times \text{sec} \times \text{cm Hg}} \qquad \text{(Ref 22)}$$

When reduced to the same units, these values are comparable, apparently based on ASTM Ep6-66(E), in which transmission is measured at 100°F (37 8°C) (where water vapor pressure is 49 mm) between 90% and 0% relative humidity (i e $dp = 0\ 90 \times 49 = 44$ mm of mercury) Since P increases exponentially with temperature[1], it will be much lower at usual field conditions The actual transmission Q will be still lower at usual field conditions, since the vapor pressure of water is also lower at lower temperatures (e g 13 mm at 60°F) The Δp will be even lower, to the extent that air or soil on the opposite side of the film is humid or moist, as for a MESL seam buried in compacted moist soil Possibly $\Delta p = 1$ mm would then be more realistic

Table XI Water vapor transmission of PE film (calculated)

Asphalt emulsion application[a]				Water to lose (total)		Water to lose (10%)	
($\frac{gal}{yd^2}$)	($\frac{lb}{ft^2}$)	Film, mil wet	Film, mil dry	($\frac{lb}{ft^2}$)	($\frac{g}{ft^2}$)	($\frac{lb}{ft^2}$)	($\frac{g}{ft^2}$)
0.3	0.123	54	33	0.0455	206	0.00455	20.6
0.1	0.041	18	11	0.0152	69	0.00152	6.9
0.03	0.012	5.4	3.3	0.0046	21	0.00046	2.1
0.01	0.004	1.8	1.1	0.0015	7	0.00015	6.9
0.003	0.0012	0.54	0.33	0.00046	2.1	0.000046	0.21

PE film α (mil)	Q, water transmission, g/(day x ft^2) Δp = 1 mm	5 mm	13 mm	Days to lose water[b] at 0.03 gal emulsion/yd^2 Δp = 1 mm	5 mm	13 mm
1	0.041	0.204	0.53	51	10	4
4	0.010	0.051	0.132	210	41	16
6	0.007	0.034	0.088	300	62	24

Note Calculations based on $P = 0.0284 \frac{g \times mil}{100\ in^2 \times 24\ hr \times mm\ Hg}$, a value applicable at 100°F (37.8°C), for field conditions, P and also ΔP would be much lower and hence transmission lower and days to lose much more.

(a) Asphalt CRS-2 emulsion is 37% water and is considered 1.18 sp. gr., or 10 lb/gal (taking asphalt itself to be 1.3 sp. gr.)

(b) Assuming 90% of emulsion water already lost during "open" time

(c) The quantity 0.03 gal/yd^3 is used on the assumption that emulsion usage on film need be only one tenth of the 0.3 gal/yd^2 recommended on the more rough and pervious non-woven fabric.

While a field test would be desirable for any likely sealer, one may consider here the rate of drying of an emulsion type adhesive between films of PE by moisture loss through the films. Rough calculations were made for representative conditions, using however the $P = 1.25$ value above which for $\Delta p = 1$ mm reduces to

$$P = 0.0284 \; \frac{\text{g} \times \text{mil}}{100 \text{ in}^2 \times 24 \text{ hr} \times \text{mm Hg}}$$

For several assumed conditions for hypothetical PE MESL seam sealing with CRS-2, Table XI shows asphalt emulsion usage, adhesive film thickness, water to lose, water transmission rate, and time to lose water through one face after joining. The possibility that moisture might diffuse through both faces, i.e. into the MESL soil as well as outward, might reduce the times. However, because field conditions would be less favorable (lower permeability, lower temperature), these times are probably optimistic. For the last 10% of water left upon assembly in the tacky asphalt to dry through one or both faces of a seam of 6-mil PE film, it would apparently take several weeks if not a year or longer.

For obtaining a good bond adequately resistant to the stresses of construction use or frost action, the necessity for escape of the last 10% (i.e. of all moisture after the tacky or assembly stage) may be questioned. So also the mechanism of escape through the film might be questioned. Although lateral diffusion of moisture through the adhesive layer to its exposed edges presumably is slow for a 6 to 12-in. overlap, it might be significant or even dominant compared with the low permeation rate through the film. These points should be considered in more extensive testing of PE film for MESL, for they might improve its acceptability and relieve concern as to sealing it.

Meanwhile, until proven otherwise, the computed results in Table XI indicate that a water emulsion sealer may have limitations for PE to PE film sealing. A solvent-based adhesive may then be better, since hydrocarbon solvents can swell and permeate PE, and the Δp will be more favorable with solvent initially absent from the soil. The associated strength loss may not be serious, may be allowed for in design and handling, and may soon return to normal. So, with precautions during the cure period, asphalt cut-back or other solvent-based adhesive may serve for PE to PE sealing (albeit not without some environmental pollution by solvent).

Incidentally, by similar computation, the hypothetical change of moisture within a MESL section may be esimated. Taking a MESL 12 in. thick, its soil density 130 lb/ft^3 and its moisture content 18%, its water content is 23.4 lb/ft^3. Assuming the value of P used above and the effective Δp to be 5 mm, the time for 1% (0.234 lb) of the moisture in 1 ft^3 to migrate through 1 ft^2 of 4 mil PE would be 5.5 years (actually even longer, since the value of P used is much too high for field conditions, also, the Δp would probably be much less than 5 mm most of the time). Use of 6 mil PE film, or PVC etc. would further increase the time. So, given good design and seals, a MESL should serve for many years.

CONCLUSIONS AND RECOMMENDATIONS

1. With suitable procedures and adhesion of seams, plastic films such as polyethylene appear of interest to supplement or replace asphalt-impregnated polypropylene non-woven fabric in MESL (membrane-encapsulated soil layer) construction.

2. Puncture strength and stiffness of plastic films such as PE increase at lower temperatures, i.e. -18°C (0°F).

3 The effect of low temperature on non-woven, spun-bonded plastic fabrics is indefinite, with much scatter of data that probably relates to the random non-uniformity of the structure Several of the non-wovens seemed to become little (if any) more puncture resistant or stiffer at -18°C (0°F) than at room temperature

4 For both non-wovens and PE film, puncture and bending strengths increase linearly with weight or thickness The slope is steeper for the non-wovens, whose strengths generally are greater on a weight basis

5 Hydrocarbon solvents like gasoline and kerosene swell PE film and cause about a 30–40% decrease in puncture strength The loss occurs within an hour but is regained on drying within a day or two in the open Thus, solvent-based sealers and adhesives may be usable if the solvent can escape sufficiently by evaporation during "open time" and by diffusion after assembly before excessive stress is experienced This could mean delay during construction or before trafficking, but may be less serious when a permanent pavement layer protects the MESL

6 Emulsion type adhesives may also be feasible if hot application and "open time" allow sufficient water to escape before assembly The impermeability of PE film would virtually block escape of remaining moisture between two films, as in a seam However, the removal of all the remaining water may not be necessary for obtaining a satisfactory seal

7 Permeability calculations indicate that a MESL of PE film should hold soil moisture stable for many years They suggest that the escape of solvent or water-based adhesives from seams will also be very slow

8 Combining the virtues of film (PE, PVC, etc) and of non-wovens by interlaminating may introduce advantages in handling and in elimination of general asphalt application in MESL projects

9 Further efforts should include continuing exploration and tests of a) improved or composite membrane systems, b) adhesives and bonding techniques and patching methods, and c) solvent and moisture permeability of film and seams

