Aluminized waxes are used to repair any damage done to the coating in subsequent operations. For example, after the door and inner door panel are formed and the coating is restored, these two parts are joined together by welding and hemming operations that may break through some of the protective coating applied in the manufacturing process. Aluminized waxes are used to coat all the seams in the bottom 6-8 in of the door. The aluminized wax runs down to fill up the joint. The inside of the door thus has three protective coatings in critical areas. Aluminized waxes are also used where the quarter panel joins the wheelhouse and along the back side of the quarter panel in the pockets on each side of the luggage compartment.

Heavy vinyl sealer is used to paint the insides of the rear wheelhouse. The lower exterior portions of the car--under the quarter panel, under the front fender, and along the rocker panel, for example, where stone damage would cause chipping and corrosion--are also sprayed with this paint. Strips of plastic are also used to line the inside of the fenders. These strips melt and flow into crevices when the car passes through the bake oven. Plastic face-shield panels are used for extensions of the hood, around the grill panel, and around the front headlight area.

Trim materials have also been improved. Research has been conducted to study the physical and chemical properties of multimetal coating systems. The concept of microporous or "cracked" chromium over nickel has led to less coating penetration by pitting. Other changes have added additional years to the durability of electroplated coatings.

The manner of fastening trim materials to the automobile has also been improved. For example, holes that were used for clip attachment of body side moldings and ornaments have been partially eliminated by using externally applied weld studs, thus minimizing the chance for moisture to enter through the hole. The contact of dissimilar metals, which causes galvanic corrosion, has been prevented by using adhesively bonded, plastic body-side moldings and aluminum-clad, stainless-steel moldings. This has prevented the unsightly corrosion of the body steel adjacent to the molding.

These improvements have resulted in Canadian automobile manufacturers announcing a 3-year warranty on cars sold in Canada. American Motors and Ford Motor Company are giving a 3-year corrosion warranty on 1980 models. The objective of General Motors is 5 years without cosmetic exterior corrosion and 10 years without perforation.

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Durable Pavement-Marking Materials

HENRY J. GILLIS

Work done by the Minnesota Department of Transportation during the past 10 years to develop and evaluate a durable yet economical road-striping material is described. The development of equipment capable of applying a two-component epoxy resin is discussed. Epoxy, polyester, and thermoplastic resins and their cost-effectiveness are evaluated. Field evaluation of the various materials consisted of visual observations, photographs, macrophotographs, and measurements of retroreflectivity. The available data suggest that epoxy can be placed on a high-volume bituminous or portland cement concrete roadway, at a thickness of 10 mils, and provide adequate delineation for 12 months or longer while remaining as economical as paint. The polyester material did not adhere well to portland cement concrete and the aggregate in the bituminous pavement. Thermoplastic was found to be generally unacceptable because it is too susceptible to removal by traffic and snowplows when placed at the manufacturer's recommended minimum thickness of 30 mils and it does not bond adequately to portland cement concrete.

For many years traffic and maintenance engineers and industries around the world have worked to improve conditions for the motorist. There is an ongoing search for new delineation materials and devices. The Manual on Uniform Traffic Control Devices (MUTCD) (1) states, "Traffic lane markings have a definite and important function to perform in a proper scheme of traffic control...they have the advantage...of conveying warnings or information to the other driver without diverting his attention from the roadway." At higher speeds, drivers must assign priorities to what they will see and react to. These priorities are (a) positional information, (b) situational information, and (c) navigational information.

If the first priority, position in the traffic lane, requires all of the driver's time, other significant forms of information will pass by unnoticed. For this reason, a well-defined roadway delineation system is important under all conditions. In most states, the restriping or replacement of paint stripes is a continuous process restricted only by weather conditions.

In Minnesota, the conventional paints currently in use for roadway delineation do not have the durability required for year-around life on roadways with a high average daily traffic (ADT) volume. Based on past research in Minnesota, epoxy resin shows promise as a durable striping material. Although the initial cost for epoxy placed is much higher than that for a painted line (three to six times), an extended service life can result in a reasonable comparison of costs over a period of time.

Epoxy was first placed in Minnesota in 1969 on a trial basis by using the extrusion method. All work done since 1970 has been done by applying a thin-film, high-pressure spray. Three formulas were selected from the initial test areas. These three formulas, which were placed on I-94 in St. Paul in 1973, were reduced to one formula based on cure time, color retention, and durability, and 182 km (113 miles) of this material was placed on the metropolitan Interstate system in 1975. In 1976, bead treatment and the capability of the epoxy to bond to itself under field conditions were studied. The results of this work led to the use of epoxy as one of the materials applied on the lower-volume, non-Interstate trunk highway system in 1977 and 1978 under a program authorized in Section 205 of the Federal-Aid Highway Act of 1973.

STUDY OBJECTIVE AND SCOPE

The objectives of this study were to evaluate three resins--epoxy, polyester, and thermoplastic--as pavement-marking materials and to develop and evaluate a spray-on epoxy/glass-bead system that would be appropriate for both bituminous and concrete pavements. This included developing automated equipment capable of applying the materials on a production basis.

In 1975 and 1976, approximately 225 km (140 miles) of epoxy skip stripe was placed on high-volume roads in the Minneapolis-St. Paul area for evaluation. Some variations were made in film thickness and bead type so that the effects of these factors on performance could be determined. Applications were also made over a range of pavement surface temperatures. About 64.4 km (40 miles) of polyester skip line was placed in 1976 as a comparison with the performance of the epoxy. In 1977 and 1978, approximately 457 000 m (1.2 million ft) of thermoplastic and 244 000 m (800 000 ft) of epoxy were placed statewide.

BACKGROUND

To understand the work done in this study, it is essential to proceed chronologically and to begin with the initial reasons for the use of durable pavement-marking materials in Minnesota. Figure 1 shows the typical condition of high-volume roadways in Minnesota in late December when conventional traffic paint is used: Very little, if any, delineation is visible. The inability of any material to remain throughout a winter is the main reason the Minnesota Department of Transportation (DOT) became interested in developing a more durable pavement-marking material.

