cantly different from that of the other three materials. The gravel specimens had the highest mean values of E_r at 241 kPa and at 620 kPa, and these values were significantly different from those of the other three types of material.

Although the resilient response depends somewhat on the type of material, the lack of consistency in the data prevents making any definite conclusions. The differences in resilient behavior were so slight as to be negligible from the standpoint of the structural response of a CRTSS.

SUMMARY AND CONCLUSIONS

Ballast materials from several sources were tested in the triaxial apparatus. In-service conditions were simulated by the use of a repeated deviator stress and a constant confining pressure. The resilient modulus characteristics were determined; the variables considered included the type of material and its gradation and density, and the stress level. Equations relating the resilient modulus to the first stress invariant were developed, and the results were analyzed with respect to the variables.

The following conclusions were reached:

1. The resilient response of a specimen of open-graded granular material is independent of its stress history so long as the specimen has not been subjected to a stress level that would cause failure.
2. The resilient moduli of no. 4 and no. 5 ballast-gradation specimens are usually slightly lower than that of a well-graded aggregate.
3. The resilient moduli of open-graded ballast materials are virtually insensitive to changes in gradation or compaction level. The dependence of resilient response on type of material is weak and inconsistent, and therefore, no conclusion is drawn with respect to material type.
4. Stress level is the variable most directly influencing the resilient modulus of granular materials. The stress-dependent nature of ballast materials can be characterized by the predictive equation:

$$E_r = K\Theta^n \quad (1)$$

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Abridgment

Snowplowable Raised Pavement Markers in New Jersey

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Pavement markings are an important source of information to the motorist for safe vehicle control and guidance under almost all circumstances of driving. One of the most difficult problems in recent years has been that of developing an economical pavement-marking system that adequately delineates the roadway both day and night, in dry and wet weather. A durable reflective marker for areas where snowplowing is common has only recently been developed to a practical level after more than 8 years of cooperative testing. This snowplowable, raised, reflective pavement marker is shown in Figure 1.

DESCRIPTION

Components

The raised, reflective pavement marker specifically designed for use on roads subject to snow removel consists of a casting, a reflector, and reflector attachments. The casting is manufactured with a hardened steel surface and has keels, rails, a web, a seat for the reflector, and notches to retain a spring clip. There are two types of reflector retention methods. One type uses a butyl adhesive pad that is attached between the bottom of the reflector and the casting, and the other type uses a spring-steel wire clip. Reflector shields are used to protect the reflector from hits by tire studs, chains, and stones and are held on top of the reflector by butyl adhesive pads or spring clips.

Experimental Installations

Markers were installed for experimental purposes at three locations in New Jersey at different times. Each installation was carried out in two parts. First, grooves were cut in the pavement with a vertical radial blade and then, at another time, the grooves were dried, cleaned with compressed air, and partially filled with epoxy, and the castings were inserted. Clear markers were placed at alternate gaps on all the lane lines, which are 10 cm (4 in) wide, and have 4.6-m (15-ft) long striping and 7.6-m (25-ft) gaps. On the median (10-cm-wide solid yellow lines), amber markers were placed every 12 m (40 ft). At the exit gores, clear markers were placed outside the 20-cm (8-in) wide lines at 6-m (20-ft) intervals. No markers were placed on the right-hand edge lines (Figure 2).

Visual Characteristics

A raised, reflective marker should provide a visual substitute for the painted line delineation in the rain at night. These markers appeared to become brighter on rainy nights under conditions in which the painted lines become more difficult to see.

DURABILITY

Castings

Pavement markers installed in areas where snowplowing is common should resist damage from snowplow operations and traffic. Snowplow operations were carried out at all three locations using both steel and tungsten carbide insert blades. The steel blades did not damage the castings, but the tungsten carbide insert blades produced some noticeable effects. On US-1, during the winter of 1973/1974, the 520 markers that had been installed in 1973 were plowed 21 times, and during the winter of 1974/1975, the markers that had been installed in 1973 and the 435 that had been installed in 1974 were plowed 11 times, always with steel blades. After three and two winters, 2 and 1 percent of the 1973 castings respectively were either missing or unusable.

