

PERMANENT CONCRETE PAVEMENT MARKINGS

By

Jun Zuo

David Darwin

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ABSTRACT

The visibility, durability, and cost-effectiveness of surface pavement markings and previous experience with permanent concrete pavement markings (PCPM) (markings with a service life similar to that of the pavement) are described. The use of durable materials, such as thermoplastics, polyesters, and epoxies, improves the service life of surface markings. However, these marking materials still exhibit problems of adhesion to pavement and rapid wear in high traffic areas. Snow removal procedures significantly reduce marking service life. Wet nighttime visibility is a continuing problem with surface markings. Previous attempts at developing PCPM have produced systems with very good durability, but poor nighttime visibility.

The potential for developing cost-effective PCPM systems that can provide both long-term durability and adequate visibility throughout the service life and the requirements for such systems are discussed. Polymers, such as epoxies, can provide superior durability and adhesion to pavement. The application of larger than standard size glass beads can improve wet nighttime visibility. The cost of PCPM systems can be significantly reduced using effective methods of placing grooves in which the marking material is placed. Generally, there is a good probability that a cost-effective PCPM system with satisfactory durability and visibility can be developed. The PCPM systems with thicknesses of 9.5 mm (3/8 in.) or less will be cost-effective for a 20-year service life, and the systems with thicknesses of 3.2 mm (1/8 in.) or less will be cost-effective for a 10-year service life.

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CHAPTER 1

INTRODUCTION

Traffic pavement markings are the delineation treatments that provide guidance, regulatory and warning information to drivers on roadways. Visibility and durability are the two basic requirements for pavement markings. Since the first painted stripes were used, many attempts have been made to improve the visibility and durability of pavement markings. Use of durable materials, such as epoxy, polyester, and thermoplastic, increases the service life of pavement markings to several times that of conventional paints. However, the durable marking materials still exhibit problems of adhesion to pavement and rapid wear in high traffic roadways. In snow areas, snow plows, chains, and studded wear significantly reduce marking service life. Pavement markings must remain visible in both daylight and nighttime conditions and in inclement weather. Wet-nighttime visibility is a serious problem with flat markings. When rain covers the markings, the light from automobile headlights is disrupted by the water film and pavement markings lose their effectiveness. The cost, down time, and safety considerations involved in the maintenance of pavement markings in high traffic volume areas make it highly desirable to extend the life of pavement markings. For many years, therefore, there has been a clear need for pavement markings that exhibit a permanence similar to that provided by the pavement itself. Such markings are defined as "permanent pavement markings."

The objective of this report is to assess the level of current technology to determine if economical, permanent concrete pavement marking systems can be developed. Based on a detailed literature and patent search, a review of current marking materials, including an assessment of durability, visibility, and cost effectiveness, and a description of previous attempts to develop permanent pavement markings are presented in this report. The possibility of

developing a permanent concrete pavement marking system (PCPM) using new technologies is discussed.

CHAPTER 2

LITERATURE REVIEW

A detailed literature review and patent search were the main tasks of this project. The literature review presented in this report involves all aspects related to the development of PCPM systems, including marking materials, durability, visibility, cost effectiveness, measuring methods, and installation methods. The patent search (from 1963 to 1994) focused on PCPM systems. To date, however, no patents for permanent pavement marking systems have been found.

2.1 Pavement Marking Systems - Types and History

In the early years of this century, the production and use of motor vehicles increased and the construction and improvement of highways expanded so rapidly that it soon became evident that a method for traffic road marking had to be devised (8). Although many claims have been made for the credit of originating the use of road markings, it is not definitely known when and where the first traffic road markings were used. *Roads and Streets* magazine (21) reported in 1936 that, the B. F. Goodrich Company, after investigating many claims, presented Edward N. Hines, for many years Road Commissioner of Wayne County, Michigan, with a plaque designating him as "Father of the Center Traffic Line."

Many types of road markings have been tried. The markings can be divided into five categories: paints, durable material stripes, preformed tapes, raised markers, and permanent markings. The first three categories are also referred as "surface markings."