In 1969 and 1970, the Minnesota DOT placed a thick (62.5-mil) epoxy resin by using the extrusion method. This proved to be an extremely durable installation but had several drawbacks: slow placement, long cure time (60 min), and poor retroreflective qualities. The poor retroreflective qualities [less than 20 as measured by the electronic retroreflectivity measuring apparatus (ERMA)] were caused by the long cure time, which allowed the glass beads to sink below the surface.

Once it was demonstrated that epoxies could be formulated to adhere to pavement surfaces, even without primers, subsequent work was oriented toward cost reduction, cure time, and retroreflectivity for night visibility. Film thicknesses of 12-20 mils were used, since this gives the typical drop-on glass beads ample projection above the material surface so as to provide retroreflectivity, resist snowplow damage, and act as an integral part of the pavement.

Since the epoxy components are more viscous than conventional paints at ambient temperatures, a special heating system was necessary. In addition, because the two components react chemically, they must be proportioned extremely accurately and mixed thoroughly. Special equipment had to be developed or existing equipment modified to spray the material.

In 1971, a trial consisting of 25 stripes of a sprayable two-component epoxy resin was placed on a portland cement concrete (PCC) pavement with an ADT of 26 000. There was no difference in adhesion between cleaned and uncleaned surfaces; it was excellent for both.

In 1972, to accelerate the evaluation of the more durable pavement-marking materials, transverse-stripe studies on both bituminous and PCC surfaces were initiated. The center 0.6 m (2 ft) of each wheel path was selected as the evaluation section. Materials were placed in a typical film thickness of 20 mils, and all received an application of drop-on glass beads. The control materials included the initial spray epoxy formula (5143) and Minnesota DOT specification 20-s-dry and chlorinated rubber-based traffic paints.

Experimental materials placed on the bituminous surface included two new epoxy formulas, 5144 and HA-1, and a polyurethane-based material. All three were durable, but the cure times for the 5144 epoxy and the polyurethane were slow compared with those for the original 5143 and HA-1 formulas.

A near-duplicate test was established on a PCC surface that had an ADT similar to that of the bituminous section. In addition to the materials placed on the bituminous surface, this section also included the original spray epoxy (5143), with additional pigment, now designated formula 5143-1; a slow-cure (30-min) epoxy, 5144; and the same material with a different catalyst, 5144-A. After field evaluation, the 5143-1 epoxy and the two new formulas, 5144 with the slow (30-min) cure time and HA-1 (10-min cure time), were selected for further evaluation. Work also continued on equipment design and fabrication.

In 1973, these three materials were placed on a 1.6-km (1-mile) section of I-94 in St. Paul. At this location, there are eight lanes on which the ADT approaches 100 000. The painted lines placed in October were completely obliterated by wear, whereas the epoxy was still 95-100 percent intact after a

Figure 1. Typical midwinter delineation conditions on high-ADT roadway in Minnesota.

Figure 2. Condition of best-formulation epoxy (HA-1) after three years (left stripe).

winter. Figure 2 shows the HA-1 material in 1979 after six years.

Although some chipping occurred in each individual stripe, this did not reduce delineation because, from a typical sight distance [45.7 m (150 ft)], a stripe can be 20-30 percent removed by chipping and still appear to be a full or complete stripe.

As a result of the successful test application on I-94 in 1973, the formula finally selected was HA-1, the fastest-curing of the three materials placed. This selection was based on cure time, application properties, adhesion to the surface, durability, and color retention.

In 1974, a maintenance contract was awarded to H.B. Fuller Company to furnish 72 L (19 gal) of HA-1 material, application equipment, and technical experts to assist Minnesota DOT personnel in the application of 1828.8 m (6000 ft) of skip stripe on a high-ADT Interstate roadway in the Minneapolis-St. Paul metropolitan area. In early June of 1975, this contract was completed. Although there were minor problems, the result looked very satisfactory. But within four days, a severe (80-90 percent) loss of material was noticed. It was established that the components had been heated too high--at 87.8°-93.3°C (190°-200°F). This advanced the polymerization too fast in the system before spraying, which reduced the wetting action of the epoxy system and the adhesive action of the material. In July 1975, the material was replaced at the proper temperatures--part A (pigmented) at 79.4°C (175°F) and part B (catalyst) at 73.8°C (165°F)--and it appeared to bond well.

In all previous work, there had been no significant difference in adhesion between sandblast-cleaned and uncleaned pavement surfaces. No cleaning was required on this contract.

In 1975, the Minnesota DOT applied for federal funds and, upon approval by the Federal Highway Administration (FHWA), a contract was let for the purchase of 3400 L (900 gal) of epoxy and polyester resins, including the application equipment and technical experts. This contract was completed in 1976.

1975-1976 PHASE: APPLICATION TO HIGH-ADT URBAN ROADWAY

Equipment

Epoxy System

The equipment used in 1973 to place the epoxy material was a system capable of heating, metering, mixing, and spraying the two-component epoxy. However, it was a basic machine and was manually operated. This severely limited the capabilities of the application system. The purpose in the 1975-1976 phase of development was to design and fabricate a fully production-capable machine to be used and operated in the same way as a typical highway striper.

