lated to Nonwoven Fabric Filtration. Univ. of Tennessee, Knoxville, M.S. thesis, 1975.
9. H.R. Cedergren. Seepage, Drainage and Flow Nets, 2nd ed. Wiley, New York, NY, 1967.
10. M. Muskat. Darcy's Law and the Measurement of the Permeability of Porous Media. In Flow of Homogeneous Fluids Through Porous Media, 1st ed., McGraw-Hill, New York, NY, 1937, pp. 55-120.
11. H.J.M. Ogink. Investigation of the Hydraulic Characteristics of Synthetic Fibers. Delft Hydraulics Laboratory, Delft, Netherlands, Publ. 146, May 1975.
12. J. Ball. Design Parameters for Longitudinal Filter Cloth Lined Subsurface Pavement Drainage Systems. State of Alabama Highway Department, Montgomery, Quarterly Rept. (Jan. 1-March 31, 1978), March 31, 1978.
13. J. Masounave, R. Denis, and A.L. Rollin. Prediction of Hydraulic Properties of Synthetic Nonwoven Fabrics Used in Geotechnical Work. Canadian Geotechnical Journal, Vol. 17, No. 4, Nov. 1980, p. 517.

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Performance of Soil-Aggregate-Fabric Systems in Frost-Susceptible Roads, Linn County, Iowa

J.M. HOOVER, J.M. PITT, L.D. HANDFELT, AND R.L. STANLEY

Results of a three-year laboratory and field evaluation of a first-generation geotechnical construction fabric applied in soil-aggregate and granular-surfaced low-volume roadways indicate that fabric systems can, under certain circumstances, reduce thaw-induced deformations and improve field performance. Eleven test sections that involved different soil-aggregate-fabric systems were constructed on subgrades that displayed varying degrees of frost-related performance. Field evaluations were conducted over three cycles of spring thaw plus summer healing. Laboratory simulation of freeze-thaw action along with strength and deformation parameters obtained through the Iowa K-test were used on a fabric-reinforced, frost-susceptible soil to provide insight into soil-fabric mechanisms and the potential for predicting field performance. Variation in the constructed soil-aggregate-fabric systems was achieved by locating fabric at different positions relative to layers of soil-aggregate or existing roadway materials, a choked macadam base course, and a thick granular backfill. Improvement was most noticeable where fabric was used as a reinforcement between a soil-aggregate surface and a frost-prone subgrade. Fabric used in conjunction with granular backfill, macadam base, and non-frost-susceptible subgrade did not appear justifiable.

Among the economic losses incurred by frost action are costs of repair and maintenance of the damaged roadway. Economic implications affect highway users if a weight-limit embargo is imposed or more severely if complete closure of the roadway is dictated by thaw-induced lack of support capacity.

In the spring, downward melting of ice lenses causes a supersaturated condition in the soil, and the diminishing layer of ice impedes gravitational drainage. During this period, a secondary roadway is vulnerable to severe traffic rutting or loss of support, skid-resistant surface aggregate is pushed into the supersaturated region, and displaced subgrade may be pumped to the surface.

It was the purpose of this investigation to evaluate the laboratory and in situ performance of a first-generation nonwoven polypropylene fabric as an interlayer reinforcement in the construction and maintenance of soil-aggregate-surface and granular-base roadways that overlie frost-susceptible fine-grained subgrades.

TEST SECTIONS

In the fall of 1976, fabric was placed in seven test sections located at two sites in Linn County, Iowa. Each section was paired with an adjacent control section constructed in the same manner as the test section except that it lacked fabric (1).

In sections 1A, 1B, 2A, and 2B at the Alburnett site (Figure 1), fabric was combined with a commonly used method to combat frost action in which the existing soil-aggregate surface course was removed, the frost-susceptible subgrade was undercut about 0.6 m (2 ft) and backfilled by using a coarse aggregate, and the soil-aggregate surface course was replaced and compacted.

Following removal of the soil-aggregate surface, the subgrade of sections 3 and 4 was shaped by using a blade grader and compacted by using a sheep's-foot roller. In section 3 a layer of fabric was placed on the subgrade prior to replacement of the soil-aggregate surfacing (Figure 2).

Sections 5 (fabric) and 6 were constructed in a manner identical to that used for sections 3 and 4, except on a frost-stable subgrade as a means of overall comparative control between stable and frost-prone subgrades and fabric-treated and untreated systems. All test sections at the Alburnett site were constructed by Linn County maintenance personnel by using conventional county-owned equipment.

Fairfax site test sections were constructed following a contracted geometrical change of the embankment that consisted primarily of widening the ditch and the shoulder, with little or no change in longitudinal profile or elevation. Fabric was incorporated between the subgrade and a contracted macadam-base surface course. Test sections 1 and 2, by using the granular-backfill-replacement method, were eliminated because of the expense incurred by using a force account for a nearly completed contract.

Fairfax sections 3 and 4 were built in an area that presumably contained frost-susceptible subgrade soils (Figure 3). Sections 5 (fabric) and 6 were built on frost-stable subgrades. A layer of fabric was placed on the subgrade in sections 3 and 5; then all sections were overlaid with 203 mm (8 in) of an open-graded macadam stone of 102-mm (4-in) top

Figure 1. Fabric test sections 1A, 1B, 2A, and 2B, Alburnett.