10 The possibilities of undesirable slippage of pavements or soil layers on smooth plastic film layers of MESL, i e due to low angle of friction, should be considered This might occur upon intense braking by a truck or large plane, and means to guard against it should be developed Laminating a non-woven to the film might accomplish this

11 Currently the leading contenders for MESL membrane are polypropylene, polyester, polyethylene or other non-wovens with an asphalt (or other) sealer, and films of PE, or (little tested here) PVC, CPE or Butyl, etc , with a suitable adhesive for seams Interlaminates may be advantageous

LITERATURE CITED

1 Alexander, A E and P Johnson (1950) *Colloid science* Oxford Oxford University Press, p 809-812

2 Baternan, C and E Lattermann (1972) On the angle of friction between high polymer films and soil ***Wasserwirtsch, Wassertech*** , vol 22, no 7, p 234-235 (in German) Translated by J M Sayward (JMS Tl-7, May 1973)

3 Bell, J R and E J Yoder (1957) Plastic moisture barrier for highway subgrade protection *Highway Research Board Preceedings*, vol 36, p 713–735

4 Bennett, R J of Phillips Petroleum Co (1972) Personal communication, visit at USA CRREL 31 August

5 Benson, J R (1953) A review of factors to be considered in the use of asphalt membrane envelopes in highway and airfield pavement design *Asphalt Paving Technology*, vol 22, p 56–91

6 Burns, C D and V C Barber (1969) Expedient surfacing and drainage of roads, streets and parking and storage areas in theater of operations I Tests July 1966–Aug 1968, U S Army Engineers Waterways Experiment Station (USAE WES), Vicksburg, Miss , Miscellaneous Paper S-69-11

7 Burns, C D., W N Brabston and R W Grau (1972) Feasibility of using membrane-enveloped soil layers as pavement elements for multiple-wheel heavy gear loads USAE WES Miscellaneous Paper S-72-6

8 Dixon, W J and F J Massey, Jr (1951) Introduction to statistical analysis New York McGraw-Hill Book Co

9 Gagle, D W and H L Draper (1972) Asphalt pavements laminated with Petromat fabric Phillips Petroleum Co (Manufacturing Dept) industrial literature

10 Harris, F R (1963) Asphalt membranes in expressway construction *Highway Research Record*, no 7, p 34–46

11 Joseph, A H and S L Webster (1971) Techniques for rapid road construction using membrane-enveloped soil layers USAE WES Instruction Report S-71-1

12 Joseph, A H , R D Jackson and S L Webster (1973) Rapid road construction using membrane-enveloped soil layers USAE WES Miscellaneous Paper S-73-5

13 Karalius, J A (1974) Effect of temperature and other variables on the strength of polyethylene and adhesives USA CRREL Technical Note (unpublished)

14 Man-Made Fiber Producers Association (1972) Man-made fiber fact book Washington, D C , p 4

15 Merten, F K and B A Brakey (1968) Asphalt membranes and expansive soils The Asphalt Institute, Information Series IS-145

16 *Modern plastics encyclopedia* (1972) New York McGraw-Hill, Inc , p 344

17 Pinchbeck, G R (1954) Base-enveloping with asphalt *Roads and engineering construction,* p 99–100, 128–129

18 Proksch, H (1972) German experiences with the replacement of granular frost blankets by other types of construction *Proceedings, 3rd International Conference on the Structural Design of Asphalt Pavements*, London, vol I, p 115–125, (sponsored by U Michigan)

19 Quinn, W F , D Carbee and T C Johnson (1973) Membrane-encapsulated soil layers (MESL) for road construction in cold regions *Road Research, Symposium on Frost Action on Roads* (held at Norwegian Road Research Lab, Oslo, Oct 1973), Reports, vol II, p 417–438, (Organization for Economic Cooperation and Development, Paris)

20 Renfrew, M W and A J Freeman (1953) Cold brittleness of polyethylene *Modern Packaging,* August, p 121–123, 173–174

21 Roff, W J , T.R Scott and J Pacitti (1971) *Handbook of common polymers* Butterworth & Co , CRC Press, p 13 (PE), p 27 (PP)

22 Reference 21, p 554–558

23 Ricard, J A (1974) Laboratory determination of the vulnerability of MESL membrane materials to puncturing USA CRREL Technical Note (unpublished)

24 Sale, J P , F Parker, Jr , and W R Barber (1973) Journal of soil mechanics and foundations division Proceedings of ASCE, vol 99 (SM12), p 1077–1089

25 Sayward, J M (in preparation) Plastic MESL membrane materials for cold regions – a brief survey USA CRREL Internal Report

26 Schaefer, D (1973) MESL road construction at Fort Wainwright, Alaska USA CRREL Technical Note (unpublished)

27 Smith, N and D Pazsint (1975) Field test of MESL (membrane-enveloped soil layer) in central Alaska USA CRREL Technical Report 260

28 Smith, N and J Karalius (1973) Construction of a MESL road test section at Elmendorf AFB, Anchorage, Alaska USA CRREL Technical Note (unpublished)

29 Staff, C E (1967) Seepage prevention with impermeable membranes *Civil Engineering*, vol 37 (Feb) (Also telephone call, J M Sayward to Staff Industries, Upper Montclair, N J , 12 Dec 1973 and literature sent to N Smith 7 Dec 1973)

30 Titus, Joan B (1967). The weathering of polyolefins Plastics Technical Evaluation Center (PLASTEC), Dover, New Jersey Picatinny Arsenal (AD 661 633) (note especially p 70, 78, 80)

APPENDIX

Detailed data tables

Complete data for the puncture and the bending tests are included in Tables AI and AII These are explained in notes at the end of each In Table AI, part A covers solvent-soaked PE film and part B temperature and thickness effects Replicates are combined into groups for concise presentation in the text in Table III and Figures 2 and 3 From Table AII, replicates, including face-up and face-down data, are combined for the simpler display in Table IV and Figure 4 in the text

Denier explanation

The term "denier" was used in the text in describing the size of filaments as used in non-woven fabrics As this term may not be familiar or fully understood, the following explanation is offered

The term " denier" is used in the textile industry for designating size of continuous filament fibers, such as natural silk and plastic filaments like nylon, rayon, PP, etc , that are man-made Denier is the weight in grams of 9000 m (29,500 ft) of the filament Denier is not necessarily exactly proportional to actual diameter, since density of the substance enters into the conversion of volume to weight Nine thousand meters of a high density plastic of a given diameter will have a greater weight, i e denier, than the same diameter of a low density plastic Thus, 1 denier PP (density 0 90 g/cm^3) has a diameter of 12 5 μm (0 000494 in or 0 494 mil), whereas 1 denier nylon (density 1 14) would be 11 μm (0 432 mil) in diameter The 3 denier diameter for Petromat (PP non-woven) corresponds then to 21 μ (0 84 mil) Measurements of Petromat fibers by micrometer indicated 0 5 to 1 0 mil (12-25 μm), a reasonable check Fibers of E2B are similar in diameter (approximately 0 8 mil) but its denier is 5 0, because polyester density is 1 38 g/cm^3

For comparison, the 1971 *Man-made fiber fact book*[14] states that women's nylon hosiery filament is commonly 15 denier (43 μm, 1 7 mil) A random check gave 1 8 mil (46 μm) by micrometer (17 denier) The fiber (individual filament) of men's nylon socks (spun multiple fiber worsted) measured about 0 3 mil (7 5 μm), corresponding to 0 5 denier For further comparison, the above non-woven fibers are of similar magnitude to the upper limit of silt particles in soil (20 μm), cloud and fog droplets (10 μm), and human hair (35 μm)