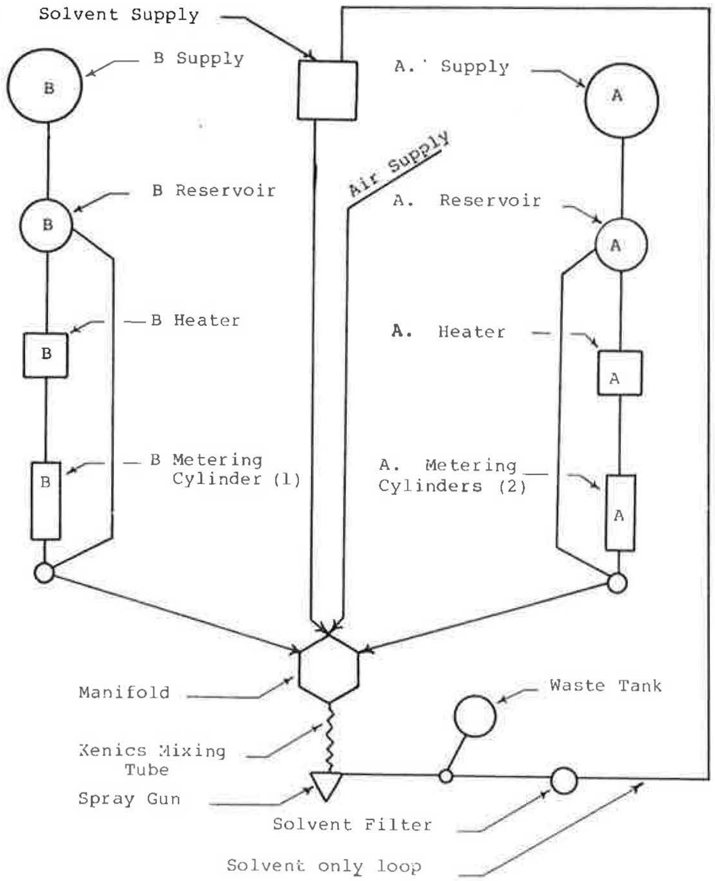
Figure 3 shows the schematic for the plumbing of the epoxy spray. The flow in both the A and B sections of the apparatus is from the reservoir (which is kept supplied as needed from the main supply tanks) to the heaters. Each component is heated to reduce viscosity, facilitate spraying, and reduce cure time. From the heaters, each component is introduced to the metering pump. The metering pump consists of a Graco Bulldog hydraulic power head with a 23:1 ratio of fluid to oil, simultaneously operating three double-acting cylinders of equal capacity. The cylinders are calibrated to deliver exactly two parts A and one part B to the manifold when the system is in a spray mode. When it is out of a spray mode, parts A and B are recirculated to their respective reservoirs.

When the system is in the spray mode, parts A and B meet at the manifold and proceed through the kenics mixer where complete mixing occurs. After the kenics mixer, the mixed components proceed to the spray gun for application. Each time the equipment goes from a spray mode to a nonspray mode, the system from the manifold through the spray gun must be cleaned with solvent. In nonspray modes, parts A and B are recirculated from the metering section back to the reservoirs, thus maintaining proper temperature in each component.

The solvent is introduced under pressure at the manifold, flushing the system from where parts A and B meet and down through the kenics mixer and spray gun. The gun is momentarily opened to flush the tip. With the gun nozzles closed, the solvent passes through the manifold, kenics mixer, and spray-gun body and is dumped in the waste tank. To purge the system of the solvent, the same procedure is followed and air is used.

The system must be flushed for any delay, for 30 s or more, to prevent the mixed components from curing in the mixing system. During long delays, prior to shutdown and before starting, the system is put in the nonspray mode and solvent is circulated

Figure 3. Plumbing of epoxy spray.



through the mixing system, the gun body, and a filter. This is an important part of the system because laminar flow in the system deposits a thin film of cured epoxy that is loosened by the solvent flush and plugs the spray gun. By recirculation through the filter, the system is kept clean.

A Graco model 205-163 material spray gun was modified by placing a Graco 205-163 gun at right angles to facilitate the flushing and cleaning operation.

In the course of development, many critical points were reached that required the development or modification of available equipment to achieve a production-capable automatic application system. The end result was a control system that is basically composed of electrically controlled air or hydraulic valves and a spray gun.

A final design is being prepared, and a system has been constructed by a major striper manufacturer. Application techniques are discussed later in this paper.

Initially, standard paint guns (Binks 21 and 33), modified to handle glass beads, were used. In certain areas where traffic volume is heavy, glass beads were poured on the epoxy stripes in an attempt to eliminate tracking of the epoxy. This proved to work so well that a free-fall system capable of flooding the epoxy stripes with glass beads at a rate of 2.4-2.9 kg/L (20-25 lb/gal) was developed.

The initial placement and several subsequent placements of epoxy were done by using sandblasting to clean the pavement surface. Because no apparent difference showed between the sandblast-cleaned surface and an uncleaned surface, it was decided that no preliminary cleaning was needed. The initial 1975 work on I-94 in St. Paul was done on a 56-km/h (35-mile/h) curve where there is regularly heavy weaving in traffic.

Laboratory tests performed on samples from these initial installation failures showed definite signs of contamination caused by the weaving traffic; oil, ethelene glycol, and rubber were very apparent. This pointed out the need for an economical system of cleaning the pavement to increase the adhesion of the epoxy to the pavement.

In 1975, it began to rain after striping had started across a long bridge. It was later noticed that the wet surface had not adversely affected the adhesion and, in fact, may have enhanced it. A decision was then made to evaluate cleaning with hot water [60°C (140°F)] at a pressure of 17.5 MPa (2500 lbf/in^2) and using an air-dry system.

Polyester System

In 1976, a two-component polyester-resin pavement-marking material was placed under the FHWA contract for comparison with the epoxy. This was done under a contract with the Clark Company of Lake City, Michigan. The application system is simpler in design than the epoxy system because the mixing requirements of polyester resins are much less critical.

Optimum Bead Type

A main objective of this study was to determine the proper bead gradation and treatment. In this portion of the study, three types of glass beads were used to determine the best bead to use with epoxy resin.

Minnesota DOT Specification Beads

Minnesota DOT specification beads were used exclusively in the 1975 phase of the study, and there was a complete loss of retroreflectivity. The loss was caused by the powdered flow treatment working as a bond breaker. The epoxy did not have sufficient time to penetrate the powder and create a bond to the glass beads. Figure 4 shows the data collected on four sections where these beads were used. The figure shows that an epoxy stripe placed in October can still be functional as a daylight traffic delineator after 18 months. Except for the initial tests in the fall of 1976, stripes with this bead type were consistently lower and reached the minimum acceptable reflectivity level within nine months after placement.