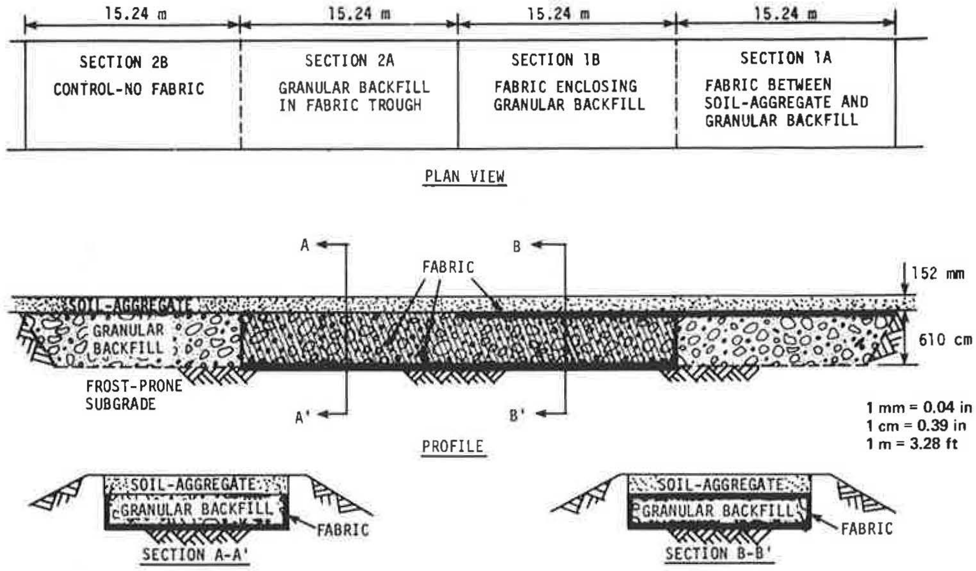


Figure 2. Fabric test sections 3 and 4, Alburnett.

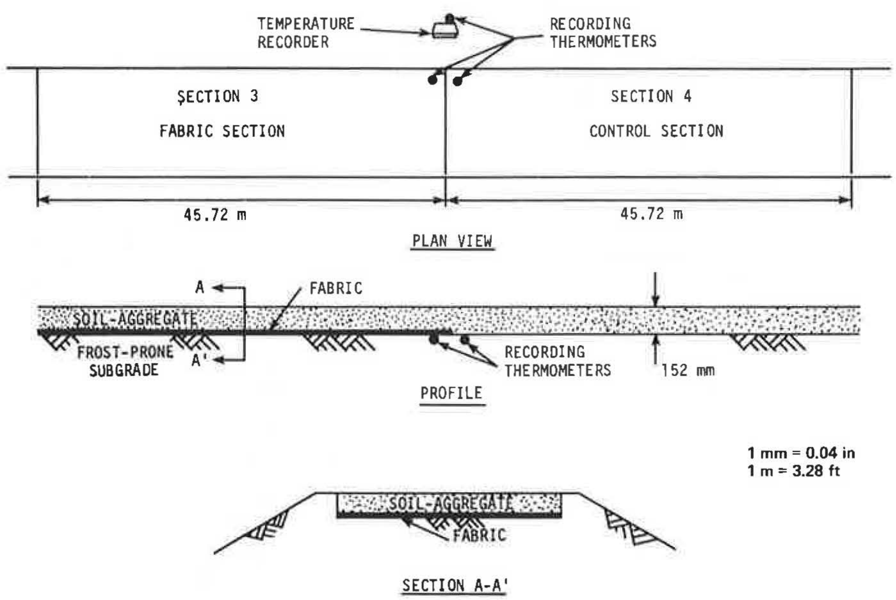


Figure 3. Fabric test sections 3 and 4, Fairfax.

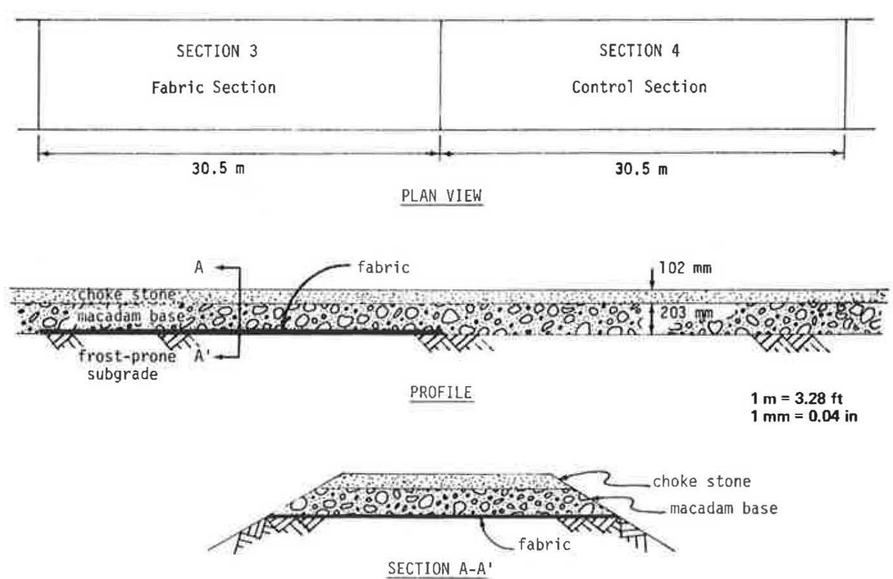


Table 1. Classification of Alburnett test sections: soil-aggregate surfaces and subgrades, October 1976.

Physical Property	Subgrade			Surface		
	Sections 1 and 2	Sections 3 and 4	Sections 5 and 6	Sections 1 and 2	Sections 3 and 4	Sections 5 and 6
Percentage of						
Gravel (76.2-4.76 mm)	0	0	0	18	28	20
Sand (4.76-0.074 mm)	52	34	39	63	56	59
Silt (0.074-0.005 mm)	32	41	42	14	10	14
Clay (<0.005 mm)	16	25	19	5	6	7
Atterberg limits						
Liquid	26.0	37.1	29.1	-	-	-
Plastic	17.4	19.5	18.1	-	-	-
Plasticity index	8.6	17.6	11.0	NP[a]	NP[a]	NP[a]
AASHTO classification	A-4(1)	A-6(9)	A-6(4)	A-1-b	A-1-b	A-1-b
Unified classification	SC	CL	CL	SW	SP	SW
Uniformity coefficient C_u	170	410	78	55	95	92

Note: 1 mm = 0.04 in.
[a]NP = nonplastic.

Table 2. Classification of Fairfax test sections: base and subgrade, October 1976.