Table AIA Puncture data – solvent effects

Nbk P	T °F	Piece No	Piece size (in)	Piece t (mil)	Gage size (kg)	Treatment	Individual test loads (g)	No of tests	Range (g)	Avg (g)	σ	Group Avg (g)	Group σ_p	Group No
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Polyethylene film, black														
35	RT	-	-	5	1/2	-	350 360 365 385 335	5	50	359	18	359	18	-
		2	2x2	4		-	270 285 285 285 260	5	25	277	12	295	11	1
		0	-	4		-	310 310 305 310 330	5	25	313	10			
		1	2x2	4		gas,3hr,dry 2days	265 285 285 300 295	5	35	286	13	286	13	2
		6	"	3_9		gas,2days,wet	160 185 185 180 170	5	25	176	11			
		4	"	4		gas,2days,wet	165 160 170 185 175	5	25	175	10	172	11	3
		5	"	4		gas,2days,wet	160 155 170 175 185	5	25	169	12			
39		6	"	3 8-4 0		gas,16days,wet	200 175 165 165 160	5	40	173	16			
		5	"	3 9		gas,16days,wet	175 175 165 180 180	5	15	175	6	173	11	4
		4	"	4 0		gas,16days,wet	170 170 175 170 170	5	5	171	5			
40		0'''	"	4 0-4 1		gas,0 5hr,wet	250 250 250 220 225 230 220 250 230 235	10	30	236	13	227	15	5
		1'''	"	4 1-4 3		gas,0 5hr,wet	195 215 230 220 230 220 220 215 220 220	10	35	218	10			
		4''	"	5 7-6 0		gas,0 5hr,wet	300 295 300 285 295 285 300 310 295 290	10	25	296	8	293	8	6
		5''	"	5 6-5 7		gas,0 5hr,wet	290 290 300 295 290 285 260 295 290 285	10	20	290	8			
		0'	"	7 0-7 4		gas,0 5hr,wet	355 360 335 330 345 340 330 360 355 355	10	30	346	11	348	10	7
		1'	"	7 2-7 4		gas,1 4hr,wet	345 335 355 340 365 357 350 345 355 360	10	30	351	9			
		3	"	4		ker,3hr,dry,2days	305 290 275 315 310	5	40	299	16	299	6	8
		9	"	4 3		ker,2days,wet	200 200 205 205 200	5	5	202	3			
		7	"	4 2		ker,2days,wet	185 190 175 190 185	5	15	185	6	197	6	9
		8	"	4 3		ker,2days,wet	205 195 190 190 185	5	20	193	8			
40		8	"	4 2-4 3		ker,16days,wet	185 190 180 195 190	5	15	188	11			
		7	"	4 3-4 4		ker,16days,wet	200 200 200 180 195	5	20	195	17	192	15	10
		9	"	4 3-4 5		ker,16days,wet	195 205 190 185 200	5	20	195	16			
40		3'''	"	4 0-4 2		ker,0 5hr,wet	205 215 205 215 210 215 195 210 215 210	10	20	210	6	214	10	11
		2'''	"	4 0-4 2		ker,0 5hr,wet	215 230 230 240 215 210 205 215 205 225	10	35	219	12			
		2''	"	5 6-5 7		ker,0 5hr,wet	300 330 310 310 295 310 300 300 310 305	10	35	307	10	306	11	12
41		3''	"	5 5-5 7		ker,0 5hr,wet	315 325 305 300 295 305 305 305 308 300	10	20	306	12			
		2'	"	7 0-7 3		ker,0 5hr,wet	365 380 355 360 390 385 375 370 360 375	10	35	372	12	378	12	13
		3'	"	7 3-7 6		ker,1 4hr,wet	395 395 390 365 385 375 363 400 390 390	10	37	385	13			

Table AIB Puncture data – temperature and thickness effects

		Piece			Gage						Group		
Nbk P	T (°F)	No	size (in)	t (mil)	Size (kg)	Individual test loads (g)	No of tests	Range (g)	Avg (g)	σ	Avg (g)	σ_p	No
1	2	3	4	5	6	8	9	10	11	12	13	14	15
Polyethylene film, black (no treatment)													
36	RT	B	-	3 9-4 0	1/2	250 265 270 270 290	5	40	269	14	302	18	14
		K	-	3 9-4 0		275 310 290 295 300	5	35	295	13			
		E	-	4 0		340 335 355 310 345	5	45	337	17			
		L	-	4 0		305 335 325 295 275	5	60	307	20			
		F	-	4 3		340 360 360 325 330	5	35	343	16	323	21	15
		J	-	4 3		315 365 320 285 310	5	80	319	29			
		A	-	4 3-4 8		303 308 275 292 282	5	26	292	14			
		G	-	4 5-4 7		350 335 360 330 310	5	50	337	19			
		D	-	4 9-5 2		380 400 355 380 405	5	50	384	20	373	15	16
		H	-	5 0		350 355 380 360 345	5	35	358	14			
		I	-	5 3-5 5		385 385 360 375 390	5	30	379	12			
		C	-	5 4-5 7		360 370 390 365 370	5	30	371	11			
37		A'	-	5 3-5 7		330 340 335 335 345	5	15	337	6	337	6	17
		B'	-	6 0-6 5		425 410 400 380 365 405	6	60	398	22	400	17	18
		B'	-	"		410 395 405 400 405	5	15	403	6			
		C'	-	7 3-7 5		430 435 405 425 445	5	40	428	15	428	15	19
41		4'''	2x2	4 0		300 285 295 282 300 265 275 290 298 288	10	35	288	12	308	15	20
		5'''	"	4 0		310 290 320 315 325 285 265 280 300 312	10	60	300	20			
		6'''	"	4 0		315 325 305 330 315 340 325 315 295 310	10	45	318	13			
		7'''	"	4 1-4 2		335 330 348 340 330 337 313 310 325 315	10	38	328	12			
		0''	"	5 5-5 6		385 395 415 415 395 405 445 400 400 418	10	60	407	17	423	19	21
		1''	"	5 5-5 6		410 410 425 430 405 415 415 425 410 410	10	25	416	8			
		6''	"	5 3-5 5		415 415 420 405 405 420 395 420 410 405	10	25	412	9			
		7''	"	5 4-5 6		425 405 405 427 413 403 380 405 435 430	10	55	413	17			
42		8''	"	5 5-5 7		435 435 420 435 420 420 395 420 435 505	10	110	432	28			
		9''	"	5 6-5 7		430 435 445 465 500 445 430 500 435 430	10	70	452	28			
		10''	"	5 4-5 6		420 405 415 475 390 425 425 415 420 420	10	85	421	22			
		11''	"	5 5-5 7		420 435 425 415 410 430 400 420 425 415	10	35	420	10			