Floating Glass Beads

The bisymmetric, or floating, type of bead was used based on recommendations from the striping industry and from other states on paints and thermoplastics. Work done in Minnesota had shown that the use of the floating bead improved retroreflective qualities substantially; in fact, it improved the retroreflective qualities of yellow paint above that of white paint with the standard Minnesota DOT specification beads. A total of 10 test sections were placed.

Figure 4 shows that the floating bead initially has about the same reflectivity as the Minnesota DOT bead but surpasses it from that point on. On the average, stripes with the floating bead reached the minimum acceptable level of reflectivity about 10.5 months after placement.

Chemically Moisture-Proofed Beads

The bead treatment and gradation used in the initial trial of the sprayable epoxy (in 1971), which involved chemical moisture proofing, still had acceptable reflectivity after three winters on a roadway with an ADT of 26 000. Because this type of treatment had been so successful in 1971, it was felt that it could be the answer to the loss-of-bead problem encountered in 1975. The data in Figure 4 show this bead to be substantially better initially and also throughout the 18-month test period. It also resulted in stripes reaching the minimum acceptable reflectivity level much later. This is the bead treatment and gradation recommended and used in the epoxy-resin pavement-marking system.

Observed Effectiveness of Epoxy

Observation has shown that the epoxy is an adequate delineator in both day and night conditions after 24 months, providing nighttime delineation under lighted roadway conditions. Observation has also shown that overhead lighting washes out the vehicle-headlight/glass-bead reflective system. Under wet-night conditions, the shiny enamel type of surface on the epoxy serves as a mirror and reflects the overhead lighting and the taillights of the vehicle ahead, which serves to amplify the delineation system for the vehicle operator.

Typically, conventional traffic paints are completely worn off each winter and therefore have no residual delineation capabilities unless they are renewed as shown in Figure 5. Figure 5 shows a plot of retroreflective qualities versus time for a conventional traffic paint placed six times and epoxy placed once in a two-year period on the I-94 test sections. There are periods in the winter season of each year when the stripes are worn off and should be painted but cannot be because of weather conditions. This would increase the number of paintings to eight in comparison with one application of epoxy.

From Figure 5, it can be determined that, for the conditions described,

1. Epoxy has better reflectivity than conventional traffic paint 60.6 percent of the time,
2. Paint has better reflectivity than epoxy 32 percent of the time,
3. The reflectivity of paint is below the minimum acceptable level 52.7 percent of the time, and
4. No form of delineation exists 18.2 percent of the time when conventional traffic paints are used.

Even without retroreflective qualities, the epoxy is still serving as a traffic delineator after 24 months and is serving as a form of delineation 100 percent of the time under lighted roadway conditions. In most cases, epoxy is superior to paint.

Application Techniques

Application techniques for an epoxy-resin pavement-marking material are very similar to those for conventional traffic paint and other sprayable pavement-marking materials. The equipment is automated in the same way as standard paint striping equipment but differs in that exact control must be maintained over component mixing ratio, temperature, and glass-bead type, treatment, and application.

Component Mixing Ratio

The component ratio of 2:1 (two parts A to one part B) must be controlled within 3 percent or the cure time, adhesion qualities, bead retention capabilities, and durability of the placed epoxy-resin stripe will be adversely affected.

Temperature

The individual components are heated separately before mixing. The temperature at the time of mixing and spraying is critical for several reasons:

1. Part B, or component B as it is properly called, contains the catalyst and is sensitive to heat. If heated above 76.7°C (170°F) repeatedly or held too long at a high temperature, it will crystallize.
2. If the components are heated to too high a temperature before mixing, they will begin to polymerize too soon and reach the gel point (partial cure) too quickly to allow the material to properly wet the pavement surface and achieve a good bond. Durability will thus be affected.
3. Glass-bead retention will also be adversely affected by the same lack of wetting action as described in item 2 above.
4. Temperatures must therefore be limited to 79.4°C (175°F) maximum for component A and 73.9°C (165°F) maximum for component B.

Glass-Bead Application

Several attempts were made to place the drop-on glass beads. A pressure system was tried but, even with three bead guns, the "instant no-track" condition required to eliminate the setting and retrieving of traffic cones could not be reached. The free-fall, drop-on system of bead application developed in this study (Figure 5) has proved to be the best for reflectivity and for achieving an instant no-track condition.

Figure 4. Effect of bead type on reflectivity.

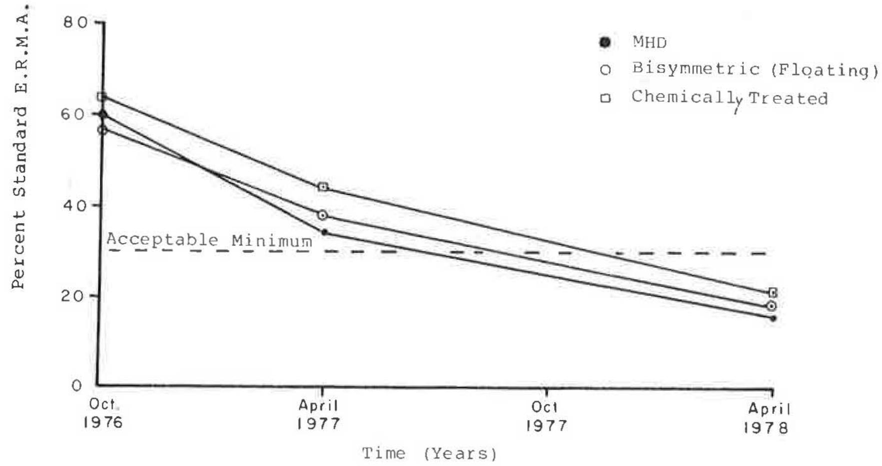
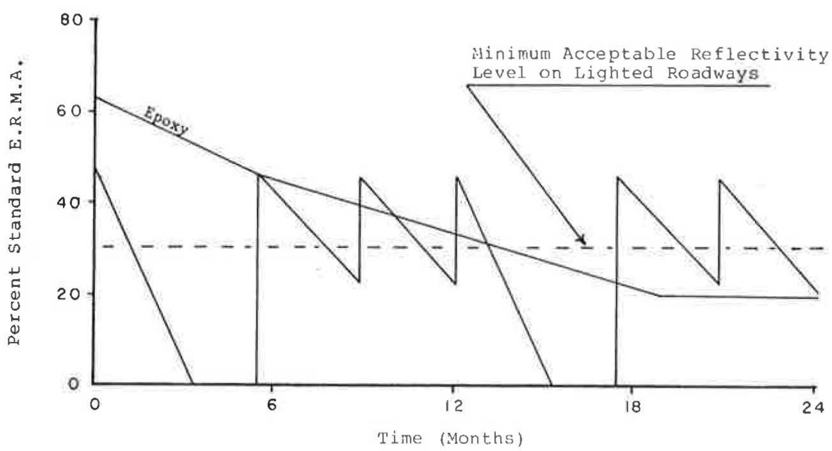