Physical Property	Subgrade		Macadam Base
	Sections 3 and 4	Sections 5 and 6	
Percentage of			
Gravel (76.2-4.76 mm)	0	0	86[a]
Sand (4.76-0.074 mm)	44	40	7
Silt (0.074-0.005 mm)	39	19	{7
Clay (<0.005 mm)	17	21	
Atterberg limits			
Liquid	22.8	33.6	-
Plastic	15.6	18.6	-
Plasticity index	7.2	15.0	NP[b]
AASHTO classification	A-4(1)	A-6(6)	A-1-a
Unified classification	CL	CL	GP
Uniformity coefficient C_u	131	114	17

Note: 1 mm = 0.04 in.
[a]Gravel size, 101.6-4.76 mm. [b]NP = nonplastic.

size. The macadam base was topped with 102 mm of choke that consisted of 19-mm (0.75-in) maximum-size road stone. In June 1977, a seal-coat wearing surface was applied, followed by a thin asphaltic-concrete overlay in spring 1978. Both sites thus provided a range of comparative subgrade test and control sections underlying (a) a commonly used soil-aggregate surface or (b) a higher type of base and surface system.

INVESTIGATIONS

Fabric Properties

The first-generation nonwoven fabric used in this study is trademarked Mirafi 140. The fabric is composed of two continuous artificial fibers--one a polypropylene, the other a polypropylene core sheathed in nylon (2). The fibers are heat-bonded into a random arrangement that produces a fabric that has equal strength in all directions (2). The fabric is claimed to be rotproof, mildewproof, insectproof, and rodentproof, and chemicals normally encountered in civil engineering applications produce no noticeable effect on the fabric (2).

Laboratory Investigation

Tables 1 and 2 present representative classification data, including those from the American Association of State Highway and Transportation Officials (AASHTO), for the materials in each section immediately prior to construction. Variability of each section was most evident with the Alburnett surface materials; this variability stemmed from periodic maintenance operations, including frequent spot spread of aggregate within a deteriorating surface.

Subgrade soils at both sites could be classified as nonuniform due to their high uniformity coefficients. More than 3 percent of the particle sizes of each subgrade soil was smaller than 0.02 mm (0.000 78 in), a particle-size distribution criterion set by Casagrande (3) for considerable ice segregation to occur in a nonuniform soil. Alburnett sections 1A through 2B and Fairfax sections 3 and 4 were classified in group A4, which represents frost-prone silty soils of high capillarity. Each was identified as frost-susceptible on the basis of past performance. Alburnett sections 3 and 4 were classified A-6 but were identified by past performance as being frost-prone.

Freeze-Thaw Tests

A limited investigation was undertaken by using a silty clay soil to determine whether inclusion of the fabric reduced cyclic and/or residual heave during freezing and thawing due to assimilation of capillary moisture. A modification of the Iowa freeze-thaw test (4) was used to measure heave of both untreated and fabric-treated specimens. Basically this test duplicates field conditions of freezing from the top while water is available at the bottom of the specimen for upward capillary moisture movement. Standard ASTM D698 soil specimens were molded at maximum density and optimum moisture content. For fabric-treated specimens, single-thickness disks of fabric 102 mm in diameter were inserted horizontally between compacted layers during molding. Elongation, or change in specimen height following freeze or thaw, was expressed as a percentage of the original height (Figure 4).

Regardless of the location of a single disk, similar elongation characteristics were observed for specimens that contained only one layer of fabric. Fabric disks at each third point significantly reduced expansion. The lower heaving observed with fabric-layered specimens may have resulted from a partial cut-off by the fabric of capillary water to the remainder of the specimen. Since the fabric was designed for use as a filter, its average pore size is equivalent to that of a medium-fine sand, a material that generally has a lower capillary conductivity than that of the silty clay soil. Surface attraction between the fabric and the water should be considerably less than that between the soil and the water, which thus inhibits the rise of capillary water. With the inclusion of fabric, any reinforcement may inhibit growth of ice lenses, which in turn may result in smaller elongations.

Figure 4. Freeze-thaw elongation-test results.

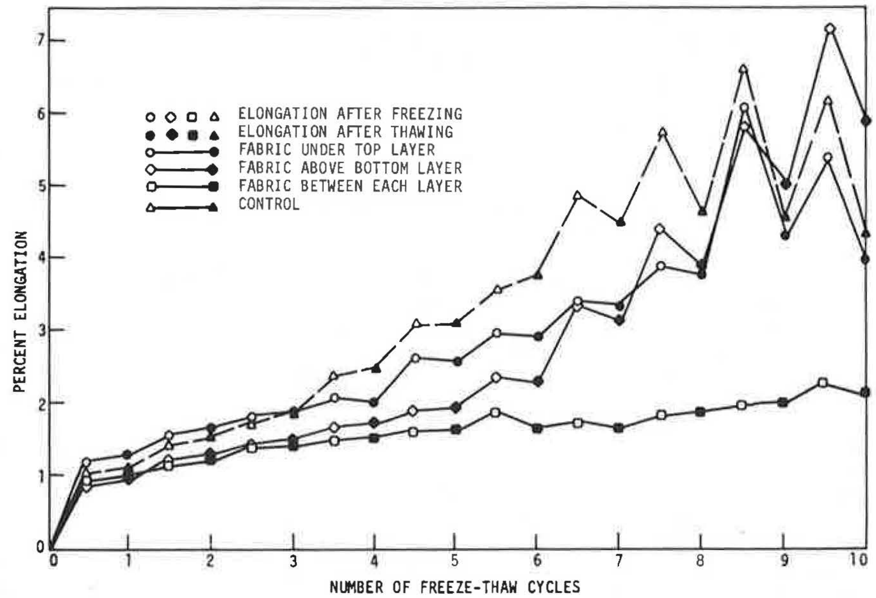


Table 3. Mean moisture density and Iowa K-test parameters for silty clay soil specimens with and without fabric.