Nbk P	T (°F)	Piece			Gage Size (kg)	Individual test loads (g)	No of tests	Range (g)	Avg (g)	σ	Group		
		No	size (in)	t (mil)							Avg (g)	σ_p	No
1	2	3	4	5	6	8	9	10	11	12	13	14	15
Polyethylene film, black (cont)													
41	RT	4'	2x2	7 0-7 3	1	470 480 510 470 477 520 495 485 495 460	10	60	486	19	488	20	22
		4'	"	7 0-7 3	1/2	480 480 535 490 495 475 505 490 485 515 490	11	60	495	18			
42		6'	"	7 0-7 1		460 475 475 488 488 500 510 517 535 525	10	75	497	22			
		5'	"	7 0-7 5		455 470 450 455 460 475 490 525 500 470	10	45	476	24			
48		a'	2 5x5	4 0-4 5		310 310 305 310 330 305	6	25	312	9	310	10	26
		c'	"	4 0-4 2		300 305 305 330 300 305	6	30	308	11			
46	0	a	"	4 2-6 5	1	700 685 600 590 520	5	180	619	74	630	108	27
		b	"	4 2-6 7		780 695 510 585 520	5	270	618	117			
		c	"	4 2-6 7		790 740 690 510 530	5	280	652	126			
		b'	"	4 0-4 3		520 520 520 490 500	5	30	510	14	510	14	28
Polyethylene film, clear													
48	RT	d	2 5x5	5 5-6 0	1/2	385 395 400 400 405 398	6	20	397	7	400	21	23
		e	"	5 5-6 5		420 430 370 430 370 390	6	60	402	29			
46	0	a	"	4 5-5 0	1	575 570 573 570 575 590	6	20	576	7	576	7	24
		b	"	5 5-6 0	1	675 675 690 690 625	5	20	685	19	680	16	25
		c	"	5 5-6 0		670 670 670 675 685	5	15	674	13			
Polyethylene film, clear (fertilizer bag)													
53	RT	1	3x4	6 4-6 8	1/2	470 490 405 480 480 480 430	7	60	474	20	473	19	29
		4	"	7 0		460 500 480 450 480 460	6	50	472	18			
56	0	2	"	6 6-7 1	1	785 790 795 755 755 760	6	35	773	19	779	57	30
		3	"	6 7-7 1		820 680 695 805 890 850 745 790	8	210	785	73			
Griffolyn (PE film-nylon web laminate)													
47	RT	55-1	1 2x3	4 2/6 9	1/2	300 305 310 310 325 310	6	25	310	8	308	20	1
53		"	8x3	"		315 330 300 300 310	5	30	311	12			
54		"	-	"		260 290 300 325 325 325 325 270	8	75	304	28			
47	0	"	3x6	"	1	535 490 500 490 530	5	45	509	22	509	22	2
47	RT	55-2	1 2x3	4 6/7 0	1/2	300 310 300 290 300 310	6	20	302	8	314	12	3
53		"	8x3	"		315 310 310 315	4	5	312	3			
54		"	-	"		310 310 340 310 350	8	40	328	16			
47	0	"	3x6	"	1	620 530 540 530 560	5	90	556	38	556	38	4

Table AIB (Cont) Puncture data – temperature and thickness effects

Nbk P	T (°F)	Piece No	Piece size (in)	Piece t (mil)	Gage Size (kg)	Individual test loads (g)	No of tests	Range (g)	Avg (g)	σ	Group Avg (g)	Group σ_p	Group No
1	2	3	4	5	6	8	9	10	11	12	13	14	15
47	RT	65-1 1	2x3	4 8/9 2	1/2	275 320 310 320 340 330	6	65	316	22			
53		"	8x3	"		320 325 315	3	10	320	5	325	21	5
54		"	-	"		320 335 365 335 340 335 345 310	8	55	339	22			
47	0	"	3x6	"	1	480 570 540 540 550 530 530 520 485	9	90	527	29	527	29	6
56	RT	85-1	-	-/4 5-16 5	1/2	355 400 390 375 470 380	6	115	395	40	395	40	7
	0	"	3x3 8	"	1	620 530 550 585 570 580	6	90	572	31	572	31	8
	RT	85-2	-	-/10-12	1/2	410 410 415 410 420 430	6	20	416	8	416	8	9
	0	"	3x3 8	"	1	535 600 600 735 800 580	6	265	642	102	642	102	10
	RT	85-3	-	-/9-11	1/2	410 400 380 400 410 390	6	30	398	12	398	12	11
	0	"	3x3 8	"	1	500 590 600 595 575 595	6	50	584	19	584	19	12
68	RT	65-2A	3x5	6	1/2	440 300 297 290 315 300 320 323 320 348	10	150	325	44			
		B		"		312 297 385 310 300 308 300 310 450 310	10	153	328	50	316	39	13
		C	3x5	"		302 282 281 313 320 290 305 295 280 280	10	33	295	15			
70	0	D	"	"	1	525 570 515 535 530 475 530 490	8	95	521	29			
		E	"	"		480 475 510 500 525 560 560 535 525 530	10	85	520	29	518	27	14
		F	"	"		515 475 500 500 545 550 525 520 505 500	10	75	514	23			
68	RT	85-4A	3x5	~9	1	452 415 410 450 410 410 505 440 430 455	10	95	438	30			
		B	"	"		470 450 450 460 445 455 440 440 560 440	10	120	461	36	450	29	15
		C	"	"		455 445 460 465 420 445 465 430 455 480	10	60	452	18			
70	0	D	"	"	1	690 733 685 695 665 700 690 720 690 670	10	68	694	20			
		E	"	"		708 665 670 660 720 710 650 685 705 695	10	70	687	24	688	23	16
		F	"	"		690 700 645 685 640 680 690 720 690 680	10	80	682	24			
68	RT	105-1A	3x5	~11	1	500 500 490 485 500 490 495 500 505 505	10	20	497	7			
		B	"	"		500 500 500 505 515 515 500 485 550 515	10	65	508	17	506	23	17
69		C	"	"		505 485 480 495 550 560 510 500 510 530	10	75	512	26			
70	0	D	"	"	1	752 745 790 800 765 750 785 775 760 800	10	55	772	21			
		E	"	"		820 810 770 840 800 800 790 820 830 835	10	70	812	22	800	21	18
		F	"	"		820 770 830 810 805 840 810 835 810 830	10	65	816	20			

