Plastic Moisture Barriers For Highway Subgrade Protection

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Most soils have sufficient strength at relatively low water content to serve as satisfactory highway subgrades and even subbases, but many of these soils are not entirely satisfactory for these purposes in practice because they are subject to excessive loss of stability with an increase in water content after construction. However, if the soils are protected against water absorption, many soils which now must be wasted could be utilized in highway construction, thus often effecting a considerable saving in highway costs.

This paper is a summary of the results of a research project designed to investigate the feasibility of using plastic films aas moisture barriers to protect highway subgrades and subbases from water absorption. Possible applications of plastic moisture barriers and the factors to be considered in the use of plastic membranes in highway design are discussed, and results of laboratory and field investigations are summarized. The principal factors discussed are: (1) the general physical properties of the plastics, (2) the permeability of plastic films, (3) the effectiveness of the plastic films in preventing water movement under pavements, (4) the strength of protected subgrade soils, (5) the reduction in highway cost resulting from the use of plastic water barriers, (6) puncture resistance of several typical films, and (7) construction of a test road using plastics.

Results of the investigation show that plastic membranes will effectively retard movement of water in both liquid and vapor phases through soils. It is concluded that, on the basis of these studies, the use of plastic moisture barriers shows promise as a method of controlling highway sub-soil moisture.

● MOST SOILS, even fine grained soils, can be compacted to have sufficiently high strengths to satisfactorily serve as highway subbases if moisture and density are properly controlled. However, under present design concepts, when these soils are used as highway subgrades, only a fraction of this ultimate strength is used as the design strength. As a result, large thicknesses of stronger and more expensive materials are required to spread the load so as not to exceed this reduced strength. This is necessary because it is known that most subgrade soils will not retain their initial strength after years of service under highway pavements. This loss of strength is usually the result of an increase in water content, which may be accompanied by volume changes from either frost action or the expansive nature of the soils. If subgrade soils, subject to these detrimental effects of increasing water content, could be isolated from external sources of water, their design strengths could be greatly increased, in many cases effecting substantial savings in the cost of the highway. In recent years, several successful highways have been constructed which incorporated bituminous membrane water barriers completely enveloping the subgrade soils (*3*) (*9*) (*15*).

This paper is a summary of a research project conducted at Purdue University, sponsored by the Bakelite Company, to investigate the feasibility of using plas-

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tic films as moisture barriers to protect pavement subgrades from changes in water content.

GENERAL USES OF PLASTIC MOISTURE BARRIERS

Two basic types of plastic water barriers were considered in the study. Either of these installations could be adapted to solve many highway sub-soil moisture problems. Both types of moisture barriers are shown in Figure 1.

The first and simplest case is a capillary and vapor cut-off extending across the roadway section. This case is represented in Figure 1 by the dashed line. Such an installation would prevent the movement of water upward from the ground water table into the pavement subgrade, and would be applicable in areas of moderate rainfall with a high ground water table. Such conditions might exist in cuts and where highways cross low wet areas on low fills. Such use of the plastic films would be inexpensive and simple to construct. It would also result in appreciable savings by reducing the sub-drainage necessary in areas subject to frost-action.

The cut-off membrane is a promising possible use of plastic water barriers in highway construction. However, in areas of fairly high precipitation, the film would also prevent the percolation of water downward out of the subgrade and cause an increase in water content directly under the pavement, resulting in a loss of stability of the pavement foundation. Hence, in areas where surface waters move into the pavement sub-soils from the shoulders, ditches, and cracks in the pavement surface, the subgrade soils must be given all-around protection. In this case, a complete envelope would be necessary. The soil would then be completely sealed on the top and sides, as well as the bottom, by a plastic envelope extending like a giant bag longitudinally under the pavement. This second application of plastic water barriers is represented in Figure 1 by the heavy line around the enveloped subbase.

The complete envelope would be more expensive and more difficult to incorporate into highway construction; however, it is a more general application and has a greater potential use than the cut-off. The following discussions will be principally concerned with the complete envelope because of its greater potential use and because the problems of its use are more difficult to analyze. Many of the factors discussed, however, will also be applicable to the problem of evaluating the cut-off type of installation.

If an enveloped subgrade soil is used as the subbase, the pavement thickness can be designed for the soil's as-compacted strength rather than for the strength at increased saturation, as is the common practice at the present time. Also, the effects of frost heave or swelling would be small. Figure 2 compares a conventional highway cross-section with one incorporating a plastic water barrier envelope. In both the conventional and the enveloped section the total thickness, *T*, would be the same; but for the enveloped case, only the thickness *S* would be select material as compared to the total thickness of select material in the

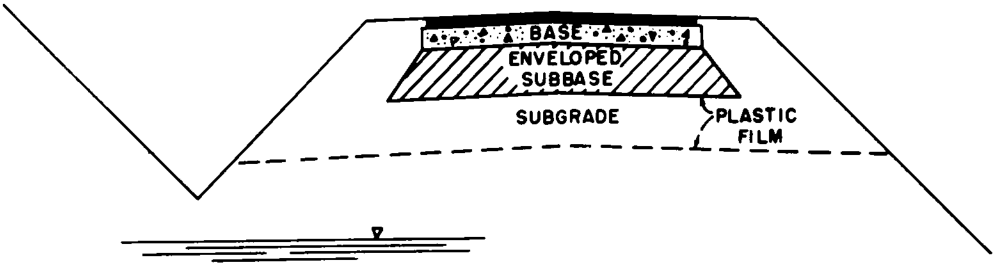

Figure 1. Pavement cross-section with plastic moisture barriers.

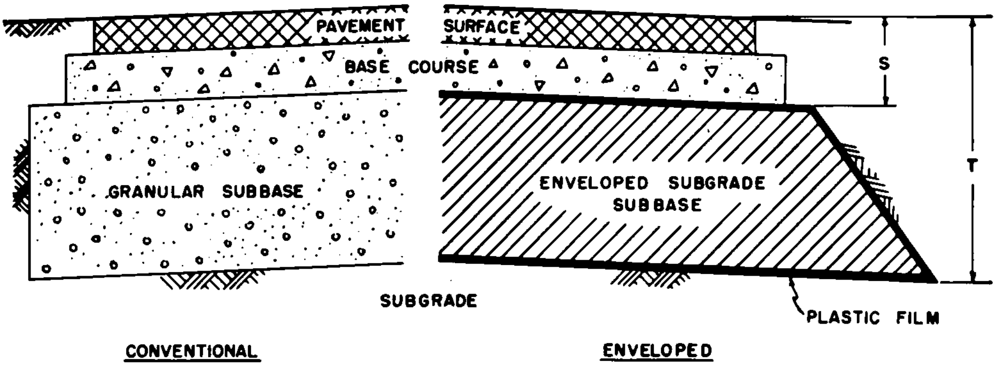

Figure 2. Comparison of conventional and enveloped sections.

normal design. The total thickness would be controlled in both cases by the strength at increased saturation of the subgrade, the depth of frost penetration, or the swell characteristics of the subgrade, but the thickness *S* in the enveloped case would be controlled by the as-compacted strength of the subgrade. Actually, the increase in saturation and, consequently, the reduction in strength of the subgrade could be greater under the envelope than under a granular subbase because evaporation would be completely prevented by the plastic membrane, and future correlation from field tests may, therefore, show that a slightly greater total thickness would be required for the enveloped section than for the conventional section. However, because most current design concepts require that pavement thicknesses be designed on the basis of the strength of the subgrade at almost complete saturation, for the purpose of this discussion the thickness of the enveloped section will be considered equal to the thickness of the conventional case.

The use of the enveloped subgrade material rather than a borrow material as the subbase would in many instances represent a considerable saving in the cost of the highway. There will also be a saving resulting from a reduction in the amount of sub-drainage required if frost damage to this granular subbase is a factor.

The plastic envelope water barrier has its greatest potential use under flexible pavements, because they require greater thickness of base and subbase materials than do rigid pavements. A plastic envelope would only be justified under a concrete pavement if some factor such as frost action or expansive soils, rather than strength, controlled the depth of subbase, because rigid pavements do not depend on their sub-soils for the majority of their strength and, therefore, usually only require thin bases. A thin base would be required, even if an envelope was used, to serve as a cushion between the plastic and the concrete. If frost action or some other factor would make it necessary to use a thick subbase, it would in many cases be more economical to utilize the strength of this base and build a flexible rather than a rigid pavement. Thus, the remainder of this discussion will be devoted primarily to the evaluation of plastic enveloped subgrade soils serving as subbases under bituminous pavements.