Treatment	Moisture Content (% dry soil wt)	Dry Density (kN/m^3)	Vertical Deformation Modulus E_v (kPa)	Cohesion c (kPa)	Angle of Internal Friction ϕ (degrees)	Lateral Stress Ratio K
Control (untreated)						
Near standard moisture and density	20.6	15.42	14 740	98.6	22.7	0.337
After freeze-thaw cycle	30.9	14.24	12 080	56.5	0.0	0.777
One fabric layer						
Near standard moisture and density	20.8	15.13	14 010	102.0	23.7	0.317
After freeze-thaw cycle	31.9	14.10	12 755	68.3	5.1	0.648
Two fabric layers						
Near standard moisture and density	21.0	15.03	11 183	113.1	23.4	0.317
After freeze-thaw cycle	29.3	14.42	12 300	69.6	8.7	0.574

Note: 1 kPa = 0.145 lbf/in^2, 1 kN/m^3 = 6.37 lbf/ft^3.

Stability Tests

All specimens except those that had fabric under the top layer were recovered after the freeze-thaw cycle, combined with additional freshly molded specimens at near-optimum moisture and maximum density, and tested by using the Iowa K-test to determine various shear and stability parameters (5-7), which are presented in Table 3.

Incorporation of fabric during compaction created a slight reduction in dry density, even in specimens that had similar moisture content. A soil must be sheared to be compacted (7). If the fabric tended to confine development of internal shear surfaces, it would thus contribute to a lowering of density.

Under standard conditions of moisture and density only, the vertical deformation modulus E_v was slightly reduced through inclusion of one fabric disk; two layers markedly decreased E_v. The much-lower E_v was due to high values of vertical strain associated with the two-layer fabric specimens during testing. After 10 freeze-thaw cycles, E_v was slightly improved due to the presence of fabric.

Near standard optimum moisture and density there was minor improvement in cohesion c and angle of internal friction ϕ of the treated specimens. Following the freeze-thaw cycle, slight improvements in c were coupled with increased ϕ, although densities were reduced and moisture content had increased. The increase in c may result from tensile strength added by the fabric; use of two layers gives the greatest improvement. The zero ϕ obtained with the control is typical of saturated clays. Higher friction angles obtained with the treated specimens appear to indicate that fabric tended to confine the propagation of continuous shear planes. Use of c-ϕ in an analysis of bearing capacity would generally indicate improved support, particularly where two fabric layers were used.

Values of lateral stress ratio K should never exceed 1.000; the smaller the K value, the greater the lateral stability of a material. Only a slight reduction in K was obtained with fabric-treated specimens near standard moisture and density. A larger reduction in K occurred with an increased number of fabric disks following the freeze-thaw cycle. Both test and treatment conditions reflect radial reinforcement provided by the fabric. However, the magnitude of reinforcement may also be indicative of the amount of elongation provided by the fabric.

In the analysis of the composite effect of the fabric-reinforced soil, only properties of the fabric should be considered. It is a composite of thermoplastic fibers that are not very resilient and have a low tensile deformation modulus. The tangent modulus at 120 percent elongation is about 20 700 kPa (3000 lbf/in^2). Since slippage may occur at the soil-fabric contact, the effective modulus of the fabric is probably lower then 20 700 kPa.

The vertical modulus E_V decreased with an increased number of fabric layers for specimens not subjected to the freeze-thaw cycle. After the soil had been degraded through capillary moisture absorption during the freeze-thaw cycle, the presence of fabric provided a slight improvement, which indicated the importance of the properties of the composite constituents. First, the effective fabric modulus, which includes its ability to bond, may have been small compared with that of the soil, which created a situation in which the soil may have reinforced the fabric. When the soil modulus was reduced by freeze-thaw action, presence of the fabric caused a slight improvement, which indicated that the roles of the individual moduli may have been reversed, and the net result was some composite reinforcement.

Composite reinforcement is affected by the degree to which fabric properties are transferred to the soil and depends on the bond achieved at the interface between the two materials. Casual observation indicated that bonding may have been achieved through partial intrusion of the soil into the fabric mesh. The more plastic the soil, the better the probable bond. This may explain why values of E_V were nearly the same for both the specimen that had one fabric layer and the specimen that had two layers following the freeze-thaw cycle; some level of bonding was established, and hence a limiting amount of reinforcement was provided.

The limiting equilibrium parameters c and ϕ were more sensitive to the effect of reinforcement before and after subjection to the freeze-thaw action. At impending failure, c and ϕ represent the shear stress on a plane oriented at an angle of 45 + (ϕ/2) degrees with the horizontal. The fabric was thus oriented to have considerable influence on these parameters. However, fabric reinforcement did not appreciably influence the friction angle for specimens not subjected to the freeze-thaw cycle, a condition that is potentially related to soil-fabric bonding.

Table 4. Comparison of dry density and moisture content of test-section subgrades, October 1976 and June 1978.

Location	October 1976 Dry Unit Weight (kN/m^3)	October 1976 Moisture Content (% dry wt)	June 1978 Dry Unit Weight (kN/m^3)	June 1978 Moisture Content (% dry wt)
Alburnett				
Fabric section 1A	16.89	17.7	15.63[a]	18.0[a]
Fabric section 1B	17.80	9.1	-	-
Fabric section 2A	-	-	18.07[b]	11.3[b]
Control section 2B	14.26	24.6	17.72	15.7
Fabric section 3	15.88	21.4	16.93	15.8
Control section 4	17.08	16.3	11.12	45.5
Fabric section 5	14.41	14.7	16.49	17.7
Control section 6	15.27	11.2	17.28	16.2
Fairfax				
Fabric section 3	19.86	11.8	17.94	12.8
Control section 4	17.96	8.6	17.37	14.5
Fabric section 5	19.36	8.8	14.92	27.1
Control section 6	20.23	13.7	14.08	32.1

Note: 1 kN/m^3 = 6.37 lbf/ft^3.
[a]Top of stone backfill. [b]Base of stone backfill.

Table 5. Comparison of subgrade fines content prior to construction, October 1976, versus fabric-subgrade contact zone, June 1978.