Reflectors

Reflector replacement is much simpler and less costly than casting replacement. The durability of a reflector is based on its resistance to damage caused by snowplows, snowplow accessories, and traffic. There was no damage to or loss of reflectors from the use of steel or tungsten carbide insert blades in summer plow and grader tests on I-95. There was damage to reflectors from nose shoes in a test in Trenton that used three versions of modified nose shoes, but there was no damage to reflectors in tests in which plow shoes and plow wheels rode over reflectors. Tire studs and other tire forces have caused reflector loss and damage. The effects of traffic on reflector loss and damage varied according to the type of assembly or model. The types of models are described below.

	Model				
Component	1	2	3	4	5
Casting	Yes	Yes	Yes	Yes	Yes
Adhesive pad B	Yes	No	No	Yes	No
Reflector	Yes	Yes	Yes	Yes	Yes
Adhesive pad D	No	No	No	Yes	Yes
Stud shield	No	No	Yes	Yes	Yes
Spring clip	No	Yes	Yes	No	Yes

In January 1974, 3 months after the 1973 installation of 520 model 3 assemblies on US-1, the markers were plowed 13 times, and 105 reflectors were lost. The missing reflectors were replaced with 49 model 1 on the northbound side and 56 model 2 assemblies on the southbound side. The results of the smaller installation of models 1 and 2 led to a test of all five models in a larger installation. After one winter, none of the models 1 and 4 was lost, but some damage was observed on all the reflectors.

The effects of traffic could have been the major cause of loss of some of the types of reflectors, while studded tires appeared to be the major cause of damage. The reflectors that were protected with shields had less damage from traffic than those without shields.

The fractures and chips on the reflective surfaces facing the motorist were counted and classified by size. The tops of the nonshielded reflectors were chipped to a large extent, while the tops of the shielded reflectors were not damaged. There were one-third more stud marks on the nonshielded reflective surfaces. A rating of the loss of and damage to each reflector model after two winters of use is shown in Table 1. The highest overall rating indicates the type with the least amount of a combination of loss and damage. A reflector with a spring clip requires 30 to 45 s to replace, whereas an adhesive-pad reflector requires 45 to 90 s. Most of the model 4 assemblies lost their shields and, as a result, experienced more damage. The adhesive does not attach well in cold weather. Many of the adhesive-pad reflectors installed in cold weather were lost due to lack of proper adherence to the castings. Considering minimum loss and damage and ease of installation and replacement, the model 5 assembly appears to be the most practical.

CONDITION OF SNOWPLOW BLADES AND ACCESSORIES

Raised pavement markers should not damage snowplow blades and accessories during normal snow-removal operations. These markers did not damage steel blades, whether on truck-mounted or grader-mounted plows, but tungsten carbide insert blades were shattered or chipped at points where they contacted the castings, and the holding steel was turned forward and made irregular, exposing the damaged tungsten carbide inserts. Both types of blades were in contact with the pavement while plowing.

COST ESTIMATE

The cost of installing and maintaining markers was estimated for one side of a four-lane divided highway with markers spaced 24 m (80 ft) apart on lane lines, 12 m (40 ft) apart on median lines, and 6 m (20 ft) apart on exit-ramp gores and one exit-ramp gore located every 2.4 km (1.5 miles). A computer program was developed to simulate a yearly replacement cycle for reflectors. The estimated cost of installing markers and maintaining reflectors over a period of 10 years is $2378/km ($3806/mile), or approximately $15/marker. The estimated cost of marking a highway, restriping the lane lines twice a year and the median solid line and the gore once a year, over a period of 10 years is $1430/km ($2282/mile). Therefore, the estimated cost in 1975 dollars of using both delineator techniques would be $3808/km ($6088/mile). This is an average annual cost of $381/km ($609/mile) as opposed to $140/km ($228/mile) for striping alone.