THE PLASTIC FILMS

Two types of plastic films were studied in this project: a vinyl and a polyethylene plastic. These are the same films that in the last few years have become so popular as raincoats, tablecloths, food packages, and many other everyday objects. The general physical properties of these films are given in Table 1.

The plastics have low permeabilities, are tough, and are highly resistant to nearly all forms of deterioration. They are not seriously affected by acids, alkalies, mold, or oxidation.

TABLE 1
GENERAL PHYSICAL PROPERTIES OF THE PLASTICS TESTED*

Property	Average Values		ASTM Test
	Polyethylene DE-2400	Vinyl VU - 5905 - 32	
Specific gravity	0.95	1.26	D792-50A
Brittle temperature, C	− 65	− 27	D746-52T
Durometer "A" hardness		75	D676-49T
Tensile strength, lb/sq in.	1,800	2,600	D412-51T D882-49T
Ultimate elongation, %	550	275	D412-51T D882-49T
Stiffness modulus, lb/sq in.:			
25 C	20,000	1,200	D1043-49T
0 C	—	17,000	
−25 C	—	120,000	
Tear resistance, Elmendroff, g/mil:			D689-44
Machine direction	—	80	
Transverse direction	—	160	
Water adsorption, 24 hr at 25 C, %	0.01	0.10	D570-42
Max. available width, ft	40	8	

* After Bakelite Co. (*1*).

The plastics would be used in the form of manufactured films. They would not be sprayed onto the soil. This point is emphasized because it is often misunderstood that the plastic would be sprayed onto the subgrade as a liquid. The film would not be sprayed onto the soil because it is more expensive to process the plastic in a liquid form and because thicker films would be required to insure complete coverage without holes. The film thicknesses under consideration are from 0.004 to 0.008 in.

The polyethylene films can presently be obtained in widths up to 40 ft and if the demand were great enough could be provided in widths up to 100 ft. This offers an advantage over the vinyl films, which are only manufactured in widths up to about 10 ft. The polyethylene is also less permeable than the vinyl. However, the vinyl film has one great advantage in that of the two types it has the greater resistance to puncture. Both films can be readily spliced by heat and pressure (heat sealing) or by special plastic adhesives. The cost of these films is approximately $0.025 per square yard per mil of thickness.

FILM PERMEABILITY

Obviously, for this application one of the most important properties of the films is permeability. A study of the movement of water through the films has shown that the term "permeability" as usually used in civil engineering is not applicable to these plastics. The term "permeability" is generally used in connection with the viscous flow of a fluid through a porous medium, but the films do not have sufficient pores to permit viscous flow and water can only move through them as individual molecules. Therefore, the permeation of the film is a form of vapor diffusion (*2*). This diffusion depends on the vapor pressure gradient across the film rather than on a hydraulic gradient as is the case for viscous flow.

The diffusion rates for the membranes were determined at several temperatures and vapor pressure gradients and were found to be very low for the films studied. From these data, curves of water transmission vs. temperature were prepared for the two types of plastic films under investigation (Figure 3). These curves make it possible to predict the moisture movement through a plastic moisture barrier if the conditions of subgrade temperature and moisture are known. Water transmission can be estimated from these curves for relative humidity gradients other than the 25 percent used in Figure 3 because at a given temperature water transmission is directly proportional to the relative humidity difference across the film.

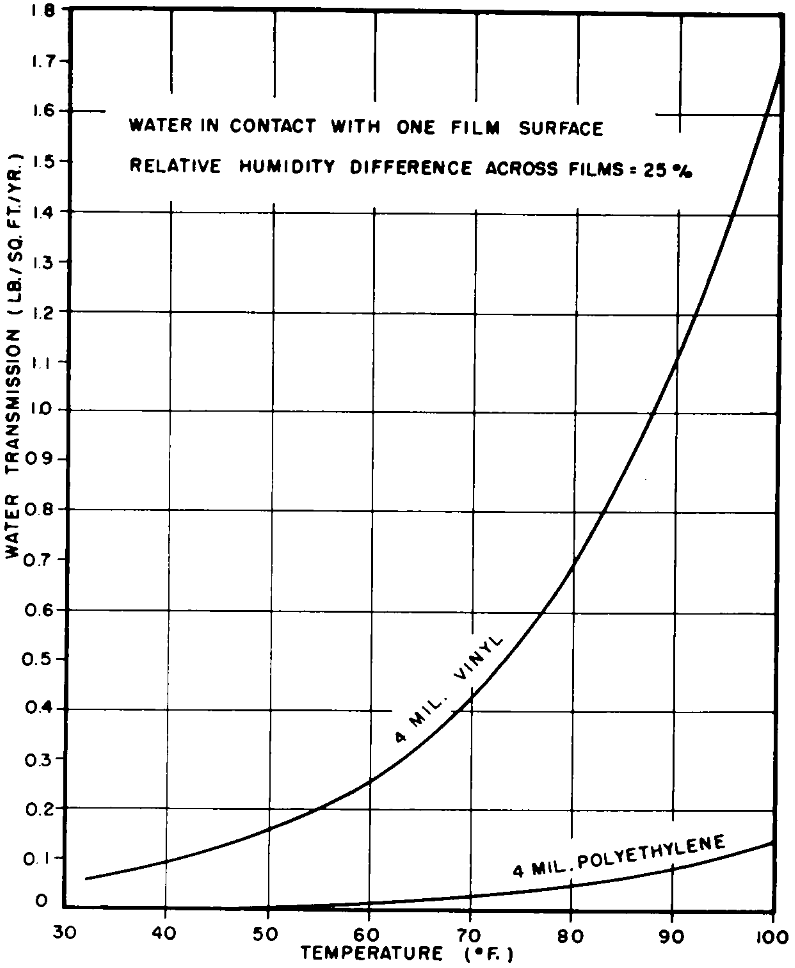

Figure 3. Comparison of water transmission vs. temperature for vinyl and polyethylene films.

EFFECTIVENESS OF PLASTIC MOISTURE BARRIERS

Moisture Movement Through the Membranes

Although the diffusion rates for the films are low, long periods of time would be involved in a subgrade moisture barrier installation; therefore, to evaluate the effectiveness of the plastics as water barriers, it is necessary to predict the vapor pressure gradients which might actually be established across the film. This is a difficult problem because all of the factors involved constantly change with time. For simplicity, an effort is made to predict only the worst possible condition and from this to determine the maximum rate of water movement through the membrane.

Soil Water Vapor Pressure. Because water can permeate the films only as a vapor and as a result of a vapor pressure gradient, the problem is one concerned with the vapor pressure relationships of soils. If a closed container were partially filled with water, evaporation would take place from the water surface and would continue until the vapor pressure in the atmosphere reached a value at which evaporation and condensation were equal. This equilibrium vapor pressure would equal the vapor pressure of a free water surface and would depend only on temperature. If a moist soil were substituted for the water in the container, evaporation would again take place until equilibrium between evaporation and condensation was established. Equilibrium would occur in the second case at a lower vapor pressure because the surface tension forces holding the water to the soil would reduce the vapor pressure of the soil water below the value for a free water surface. The magnitude of this reduction in vapor pressure would be a function of the water content of the soil. Therefore, if the relative humidity of the soil is defined as the ratio of the soil water vapor pressure to the vapor pressure of free water at the same temperature, it has been shown (*8*) (*17*) that a given soil under a given set of conditions will have a distinctive relative humidity vs. water content curve.

Figure 4 is a typical soil relative humidity vs. water content curve. This curve is for a silty clay. The curve for any soil would have a similar shape, but would be shifted to the left for silts and sands and to the right for clays. The actual values on the curve are not important because they would vary depending on the density and structure of the soil. However, the positions of the various soil-water relationships on this curve are important. The Atterberg limits and the optimum water content all fall high on the curve. Even the shrinkage limit occurs at a relative humidity in excess of 90 percent.