Location	Section No.	Fines That Passed No. 200 Sieve (%) Oct. 1976 Subgrade	Fines That Passed No. 200 Sieve (%) June 1978 Fabric-Subgrade Contact Zone	Remarks
Alburnett	1A	48	60	Fabric between soil-aggregate surface and granular backfill
	2A	48	59	Granular backfill in fabric trough
	2B	48	59	Control (granular backfill only)
	3	66	64	Fabric over frost-prone subgrade
	4	66	67	Control (frost-prone subgrade)
	5	61	63	Fabric over stable subgrade
	6	61	77	Control (stable subgrade)
Fairfax	3	56	59	Fabric over frost-prone subgrade
	4	56	55	Control (frost-prone subgrade)
	5	41	68	Fabric over stable subgrade
	6	41	66	Control (stable subgrade)

Field Investigation

In Situ Moisture and Density Tests

Considerable variation in both density and moisture content existed within the subgrades of both sites at the time of construction (Table 4). Such variations occur in most county or local roads because of variability in transpiration and evaporation rates, subgrade drainage, and other material properties due to use of locally available materials only. Subgrade drainage is highly dependent on ditch conditions. The Alburnett site was fairly flat and had shallow ditches, whereas at the Fairfax site ditches had been widened and deepened.

In situ moisture and density tests were again performed in the subgrades of each test and control section approximately 20 months after construction (Table 4). With the exception of Alburnett sections 3 and 4 and Fairfax sections 5 and 6, no consistent trends between fabric and control sections or between times of testing were observable. At least a limited degree of moisture and density stability was indicated within fabric section 3. Control section 4 indicated a significant decrease in subgrade density coupled with a severe increase in moisture content.

Fairfax sections 5 and 6 (Table 4) indicate significant decreased density and increased moisture content. Comparison of sections 3 and 4 and 5 and 6 indicates a probable loss of stability within sections 5 and 6. This loss, however, was only partly reflected in other in situ data obtained on the roadway surface, which is due at least in part to the rigidity of the macadam base that bridges a potentially weakened subgrade. Control sections 4 and 6 showed slightly lower density and greater moisture content than their respective fabric sections.

Movement of Fine-Grained Particles

Particle size tests were performed on soil samples removed in June 1978 from the fabric-subgrade contact zone or an equivalent depth in the control sections. Table 5 presents a comparison of the total fines content of the subgrade soils prior to construction versus that of the fabric-subgrade contact zone in June 1978. No evidence was obtained to suggest that the fabric prevented migration of fines due to capillary and/or percolation water movement. However, the data indicate that a movement and/or entrapment of fines from either the soil-aggregate surface or subgrades occurred within several of the test sections during the 20-month period. In addition, the data suggest no greater entrapment of fines through use of fabric than through use of either the granular backfill at

Alburnett or the macadam base at Fairfax.

Samples of those sections that indicated a potential of silt and clay movement were subjected to x-ray diffraction analysis to discern any variability of mineralogy in the fabric-subgrade contact soils due to intrusion, particularly of the soil-aggregate surface or the macadam base. No minerals characteristic of either were observed. The traces were characteristic only of the two site subgrade materials. Therefore it may be assumed that movement of fines was predominantly from the subgrades through capillary activity.

Climatic Conditions

Ambient air and subgrade temperatures were recorded at Alburnett sections 3 and 4 in order to observe any insulating effect attributable to the fabric. No differences were observed in temperature recorded at the surface of the subgrades during the 1976-1977 freeze-thaw season, a period that coincided with the coldest fall experienced in Iowa in this century and the coldest winter since 1936 (8). Data generated during the second winter (1977-1978) seemed to indicate a subgrade-insulating effect due to the fabric. Whether or not such an effect was valid was relatively inconclusive, since operational problems occurred with the recorder during this period.

Average monthly precipitation near the test sites showed that by the end of February 1977, drought had reduced available subsoil moisture to an average 98 percent less than normal (8). Above-normal rainfall was recorded in March 1977, rainfall remained below normal until July and was significantly greater than normal through October, and by December 1977 available subsoil moisture was only 12 percent below normal. Through September 1978, precipitation was nearly normal.

The above discussion makes evident the extreme variability that may exist in central Midwestern climatic conditions from year to year, especially subsurface moisture. Extended periods of subfreezing temperatures occur during the winter months. Yet with low subgrade moisture conditions, freezing temperatures may not create detrimental frost action in a roadway. Such conditions existed during the winter of 1976-1977. No heaving or boiling was visible in any of the test or control sections at either site.

Precipitation received during the fall of 1977 provided subgrade-moisture conditions that created both heave and boil softening in the second winter following fabric placement, although no heave or boil was evident at the Fairfax site. During April 1978, Alburnett section 3 showed some alligator checking within the soil-aggregate surface. Considerable alligatoring and checking were visible within control section 4 coupled with slight rutting and shoving of the surface course. No surface signs of boil softening were visible within the non-frost-susceptible sections 5 and 6.

In April 1979, heave and boil conditions were nonexistent at Fairfax and similar to those of 1978 at Alburnett. The area immediately adjacent to section 2B was significantly softened and rutted. Alligator cracking, checking, rutting, and shoving were visible in both sections 3 and 4. Sections 5 and 6 also showed slight evidence of heave and boil conditions.

Field Performance

Performance evaluation consisted of K-tests on undisturbed roadway samples and periodic in situ spherical-bearing-value tests, Benkelman-beam tests, and plate-bearing tests. Only limited portions of the Benkelman-beam and plate-bearing tests will be reported here, since each was indicative of the support capacity of the roadway during the most severe periods of thaw activity.

Benkelman-Beam Tests

The Benkelman beam measures roadway surface deflections under a slowly moving wheel load and essentially evaluates the flexural capabilities of the composite vertically profiled components. Each rear dual tire of a loaded test truck was maintained at an air pressure of 520 kPa (75 lbf/in^2), which supported a 76.9-kN (17 300-lbf) single-rear-axle wheel load; maximum allowable single-axle loading in Iowa is 80 kN (18 000 lbf). All deflection measurements were averaged for each individual section.