Paints

Traffic paints, generally accepted as pavement markings since the 1920's (8), have been used longer than any other marking materials and, even today, are still the most commonly used materials for pavement markings. The earliest research on traffic paints was done by Mattimore (33). Mattimore listed seven factors that, in his opinion, were the most important for the selecting paint and for which laboratory tests should be developed: consistency, spreading rate, hiding power, drying time, light resistance, visibility, and durability. The currently used standard methods and specifications for traffic marking paints are ASTM D 713 (55), ASTM D 868 (56), ASTM D 913 (57), ASTM D 969 (58), ASTM D 4451 (62), AASHTO M 247 (49), AASHTO M 248 (50), and AASHTO M 309 (52), which cover color, bleeding, wear, glass beads, and use. Because of their wide use, paints are often used as the cost and performance standard to which other pavement markings are compared.

Durable material stripes

Many durable materials, such as thermoplastics, polyesters, and two component epoxies have been tried for pavement markings. The use of these materials has improved the service life of pavement markings.

Thermoplastics for use as pavement marking materials were developed in Great Britain before World War II (19). Thermoplastic marking materials are solids at ambient temperatures and liquids at elevated temperatures [typically 210 to 230° C (420 to 450° F)]. They are a mixture of resins, glass beads, pigments, and fillers and are applied at elevated temperature by spray or by extrusion equipment, and cool rapidly on the road to form solid marking materials. ASTM D 4797 (65), ASTM D 4960 (66), and AASHTO M 249 (51) provide the standard test methods and specifications for thermoplastic marking materials. The Kansas Department of

Transportation (KDOT) has its own specification for the thermoplastic marking materials (73). Thermoplastic marking materials have very good performance on asphaltic pavement. However, many adhesion problems have been encountered with their application on portland cement concrete pavement.

Polyester marking materials are two-component thermosetting systems. The first component, which comprises 95 to 99 weight percent of the total system, is composed most often of polyester resin, styrene monomer, wetting agent, adhesion promoter, pigment (titanium dioxide or lead chromate), and calcium carbonate. The second component, which comprises 1 to 5 weight percent of the total system, is most often a methylethyl-ketone peroxide catalyst, which, when mixed with the first component, causes it to convert to a hard, durable material. Polyesters are applied to a wet-film thickness of approximately 400 μm (15 mils) and the hardened line retains the same thickness. The minimum application temperature is 10° C (50° C) and drying times normally vary in the range of 10 to 45 minutes, depending on the ambient temperature and the formulation (19). Glass beads are premixed into the first component and/or applied by drop-on method. Much of the original developmental research on polyester pavement-marking materials was done by the Ohio Department of Transportation and the Glidden Company during the 1970's (16). The objective was to develop a thin-film marking material that would not be affected by snow plows and would be more durable than traffic paints. Generally, polyesters perform well on asphaltic pavement. However, they are not recommended for use on portland cement concrete pavement due to adhesion problems. Some state DOT's have their own specifications for polyester markings.

Epoxies are another form of two-component thermosetting materials. In a typical two-component epoxy marking material, the first component contains the type A epoxy resin, the

pigment (titanium dioxide or medium chrome yellow), extenders, fillers, and glass beads. The second component is the catalyst. An amine is often used. The ratio of the first to the second component can be in the range from 1:1 to 5:1, depending on the specific chemistry of the system. The set or hardening time is largely controlled by the selection of the second component (19). Epoxies are applied to a wet-film thickness of 250 to 500 μm (10-20 mils), producing a hardened line with the same thickness. Premixed and/or drop-on glass beads are used. The original developmental work on two-component epoxy marking materials was done by the Minnesota Department of Transportation and the H. B. Fuller Company during the 1970's (24). Epoxy marking materials have been applied to both asphaltic and portland cement concrete pavements with success. They have been widely used in almost every state because of their unusually good adhesive and durability properties. KDOT has a specification for epoxy marking materials (74). Many other states also have their own specifications.