DISCUSSION AND FUTURE RESEARCH NEEDS

These markers appear to be adequate for use in areas where tungsten carbide insert blades are not used directly on the pavement. Damage to the inserts can be avoided by keeping the blade off the pavement; otherwise, steel blades should be used. The use of a steel blade bolted over a carbide insert blade as in Sheboygan County, Wisconsin, should be evaluated. Nose shoes could be modified to prevent premature loss of reflectors or the entire nose-shoe assembly could be removed, if it were not deemed advisable to retain the extra metal for protection of the side plate on the leading side of funnel type plows. The function of nose shoes should be thoroughly investigated before modification recommendations are made.

The highways in central New Jersey on which the markers were tested were an expressway and a freeway that are considered major intercity routes—US-1 and I-95—that have a two-way average daily traffic of up to 60 000 vehicles. The snowfall is about 51 cm/year (20 in/year). The markers in these locations are plowed about 10 to 15 times/year, mostly with steel-edged blades resting on the pavement. In 1974, nose shoes were either not used or were modified.

Figure 1. Experimental reflector assemblies.

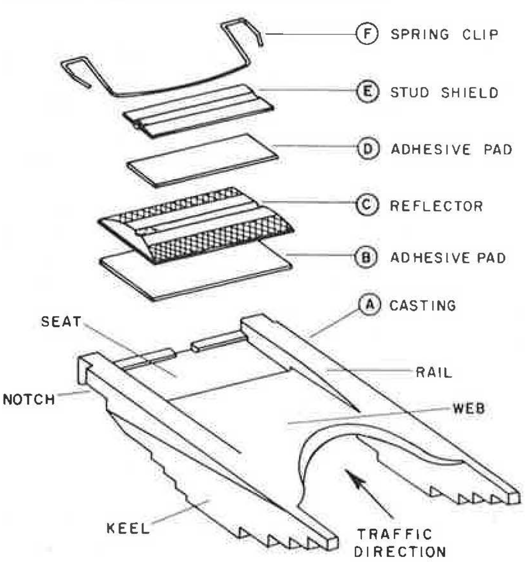

Figure 2. New Jersey system of marker placement.

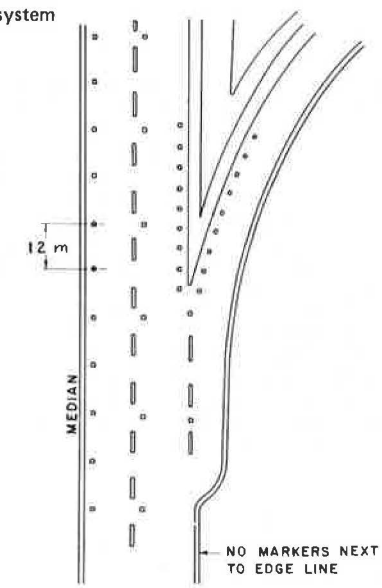

Table 1. Rating of reflector loss and damage after two snow seasons by type of assembly.

		Model 1 (N = 94)		Model 2 (N = 88)		Model 3 (N = 86)		Model 4 (N = 84)		Model 5 (N = 82)	
Percentage Damage Category	Rating Factor	Percentage of Reflectors Lost	Rating	Percentage of Reflectors Lost	Rating	Percentage of Reflectors Lost	Rating	Percentage of Reflectors Lost	Rating	Percentage of Reflectors Lost	Rating
0	1.000	20.21	20.21	23.86	23.86	31.40	31.40	30.95	30.95	46.34	46.34
1 to 25	0.875	23.40	20.48	30.68	26.85	18.60	16.28	21.43	18.75	12.20	10.68
26 to 50	0.625	15.96	9.98	17.05	10.66	9.30	5.81	11.90	7.44	7.32	4.58
51 to 75	0.375	8.51	3.19	6.82	2.56	2.33	0.87	9.52	3.57	3.69	1.38
76 to 100	0.125	14.89	1.86	5.68	0.71	2.33	0.29	11.90	1.49	6.10	0.76
Missing	0	17.02	0.00	15.91	0.00	36.05	0.00	14.29	0.00	24.39	0.00
Overall rating	—	—	55.72	—	64.64	—	54.65	—	62.20	—	63.74

Note: After the first winter, of the original 435 assemblies, 1 casting and 31 reflectors were missing. After the second winter, an additional 4 castings and 61 reflectors were missing. Only steel blades with modified nose shoes were used both winters. Total snow accumulation was 62.5 cm (24.6 in) during the second winter.