Figure 5. Retroreflective qualities of one epoxy application versus six placements of conventional traffic paint over two-year period.



As noted previously, the application of epoxy as a delineation system requires specialized equipment. When properly designed and built, however, the equipment is as easy to operate and maintain as a standard high-capacity paint striper. The cure time is longer than that for conventional paints and requires flooding with glass beads to compete with fast-drying conventional paints on a labor and equipment basis.

Curing and "No-Track Time"

In 1975, epoxy material was placed on both PCC and asphaltic concrete pavement surfaces. In 95 percent of this work, traffic cones were used to protect the epoxy stripes. Cure time ranged from 5 to 25 min, and the variation in cure time was caused by pavement surface temperatures: The higher the pavement temperature, the faster was the cure. A significant observation was made at an extremely cold surface temperature [-3.9°C (25°F)]: On the cold surface, the sprayed epoxy cooled rapidly and thickened, which lengthened the cure time well beyond that expected.

Five percent of the striping was done in areas where, in spite of traffic cones, it was known that traffic could not be stopped from crossing the fresh, uncured epoxy line. At one of the first installations where this problem was encountered, a bag of glass beads was opened and poured directly onto the fresh stripe and the traffic cones were removed. This allowed traffic to pass over the stripes on the glass beads and not contact the epoxy resin, which gives an instant no-track system. It was felt that, because of the cost of coning and because crew members are exposed to danger while they set and retrieve cones, the flooding with glass beads would be a worthwhile investment.

Flooding with glass beads reduced the epoxy striping operation to the same two- or three-vehicle striping train as is used in Minnesota in the application of conventional fast-drying paint.

Weather Conditions

Weather conditions were considered a major variable to be evaluated in the 1975 epoxy program. Material was placed at pavement surface temperatures ranging from -3.9° to 37.8°C (25°-100°F) with the majority placed at 21.1°-26.6°C (70°-80°F). The only variation in the material caused by temperature was cure time. The increase in cure time at extremely cold temperatures did not hold up or delay the production schedule. The striped area had no tracking because of the increased viscosity.

Sky cover varied from cloudy and cold to clear and sunny. Pavement surface conditions ranged from dry to free water on the surface. None of these variations had any significant effect on the serviceability of the epoxy.

Snow and Ice Control

The average annual snowfall in the metropolitan area where the high-ADT test sections were located is 1.14 m (45 in). Minnesota DOT standard snow-removal and ice-control procedures were used on all test areas. Since no records were kept of snowplow passes, no correlation can be made between snowplow passes and wear. Sanding and salting records are extremely difficult to evaluate because of the method of record keeping and the overlap of servicings by different maintenance crews at a given location.

All state DOT plows are equipped with tungsten-carbide blades and are placed directly on the pavement surface. Because a 15-mil thickness of epoxy is less than the inherent texture in a pavement surface, it is felt that the actual snowplowing does not contribute significantly to the wear of epoxy stripes; the combination of sanding, salting, and tire action is thought to be the most significant cause of stripe deterioration. The chipping that does occur is caused by lack of adhesion of the epoxy to the contaminated pavement surface.

The polyester stripes were damaged by winter wear, and again the damage was from chipping caused by poor adhesion to the pavement surface.

The 30-mil-thick thermoplastic stripes were severely damaged by snowplows. The surface was scraped so that the glass beads were removed and the filler crystals exposed.

1977-1978 PHASE: APPLICATION TO HIGH-ADT URBAN AND LOW- TO MEDIUM-ADT RURAL AREAS

As the evaluation of epoxy and polyester resins as pavement-marking materials on high-ADT urban roadways approached completion in 1976, a durable-marking-materials program on rural and urban trunk highways, funded by FHWA Section 205 safety funds, was begun. Two materials were used: hot-spray thermoplastic and the two-component epoxy-resin system developed in the 1975-1976 phase of the study. The glass beads used were bisymmetric beads on thermoplastic and chemically moisture-proofed beads on epoxy resin. The materials were placed as follows:

	Material	
Application	Thermoplastic	Epoxy
Bituminous surfaces	X	X
PCC		X
Undivided roadways		
Edge and centerline	X	X
Centerline only	X	
Divided roadways, centerline only	X	X
Urban roadways	X	X
Rural roadways	X	X
ADT		
160-60 000+	X	
825-11 000+		X

A total of 89 085.5 kg (98.2 tons) of thermoplastic and 14 383 L (3800 gal) of epoxy were purchased, including equipment and technical experts for placement. Yellow and white were included for both materials.

Table 1 compares the performance of epoxy resin and thermoplastic resin when both were placed as pavement-marking materials in Minnesota in 1977 and 1978. All thermoplastic was placed in the fall of 1977. The epoxy resin was placed in the fall of 1977 and 1978, and this accounts for the smaller number of test sections in the 12- and 18-month data for the epoxy resin.