Preformed marking tapes

Preformed marking tapes are marking products manufactured from plastic or other polymers and shipped to the construction site in a roll or as a precut length. Tapes generally consist of a resin binder, pigment, glass beads, and fillers. They can be placed on pavements using adhesive. Since tapes are manufactured under controlled conditions, there should be a more uniform level of performance built into the product, but they are also more expensive than other marking materials. There are two kinds of marking tapes, temporary tapes and regular tapes. Temporary tapes are often used around construction zones. Once construction is completed, the tapes are removed by hand. Regular tapes are used for permanent installations, so they are also called permanent tapes. Some tapes have a profiled or patterned surface, which can improve wet-nighttime visibility.

Pavement surface preparation is more critical for the performance of tapes than for the other marking systems. If applied properly, preformed marking tapes can be one of the more durable marking systems. ASTM D 4505 (63) and ASTM D 4592 (64) provide the standard specifications for preformed tapes. KDOT has its own specifications for temporary and permanent tapes (71, 72).

Raised markers

Raised markers are delineation devices that project above the pavement surface. The earliest use of raised markers was in 1920's. It was reported (1927) that Chicago used a "row of button-shaped metal studs set in the pavement to mark off safety zones and to form such messages as 'stop' and 'to right'" (14). Later on, raised reflective markers were developed to improve the nighttime visibility of traffic lines. Raised markers can be divided into three categories, nonsnowplowable, snowplowable, and recessed markers. Nonsnowplowable markers are placed on pavement surfaces with adhesive that cannot resist a snowplow. Snowplowable markers are mounted in a metal housing and embedded in the pavement, so that the markers can sustain direct contact from a snowplow blade. Recessed markers are placed into grooves so as not to be hit by snowplow blades. Raised markers provide very good wet nighttime visibility. However, their daytime visibility is not as good as that of other marking systems if the spaces between the markers are very large, and the initial cost of raised markers is very high. ASTM D 4280 (60) and ASTM D 4383 (61) provide standard specifications for the application of raised markers.

Permanent markings

Traffic control information and guide lines can be permanently built into pavements, to provide so called "permanent" or inlaid markings. Sawyer (43) reported that a white brick

center line was placed in a brick road in Ohio in 1924, possibly representing the first use of permanent markings used in the United States. The cost of the white brick lines was as high as \$185 per mile, a significant cost in 1924.

The *Engineering News-Record* (1932) reported on the practices of inlaid-stripe construction during pavement placement in New Jersey and in various cities such as Seattle, San Francisco and Los Angeles (48). The materials used for the stripes were white cement, white shiny sand and diatomaceous earth. Formwork was used for installing the inlaid materials during the paving operation.

The initial cost of permanent markings has been so high that they have been seldom used on rural highways. In the literature search carried out for this study, for the period 1974-1994, only two reports (4, 20) on the application of permanent markings were found. These reports are described in Section 2.6. A patent search found no patents on permanent markings between 1963 and 1994.

2.2 Durability of Pavement Markings

Durability is one of the basic characteristics of pavement markings. There are many factors that affect durability, including surface preparation, application procedures, the type of pavement, the type of traffic, the traffic volume, and factors involved with snow-removal, such as salt and sand, snow plows, studded tires, and chains. The desired result should be that the pavement markings have a long service life and ultimately wear off. However, bad surface preparation and improper application procedures often result in the premature failure of pavement markings. Some materials, for example polyester and thermoplastic, do not bond well to portland cement concrete pavement. Generally, the service life of pavement markings is inversely

proportional to traffic volume: the higher the traffic volume, the shorter the service life. Salt and sand, studded tire wear, snow plows and tire chains cause a serious loss of marking materials and significantly reduce service life.

Marking materials

Traffic marking paints have the shortest service life of the marking materials. They wear off rapidly on high traffic volume highways and are rapidly removed by snow-removal actions. Their service life is between 2 to 12 months depending on traffic volume (19).