About 10 to 12 percent of the passenger automobiles in the area had studded rear tires. These tires seem to be the main cause of reflector wear, and where they are allowed, the use of shields on reflectors is advantageous. Under conditions in which the lifetime of reflectors is short, the ease of replacement when spring clamps are used and the consequent lower labor costs may balance the higher reflector loss of this type of assembly. Further study of large-scale installations of the marker over a period of 3 or more years in several areas with a wide range of snowfall rates and uses of studded tires should provide useful information for predicting annual losses. The relation between the amount of reflector surface damaged and the nighttime visibility of the reflector should be investigated. This information could be used to determine when replacement is warranted.

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Test for the Adhesion of Thermoplastic Highway-Marking Materials

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A new method for evaluating the adhesion between thermoplastic highway-marking materials and pavement surfaces is described. The specimen consists of a small square block of paving material (e.g., Portland cement concrete, asphaltic concrete, or some other) with a layer of thermoplastic bonded to one surface. An orifice penetrates the block and opens into a small circular area intentionally not bonded. A blister is formed by forcing fluid through the orifice until the diameter of the unbonded area begins to grow. The pressure used to inflate the blister and the height at the center of the blister are simultaneously recorded. From these measured data, the characteristic adhesive strain energy release rate is calculated. The analytical expressions necessary for the calculations are given, as is a discussion of the significance of the results to the highway engineer. Several exploratory tests were performed and the results are reported. The results demonstrate the sensitivity of the test to the adhesion of the thermoplastic to the pavement surface. Thus, the test can be used to quantify the effect on adhesive strength of those field conditions that can be reproduced in the laboratory.

Thermoplastic highway-marking materials have several advantages over conventional paints. These include better durability, improved color retention, and greater nighttime visibility, especially during periods of heavy rainfall. However, they also have disadvantages: (a) a tendency to flake during the winter (1) and (b) a tendency to blister shortly after placement, especially in the southern states. Figure 1 shows both phenomena and the accelerated degradation that results under the action of traffic.

Both of these disadvantages are related to the degree of adhesion between the marking material and the pavement. This adhesive strength varies, depending on the type of pavement, the time of cure, and the environment. The type of pavement is extremely important; the thermoplastics are much more durable on asphalt than on portland cement concrete. On either, the durability can be improved by the application of a chemical bonding agent before placing the thermoplastic.

Many makeshift methods of testing adhesion to pavements have evolved; however, the results are qualitative and can be only used for comparative purposes. Thus, the selection and method of applying these thermoplastics and primers has generally been left to the judgment of the responsible engineer. This judgment is typically developed through field experience and performance testing—a long, costly process.

A laboratory test toward the same end is suggested here. The test is based on the validity of the energy approach to adhesive fracture. A similar test was originally proposed for use with conventional paint in 1961 by Dannenberg (2). The approach has recently been developed and discussed in detail in a series of papers by Williams and his coworkers (3, 4, 5, 6). These studies concluded that there exists a system parameter (γ), the characteristic adhesive fracture energy, that quantitatively reflects the resistance of a bonded surface to the growth of an unbonded area. This parameter may be sensitive to the rate of loading and the temperature, but is independent of geometry. If the stiffnesses of the adherends and the γ are known, a stress analysis of any geometry can be used to establish the critical balance between the change in the potential energy of the system and γ. The following discussion of the analytical expressions for the energy balance of the blister-test geometry is based on the references cited above.

ANALYTICAL APPROACH

Consider an axially symmetric structure consisting of a flat infinite surface covered by a layer of a second material. The covering layer is bonded to the surface, except for a circular area centered about an axis of symmetry. An orifice smaller in diameter than the unbonded area penetrates the substrate (Figure 2a).

To perform the test, a fluid is forced through the orifice, causing the unbonded portion of the covering plate to deform upward, i.e., blister. The fluid used can be either compressible or incompressible. If it is