Nbk P	T (°F)	Piece No	Piece size (in)	Piece t (mil)	Gage Size (kg)	Individual test loads (g)	No of tests	Range (g)	Avg (g)	σ	Group Avg (g)	Group σ_p	Group No
1	2	3	4	5	6	8	9	10	11	12	13	14	15
Tyvek (non-woven polyethylene)													
52	RT	1058'	3x5	4 5-6 5	5	1500 1550 1200 1180 1300 1280	6	370	1335	155	1335	155	1
51	0	1058	"	"		1600 1700 1250 1200 950 1150	6	750	1308	285	1308	235	2
52	RT	1056'	"	4 5-20		1300 1350 1670 1480 950 1900	6	950	1442	327	1442	327	3
51	0	1056	"	"		1080 1450 1300 1250 1000 1070	6	450	1192	171	1192	171	4
52	RT	1075'	"	6 3-8 0		1550 1700 1630 1750 1300 1600	6	350	1672	95	1672	95	5
51	0	1073	"	"		1800 1650 1400 1920 1550 1700	6	400	1670	183	1670	183	6
53	RT	1085'	"	7 5-9 5		1920 2470 2530 2680 2470 2320 2250	7	760	2377	245	2377	245	7
51	0	1085	"	"		2300 1750 2200 1500 1900 2100	6	800	1958	301	1958	301	8
53	RT	1079'	"	2 5-10 5		1050 2050 2100 1880 1600 1900	6	450	1897	165	1897	165	9
51	0	1079	"	"		2150 1650 2000 1480 2070 2080	6	300	1958	273	1958	273	10
Reemay (non-woven polyester)													
53	RT	2024'	3x5	10 0-12 0	5	1020 580 930 800 1080 880	6	500	882	178	882	178	1
52	0	2024	"	"	1	620 650 600 530 570 660	6	130	605	49	605	49	2
53	RT	2431'	"	12 0-16 0		535 500 425 480 400 600	6	200	490	73	490	73	3
52	0	2431	"	"		380 450 600 465 550 360	6	240	468	94	468	94	4
53	RT	2033'	"	18 5-16 5	5	1280 1220 1350 1200 980 1320	6	370	1225	133	1225	133	5
52	0	2033	"	"	1	720 720 780 830 760 930	6	210	790	80	790	80	6
53	RT	2440'	"	16 7-18 0		680 645 710 750 750 710	6	105	708	41	708	41	7
52	0	2440	"	"		580 740 890 700 705 660	6	310	712	103	712	103	8
53	RT	2354'	"	18 0-23 0		800 930 750 950 800 680	6	270	818	104	818	104	9
52	0	2254	"	"		735 675 490 700 815 620	6	325	622	110	622	110	10
53	RT	2470'	"	23 5-27 0	5	1350 1240 1270 1450 1230 1550	6	320	1348	129	1348	129	11
52	0	2470	"	"		1450 1350 1430 1150 1730 1550	6	580	1443	194	1443	194	12
Typar (non-woven polypropylene)													
53	70	3201'	3x5	7 5-11 0	1	705 570 910 260 350 800	6	650	609	220	650	220	1
51	0	3201	"	"		705 450 640 590 705 610	6	255	617	94	255	94	2
53	70	3301	"	10 0-11 0	5	1500 1300 470 1600 1380 2380	6	1910	1438	613	1438	613	3
51	0	3301'	"	"		2020 1200 1650 1750 1650 1850	6	820	1681	276	1681	276	4

Table AIB (Cont) Puncture data – temperature and thickness effects

Nbk	T	Piece			Gage	Individual test loads	No of	Range	Avg		Group		
P	(°F)	No	size (in)	t (mil)	Size (kg)	(g)	tests	(g)	(g)	σ	Avg (g)	σ_p	No
1	2	3	4	5	6	8	9	10	11	12	13	14	15
Typar (cont)													
53	RT	3351'	3x5	10 3-14 2		1530 1250 1600 1730 2000 1470	6	750	1597	253	1597	253	5
51	0	3351	"	"		1450 1230 1950 2300 1620 1300	6	650	1642	413	1642	413	6
48	RT	W3	3x6	11 3-14 2		1500 1500 1330 1050 720 1700 1670 1400	8	980	1359	329			
		4	"	12 3-15 0		670 1550 1000 2320 1600 1750	6	1650	1482	580	1412	196	7
52		8	"	15 0		1800 1650 2400 750 1500 278	6	2122	1396	763			
51	0	2	"	11 1-15 0		2250 1900 1500 1550 2250 2000	6	750	1908	328	1771	154	8
		7	"	11 0-13 4		1030 850 1700 1750 1400 1500	7	1800	1554	586			
Cerex (non-woven nylon)													
67	RT	1 0d	3x5	3 8-5 3	1	540 470 520 410 630 725 360 640 430 520	10	365	524	114	530	105	1
		b	"	"		540 560 400 510 380 565 500 620 575 700	10	320	535	95			
69	0	a	"	"		580 655 820 735 745 635 845 655 550 535	10	310	676	108	676	120	2
		c	"	"		895 750 530 475 725 720 725 565 590 790	10	420	676	131			
68	RT	2 0d	"	9-14		585 730 485 755 735 855 770 520 740 1010	10	525	722	160	808	133	3
		b	"	"		995 800 995 925 990 740 745 890 960 910	10	255	895	100			
69	0	a	"	"	5	1600 1450 1230 1380 1480 1250 1430 1425 1350 1080	10	520	1368	148	1244	149	4
		c	"	"		1080 1080 1200 1180 1370 830 1000 1056 1280 1120	10	540	1119	151			
68	RT	3 0d	"	10-12		2070 1900 1700 1900 2130 1820 1840 1720 1750 1800	10	430	1863	143	1912	153	5
		b	"	"		2100 1900 2070 1950 2100 1940 1950 1950 1555 2100	10	545	1962	163			
69	0	a	"	"		2230 2130 2350 2340 2040 1830 1800 2100 2150 2400	10	600	2137	206	2086	204	6
		c	"	"		2430 2080 2320 1900 1800 1950 2100 1900 1890 1980	10	630	2035	202			
Butyl rubber, reinforced (32 mil)													
48	RT		3x3 5	28 5-29 0	1	582 630 660 650 620	5	78	670	106	670	105	1
53			"	"		635 600 638 595 650 680	6	85	671	105			
52	0		"	"		790 865 860 830 870 855	6	80	845	30	845	30	2
Butyl rubber, unreinforced (60 mil)													
48	RT		3x3 5	67 0-68 5	5	1850 1920 1950 1850 1950 1850	6	100	1895	50	1973	60	3
53			"	"		2130 2100 2050 1980 2000 2040	6	150	2050	57			
51	0		"	"		2500 2950 2750 2830 2900 2573	6	450	2750	180	2750	180	4

Nbk P	T (°F)	Piece No.	Piece size (in.)	Piece t (mil)	Gage Size (kg)	Individual test loads (g)	No of tests	Range (g)	Avg (g)	σ	Group Avg (g)	Group σ_p	Group No.
1	2	3	4	5	6	8	9	10	11	12	13	14	15
Petromat (non-woven polypropylene)													
47	RT	1	3x6	14 7-16 5		2000 2850 2300 4220 4500 2230 2800 1440 1750 2830	10	3060	2592	1032	2125	873	1
		10	"	13 0-14 0		1700 3400 1500 1280 2850 2250	6	2120	2163	830			
52		13	"	13 3-15 7		2150 1680 1280 1850 2470 1880	6	1190	1885	405			
		15	"	13 2-15 0		2450 2680 680 1280 3200 1120 1600	7	2250	1859	927			
51	0	2	"	14 0-15 0		1650 3350 3000 2880 1850 1750	6	1700	2413	745	2332	1042	2
		11	"	13 5-16 0		1800 1550 670 3500 1350 2150 4150	7	3480	2167	1234			

NOTES TO TABLE AI (Puncture)

Col. 1 Page no in notebook 6012
2 Temperature, °F, RT- room temperature (65-75°)
3 # = sample piece number
4 Size in inches
5 t = thickness, mils, often given as range For Griffolyn, figure before slash is within web (not measurable for 3-or 4-ply), second figure on web intersections
6 Chatillon gage sizes, kg (same size until another cited)
7 Treatment (solvent soak, etc)
8 Puncture load, g, individual tests
9 No of tests
10 Range between max to min loads, g
11 Average puncture load
12 σ = std deviation (avg ± 1σ includes true value 68% of time)
13 Group average of several samples of same treatment, thickness, or temperature
14 σ_p = pooled value for group (from combined data where several pieces tested)
15 Group no (designation on bar graph, Figure 2A)