The term failure is defined as retroreflectivity readings of less than 30 percent of standard Minnesota DOT ERMA, which requires repainting as soon as possible. The six-month (or spring 1978) data show a high number of failures caused by dirt and a salt-film coating on the stripes at the time of the early spring (March and April) testing. This explanation becomes more plausible when the 12-month (fall 1978) data show the number and percentages of failures to be significantly lower for both thermoplastic and epoxy. The 18-month (spring 1979) data again show an increase in failures, but these data were acquired in May and June of 1979, which should have allowed enough time for rainfall to clean the stripes prior to testing.

The significant point to be made is the high number and percentage of failures of the thermoplastic in comparison with those of the epoxy resin. Thermoplastic failed because it was either worn off or plowed off the pavement surface or because the glass beads were removed and sheared off by snowplows as a result of the greater thickness of the material (30 mils).

Epoxy failed basically because of adhesion problems caused by contamination of the pavement surface (i.e., oil, rubber, and ethylene glycol). The majority of failures were in traffic weaving areas; areas of natural traffic drift, such as curves; and under bridges, where traffic carries contaminants and rainfall does not flush them off.

Delineation

Pavement markings have definite and important functions to perform in the proper scheme of traffic control. In some cases, they are used to supplement the regulations or warnings of other devices such as traffic signs or signals. In other instances, they are used alone and produce results that cannot be obtained by using any other device. In such cases, they serve as a very effective means of conveying certain regulations and warnings that could not otherwise be made clear.

Pavement markings have definite limitations: They are obliterated by snow, may not be clearly visible when wet, and may not be very durable when subjected to heavy traffic.

A delineation system has two elements: daytime and nighttime delineation. Both are necessary to the motoring public and are analyzed here separately.

Daytime Delineation

Daytime roadway delineation is not as critical as nighttime delineation because the overall topography of the roadway typically provides the driver with sufficient guidance information. Many people who are responsible for road striping are of the opinion that, if a stripe is not solid (that is, as originally placed), it should be redone. Many gallons of paint are used each year because someone decides "Those stripes look bad" or "We always paint that area at this time every year."

In dealing with durable pavement-marking materials, old habits in evaluating stripes must be set aside. An inspection trip over a section of highway that has been striped with epoxy, polyester, or thermoplastic will show some chipping after a period of time. When viewed from some distance, newly placed skip stripes appear to join together to form a solid, continuous line. This same phenomenon occurs on each individual stripe when chipping exists. This means that the average driver does not see the chipping until it becomes very severe--i.e., until probably more than 50 percent of the stripe is removed. At the present time, epoxy does chip because of poor adhesion caused by various types of surface contaminants.

Another phenomenon that has become apparent is that a nonbeaded stripe may show up under dirt and snow or slush and sand better than a beaded stripe because the nonbeaded stripe "holds" a minimum of dirt. The shiny enamel type of surface on the epoxy

Table 1. Performance of pavement-marking materials tested in Minnesota in 1977 and 1978.

Material	Number of Test Sections	Number of Months	Failures	
			Number	Percent
Thermoplastic	44	6	41	93
		12	34	77
		18	38	86
Epoxy	51	6	12	24
	25	12	2	8
	25	18	4	16

Note: Differences in the number of epoxy test sections are accounted for by the incomplete work in 1977.

Figure 6. Conventional traffic paint: new and one year old.

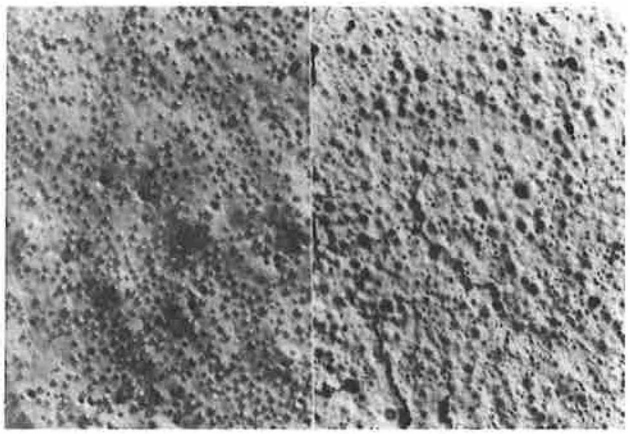
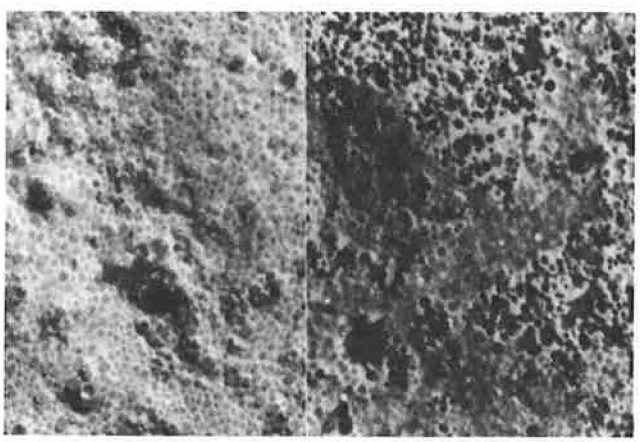


Figure 7. Polyester resin: new and two years old.



is even better for this reason. Another distinct advantage of epoxy is the fact that it is so much more durable than a conventional paint and can be placed on both asphaltic concrete and PCC, whereas other durable materials cannot.

Placement of epoxy on the Interstate system in the Minneapolis-St. Paul metropolitan area and on rural roadways in Minnesota has given the motoring public an adequate daytime pavement-marking system throughout the year, which was never possible with conventional traffic paints.

Nighttime Delineation

Delineation at night is related to daytime

Figure 8. Epoxy: new and two years old.