For any normal soil condition, the water content would be greater than the shrinkage limit and the relative humidity inside the envelope would always be almost as high as the relative humidity outside; diffusion, therefore, would be low. The maximum vapor pressure outside the envelope would occur at complete saturation of the soil and would correspond to a relative humidity of almost 100 percent. The relative humidity of the soil inside the envelope as compacted would be approximately 99 percent. The vapor pressure difference

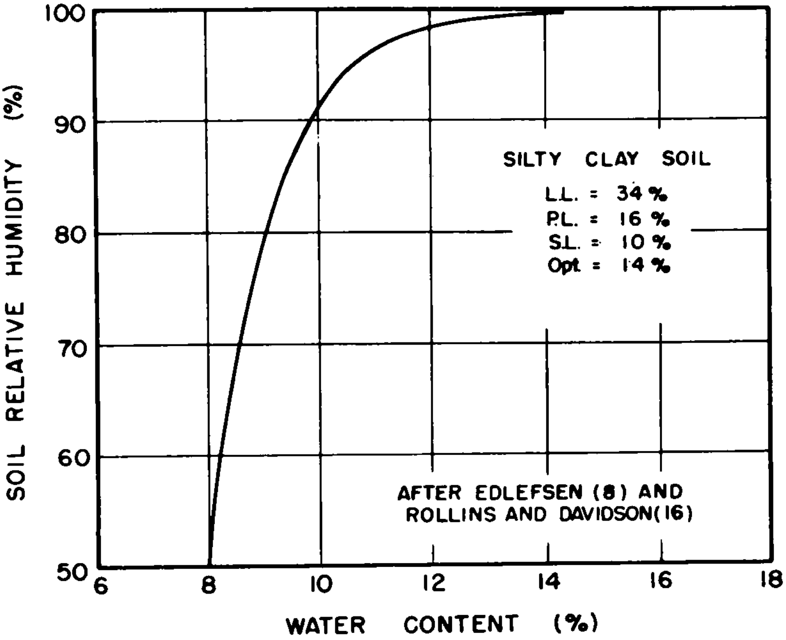

Figure 4. Relationship between soil relative humidity and water content.

across the film would then be only about 1 percent of the vapor pressure of a free water surface. For this very low pressure, diffusion would be negligible.

Soil Water Migration. The vapor pressure gradient across the film could be increased if a redistribution of the water within the enveloped soil were to take place after construction. Such a redistribution would cause a corresponding increase in water movement into the envelope.

The water in the enveloped soils, as compacted, is held by surface tension so that it is not free to move under the influence of gravity. This does not mean, however, that this held water is not free to migrate. It can move either as a vapor or as a liquid, and because the soil would be placed at essentially a uniform water content, these movements would have to be the results of thermal gradients within the enveloped soil mass (*17*).

As the air temperature drops in the fall of the year, the temperature of the soil near the surface (in the top of the envelope) would be lowered more rapidly than the soil at greater depths (in the bottom of the envelope). The soils at both elevations would have the same initial water content and, therefore, the same initial relative humidity, but actual vapor pressure would be higher in the soil with the higher temperature. This would establish a vapor pressure gradient, and water in the vapor phase would migrate from the area of high temperature to the area of lower temperature (*7*). In this example, the movement would be from the bottom of the envelope to the top. The water content, hence the relative humidity of the soil adjacent to the lower membrane of the envelope, would be lowered, the gradient across the film would be increased, and the water movement into the enveloped soil would be increased. Experiments by MacLean and Gwatkin (*14*) on the vapor movement of soil water show that the redistribution of water within the envelope would be small if the soils were initially compacted with water content in excess of about 60 percent of saturation. If the water content was greater than this amount, there would not be sufficient air voids to permit appreciable vapor movement.

If the temperature was lowered further until freezing occurred within the upper portion of the enveloped soil, water movement would occur in the liquid phase. As soil water freezes, forces not fully understood develop which draw water to the ice crystals from the water film surrounding the soil particles (*12*). This would produce a water deficiency in the absorbed films near the freezing front, which would be compensated for by movement of water from lower areas. These freezing forces are of considerable magnitude and could cause appreciable accumulations of water in the frozen area if sufficient water was available from below the frozen zone. Even in a closed system, such as an enveloped soil, the accumulation of water in the frozen zone and the reduction in water content in the lower unfrozen zone could be significant. Experiments conducted at the Corps of Engineers Frost Effects Laboratories show that the soil water content in this lower unfrozen area could possibly be decreased to a value slightly below the shrinkage limit of the soil (*6*). This would be the most critical case for water transmission into the enveloped soil ever likely to exist. The water would tend to redistribute itself uniformly throughout the envelope upon thawing.

Water Transmission Estimates. If the optimum condition, mentioned previously, of water content of saturation below the envelope and slightly below the shrinkage limit in the lower portion of the enveloped soil would occur, the vapor pressure gradient across the lower membrane of the envelope would correspond to a relative humidity difference of about 25 percent (100 percent outside and about 75 percent inside). Figure 3, a plot of the water transmission through the film vs. temperature for the condition of 25 percent relative humidity difference across the film, shows that, at temperatures which might occur at the depth of the lower membrane (below about 50° F) during freezing of the upper layers, diffusion through the polyethylene would be negligible and through the vinyl would be less than 0.15 lb per sq ft per year. If the envelope were 6 in. thick, that water transmission rate would correspond to an increase in water content of the enveloped soil of approximately 0.3 percent per year.

It is evident that the maximum gradient could not exist 100 percent of the time, as it requires a freezing condition. During the yearly temperature cycle, the vapor pressure gradient would vary from the maximum to zero. Also, the temperature of 50° F assumed for the temperature at the depth of the lower membrane is too high for an extended period of time with a freezing front less than 6 inches away. Furthermore, as water would move into the enveloped soil, the relative humidity inside the envelope would increase, causing a reduction in the vapor pressure gradient and thereby reducing the rate of water transmission through the film. These three factors would work together to reduce the rate of increase of the water content of the enveloped soil so that the maximum increase in water content of the enveloped soils would be less than 1 percent in 10 years for a vinyl envelope and 1 percent in 100 years for a polyethylene envelope. Thus, the films, especially the polyethylene, are very effective water barriers, and no special control of compaction water content would be needed to keep water transmission rates low.

Strengths of Enveloped Soils

Method of Evaluation. For the plastic moisture barrier envelopes to be effective, not only must the plastics be good water barriers, but also the enveloped soil must possess sufficient strength to replace a significant thickness of subbase material. To evaluate this problem, some method of determining the supporting capacity of the enveloped soils and of comparing them with non-enveloped soils was required. The California Bearing Ratio (CBR) design procedure as used by the U. S. Army Corps of Engineers was selected for this purpose (*4*). The CBR value of enveloped subbase was obtained by testing the soils immediately after molding without soaking in water. This value, referred to as the unsoaked CBR, was compared with the standard soaked CBR value obtained after the test specimens had been immersed in water for four days.

Two soils, a silty clay and a plastic clay, were tested, and compaction and CBR curves were obtained (Figures 5, 6, 7 and 8). A summary of the properties of the two soils tested is presented in Table 2. The CBR testing procedure used was the Corps of Engineers procedure (*4*). Other testing procedures followed were essentially as outlined by Lambe (*13*).

Discussion of Results. Most flexible pavement design criteria specify a minimum thickness of bituminous surface and base course of material with some minimum stability. In the CBR method, these materials must have a CBR value of not less than 80 percent. It is impossible, at least for the fine-grained soils, to raise a soil's CBR value above 80 percent by simply protecting it from the entrance of water; therefore, a plastic envelope would never completely eliminate the need for a base course of select granular material.

For construction with plastic subgrade

TABLE 2
SUMMARY OF PROPERTIES OF SOILS TESTED

Property	Silty Clay	Clay
Atterberg limits, %:		
Liquid limit	40.1	80.3
Plastic limit	22.2	35.6
Plasticity index	17.9	44.7
Percentage finer than:		
No. 4	100	100
No. 10	97	99
No. 40	91	97
No. 200	81	90
Moisture-density:		
Standard Proctor:		
Max. dry wt., lb/cu ft	109.4	85.8
Opt. water content, %	17	31
Modified AASHO:		
Max. dry wt., lb/cu ft	118.8	95.7
Opt. water content, %	14	27
Classification:		
Corps of Engineers	CL	CH
HRB	A-6	A-7-5
CAA	E7	E12