Thermoplastics have been widely used as durable marking materials in the United States. Control of the application temperature is the key to the successful performance of these marking materials. Fig. 1 shows the bond strength to portland cement concrete as a function of temperature. An application temperature of 220° C (425° F), which, as can be seen in Fig. 1, provides near optimum bond strength for the materials, is required by most application specifications (19). The pavement temperature should be a minimum of 13° C (55° F) (47). Thermoplastics should be applied to clean dry pavement. It is generally agreed that the application of thermoplastics to portland cement concrete should be preceded by a surface treatment with an epoxy primer. There is some disagreement on the durability of thermoplastics applied on portland cement concrete. Some states do not recommend the use of thermoplastics on portland cement concrete because of adhesion problems, such as popping, breaking and chipping. Although 3-mm-thick (120 mils) thermoplastics applied to portland cement concrete are believed to have 4-5 year life expectancy in 150-900 mm (6-36 in.) snowfall areas and 4.5-6 year life expectancy in 0-150 mm (0-6 in.) snowfall areas (19), many failures of thermoplastic markings due to improper application and other unexpected reasons have occurred. Research by the Colorado Department of Highways in 1989 (25) indicated that the thermoplastic marking was

almost completely lost (only 15 percent remained) due to breaking up and chipping off within 20 months, even though it was properly applied. An investigation by the Florida State Department of Transportation (47) showed that the service life of thermoplastic on portland cement concrete is about 2 to 2.5 years in Florida. Failure was by a loss of bond, with about 40% of the stripe missing at the end of the service life. For the failed markings, it was found that the marking films were brittle and full of gas pockets and that there were additional open holes 12.5 mm (1/2 in.) to 25 mm (1.0 in.) in diameter.

Polyester marking materials exhibit very good durability when placed on aged asphaltic concrete. However, they are not recommended for use on new asphaltic concrete unless a primer is first applied. Two weeks after paving, a primer is no longer necessary (19). The opinion seems to be different for portland cement concrete. In a study of durable marking materials, including epoxy, polyester, and thermoplastic, Gillis (24) concluded that polyester did not adhere well to portland cement concrete. The polyester stripes were damaged by winter wear, and due to chipping caused by poor adhesion to the pavement surface.

Two-compound epoxy marking materials exhibit excellent bond to both asphaltic concrete and portland cement concrete. The early research done by the Minnesota Department of Transportation during the 1970's resulted in the development of a thin epoxy pavement marking system that is recommended for use on high-volume roadways, regardless of pavement type, especially in the snow-belt states (24). New York's experience with durable marking materials indicates that with 30,000 m (100,000 ft) of epoxy markings installed in 1978, some performed well, and remained in service after 5 years, but others experienced bond failure during the first winter due to a malfunction in the spray equipment (12).

During the 1970's, the Amicon Corporation (33) conducted a development and testing

program involving the formulation, laboratory evaluation and limited field testing of a series of fast-curing, solvent-free epoxy and urethane compounds for traffic lane markings with improved durability. The wear mechanism of the epoxy marking materials was studied by simulated wear testing, simulated snowplow testing, and limited highway field testing including transverse stripe testing and real wear of longitudinal stripes considering traffic distribution and lane changing. The following conclusions were drawn from the tests.

- a. From simulated snowplow tests:
 - snowplows have little or no effect on stripes less than 0.8 mm (30 mils) thick;
 - snowplows wear the leading and trailing edges of a stripe;
 - snowplows tend to shear glass beads in the tougher epoxies.
- b. From simulated tire tests and highway field tests:
 - tire wear plays a major role in the loss of glass beads;
 - stripe wear failure by tires is at least ten times slower than by snowplow;
 - epoxies wear better than conventional paints.

Permanent marking tapes are usually made of plastic. The use of marking tapes has been increasing in recent years due to improved materials and reduction in maintenance effort when the tapes are properly applied (32). The pavement surface should be cleaned and primer application may be necessary, according to the manufactures, before tape application. A pavement temperature of at least 21° C (70° F) is recommended for application (41). To avoid snowplow damage, marking tapes are sometimes placed into grooves on the existing pavement or on a new asphaltic concrete pavement while the pavement is still warm and rolled into the surface with the compaction roller (18).