As a qualitative measure of flexibility of the vertical profile of each section, a relative stiffness factor was computed by dividing the load on one set of dual wheels by the average maximum deflection. The more flexible the profile components, the greater the deflection but the lower the relative stiffness. Figures 5 through 7 illustrate the range of variability of stiffness versus time for both sites.

Deflections and stiffness of sections 1A through 2B were respectively lower and higher than those of other Alburnett sections, which indicated that added strength was provided by the granular backfill 0.6 m (2 ft) thick. Deflections in sections 5 and 6 were consistently lower than those in sections 3 and 4, a condition compatible with the assumption that sections 5 and 6 were founded on less-frost-susceptible subgrades. If sections 5 and 6 were a datum for comparison with all other sections, the granular backfill and/or backfill coupled with fabric increased stability and performance characteristics of the frost-susceptible subgrade above those attainable within the non-frost-susceptible subgrade. Likewise, use of the fabric within frost-susceptible sections 3 and 4 did not improve deflection and stiffness performance to that of the non-frost-susceptible sections 5 and 6.

Immediately following a spring thaw, deflections of a secondary roadway may be high while stiffness values are low; each characteristic reverses and improves with time as gravitational moisture movement and/or capillary transpiration and evaporation occur. In general, such conditions were noted each season within each site. The principal exception occurred in August 1977 when exceptionally high rainfall finally broke the preceding drought.

Performance of a roadway will usually be increased following any subgrade, base, or surface improvement. The improvement slowly diminishes with time due to various combinations of traffic density, loading, environmental factors, and material fatigue and deterioration. In general, Figures 5 through 7 intimate such a diminution of support performance. A linear regression of relative stiffness versus time data within the Alburnett sections would indicate a slight slope downwards and to the right by using the data of each succeeding season, beginning in the spring of 1977. It cannot be concluded, however, that a seasonal decrease in performance was due strictly to the previously noted material factors, since the effect of both low and high subgrade moisture during the study period may not have provided a normal data base for such conditions.

During the three seasons of study, deflection and stiffness performance within Alburnett sections 1A through 2B indicated that sections 1A and 1B were generally superior and that performance decreased from section 2A to control section 2B (Figure 5). Section 1A contained fabric between the soil-aggregate surface and granular backfill, whereas fabric encapsulated the granular backfill within section 1B. If it may be assumed that the subgrade moisture of the 1977 season was atypical, section 1A could be regarded as generally providing the best benefits of cost versus stability for the granular-backfill treatment of this frost-prone subgrade soil.

It is apparent from Figure 6 that use of fabric improved deflection and stiffness characteristics over each of the three seasons of study. Disregarding the earlier data of August 1977, improvement of deflection and stiffness values through fabric use ranged from a low of about 6 percent in July 1978 to a high of 90 percent in April 1979. Although the latter percentage of improvement in fabric section 3 is significant, it should be noted that average maximum deflections recorded at this time were in excess of 6.35 mm (0.25 in) for section 3 and approached 12.7 mm (0.5 in) for section 4. These values are higher than the limiting deflection criteria for several methods of flexible pavement design.

Alburnett sections 5 and 6 showed basically no variability during the 1977 boil and heal season, a slight variability during 1978, and some definite variation in 1979, particularly following thawing. Healing occurred rather quickly, however, within both the 1978 and 1979 seasons.

Relative stiffness for each Fairfax section versus time showed a range similar to that obtained for Alburnett sections 1A through 2B and may be attributed to a similarity between the Alburnett granular backfill and the Fairfax macadam base. Unlike the Alburnett sections, however, use of

Figure 5. Benkelman-beam relative stiffness versus time, Alburnett sections 1A-2B.

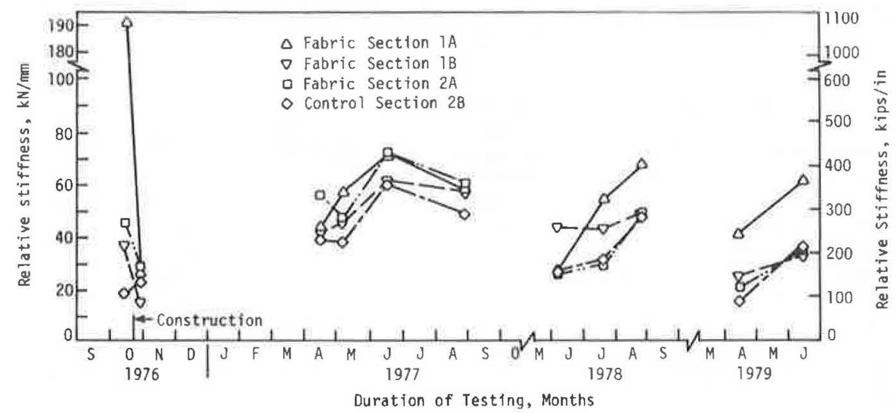


Figure 6. Benkelman-beam relative stiffness versus time, Alburnett sections 3 and 4.

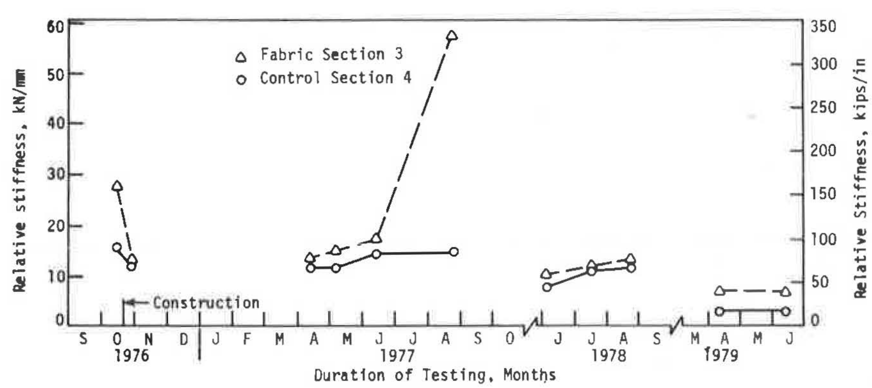
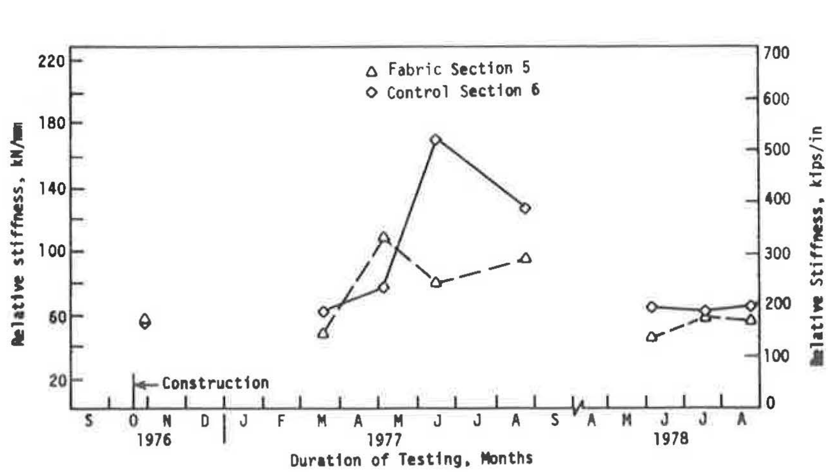