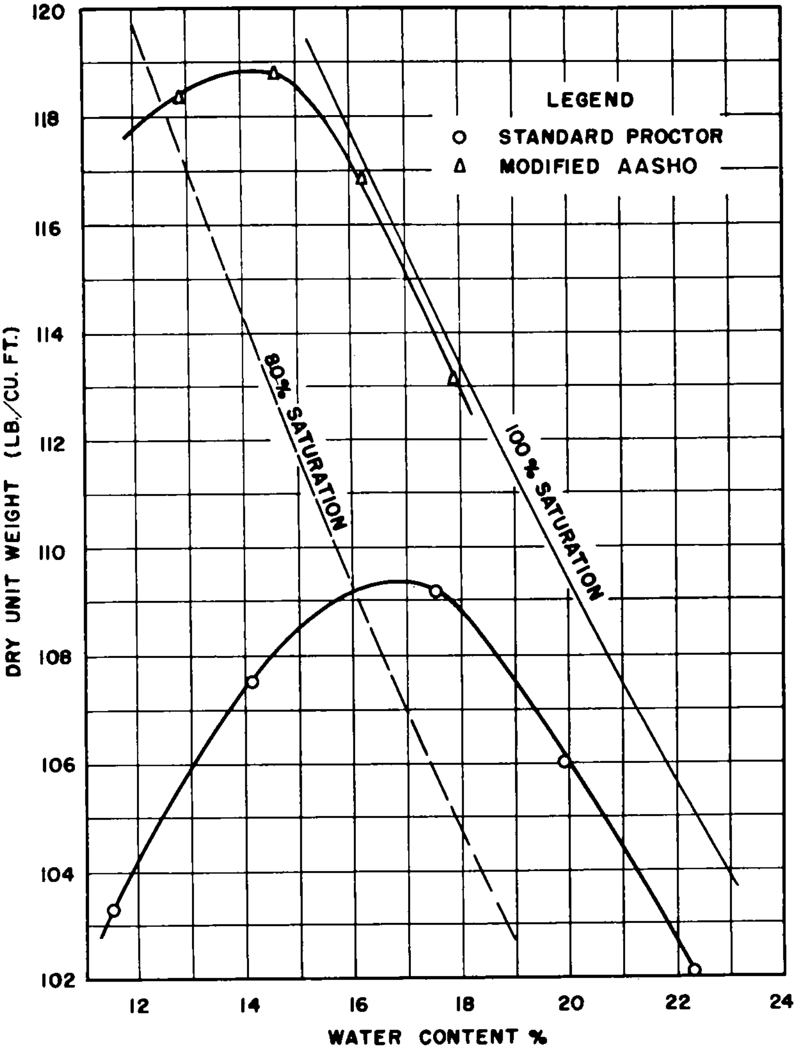

Figure 5. Compaction curves for silty clay soil.

envelopes, the minimum allowable thickness of surface and base course would be 6 in. This thickness satisfies the Corps of Engineers criteria by allowing for 2 in. of bituminous surface and 4 in. of base course. Laboratory experiments indicate that to minimize damage to the plastic film during construction, the compacted depth of base course material should be greater than twice the maximum aggregate size. Hence, if the surface thickness is increased or if the maximum aggregate size is greater than 1½ in., the minimum thickness of surface plus base course must be increased accordingly.

For the enveloped subbase to be utilized to its fullest advantage, it must not require a thickness of surface and base course greater than the specified 6-in. minimum. From the Corps of Engineers flexible pavement design curve (Figure 9), the CBR value which requires just 6 in. of cover material was determined to be 25 percent for a 9,000-lb wheel load.

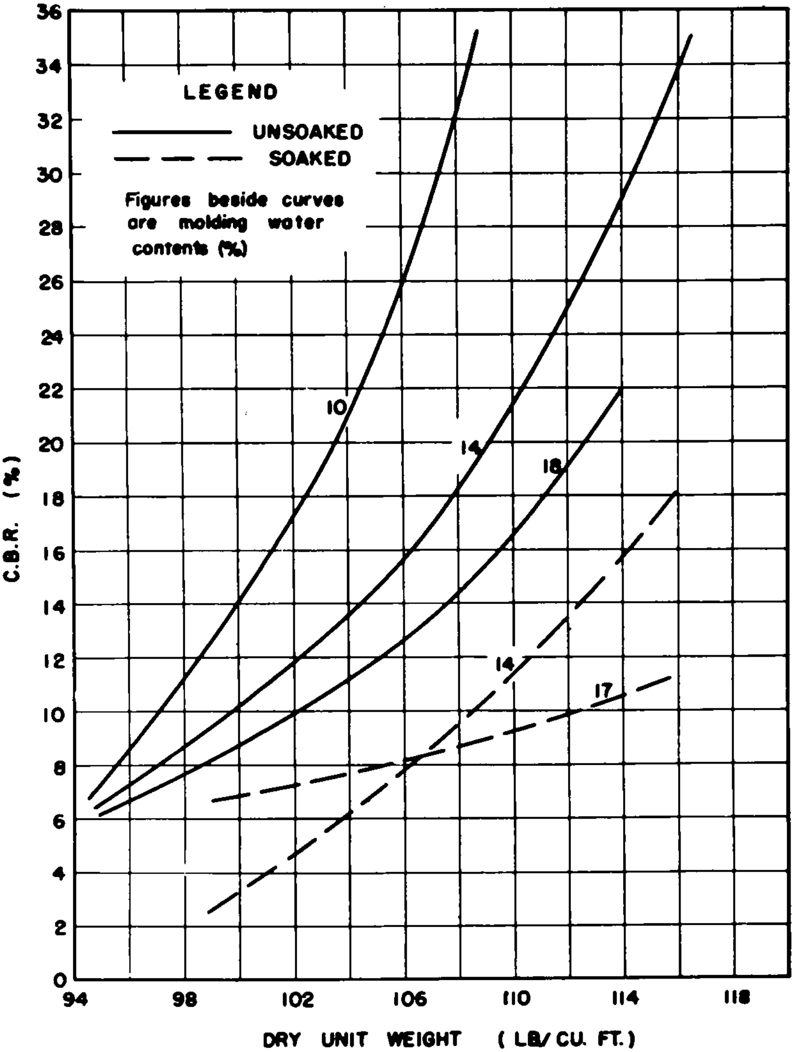

Figure 6. CBR vs. molded dry unit weight for silty clay soil.

Therefore, to derive the most benefit from the plastic moisture barrier, it must be practical to place the enveloped soil in such a condition that it will have an unsoaked CBR of at least 25 percent.

A study of Figures 5 through 8 showed, at least for the more plastic soils, that many soils could be compacted to have unsoaked CBR values in excess of 25 percent without resorting to exceptionally high densities or unusual water contents. But, as pointed out previously, some redistribution of the water within the envelope would occur under conditions favorable to frost action, causing a concentration of water in the upper part of the envelope. This increase in water content would be undesirable because it would bring about a loss of stability in the upper portion where stresses from traffic loads would be the greatest.

The freezing studies by the Corps of Engineers (*6*) mentioned previously indicate that such moisture concentration

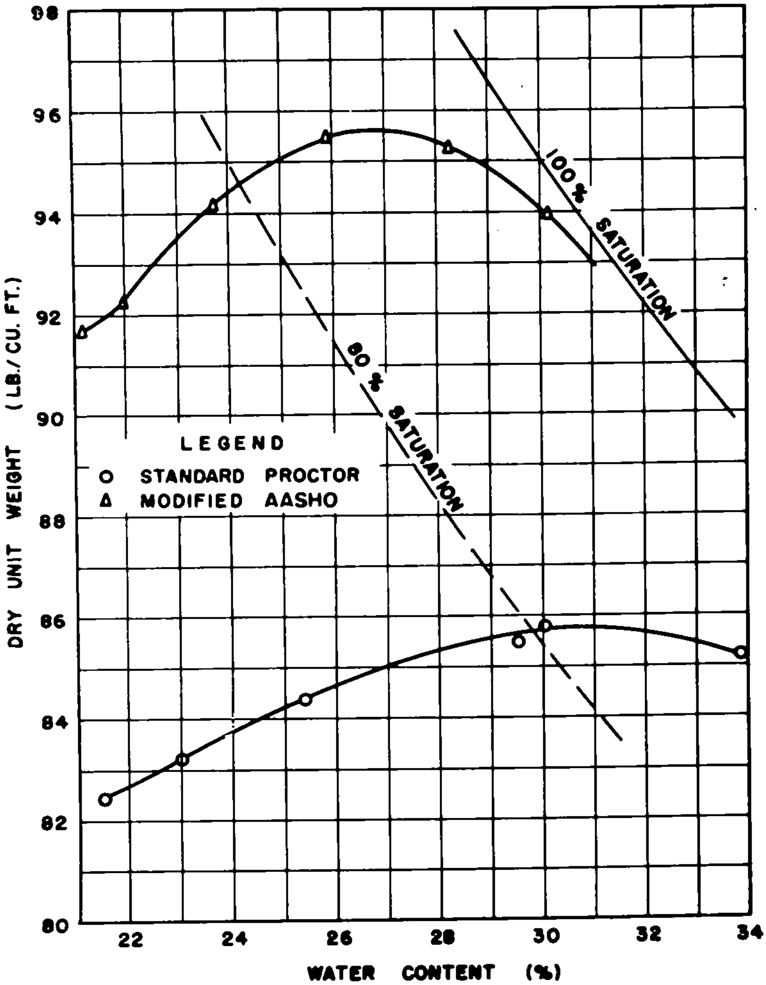

Figure 7. Compaction curves for clay soil.

would be small if the enveloped soils were initially compacted at less than about 80 percent of saturation. Even if this condition was satisfied, if the soils were of such a nature that water was relatively free to move from freezing forces and if the climate was such that the freezing condition would exist for long periods of time, the water content in the upper soil might increase by 2 or 3 percent.