The Colorado Department of Highways investigated 10 different preformed marking tapes

between 1987 and 1989 (25). A 20-month durability test provided the following results:

<u>Type of Tape</u>	<u>Percentage Intact on</u>	
	<u>Asphalt</u>	<u>Concrete</u>
Pavemark	100	94
Sarolite	70	70
Seibulite	100	75
Volare	97	95
Cataphote	100	99
Cataphote w/o primer	97	-
3M-std	100	95
3M-350	100	100
Prismo primerless	95	70
Prismo w/ primer	90	60

The results show that preformed marking tapes performed better on asphalt than on concrete. All of the tapes had excellent durability (more than 90% intact) on asphalt pavement except Sarolite which was 70% intact. On concrete, only half, Pavemark, Volare, Cataphote, 3M-std, and 3M-350, were 90% or greater intact.

Measuring durability

Measuring the percentage intact or the loss of marking material is the common method for evaluating durability in the field. ASTM D 713 (55) is a standard test method for the determination of the relative service life of fluid traffic marking materials such as paint, thermoplastic, epoxy, and polyester products under actual road conditions using transverse test lines. ASTM D 913 (57) is a standard test method for evaluating the degree of resistance to wear of traffic paint. For evaluating the durability of marking materials in the laboratory, tests that simulate tire wear and snowplow action have been used in some projects (33, 42). The test apparatus usually consists of a support beam, snowplow or tire, test slab, motor drive, and counter. Basically, marking materials are placed on a test slab of highway pavement (concrete or asphalt) in the shape of a pie section. The test slab is rotated beneath the horizontal support

beam and worn with a series of miniature tires or snowplows. Vehicle or snowplow weight can be simulated by compressing a set of springs. Vehicle speed can be controlled by means of a variable speed motor. The total number of cycles can be monitored by a revolution counter (33).

2.3 Daytime Visibility

Visibility is another basic characteristic for pavement markings. As delineation treatments, pavement markings must provide adequate visibility in both daytime and nighttime and in adverse weather conditions. Durability, color retention and contrast, and weather conditions are the main factors that affect the daytime visibility of pavement markings.

There is, of course, an interrelation between durability and visibility. Loss of marking material will reduce visibility. Chaiken (15) pointed out that, for thermoplastic markings, once 40-60 percent of material has been lost, the markings lose their delineation effectiveness. The Florida Department of Transportation recommends 50 percent intact as the terminal point for thermoplastic markings (47). This terminal point may also be an effective limit for the other types of markings.

Color retention and contrast between marking and pavement surface are the other factors that affect the visibility of markings, especially on portland cement concrete. Most marking materials have very good initial daylight reflectance. However, the daylight reflectance of some materials, such as thermoplastics, decreases noticeably with age, although, it is generally still satisfactory (15). Anderson (4) reported that the Concessive 1064 epoxy material (white) used for inlaid markings became discolored to a creamy white after one and half years, which reduced the contrast between the markings and portland cement concrete surface.

The contrast of pavement markings is defined as the difference between marking and

background (pavement) luminance¹ (or luminance factor²) divided by background luminance (or luminance factor) (46). A pavement marking can only be differentiated from the pavement surface if its luminance differs from the luminance of the pavement surface. Lower contrast will reduce the visibility distance of pavement markings. Blackwell (9) studied relations between the size of a circular object, ambient luminance, luminance threshold and contrast threshold. The "threshold" is a certain value (luminance or contrast) needed under specified conditions to make an object (stripe) just visible to the observer. Based on Blackwell's study, Allen (3) built a relationship between the contrast threshold and the visibility distance (see Fig. 2a). Allen curves show that, for markings of specific size and under sunset or cloudy conditions, greater contrast between pavement markings and pavement is required for visibility as the distance from the markings is increased. For a given visibility distance, if the contrast between the pavement marking and the pavement is smaller than a corresponding contrast threshold, the pavement marking will be invisible. Serres (44) reported contrast measurements under daylight conditions on dry and wet road surfaces. The contrast was measured in a range from 0.04 to 4.6 on dry and from 0.04 to 7 on wet pavement surfaces and most of the contrasts were above 0.1, corresponding to a visibility distance of 75 m (250 ft) for a 0.1 m × 4.57 m (4 in. × 15 ft) stripe based on the Allen curves (Fig. 2a). Meseberg (36) determined the range of luminance factors of road markings and road surfaces from a large number of measurements on the German road-network and calculated the contrast threshold for different types of road surfaces, road markings, and road surfaces under dry and wet conditions. He observed a minimum contrast of 0.25,