Table AII Bending test data – temperature effects

Nbk P	T (°F)	Piece Designa	Piece No	Piece Lgth (cm)	Piece t (mil)	Bend ⊥ to dir	g/piece face up	g/piece face down	g/dm face up	g/dm face down	Factor to id RT pc up	Factor to id RT pc down	all face up no	all face up avg	all face up σ	all face down no	all face down avg	all face down σ	all both up & down no	all both up & down range	all both up & down avg	all both up & down σ_p	Factor to RT Load up	Factor to RT Load down	Factor to RT Load both
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
		Polyethylene film, black																							
60	RT	4 2±mil	IVa'	12 7	4 0-4 5	T	1 0	1 0	0 8	0 8			2	0 88	0 09	2	0 80	0	4	0 4	0 84	0 1			
			c'				1 2	1 0	95	8															
	0		a'				2 0	3 0	1 6	2 4	2	3	2	1 60	0	2	2 20	0 28	4	0 8	1 90	0 2	1 8	2 8	2 3
			c'				2 0	2 5	1 6	2 0	1 7	2 5													
		Polyethylene film clear																							
60	RT	6 0±mil	IIId	12 7	5 5-6 5	T	2 5	1 5	2 0	1 2			2	1 80	0 28	2	1 60	0 57	4	0 4	1 7	0 4			
			e				2 0	2 5	1 6	2 0															
	0		d				5 5	6 0	4 3	4 7	2 1	3 9	2	5 30	1 41	2	4 7	0	4	2 0	5 0	1 0	2 9	2 9	2 9
			e				8 0	6 0	6 3	4 7	3 9	2 4													
		Polyethylene film, clear (bag)																							
60	RT	7 2±mil	4A'	10 0	~7	T	1 0	2 0	1 0	2 0			4	1 38	0 48	4	2 12	0 48	8	1 5	1 75	0 5			
63			3B'				1 5	2 5	1 5	2 5															
			2B'				2 0	2 5	2 0	2 5															
60			1A'				1 0	1 5	1 0	1 5															
	0		4A				3 0	5 0	3 0	5 0	3 0	2 5	4	3 62	0 48	4	5 12	0 63	8	3 0	4 38	0 6	2 6	2 4	2 5
			3B				4 0	5 0	4 0	5 0	2 7	2 0													
			2B				4 0	6 0	4 0	6 0	2 0	2 4													
			1A				3 5	4 5	3 5	4 5	3 5	3 0													
		Griffolyn (polyethylene - nylon web laminated)																							
30	RT	55-1	-	15 2	4 2/6 9	M(?)	2 0	1 0	1 3	0 7	see last		1	1 3	-	1	0 7	-	2	0 6	1 00	0 4			
33	0		-		"		3 3	2 8	2 2	1 8	columns		1	2 2	-	1	1 8	-	2	0 4	2 00	0 3	1 7	2 6	2 0
29	RT	55-2	-	15 2	4 6/7 0	M(?)	1 8	0 8	1 2	0 5			1	1 2	-	1	0 5	-	2	0 7	0 85	0 5			
33	0		-		"		5 0	1 0	3 3	0 7	"		1	3 3	-	1	0 1	-	2	2 6	2 00	1 8	2 7	1 4	2 4
29	RT	65-1	-	15 2	5 1/9 2	M(?)	3 0	2 0	2 0	1 3			1	2 0	-	1	1 3	-	2	0 7	1 65	0 5			
33	0		-		"		6 0	4 0	4 0	2 6	"		1	4 0	-	1	2 6	-	2	1 4	3 30	1 0	2 0	2 0	2 0
60	RT	85-1	A'	12 7	(5 1)/10 5	M(?)	4 0	4 0	3 1	3 1			2	3 4		2	3 7		4	1 2	3 55	0 7			
63			B'	9 4	"		3 5	4 0	3 7	4 3															
60	0		A	12 7			10 0	10 3	8 0	8 3	2 6	2 7	2	6 95		2	8 45		4	2 7	7 70	1 1	2 0	2 3	2 2
63			B	9 4			5 5	8 0	5 9	8 6	1 6	2 0													

Nbk P	T (°F)	Piece Designa	Piece No	Piece Lgth (cm)	Piece t (mil)	Bend ⊥ to dir	g /piece face up	g /piece face down	g /dm face up	g /dm face down	Factor to id RT pc up	Factor to id RT pc down	all face up no	all face up avg	all face up σ	all face down no	all face down avg	all face down σ	all both up & down no	all both up & down range	all both up & down avg	all both up & down σ_p	Factor to RT Load up	Factor to RT Load down	Factor to RT Load both
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
	Griffolyn (Cont)																								
60	RT	85-2	A'	12 7	(5 1)/11	M(?)	7 0	1 0	5 6	0 8			2	4 90	0 99	2	2 00	1 70	4	4 8	3 45	1 4			
63			B'	9 5			4 0	3 0	4 2	3 2															
60	0		A	12 7			6 0	10 5	4 8	8 4	0 9	1 05	2	5 85	1 48	2	9 00	0 85	4	4 8	7 42	1 2	1 2	4 5	2 2
			B	9 4			6 5	9 0	6 9	9 6	1 6	3 0													
60	RT	85-3	-	12 7	5 1/10	M(?)	5 0	5 0	4 0	4 0			2	4 65	0 92	2	4 10	0 14	4	1 3	4 38	0 7			
63			A'	9 5			5 0	4 0	5 3	4 2															
60	0		-	12 7			11 0	10 5	8 8	8 4	2 2	2 1	2	9 7	1 27	2	9 0	0 84	4	2 2	9 35	1 1	2 1	2 2	2 1
			-	9 4			10 0	9 0	10 6	9 6	2 0	2 3													
	Griffolyn (new, large samples)																								
67	RT	65-2	A	12 7	6/8 5	T	2 0	2 0	1 6	1 6			3	1 40	0 17	3	1 90	0 26	6	0 8	1 65	0 3			
			B				1 7	2 7	1 3	2 1															
			C				1 7	2 5	1 3	2 0															
	0		D				3 5	8 0	2 8	6 3	see last columns		3	3 30	0 56	3	5 50	0 80	6	3 5	4 40	0 8	2 4	2 9	2 7
			E				5 0	7 0	3 9	5 5															
			F				4 0	6 0	3 2	4 7															
67	RT	85-4	A	12 7	9/12	T	5 0	5 0	3 9	3 9			3	4 43	0 92	3	3 67	0 40	6	2 3	4 05	0 8			
			B				5 0	4 0	3 9	3 2															
			C				7 0	5 0	5 5	3 9															
	0		D				14 0	14 5	11 0	11 4	see last columns		3	11 67	2 27	3	11 93	0 92	6	4 4	11 70	2 0	2 6	3 2	2 9
			E				12 5	14 5	9 3	11 4															
			F				18 0	16 5	14 2	13 0															
67	RT	105-1	A	12 7	11/16 5	T	13 0	8 5	10 2	6 7			3	8 67	1 55	3	6 70	0 40	6	3 9	7 68	1 3			
			B				9 0	8 0	7 1	6 3															
			C				11 0	9 0	8 7	7 1															
	0		D				26.0	25 0	20 4	19 7	see last columns		3	22 27	2 57	3	22 33	3 27	6	6 3	22 30	2 7	3 9	3 3	2 9
			E				27 0	33 0	21 2	26 0															
			F				32 0	27 0	25 2	21 3															