Therefore, in these cases, the soil would have to be initially compacted so that an increase in water content of approximately 2 percent would not reduce the CBR value below 25 percent. For example, the silty clay soil could be placed at a water content of 14 percent and at a density of 114 lb per cu ft. The degree of saturation would then be below 80 percent, the initial CBR value would be about 29 percent, and the reduced CBR, after freezing, would be about 25 percent. Even in this case, the compactive effort required would be only approximately 95 percent of modified AASHO compaction at near modified optimum water content, which, while it is not presently common for highway construction, would not be overly difficult to obtain by conventional compaction procedures. If a water content

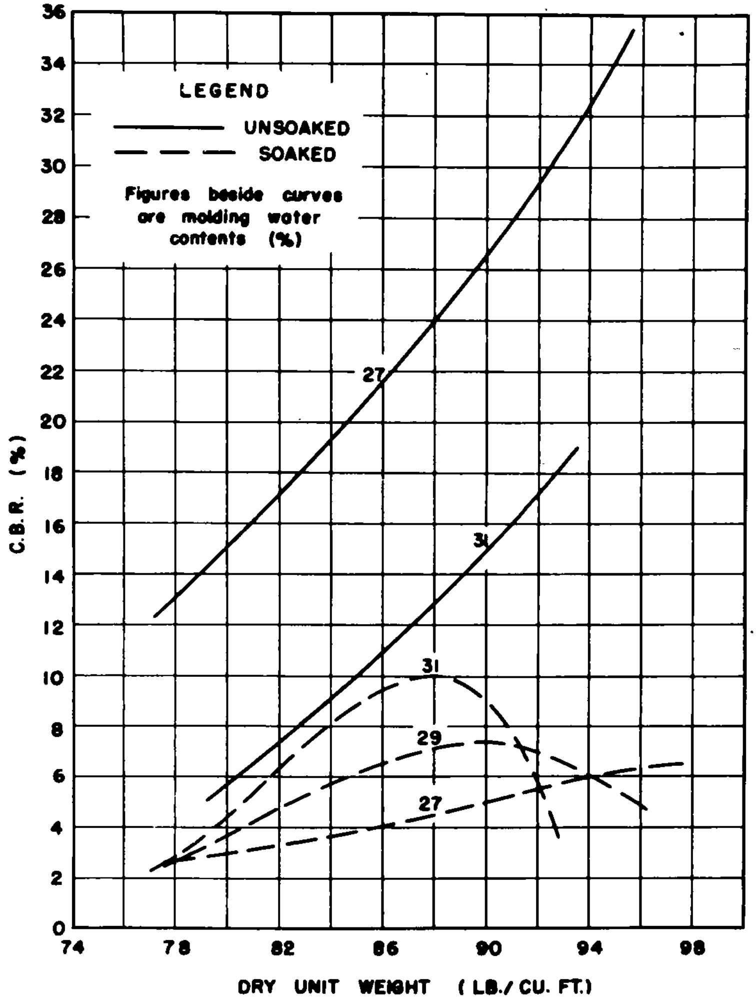

Figure 8. CBR vs. molded dry unit weight for clay soil.

below 14 percent were used, density, and hence the compactive effort, could be reduced. For example, a water content of 10 percent would require a dry density of less than 108 lb per cu ft rather than 114 lb per cu ft to give an unsoaked CBR value of 25 percent.

If the enveloped soils are not subject to frost action, any water content which can be obtained by practical field methods and which is suitable for compaction by conventional methods can be used as far as moisture migration and loss of strength are concerned.

ECONOMICS OF MOISTURE BARRIER CONSTRUCTION

Procedure and Assumptions

Assuming that the enveloped subgrade soil can be compacted to a design CBR of 25 percent or greater, the total required thickness of surface and granular material is 6 in. Without the envelope, the total thickness of aggregate required is some finite value which is controlled by the soaked CBR of the subgrade. The amount of granular material replaced by

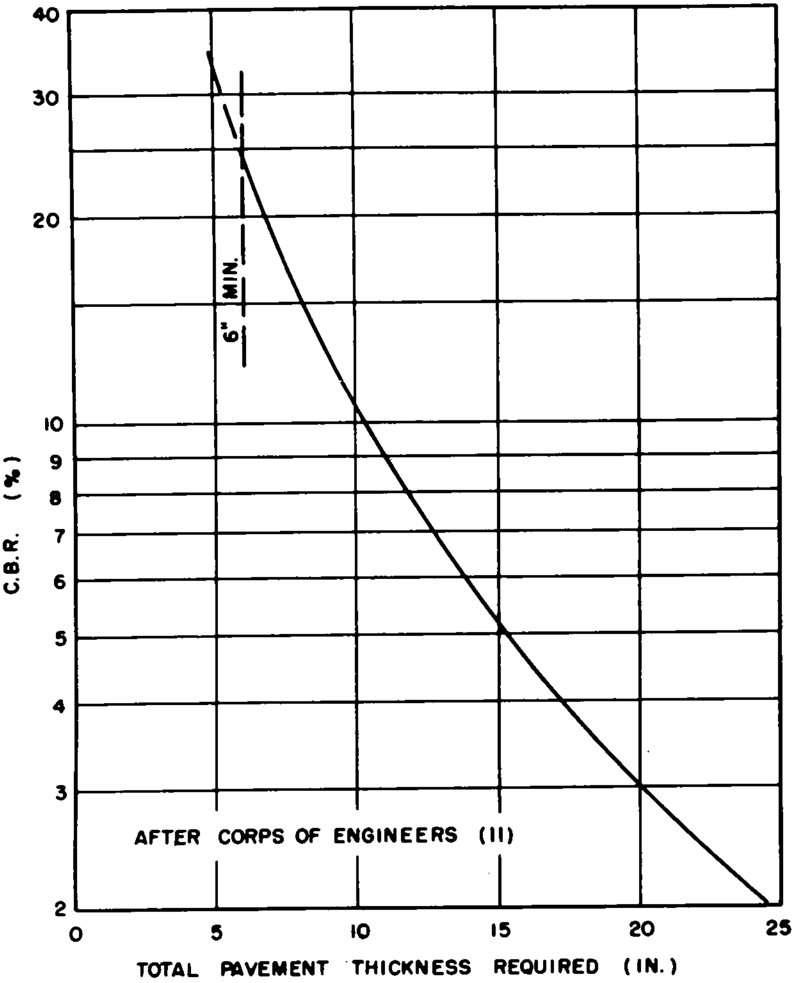

Figure 9. Flexible pavement design curve for highways, 9,000-lb wheel load.

the enveloped subgrade soil would be this total thickness minus 6 in. For example, assume a soaked CBR of subgrade soil equal to 5 percent. Then, from the design curve, the total pavement thickness required would be 16 in. This thickness minus 6 in. equals 10 in., and is the thickness of granular subbase material replaced. The relative economics of the two methods of design can be obtained by comparing the cost of 10 in. of suitable granular material in place with the cost of constructing a 10-in. thick envelope.

The cost of the plastic required per mile of two-lane pavement would be approximately $4,000 to $5,000. However, it is difficult to predict accurately the cost of incorporating a plastic envelope into highway construction because some of the construction procedures have not been worked out in detail. Nevertheless, some assumptions were made and estimates computed. These estimates are believed to be at least of the correct order of magnitude.

The cost estimates for membrane construction were based on assumptions which considered the following:

1. A flexible (bituminous) pavement

surface 24 ft wide with a subbase 27 ft wide and an enveloped cross-section having a perimeter of 56 ft.

2. An envelope with 4-mil polyethylene film at 10¢ per sq yd for the bottom and sides of envelope and 8-mil vinyl film at 20¢ per sq yd for the top membrane, giving an average price of plastic film of 14½¢ per sq yd.