¹ Luminance is the measurable photometric quantity related to visual brightness.

² Luminance factor is the ratio of the luminance of a surface to that of a perfect diffusing surface, when illuminated and viewed under the same geometric conditions.

providing a visibility distance above 75 m (250 ft) according to the Allen curves (Fig. 2a).

Daytime situations are not considered as critical as nighttime conditions for pavement markings because other delineation information is available to vehicle operators. In most cases, if the nighttime visibility of pavement markings is acceptable, their daytime visibility is also acceptable. However, this is not to say that the daytime visibility of pavement markings is not important. Where markings are used as regulatory or warning devices, such as center lines and railroad symbols, they must be effectively visible (6). Some treatment, such as placing black stripes adjacent to the white or yellow marking stripes, can increase the contrast between marking and pavement and improve the visibility of markings (30).

2.4 Nighttime Visibility and Retroreflectivity of Pavement Markings

Nighttime visibility is the most important quality criterion for pavement markings. Many markings fail not because of wear, but because of the loss of nighttime visibility. Under wet-nighttime conditions, most surface markings have inadequate retroreflectivity due to water film that disrupts automobile highlights. For many years, a lot of effort has been expended on measuring and improving the retroreflectivity of pavement markings.

Minimum retroreflectivity requirements

Retroreflectivity of pavement markings is the characteristic by which the marking reflects and returns a relatively high proportion of light in a direction close to the direction from which it comes (54). Specific luminance, a retroreflective characteristic of materials, is a surface property and is defined as the ratio of the luminous intensity of the projected surface to the normal illuminance at the surface on a plane normal to the incident light (54). The unit of specific luminance is measured candelas per square meter per lux ($\text{cd}/\text{m}^2/\text{lx}$) and units of

$\text{mcd/m}^2/\text{lx}$ are often used to avoid fractional values. [see Appendix I for definitions of the terms and units used to describe retroreflectivity.]

In a study of driver visibility requirements for roadway delineation, Allen et al. (3) evaluated the contrast and visibility distance of pavement markings using a driving simulator and field testing of subjects with an instrumented vehicle. Allen suggests that a minimum marking contrast of 2, which results in about 45 m (150 ft.) visibility distance from Allen curves (Fig. 2b), be required for adequate steering performance under clear nighttime conditions.

Elthen and Woltman (23) evaluated the minimum retroreflectance required for nighttime visibility of pavement markings under dark and lighted (dry) conditions using a subjective rating method along with a portable photometer (Ecolux) measurements. They concluded that a minimum specific luminance of $100 \text{ mcd/m}^2/\text{lx}$ is needed for a minimum acceptable level of retroreflectivity of pavement markings under dark conditions, and at least $300 \text{ mcd/m}^2/\text{lx}$ for an acceptable level under lighted conditions.

King and Graham (29) evaluated the nighttime visibility of pavement markings. Minimum retroreflectivity values of $93 \text{ mcd/m}^2/\text{lx}$ for dry night conditions and $180 \text{ mcd/m}^2/\text{lx}$ for wet night conditions were measured based on subjective evaluations and quantitative measurements under controlled and repeatable laboratory conditions.