Table A11 (Cont) Bending test data – temperature effects

Nbk P	T (°F)	Piece Designa				Bend ⊥ to dir	g /piece face		g /dm face		Factor to id RT pc		all face up			all face down			all both up & down				Factor to RT Load		
			No	Lgth (cm)	t (mil)		up	down	up	down	up	down	no	avg	σ	no	avg	σ	no.	range	avg	σ_p	up	down	both
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
	Tyvek (duPont's spun-bonded polyethylene)																								
62	RT	1056	B'	12 7	4 5-7	T	1 5	2 0	1 2	1 6	see last		1	1 2	-	1	1 6	-	2	0 4	1 40	0 3			
59	0		B				2 0	1 5	1 6	1 2	columns								2	0 4	1 40	0 3	1 0	1 0	1 0
59	RT	1058	A'	12 7	4 5-6 5	T	1 0	1 0	0 8	0 8			2	1 0	0 28	2	1 0	0 28	4	0 4	1 00	0 3			
62			B'				1 5	1 5	1 2	1 2															
59	0		A				2 5	3 5	2 0	2 8	"		2	1 80	0 28	2	2 40	0 57	4	1 2	2 10	0 5	1 8	2 4	2 1
			B				2 0	2 5	1 6	2 0															
59	RT	1073	A'	12 7	6 3-8	T	3 0	5 0	2 4	4 0			2	2 40	0	2	3 60	0 57	4	1 6	3 00	0 4			
62			B'				3 0	4 0	2 4	3 2															
59	0		A				5 0	6 0	3 9	4 7	"		2	4 50	0 85	2	4 50	0 85	4	1 2	4 50	0 8	1 9	1 2	1 5
			B				6 5	5 5	5 1	4 3															
59	RT	1079	A'	12 7	75-10 5	T	4 0	6 0	3 2	4 7			2	3 2	0	2	5 3	1 85	4	2 7	4 25	0 6			
62			B'				4 0	7 5	3 2	5 9															
59	0		A				10 0	13 0	7 9	10 2	"		2	6 50	1 98	2	8 88	1 91	4	5 1	7 68	2 0	2 0	1 7	1 8
			B				6 5	9 5	5 1	7 5															
59	RT	1085	A'	12 7	7 5-9 5	T	4 0	5 0	3 2	3 9			2	3 2	0	2	5 1	1 70	4	3 1	4 15	1 2			
62			B'				4 0	8 0	3 2	6 3															
59	0		A				8 0	11 0	6 3	8 7	"		2	5 5	1 13	2	6 70	2 83	4	4 0	6 10	2 2	1 7	1 1	1 6
			B				6 0	6 0	4 7	4 7															
	Reemay (duPont's spun-bonded polyester)																								
59	RT	2024	A'	12 7	10-12	M	5 0	6 0	3 9	4 7			2	3 35	0 78	2	4 1	0 85	4	1 9	3 72	0 8			
62			B'				3 5	4 5	2 8	3 5															
59	0		A				7 5	6 5	5 9	5 1	"		2	3 95	2 76	2	3 75	1 91	4	3 9	3 85	2 4	0 9	1 1	1 0
			B				2 5	3 0	2 0	2 4															
59	RT	2033	A'	12 7	13 5-16 5	M	6 0	7 0	4 7	5 5			2	6 30	2 26	2	6 30	1 13	4	3 2	6 30	1 8			
62			B'				10 0	9 0	7 9	7 1															
59	0		A				7 5	10 0	5 9	7 9	"		2	6 10	0 28	2	6 30	2 26	4	3 2	6 20	1 6	1 0¯	1 0	1 0¯
			B				8 0	6 0	6 3	4 7															
59	RT	2254	A'	12 7	18-23	M	6 4	5 0	5 0	3 9			2	4 45	0 77	2	4 0	0 14	4	1 1	4 22	0 6			
62			B'				5 0	5 2	3 9	4 1															
59	0		A				8 0	9 0	6 3	7 1	"		2	4 15	3 04	2	5 50	2 26	4	5 1	4 82	2 7	0 9	1 4	1 1
			B				2 5	5 0	2 0	3 9															

		Piece				Bend	g /piece		g /dm		Factor to								all both up & down						
Nbk	T			Lgth	t	⊥ to	face		face		id RT pc		all face up			all face down			no	range	avg	σ_p	Factor to RT Load		
P	(°F)	Designa	No	(cm)	(mil)	dir	up	down	up	down	up	down	no	avg	σ	no	avg	σ					up	down	both
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
	Reemay (cont)																								
59	RT	2470	A'	12 7	23 5-27	M	12 0	14 0	9 5	11 0			2	9 90	0 57	2	12 2	1 70	4	3 9	11 05	1 3			
62			B'				13 0	17 0	10 3	13 4															
59	0		A				17 0	16 0	13 4	12 6	see last		2	13 20	0 28	2	11 80	1 13	4	2 4	12 5	0 8	1 3	1 0	1 1
			B				16 5	13 0	12 0	11 0	columns														
59	RT	2431	A'	12 7	12-16	M	2 0	1 0	1 6	0 8			2	1 20	0 57	2	0 8	0	4	0 8	1 0	0 4			
62			B'				1 0	1 0	0 8	0 8															
59	0		A				1 5	1 0	1 2	0 8	"		2	0 8	0 57	2	0 6	0 28	4	0 8	0 7	0 4	0 67	0 75	0 7
			B				0 5	0 5	0 4	0 4															
59	RT	2440	A'	12 7	16 7-18	M	3 0	2 5	2 4	2 0			2	2 6	0 28	2	2 4	0 57	4	0 8	2 5	0 4			
62			B'				3 5	3 5	2 8	2 8															
59	0		A				3 2	3 0	2 5	2 4	"		2	2 05	0 64	2	2 0	0 57	4	0 9	2 02	0 6	0 79	0 83	0 8
			B				2 0	2 0	1 6	1 6															
	Typar (duPont's spun-bonded polypropylene)																								
60	RT	3201(tan)	A'	7 6	7 5-11	M	1 5	1 0	2 0	1 3			2	2 0	0	2	1 22	0 77	4	0 8	1 62	0 6			
63			B'	12 5		T	2 5	1 5	2 0	1 2															
60	0		A	7 6		M	4 0	3 5	5 3	4 6	2 6	3 5	2	4 65	0 92	2	3 10	2 12	4	3 7	3 88	1 6	2 32	2 77	2 4
			B	12 5		T	5 0	2 0	4 0	1 6	2 0	1 3													
60	RT	3301(blk)	A'	7 6	10-14	M	4 0	2 0	5 3	2 6			2	5 85	0 78	2	3 30	0 99	4	11 4	4 58	0 9			
63			B'	12 5		T	8 0	5 0	6 4	4 0															
60	0		A	7 6		M	3 5	10 0	13 2	10 7	2 5	4 1	2	17 8	6 7	2	7 2	5 0	4	18 9	12 5	5 9	3 0	2 2	2 7
			B	12 5		T	28 0	4 5	22 5	3 6	3 5	0 9													
61	RT	3351(gray)	A'	7 6	10 3-14 2	M	3 5	5 0	4 6	6 6			2	5 55	1 27	2	5 9	0 99	4	2 0	5 7	1 2			
63			B'	12 5		T	8 0	6 5	6 4	5 2															
61	0		A	7 6		M	8 0	11 5	10 5	15 2	2 3	2 3	2	14 05	5 05	2	10 6	6 38	4	12 2	12 32	5 8	2 5	1 8	2 2
			B	12 5		T	22 0	7 5	17 6	6 0	2 7	1 2													