3. The cost of handling the film to be 5¢ per sq yd.

4. A cost of 1¢ per lin ft of seal for sealing the envelope with two sealed joints required.

5. The classified embankment inside the envelope to cost $1.00 per cu yd in place.

6. The minimum thickness of envelope practical for construction to be 6 in.

7. A 6-in. thickness of surface plus base course as the minimum allowable.

8. A maximum wheel load of 9,000 lb. These values are subject to local variations resulting from differences in specifications and in unit prices between different sections of the country, but they are typical for some sections.

Results and Discussion

Figure 10 compares the estimated costs of normal and enveloped construction. A range of values was used instead of making the estimate for one specific case be-

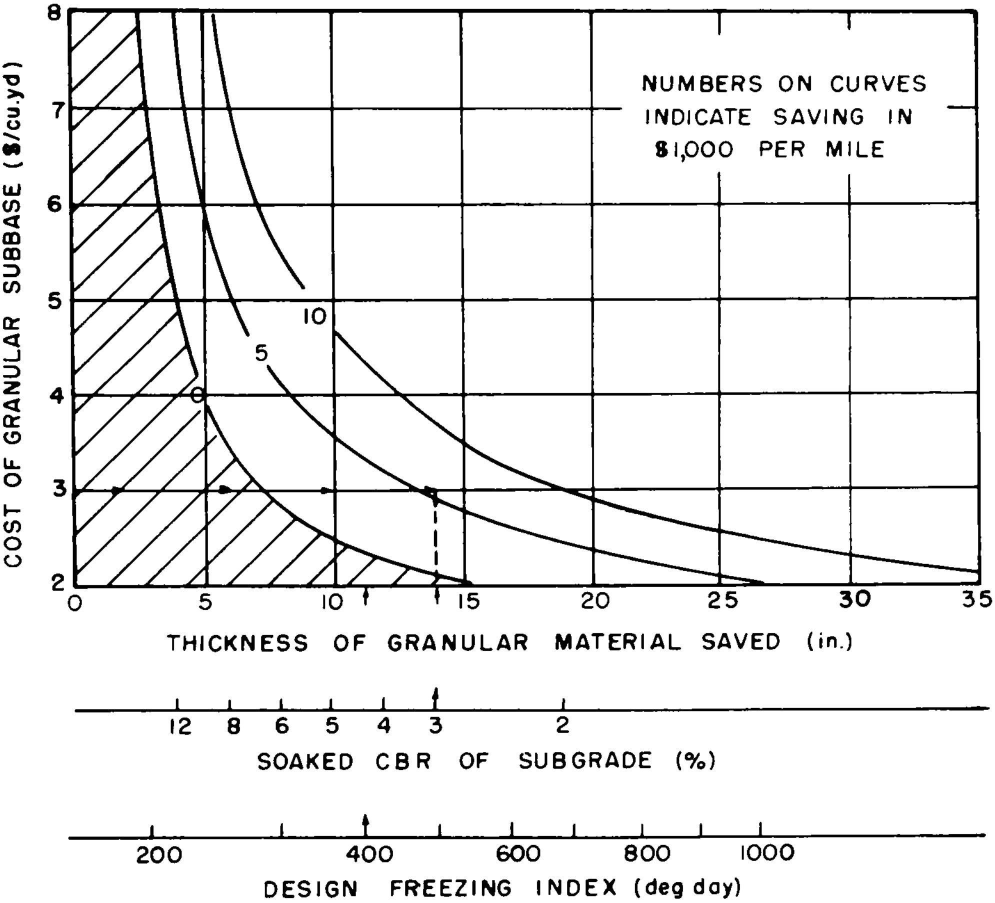

Figure 10. Approximate saving from use of enveloped subbase.

cause the prices of subbase materials have greater variations from location to location than the other items listed, and by this method it can be seen whether or not the possibility of using plastic envelopes is economical for the prices prevalent in any specific area. The horizontal scale shows the thickness, in inches, of granular material that could be replaced by the enveloped subgrade. The curves are plots of points which represent savings of approximately 0, $5,000 and $10,000 per mile of two-lane pavement. The shaded area represents conditions where the envelope method of construction would be more expensive than conventional construction. To use this curve, it is necessary to know the cost of the granular subbase and the thickness that could be replaced with protected subgrade material.

For convenience, the values of CBR of subgrade and freezing index (5) are given for their appropriate saving in granular material. For example, again referring to a CBR equal to 5 percent, the savings would be 10 in. of base; therefore, in the construction of Figure 10, CBR of 5 percent was placed directly under the thickness of 10 in. The other values of CBR were placed in a similar way. The same general scheme was followed with the freezing index (FI). To illustrate, assuming an FI of 500 degree-days, a total pavement thickness of 20 in. would be necessary to prevent freezing of the subgrade. This total thickness of 20 in., minus 6 in. for surface and base course, would leave 14 in. of granular subbase replaced; note that the freezing index of 500 was located directly under the thickness of 14 in. With this information, it is not necessary to compute the thickness saved. The CBR or FI, whichever would control the design, can be used directly.

As an example, assume that temperature records for a given site indicated a freezing index of 400 degree-days and a soil with a soaked CBR of 3 percent. From Figure 10, on the basis of freezing index the thickness saved would be 12 in., whereas for a soaked CBR of 3 percent the saving would be 14 in. For this case the latter is the critical value, and the enveloped pavement design would be 14 in. of enveloped soil plus 6 in. of base and surface. If the subbase cost $3 per cu yd, the enveloped soil design would be about $6,000 per mile cheaper than one using no envelope.

From this figure, it is possible to establish the general range of economic applicability of plastic envelope moisture barriers. It is seen that if frost action or volume change were not important factors the envelopes would only be economical for use with soils which had soaked CBR values less than about 6 or 8 percent or when subbase materials were very expensive. However, when frost action is important, this chart shows that there would be an appreciable saving whenever FI > 400. Also, there are large areas of highly expansive soils in some of the southern states which require pavements at least 18 in. thick to give sufficient confining pressures to prevent excessive swell of the subgrade soils. In this case, subtracting 6 in. for surface and base leaves a 12-in. saving by the use of plastic water barriers, and entering the figure for 12 in. of granular material replaced gives large savings even at relatively low subbase prices.

In the preparation of Figure 10, no allowance was made for savings from the reduction of sub-drains required. The cost of subbase construction for the two designs was the only item considered. Drainage would have to be considered separately because the possible reduction in sub-drains would vary widely from job to job. The plastic envelope moisture barriers would reduce only the need for drainage of the subbase. Subbase drainage is usually required only for frost-susceptible subbases. If subgrade drainage is required for the conventional design, it would also be required for the enveloped case. This item must not, however, be neglected; it could result in large savings from the use of plastic moisture barriers.

In some instances, where conventional designs have not proven entirely satisfactory, the membranes might be considered as an inexpensive form of pavement life insurance, even though they may be slightly more expensive than standard methods.

LABORATORY DESTRUCTION TESTING OF THE PLASTIC FILMS

Procedure

To limit the amount of field testing required and to obtain data for planning of the field tests, laboratory tests of the resistance of the films to puncture by granular materials were performed.

The general procedure for these tests was: (a) a sample of the film to be tested was placed over a compacted subgrade material, (b) a granular material was placed over the film, (c) a load was applied through a piston to the granular material, (d) the stress on the film was computed by the Boussinesq method, and (e) the damage to the film was evaluated by visual inspection of the film after testing. The general test setup is shown schematically in Figure 11.

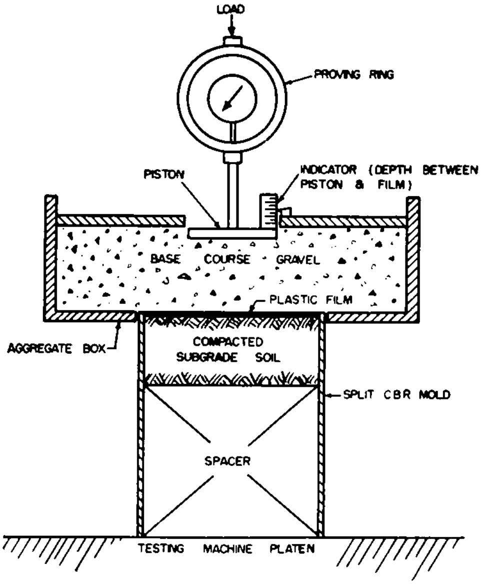

Figure 11. Schematic diagram of assembled film destruction test apparatus.