Based on studies by Blaauw (10) and survey data obtained by Serres (44), the International Commission on Illumination (CIE) recommends values of $150 \text{ mcd/m}^2/\text{lx}$ and $60 \text{ mcd/m}^2/\text{lx}$ for dry and wet conditions, respectively, as the minimum retroreflectivity requirements for the nighttime visibility of marking stripes (46).

Table 1 summarizes the results of previous studies of minimum retroreflectivity requirements for the nighttime visibility of pavement markings. The results indicate that it is

reasonable to use 100 mcd/m²/lx or 150 mcd/m²/lx as the minimum retroreflectivity requirement under dry-nighttime conditions for marking stripes. However, the results seems to show that no universally acceptable minimum retroreflectivity requirement exists for the wet-nighttime visibility.

France and Germany have their own retroreflectivity standards. The French use a minimum reflectivity value of 150 (mcd/m²/lx), as measured with an Ecolux retroreflectometer, and the Germans use a range of values from 150 to 70 (mcd/m²/lx) according to traffic conditions, as measured with a German-made retroreflectometer (6,41). In the United States, ASTM D 4280 (60) and ASTM D 4383 (61) provide the retroreflectivity requirements for reflective raised markers. ASTM D 4505 (63) and ASTM D 4592 (64) provide initial retroreflectivity requirements for preformed plastic tapes. In ASTM D 4045 (63), a minimum retroreflectivity of 100 (mcd/m²/lx) is used for Type V tape (tape that has a surface pattern with retroreflective elements exposed on the raised areas and faces and intermixed within its body).

Role of glass beads

Glass beads have been used for approximately 50 years to make pavement markings reflective in the dark. If properly embedded in a marking material, glass beads have the ability to collect incident light and reflect part of that light back toward its source (28). Even today, use of glass beads is still the overwhelming choice for providing nighttime visibility for pavement markings, since no other low cost materials have been found to substitute for glass beads. Ceramic beads have been tried on some preformed tapes with profiled or patterned surfaces. However, no performance data on ceramic beads has been reported, as yet, in the literature.

The method of application of glass beads is one of the most important factors affecting the service life and visibility of pavement markings. For surface markings, it has been shown

that the thickness of the markings, the size and embedment of glass beads, the application methods (premixed in the material or drop-on or both), and the application rate are the key parameters.

The principles of glass bead reflectorization were first studied by Pocock and Rhodes (40) and subsequently demonstrated by Dale (17). Dale (17) showed that the optimum embedment of glass beads for retroreflective markings is 60% of the bead diameter. Retroreflectivity will drop to zero if the embedment is less than 50% and will decrease rapidly when the embedment exceeds 70%. Dale also explained the reason why the wet-nighttime visibility of markings is very poor: small glass beads often become submerged in a film of water so that light from headlights bounces off the water surface and never reaches the glass beads. As a result, Dale recommended the use of large glass beads. He estimated that 6 mm (0.25 in.) diameter of glass beads would be needed to overcome a 1.0 mm (40 mil) film of water.

Agent and Pigment (2) evaluated the effect of glass beads with different sizes and refractive indices on the nighttime visibility of regular paint. Table 2 shows the fine, regular, and coarse gradations of glass beads used for that study. Agent and Pigment found that the fine beads exhibited the best long-term reflectivity of the three gradations because smaller beads are not easily dislodged from paint. The regular paint markings with coarse glass beads had the lowest reflectivity due to a loss of the beads.

Kalchbrenner (28) evaluated the performance of large glass beads in durable marking materials under rainfall and wet night conditions. The rainfall conditions were simulated in a "rain tunnel" at three different rates of precipitation, 6 mm/hr (1/4 in./hr), 13 mm/hr (1/2 in./hr), and 19 mm/hr (3/4 in./hr). The wet night evaluation was carried out in the field using a portable Mirolux retroreflectometer. Since the durable materials have stronger adhesion to pavement than

traffic paint and, generally, the dry thickness of the durable materials is greater than traffic paint, the use of large glass beads becomes possible without losing durability. Kalchbrenner showed that the retroreflectivity of large glass beads [850 μm to 1180 μm (10 to 20 mesh)] in durable materials was obviously higher than that of regular glass beads for both initial and long-term performance, especially under wet conditions.