Figure 7. Benkelman-beam relative stiffness versus time, Fairfax sections 5 and 6.



fabric between the Fairfax subgrade and macadam base provided no basic improvement in deflection and stiffness, particularly at the critical stage of frost-boil development following spring thaws. It is thus apparent that use of fabric within the macadam-based Fairfax site provided no improvement in deflection and stiffness performance of the roadway, regardless of subgrade variations.

With the primary exception of Alburnett sections 3 and 4, most Benkleman-beam rebound measurements at both sites were nearly equivalent to maximum deflections, which indicates that each roadway is undergoing predominantly elastic strain during loading. Use of elastic theory, in which deformations are dirctly proportional to applied stress, thus appeared reasonably valid in analysis of deflection results. By using the 1977 Alburnett data, fabric sections 1A, 1B, and 2A decreased average deflection by 10 percent compared with control section 2B, which indicates that the stress at the subgrade surface was about 10 percent less in these sections. Alburnett sections 3 and 4 indicated about 25 percent reduction in potential subgrade stress by the use of fabric, whereas sections 5 and 6 indicated only a 7 percent stress reduction by the use of fabric on a stable subgrade.

By making assumptions of the Poisson ratio and the configuration of wheel loadings, values of the modulus of elasticity could be back-calculated for each of the Alburnett sections through use of Boussinesq theory. Values of the modulus of elasticity for the 1977 Alburnett sections thus ranged from about 24 138 to 107 586 kPa (3500-15 600 lbf/in^2); the latter value was found in the granular-backfill sections. The higher value is within a typical range for dense sand and gravel, whereas the lower value is typical of silty or sandy clays, each of which existed within the Alburnett sections.

Trends regarding the laboratory stability tests and in situ fabric use as a structural reinforcement were obtained. The K-test vertical deformation modulus E_v and lateral stress ratio K (Table 3) are in principle related to Benkelman-beam relative stiffness. Laboratory stability tests indicated that fabric should produce a slight reduction in composite stiffness. Figures 5 and 6 indicate a decrease in relative stiffness following construction. After subjection to the freeze-thaw cycle, laboratory tests predicted a slight increase in E_v; field tests made in April 1977 showed some nominal improvements in relative stiffness. Incorporation of fabric predicted an improved $c-\phi$ relationship following the freeze-thaw cycle, which should then tend to improve as moisture content was reduced through healing. However, portions of the soil matrix and/or soil-matrix-fabric bond might be expected to reduce gradually through continued freeze-thaw cycling and moisture absorption, which reduce K and $c-\phi$ capabilities, an action not unlike the gradual reduction of field relative stiffness values versus time. Fluctuations of relative stiffness due to changes in field moisture content could also be anticipated on the basis of the data in Table 3. Thus the laboratory and in situ data emphasize that simple laboratory testing methods may provide predictive criteria for designed in situ use of a soil-aggregate-fabric system.

Plate-Bearing Tests

Plate-bearing tests 33 cm (12 in) in diameter were used in conjunction with the Benkelman beam during the latter phases of performance evaluation of the Alburnett sections. The modulus of subgrade reaction k was defined by

$$k = P/\Delta \qquad (1)$$

where P is the plate stress at 70 kPa (10 lbf/in^2) and Δ is the corresponding deformation value (9). Values of k are presented in Table 6.

Deformation moduli were computed from the Burmister (10) relation

$$E = \pi p D(1 - \nu^2)/4W \qquad (2)$$

where

p = plate stress,
D = plate diameter,
ν = Poisson ratio (estimated at 0.33), and
W = plate settlement at 520 kPa (75 lbf/in^2) plate stress (Table 6).

This expression was developed for a rigid plate on a homogeneous material. However, the resulting deformation modulus was thought to be a valid indicator of net response of the composite system.

Table 6 also presents values of deformation modulus as calculated from Equation 2 for Benkelman-beam deflections under 520 kPa contact pressure, since both plate and tire contact areas were equivalent.

Although loading rates of beam and plate tests were different, Table 6 indicates a high degree of correlation between deformation values at 520 kPa stress and modulus of deformation E determined from the two tests. Three exceptions are noted, in which

Table 6. Comparison of plate-bearing and Benkelman-beam test results, Alburnett sections.