Two subgrade soils were used. The same soils were used in this study as were used in the first phase of the investigation. One granular base material was used. This material was a well graded glacial gravel of 1½-in. maximum size from Lafayette, Ind. The CBR value of this material was well in excess of 80 percent (about 100 percent).

The vinyl and polyethylene plastics were tested in 4-mil and 8-mil thicknesses. A few of the new modified polyethylene compounds were tested in thicknesses from 4 to 10 mils.

The plastic film samples were given a visual inspection after the test and a hole was considered to constitute failure of the specimen. Microscopic inspections of the films showed that all holes in the films resulting from the tests were visible to the unaided eye if a strong light was used behind the film. No microscopic holes were found. This was probably a result of the elastic characteristics of the films.

The data recorded from these tests were: (a) water content, density, CBR, and type of subgrade soil; (b) maximum compaction stress, in psi, on the film; and (c) whether or not the film failed (had holes).

Results

A total of 66 destruction tests was performed on the various films. The results of these tests are summarized in Figure 12. This figure shows the maximum allowable stress on the films under a gravel base material during the compaction of the gravel, plotted as a function of the unsoaked CBR of the underlying subgrade soil.

The preliminary tests performed during the development of the procedure outlined previously, and visual inspection of the test specimens after testing, indicated the following results, which are not shown by the recorded test results:

1. The damage to the film is reduced if the compacted depth of granular material is at least twice the maximum aggregate size.
2. The polyethylene films are sometimes strained past the elastic limit with-

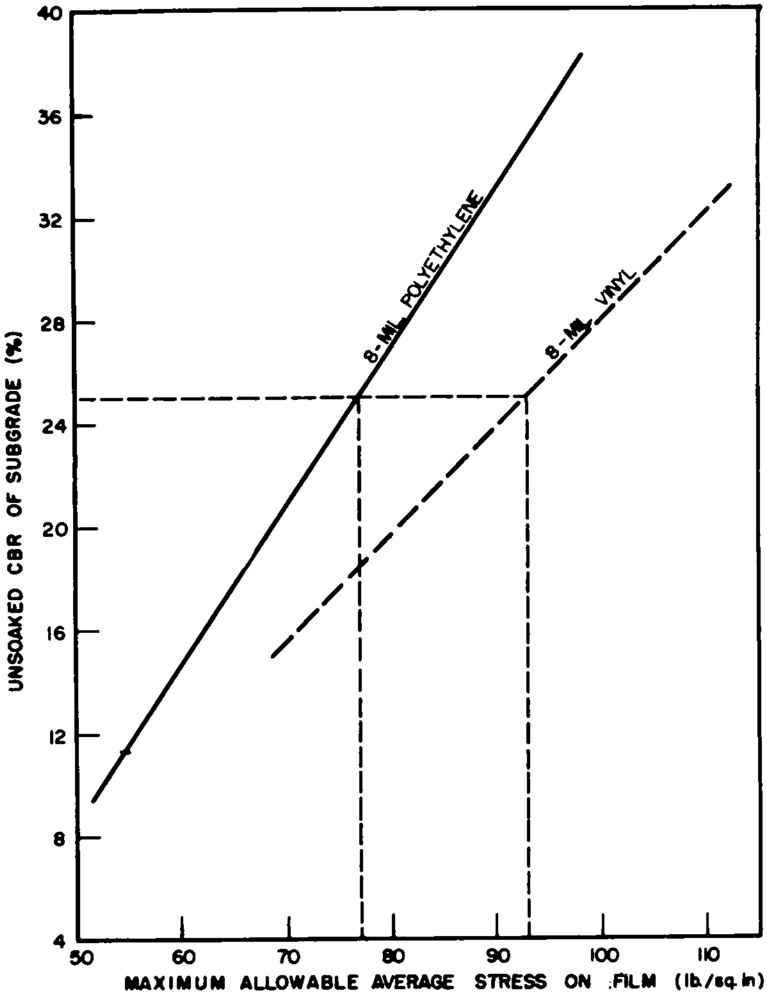

Figure 12. Approximate allowable stress on the films vs. unsoaked CBR of subgrade.

out rupturing, thus leaving areas of greatly reduced thickness. This does not occur with the vinyl films, which appear to be essentially elastic to the point of failure.

3. Damage to the films is reduced if the granular material is lightly compacted before the load is applied. This slight compaction reduces the movement of the aggregate grains in contact with the films. Such movements seem to contribute to the failure of the films.

4. Occasionally the films are torn by one of the larger aggregate pieces, but a much greater number of failures are caused by puncture of the film by the finer particles (about 0.1-in. diameter) being pressed into the film by larger pieces.

Discussion of Results

The results are plotted as a function of the unsoaked CBR value of the underlying soil. This is not strictly valid because although stress on the film causing failure is a function of the supporting power of the soil immediately under the film, it is a very complex relationship that is not adequately evaluated by the CBR test. The damage to the film for a given load is dependent on the soil type, water content, rate of loading, and size of the loaded area. These factors are not properly measured by the CBR test. All that can be said is that for a given soil as the penetration resistance increases, the stress on the film that will cause failure increases. The results shown in Figure 12 only give qualitative results for the films tested. Quantitatively the results are only approximate for the soils used in the tests.

The quantitative accuracy of these results is further reduced by the fact that the load is spread more rapidly by a granular material than is indicated by the Boussinesq theory. Experiments by Herner (*10*) indicate that this is true, and it was further supported by some tests performed in the study. The total load on the plastic and the supporting soil in the destruction tests was obtained by substutiting a 6-in. diameter steel plate mounted over a proving ring for the supporting soil. Assuming the Boussinesq stress distribution on a horizontal plane, the maximum stress on the film was determined to be approximately 60 percent of the theoretical value. Therefore, the allowable psi value indicated in Figure 12 is too high. If, in determining the proper compaction equipment to be used for the compaction of a base course over a plastic envelope, the stress on the film from the compaction pressure is figured by the Boussinesq formula, the stresses computed will be too large and the error in allowable psi on the film, determined from Figure 12, will be partially compensated for. However, the stresses indicated in Figure 12 will still be high because the larger loaded area during actual field compaction will reduce the error between computed and actual vertical stresses for the thicknesses of base courses employed.

The designation of failure or no failure of the test specimens on the basis of one hole constituting failure is arbitrary and open to some question. The arrangement of the granular particules in the test was completely uncontrolled and just because for two or three tests at given conditions no failures occurred does not mean that a failure would never occur for the same psi and CBR of the soil. Also, the effect of a few small holes on the over-all performance of a pavement is not known. Possibly this can be evaluated in the field test.

From the laboratory film destruction tests, the following conclusions appear to be justified:

1. Vinyl films are superior to all of the polyethylene films tested with respect to puncture resistance.
2. A vinyl film for the top membrane of an envelope must be at least 8 mils thick.
3. The damage to the films can be reduced by (a) increasing the CBR of the subgrade, (b) lightly compacting the base material before the heavy compaction loads are applied, and (c) maintaining the compacted thickness of the base course greater than twice the maximum aggregate size.

TEST ROAD CONSTRUCTION

Problems of Construction

The theoretical and laboratory studies previously presented have indicated the feasibility of using plastic moisture barriers in highways. The data have shown that the rate of moisture movement through the soil is low and that the material has sufficient resistance to puncture if several precautions are taken. There remain, however, several questions, as follows:

1. Can the plastic be adapted to modern construction practices?
2. Will moisture migration due to temperature differential within the envelope be detrimental?
3. Will small punctures that may develop during construction and traffic be detrimental?

To answer these questions a test road was built in the vicinity of Lafayette, Ind. The soils at the test site are glacial drift and are the same as the silty clay materials used in the laboratory phase of this project. The test strip was designed as a partial factorial with depth of enveloped subgrade varied from 6 to 11 in. Each section was 50 ft in length. For the enveloped sections the following designs were used:

6-in. envelope and 6-in. subbase
9-in. envelope and 3-in. subbase
11-in. envelope and no subbase

Figure 13 shows the typical cross-section for the 6-in. envelope. Control sections with no plastic were built as duplications of the foregoing. A light 1-in. bituminous wearing surface was then placed over the entire area.

Designs as given in the foregoing are admittedly light for present day traffic. However, it was felt that the sections should be slightly underdesigned so that small differences between the enveloped and natural section would show up at the earliest possible time after being exposed to traffic. Also, it is reasonable to assume that the feasibility of the plastic (regarding handling with construction equipment) is independent of depth of envelope. The same should also be true to less extent in connection with moisture migration within the envelope. It is planned to make moisture content determinations in the envelope periodically throughout the seasons and to subject the test road to accelerated traffic during the spring of 1957.