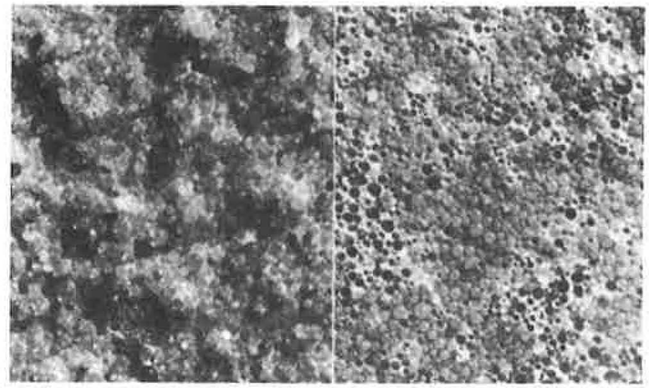
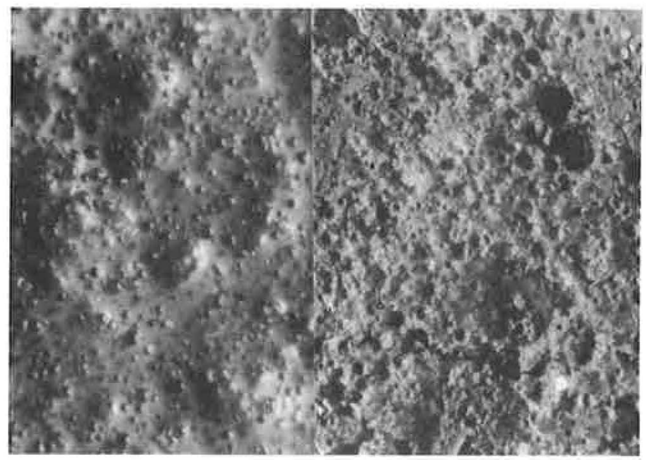


Figure 9. Thermoplastic: new and one year old.



delineation in that it uses the daytime delineator as its color medium. The addition of glass spheres to the daytime delineation system gives the color (white-yellow) to the light the spheres reflect back to the driver for nighttime visibility.

Figures 6-9 are composite macrophotographs (about eight times actual size) of conventional traffic paint and the three durable materials, new and after one or two winters of use. Figure 6 shows a conventional traffic paint. In Figure 7, which shows a polyester resin, sufficient beads remain after two years to produce an acceptable retroreflective value. Unfortunately, the "It doesn't look too good--paint it" philosophy prevailed, and the majority of the material was overstriped after one year. Figure 8 shows an epoxy resin that continued to exhibit acceptable retroreflective value after two years. In Figure 9, which shows thermoplastic, very few glass beads remain after one year, and many pieces of filler crystals have been exposed by snowplowing. The material placed on the high-ADT urban system was 90 percent removed by spring. The retroreflective qualities were virtually nonexistent after one winter's service, and a moratorium was placed on the use of thermoplastic pavement-marking materials in Minnesota.

Cost Comparison

Table 2 gives cost figures associated with the three durable-type pavement-marking materials used in this study and conventional traffic paint. It is assumed in the table that the cost of labor and equipment operators is equal for all four materials. The major difference per lineal foot is material and bead cost. Beads are applied to paint, polyester, and thermoplastic in approximately the same amount, and therefore the cost is shown to be equal. Epoxy requires flooding with glass beads at a rate four times that of paint to achieve the instant-no-track condition.

The basic total cost of epoxy placed is shown to be four times as high as that of conventional traffic paint, 44 percent higher than that of polyester, and 89 percent higher than the cost of thermoplastic. However, if the visible life of each material is considered, after one year epoxy equals paint in cost per lineal foot per day. If the epoxy has a life of two years, the cost is exactly half the cost per lineal foot per day of conventional paint, based on 4 paintings/year.

Four major points must be considered when one compares the three durable materials with conventional paint:

1. Conventional traffic paint has a very short life in comparison with durable materials on high-ADT (>70 000) roadways.
2. Two of the durable materials, polyester and thermoplastic, are not compatible with PCC pavements.
3. The reflectivity of thermoplastic does not survive one winter season in Minnesota.
4. On high-ADT roadways, conventional traffic paint does not survive the winter season reflectively or otherwise.

One additional point to be made concerning the economics of using epoxy is that it is a relatively new product in the pavement-marking field. Because of this, it is felt that material costs should go down as production goes up.

Table 2. Cost comparison of pavement-marking materials.

Item	Epoxy	Paint	Polyester[a]	Thermoplastic[a,b]
Cost (¢/ft)				
Material[c]	0.14	0.0125	0.093	0.063
Beads[c]	0.011	0.003	0.003	0.003
Application[c]	0.024	0.024	0.024	0.024
Traffic delay[d]	0.002	0.002	0.002	0.002
Traffic increase[d]	0.003	0.003	0.003	0.003
Total	0.18	0.045	0.125	0.095
Length of visible life (days)	365	90	365	180
Cost per day of visible life (¢/ft)				
1 year	0.000 49	0.0005	0.000 34	0.000 26
2 years	0.000 25	0.0005	0.000 34	0.000 26

[a]Not compatible with PCC.
[b]Not reflective after one winter in Minnesota.
[c]Based on 1977 prices.
[d]Based on Bernard Chaiken (1969), updated for inflation.

<u>Material Service Life and Cost by ADT</u>

Table 3 gives projected cost comparisons for applications of paint, epoxy, and thermoplastic for three ADT levels (and for polyester for the intermediate ADT level). These comparisons are based on number of applications over two years and four years and on the service life of each material in days.

For an ADT of <5000, a two-year epoxy life equals that of paint when the epoxy is placed at a 15-mil film thickness. A 10-mil-thick application of epoxy, at two years, shows a savings of 5 cents/ft. In addition, using epoxy requires less equipment and energy to service the same road distance.

For an ADT of 5000-15 000, paint equals epoxy in cost at two years. After that length of time, epoxy costs less on lower-volume roads.