		Plate-Bearing Test				Benkelman-Beam Test	
Section	Date	Subgrade Reaction (N/cm^3)	Deformation Modulus E (kPa)	Deformation (mm) at 520 kPa	Permanent Deformation (mm)	Deformation Modulus E (kPa)	Deformation (mm) at 520 kPa
3	4/13/79	51	7 240[a]	15.24	6.35	25 220	4.37
4	4/13/79	18	3 570[b]	20.32	10.16	8 694	12.67
5	4/13/79	271	36 200	3.05	4.57	38 050	2.90
6	4/13/79	194	30 164	3.66	7.11	31 433	3.10
1A	6/14/79	603	124 100	0.89	1.27	111 240	0.99
1B	6/14/79	388	76 200	1.45	1.27	65 734	1.67
2A	6/14/79	388	72 400	1.52	1.27	58 626	1.88
2B	6/14/79	543	94 460	1.17	0.25	81 860	1.35
3	6/14/79	90	7 690	14.35	11.43	10 500	10.49
4	6/14/79	42	3 530[c]	20.83	12.70	8 294	13.51
5	6/14/79	453	51 710	2.13	1.02	51 035	2.16
6	6/14/79	453	57 915	1.91	1.52	55 620	1.98

Note: 1 N/cm^3 = 3.684 lb/in^3; 1 kPa = 0.1450 lbf/in^2; 1 mm = 0.04 in.
[a]Determined at 414 kPa. [b]Failure occurred at 138 kPa. [c]Determined at 345 kPa.

plate deformations exceeded the capacity of the measuring device before a 520-kPa stress could be achieved. In one test (section 4, April 1979), stress levels above 138 kPa (20 lbf/in²) could not be attained. The section failed; thus a state of limiting equilibrium was achieved.

The magnitude of permanent deformation that occurs after unloading of secondary roads (Table 6) is affected by the use of local soil-aggregate systems, which will nearly always undergo some permanent deformation. Acceptable permanent deformation has not been universally resolved, but experience suggests that 13 mm (0.5 in) represents an upper limit. The April tests for sections 3 and 4 tend to substantiate this limit, since section 3 was performing adequately whereas section 4 was near the threshold of unsatisfactory performance.

Relative performance of comparable fabric versus nonfabric sections was indicated by nearly all parameters developed from the plate-loading tests. The April tests on frost-prone subgrade sections 3 and 4 showed a 2.8 improvement factor for both k and E. On the less-frost-susceptible subgrade sections 5 and 6, fabric increased k by a factor of only 1.4 and E by 1.2, which supports the contention that fabric benefits may not be realized until the soil is weakened through frost action or lack of drainage. Further support for this concept was evident for sections 3 through 6 in June 1979 (Table 6), which represents performance after the frost boils had at least partly healed. Improvement factors for both k and E on frost-prone subgrade sections 3 and 4 were reduced to 2.2. For sections 5 and 6 (non-frost-prone subgrade), k indicated no improvement, whereas E-values suggested that fabric actually decreased system stiffness. In addition, permanent deformations were smaller when fabric was present, and a more pronounced difference in corresponding sections occurred when the system was soft.

Section 1A produced improvement factors of only 1.1 for k and 1.3 for E. For sections 1B and 2A, k- and E-values were lower than those for the comparable nonfabric section. Thus little was gained by using fabric in conjunction with a thick granular backfill under subgrade and environmental conditions similar to those prevalent for this field study.

CONCLUSIONS

The following general conclusions are based on both laboratory and field performance parameters:

1. Laboratory and in situ data indicate a reinforcement capability when fabric is interlayered between a soil-aggregate surface and a frost-susceptible subgrade.
2. Laboratory freeze-thaw tests of a fabric-interlayered frost-susceptible fine-grained soil indicate a reasonable control of freeze-thaw elongation.
3. Laboratory stability and strength tests of a fabric-interlayered frost-susceptible fine-grained soil indicate a degree of improvement of all parameters due to reinforcement both prior to and after subjection to the freeze-thaw cycle.
4. The fabric performed most favorably during the three-year study as a reinforcement between a soil-aggregate surface and frost-prone subgrade.
5. Use of the fabric in conjunction with granular backfill in an undercut frost-susceptible subgrade soil did not appear significantly justifiable.
6. Use of the fabric did not appear justifiable as a reinforcement (a) between a soil-aggregate surface and non-frost-susceptible subgrade or (b) between a macadam base and either frost-susceptible or non-frost-susceptible subgrade.
7. Field soil moisture may be a highly relevant factor in soil-fabric bonding characteristics and should be studied in much greater detail.
8. Laboratory investigations similar to those performed in this study should be expended in order to increase performance predictability of in situ fabric reinforcement effectiveness in frost-susceptible secondary road materials.

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REFERENCES

1. J.M. Hoover, J.M. Pitt, L.D. Handfelt, and R.L. Stanley. Performance of Soil-Aggregate-Fabric Systems in Frost-Susceptible Roads, Linn County, Iowa. Celanese Fibers Marketing Co., Charlotte, NC, Final Rept., May 1980.
2. Celanese Fibers Marketing Company. Mirafi 140 Construction Fabric. Celanese Corporation, Charlotte, NC, Publ. PM-5, 1975.
3. A. Casagrande. Discussion of paper, A New Theory of Frost Heaving, by A.C. Benkelman and F.R. Olmstead. HRB, Proc. Vol. 11, 1931, pp. 168-172.
4. K.P. George and D.T. Davidson. Development of a Freeze-Thaw Test for Design of Soil-Cement. HRB, Highway Research Record 36, 1963, pp. 77-96.
5. R.L. Handy and J.M. Hoover. Testing Device for Measuring Lateral Pressure Induced on a Material by a Vertical Applied Pressure. U.S. Patent 4,047,425, U.S. Government Printing Office, Sept. 13, 1977.
6. R.L. Handy, A.J. Lutenegger, and J.M. Hoover. The Iowa K-Test. TRB, Transportation Research Record 678, 1978, pp. 42-49.
7. J.M. Hoover and R.L. Handy. Chemical Compaction Aids for Fine-Grained Soils, Volumes 1 and 2. Office of Research and Development, FHWA, U.S. Department of Transportation, Rept. FHWA-RD-79-63, June 1978.
8. Climatological Data, Iowa Section, Volumes 87 and 88. National Climatic Center, Asheville, NC, 1976 and 1977.
9. E.J. Yoder and M.W. Witczak. Principles of Pavement Design. Wiley, New York, 1975.
10. D.M. Burmister. The Theory of Stresses and Displacements in Layered Systems and Applications to the Design of Airport Runways. HRB, Proc. Vol. 23, 1943, pp. 126-148.

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