Construction of Test Section

The method of construction used was relatively simple. First. the subgrade which was to be enveloped was excavated and stockpiled at one end of the test strip. The subgrade below the envelope was then compacted in place with a 10-ton roller. Next, the lower membrane was placed (see Figure 14). The lower membrane consisted of 4-mil polyethylene, which was received on the job in rolls. For this case, the polyethylene was 24 ft wide, but it is possible to use plastic of various widths depending on the design. Figure 15 shows the lower membrane in place.

Next, the subgrade was placed on the lower membrane and compacted with a sheepsfoot and a smooth-wheel roller. The subgrade in the envelope was compacted to at least 100 percent of the standard Proctor peak value. Control sections (without plastic) were built up in the same manner, except that instead of

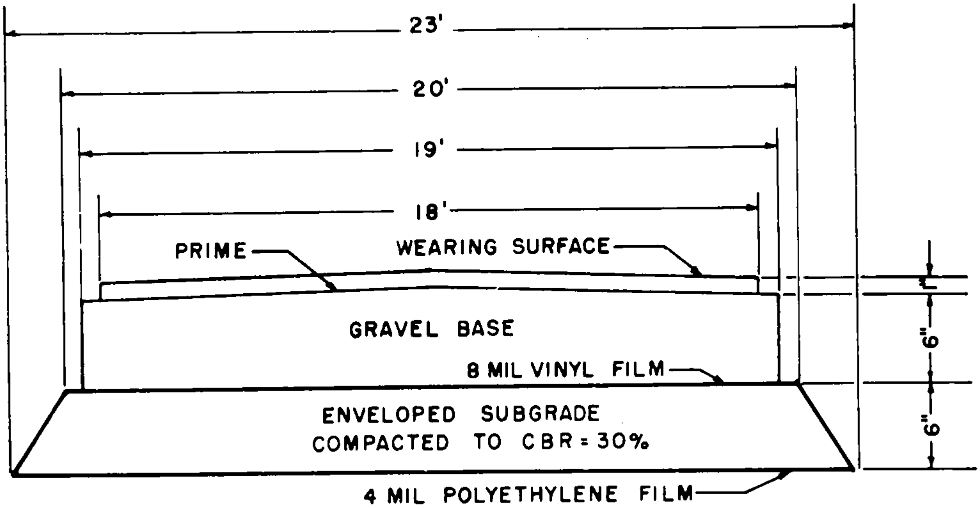

Figure 13. Typical cross-section for 6-in. envelope.

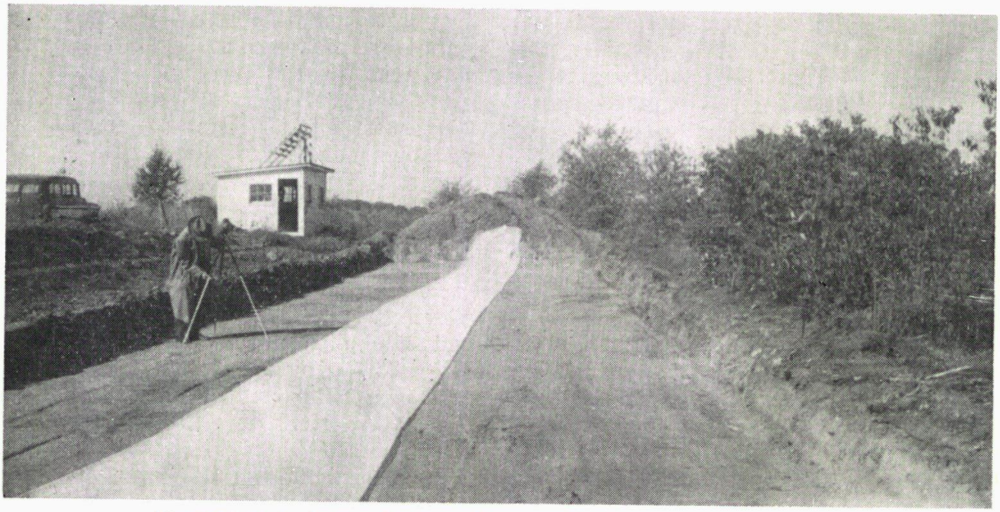

Figure 14. Polyethylene (4-mil) ready to be placed as lower membrane.

Figure 15. Polyethylene (4-mil) in place.

complete excavation the subgrade was merely scarified and recompacted.

After compaction, the upper membrane consisting of 8-mil vinyl was placed (Figure 16). Sealing the the edges was accomplished with adhesives, as shown in Figures 17 and 18. This particular method of sealing is not intended to be adaptable to routine construction; new semi-automatic methods of heat sealing can be developed which will enable the procedure to be much less time consuming.

Table 3 shows as-built data for both the treated and untreated sections. The subgrade was compacted at moisture contents slightly below standard optimum. Estimated laboratory CBR at molded moisture and density conditions ranged from 30 to 35 percent.

Special Problems

Several problems were encountered during the construction operation. For the most part, these were easily over-

Figure 16. Placing 8-mil vinyl.

come with adequate inspection. Laboratory tests have shown that little danger of puncture of the envelope by base course materials exists as long as the subgrade in the envelope is compacted to high densities and the depth of base is

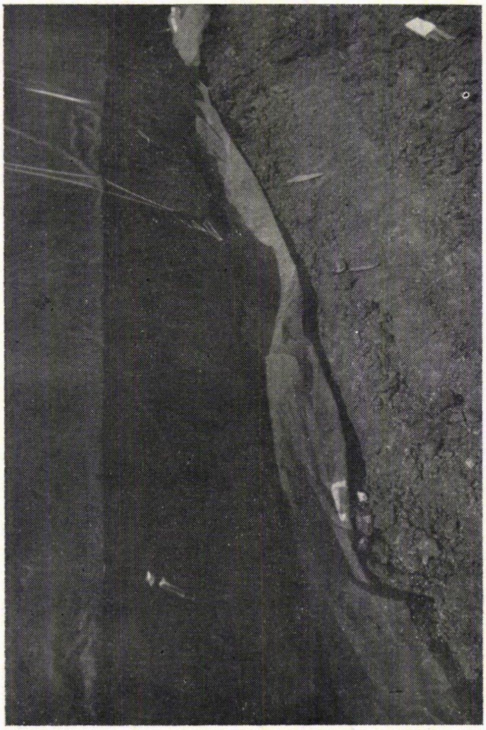

Figure 17. Edge of envelope, showing polyethylene and vinyl films ready for seal.

Figure 18. Sealing polyethylene and vinyl plastics with adhesives.

TABLE 3
AVERAGE TEST RESULTS ON ENVELOPE AND BASE COURSE MATERIALS

	L.L., %	P.I., %	Moisture, %	Dry Density, lb/cu ft	Lab. CBR, % Molded	Lab. CBR, % Soaked
Enveloped subgrade	35	18	13.5	115.5	35*	18*
Control subgrade	38	19	12.8	112.0	30*	15*
Base on envelope	—	NP	6.0	138.4	80+	80+
Control base	—	NP	5.8	136.0	80+	80+

* Estimated from Figure 6.

maintained at least two times the maximum size of aggregate. This was substantiated during construction of the field installation. No puncture of the upper membrane was found by visual inspection through a large number of holes dug through the base after compaction was completed.

Special care was taken during construction to keep tracked equipment from coming in contact with the film. However, in several cases the bulldozer traveled across the plastic with no apparent ill effects. Rubber-tired equipment had no visible effect on the plastic.

The principal problem encountered deals with the grading operation prior to compacting the envelope. The plastic is smooth; therefore, there was a tendency for the soil to slide on the plastic during grading. This was overcome by making certain the loose soil under the blade of the grader was at least 6 to 7 in. deep.

Some difficulty was encountered in placing the edges of the enveloped soil tightly against the sides of the trench. This was remedied by extending the trench and the envelope several feet beyond the required amount and then compacting soil on top of the envelope after sealing (See Figure 13).

The field construction program has substantiated the laboratory data concerning the use of plastic as a construction material. Regarding puncture of the membrane, the major danger exists with small sharp objects that may cause very high stresses in the plastic. The material has sufficient tensile strength and ultimate elongation to practically eliminate possibility of tear from construction equipment. It is believed that to follow normal inspection procedures is all that is required to construct an adequate plastic barrier. Ruptures of the films, should they occur, are easily repaired if discovered before they are buried.

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