For an ADT of 70 000, the cost is the same for 16 paintings (over four years) and four 15-mil-thick epoxy applications; for 12 paintings (over two years) and four 10-mil-thick epoxy applications, epoxy is 2 cents cheaper. Again, the thermoplastic is more expensive: 76 cents/ft over two years. In addition, thermoplastic is not acceptable for use on PCC. Again, epoxy has the added advantage of requiring the use of less equipment, consuming less energy, and providing an effective pavement-marking system 12 months out of the year. There has not been sufficient experience with polyester on high-ADT roadways to include it in the high-ADT cost comparison.

These data indicate that epoxy is basically cost effective when placed by Minnesota DOT crews. When epoxy is placed in areas where two or more paintings per year are normally done, it saves energy. Fewer paintings means a decrease in the use of state DOT equipment. For example, reducing three paintings on I-94 and other metropolitan-area roads to one epoxy application releases the vehicle used for painting

Table 3. Comparison of service life and cost of pavement-marking materials by ADT level.

			Two Years		Four Years	
ADT	Material	Service Life (days)	Number of Applications	Cost (¢/ft)	Number of Applications	Cost (¢/ft)
<5000	Paint	365	2	9	4	18
	Epoxy	>730				
	10 mils		1	13		
	15 mils		1	18		
	Thermoplastic	<180	4	38	8	76
5000-15 000	Paint	180	4	18	8	36
	Epoxy	>730				
	10 mils		1	13		
	15 mils		1	18		
	Thermoplastic	<180	4	38	8	76
	Polyester	365	2	25	4	50
70 000	Paint	90	12	54	16	72
	Epoxy	365				
	10 mils		4	52		
	15 mils		4	72		
	Thermoplastic	<180	8	76		

for work in other areas, which in turn reduces fleet requirements.

CONCLUSIONS

Epoxy

1. Epoxy adheres to both PCC and asphaltic concrete.
2. Epoxy can be applied in the same way as conventional traffic paints.
3. Epoxy can be placed on a wet pavement (where there is no free water), whereas other currently available materials cannot.
4. The temperature of the two epoxy components used in this study must be controlled. Part A (pigmented) has a maximum temperature of 85°C (185°F), and part B (catalyst) has a maximum temperature of 79°C (175°F). This must be adhered to regardless of ambient temperatures. A higher component temperature will result in too rapid polymerization and an epoxy stripe that does not bond to the pavement surface.
5. Epoxy withstands high traffic volumes, Minnesota winters, sanding, salting, and plowing and provides a delineation system that performs effectively for 12 months or more.
6. In most cases, the pavement surface can be adequately cleaned for epoxy placement by using an economical material (i.e.,water).
7. The equipment and expertise are available to build a striper that is capable of placing both paint and epoxy.
8. Epoxy is economically justified for use on high-volume and some lower-volume roadways.
9. Epoxy will bond to itself and many other materials. However, if it is placed over materials such as conventional paints, its bond to the pavement will only be as good as the adhesion of that material. Therefore, it should not be placed over other pavement-marking materials unless they are substantially worn off or removed.
10. A 20-30 percent/stripe removal by chipping does not seriously affect the delineation provided by the stripe.
11. Overhead illumination reduces the retroreflective capability of the glass-bead/vehicle-headlight system.
12. The end result of this study is an epoxy-resin pavement-marking system that can be recommended for use on high-volume roadways, regardless of pavement type, especially in the snow-belt states.
13. Epoxy placed at a thickness of 10 mils can be an effective pavement-marking system on high-ADT roadways.
14. The use of epoxy can reduce equipment requirements and energy consumption.
15. The use of epoxy reduces environmental pollution because, unlike paint, it is 100 percent solids and contains no solvent that is evaporated into the atmosphere.

Polyester

1. Polyester adheres well to bituminous materials but not to exposed aggregate.
2. Polyester does not adhere well to PCC.
3. Application costs for polyester are higher than those for paint or epoxy because cones must be placed to protect the stripe during the longer cure time.
4. The retroreflective qualities of polyester were better after one year than those of conventional paint.

Thermoplastic (Spray)

1. Thermoplastic does not last through one winter on high-ADT urban roadways in Minnesota.
2. Thermoplastic does not meet Minnesota DOT standards for reflectivity after one winter.

RECOMMENDATIONS

1. Epoxy should be used as a durable pavement delineation system on high-volume roadways and considered for use on lower-volume roadways.
2. Surface cleaning such as sandblasting and hydroblasting should be used in specified areas, such as on curves, under bridges, in areas where traffic weaving is heavy, and on the extreme right skip line on multilane roadways that have frequent entrances and exits.
3. The inherent surface laitance of new PCC surfaces must be removed by sandblasting or hydroblasting to attain the adhesion needed for durability of epoxy.
4. Currently available equipment should be improved so that epoxy can be placed at a faster speed.
5. New epoxy formulations should be sought to create a competitive bidding situation and reduce material cost.
6. Currently available polyester and thermoplastic resins should not be considered for use on PCC surfaces under climatic conditions such as those in Minnesota.
7. Research should be done to develop an instant-no-track polyester system for use on bituminous surfaces.
8. Thermoplastic (spray) should not be considered for use in Minnesota unless snowplows are equipped with shoes.
9. Epoxy should be used for environmental reasons and to conserve energy.
10. Glass beads other than those recommended in this study should not be used without adequate testing.

ACKNOWLEDGMENT

The epoxy evaluated in this paper was produced by H. B. Fuller Company, the thermoplastic by Prismo, Inc., and the polyester by Glidden-Durkee. The beads used with the polyester resin were furnished by the Cataphote-Ferro Corporation. The beads used with the thermoplastic were bisymmetric (floating) and were furnished by Canasphere Corporation. The work done in this study included several years of experimentation before the involvement of and funding by FHWA.

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REFERENCE

1. Manual on Uniform Traffic Control Devices for Streets and Highways. Federal Highway Administration, U.S. Department of Transportation, 1971.

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