Table AII (Cont) Bending test data – temperature effects

Nbk P	T (°F)	Piece Designa	Piece No	Piece Lgth (cm)	Piece t (mil)	Bend ⊥ to dir	g /piece face up	g /piece face down	g /dm face up	g /dm face down	Factor to id RT pc up	Factor to id RT pc down	all face up no	all face up avg	all face up σ	all face down no	all face down avg	all face down σ	all both up & down no	all both up & down range	all both up & down avg	all both up & down σ_p	Factor to RT Load up	Factor to RT Load down	Factor to RT Load both
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Typar, Sample from WES - tests in machine and transverse directions segregated																									
29	RT	(tan,	II 10	15.2	10 5-15 5	M	12 0	7 0	7 9	4 6			2	7 55	0 54	2	5 6	1 4	4	3 3	6 58	1 1			
61		fluffy)	A'8				11 0	10 0	7 2	6 6															
32	20		8				26 0	13.0	17 1	8 6			1	17 1	-	1	8 6	-	2	8 5	12 85	6 0	2 3	1 5	2 0$^-$
	0		7				27 0	10 0	17.8	6 6															
			9				35.0	22 0	23 0	14 5	see last		4	5 92	1 7	4	4 32	1 4	8	5 3	5 12	1 6			
61			A8				12 5	14 5	8.2	9.5	columns														
29	RT		II 3	15 2	10.5-15 5	T	6.0	4 0	3 9	2 6															
			4				10 0	6 0	6.6	3 9			4	5 92	1 7	4	4 32	1 4	8	5 3	5 12	1 6			
61			A'3				8 0	7 5	5 3	4 9															
			A'4				12 0	9.0	7 9	5 9															
32	20		1				15.0	12 0	9 9	7.9	"		2	11 55	2 3	2	7 9	0	4	5 3	9 72	1 6	2 0	1 8	1.9
			5				20 0	12 0	13 2	7 9															
	0		2				21.0	14.0	13 8	9.2															
			6				30 0	13.0	19.7	8 6	"		4	13 22	4 7	4	8 58	0 7	8	12 1	10 90	3 4	2 2	2 0	2 1
61			A3				14 5	11.5	9.5	7 6															
			A4				15 0	13.5	9 9	8.9															
Typar, Sample from WES - tests in both directions lumped																									
	RT			15 2	10 5-15.5	M&T							6	6 5	1 6	6	4 8	1 4	12	5 3	5 6	1 5			
	20					M&T					"		3	13 4	3 6	3	8 1	4	6	9 2	10 8	2 6	2 1$^-$	1 7	1 9
	0					M&T					"		7	14 6	5 7	7	9 3	2 5	14	16 4	11 9	4 6	2 2$^+$	1 9$^+$	2 1
Butyl rubber (from Enjay)																									
60	RT reinf		32mil	9.0	29	-	6 0	5 0	6 7	5 6			1	6 7	-	1	5 6	-	2		6 2	0 8			
	0 (Hodgman)						9.0	11 0	10.0	12.2	"		1	10 0	-	1	12 2	-	2		11 1	1 6	1.5	2 2	1 8
	RT unreinf		60mil	9.0	67-68	-	80.0	72 0	88 9	80 0			1	88 9	-	1	80 0	-	2		84 4	6 3			
	0 (Goodyear)						130.0	105 0	144 4	116 7	"		1	144.4	-	1	116 7	-	2		130 6	19 6	1 6	1 5	1 6

Nbk	T	Piece				Bend	g /piece		g /dm		Factor to id RT pc		all face up			all face down			all both up & down				Factor to RT Load		
P	(°F)	Designa	No	Lgth (cm)	t (mil)	⊥to dir	face up	down	face up	down	up	down	no	avg	σ	no	avg	σ	no	range	avg	σ_p	up	down	both
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
	Cerex (Monsanto's spun-bonded nylon)																								
66	RT	1 0 Oz	d	12 7	3 8-5 3	M	0	0 5	0	0 39			2	0	0	2	0 36	0 04	4	0 39	0 18	0 0			
			b				0	0 4	0	0 32															
	0		a				1 0	1 0	0 79	0 79	see last		2	0 67	0 17	2	0 99	0 27	4	0 63	0 83	0 2	∞	2 75	4 6
			c				0 7	1 5	0 55	1 18	columns														
66	RT	2 0 oz	d	12 7	3 8-5 3	M	7 0	9 5	5 5	7 5			2	6 30	1 13	2	7 50	0	4	2 0	6 90	0 8			
			b				9 0	9 5	7 1	7 5															
	0		a				6 0	9 0	4 7	7 1	"		2	4 70	0	2	7 10	0	4	0	5 90	0	0 75	0 9^{+}	0 9^{-}
			c				6 0	9 0	4 7	7 1															
66	RT	3 0 oz	d	12 7	3 8-5 3	M	7 5	10 5	5 9	8 3			2	5 70	0 28	2	9 30	1 41	4	4 8	7 50	1 2			
			b				7 0	13 0	5 5	10 3															
	0		a				10 0	13 0	7 9	10 3	"		2	8 30	0 57	2	12 25	2 76	4	6 3	10 28	2 0	1 5^{-}	1 3	1 4^{-}
			c				11 0	18 0	8 7	14 2															
	Petromat (Phillips' spun-bonded polypropylene)																								
22	RT		I 1	15 2	13-19	T	13 0	11 0	8 6	7 2			6	8 75	0 89	6	7 55	0 90	12	3 3	8 14	0 9			
			5				13 5	14 0	8 9	9 2															
61			A'1				13 0	11 0	8 6	7 2															
			A'10				11 0	10 0	7 2	6 6															
			A'13				15 0	11 0	9 9	7 2															
			A'15				14 0	12 0	9 2	7 9															
21	20		3			T	10 0	12 0	6 6	7 9	"		4	12 18	5 70	4	9 72	2 74	8		10 95	4 5	1 4	1 3	1 35
			4				14 0	11 0	9 2	7 2															
			7				30 0	20 0	19 7	13 2															
			8				20 0	15 0	13 2	10 6															
21	0		2			T	20 0	20 0	13 2	13 2	"		6	14 40	2 69	6	11 62	1 59	12		13 01	2 2	1 65	1 55	1 6
22			6				22 0	19 0	14 5	12 5															
61			A1				20 0	15 5	13 2	10 2															
			A10				15 0	14 0	10 6	9 2															
			A13				26 0	19 5	17 1	12 8															
			A15				27 0	18 0	17 8	11 8															

Notes to Table AII (Flexibility)

Column	
1	Page no in notebook 6012
2	Temperature, °F, RT = room temperature (65-75°F)
3	Designation of sample - name, code no , color or thickness, second no for Griffolyn is sample no (See Table I)
4	Sample piece number
5	Length parallel to fold
6	t = representative thickness, mils For Griffolyn, figure before slash is within web (not measurable for 3 or 4 ply), second figure on web intersections
7	Direction $\perp$ to axis of bend, MD = machine direction, TD = transverse direction (same until another cited)
8,9	Bending load observed up = face up (concave up if notable, even if label on reverse) down = face down
10,11	Bending load normalized to g/dm (g/10 cm)
12,13	Factor of $\left(\frac{\text{low temp load}}{\text{RT load}}\right)$ - shown here only in a few cases where identical piece tested at RT and 0°F (composite values in col 24-26)
14-16	No of samples, avg load (g/dm), σ (std deviation) for face-up tests (avg $\pm 1\sigma$ includes true value 68% of time)
17-19	Ditto for face down
20-23	Ditto for combined face up and face down, showing also range between highest and lowest value Here σ_p is pooled value (from up and down data combined)
24-26	Factor as in 12,13, composite for combined avg results