Two application methods, single-drop and dual-drop, were evaluated by Kalchbrenner (28). For the dual-drop application, large glass beads were applied first, and followed by a second drop-on of binder-specific standard size beads (beads selected for use with the specific coating treatment). The evaluation indicates that both single-drop and dual-drop applications provide similar initial wet-night visibility performance and dry retroreflectivity; the dual-drop application gives slightly improved long-term dry retroreflectivity.

Potters Industries began experimenting with large glass beads both in the laboratory and in the field in 1984 (28). The effort has clearly demonstrated the effectiveness of large-bead systems. One large-bead system is sold by Potters for use in epoxy, polyester, and thermoplastic pavement markings (28). Table 3 shows the gradation specifications and recommended application rates of the systems.

O'Brien (39) evaluated embedment and retroreflectivity of drop-on regular-size glass beads in thermoplastic markings. The test results reveal that the optimum application rate of drop-on glass beads is 0.5 kg/m^2 (10 $\text{lb}/100 \text{ft}^2$). A 0.3 kg/m^2 (6 $\text{lb}/100 \text{ft}^2$) rate provided minimum acceptable brightness as compared with the higher application rates. When the application rate exceeded 0.5 kg/m^2 (10 $\text{lb}/100 \text{ft}^2$), the glass beads began to overlap, and bead embedment diminished. The use of coated (moisture proofed) spheres resulted in optimum embedment of 60-65 percent in thermoplastic systems and the initial retroreflective properties

were excellent. The embedment of uncoated beads were generally greater than 80 percent.

In a study of different types of pavement markings as related to retroreflectivity and wear, Lundkwis (31) investigated different additions, makes, and size of glass and plastic beads, in thermoplastic markings. He concluded that 1) a thermoplastic compound containing 20% glass beads and 5% plastic beads by weight exhibits high retroreflectivity and acceptable durability, 2) plastic beads raise retroreflectivity without reducing durability, and 3) marking compounds containing solely small beads ($< 100 \mu\text{m}$ in diameter) provided a low specific luminance reading.

The International Commission on Illumination (46) published laboratory experimental results of retroreflectivity as a function of application rate and depth (embedment) of glass beads for two particle size classes [315-500 μm (12.4-19.7 mils) and 125-315 μm (4.92-12.4 mils)]. The curves are shown in Fig. 3. The followings may be noted on these curves:

- a. Retroreflection decreases rapidly with increasing application rate of glass beads with a embedment of 50-55 percent of bead diameter. However, the application rate with 50-55 percent embedment that gives the best retroreflection is not recommended because the action of traffic is considerable on beads that are not deeply embedded.
- b. Retroreflection increases with the application rate of glass beads with embedment of 80-95 percent of bead diameter.
- c. For embedment between 60 to 80 percent of bead diameter, the retroreflection increases initially with the application rate and then decreases.
- d. These results show the primary importance of the depth of bead embedment on the retroreflection level. It is pointless to have an efficient application rate if the depth is not effectively controlled.

Performance of markings

As mentioned before, markings with large glass beads have better retroreflection than markings with standard glass beads in wet night conditions. Attaway et al. (7) shows that, while the reflectivity performance of markings with large glass beads show no improvement over markings with regular drop-on beads under dry nighttime conditions, their performance is much better under wet nighttime conditions. The evaluation results obtained by King and Graham (29) indicate that, under actual rainfall conditions in the field, epoxy markings with larger glass beads are visible at twice the distance of similar markings with standard beads.

There is common agreement that the nighttime visibility of thermoplastic materials is somewhat better than that of other marking materials, especially under wet night conditions (15). Field evaluation of thermoplastic using a portable retroreflectometer by the North Carolina State Department of Transportation (NCDOT) (6) shows that white thermoplastic provides acceptable service (based on an acceptable level of retroreflectivity of 100 mcd/m²/lx as measured with an Ecolux) under a wide range of traffic conditions in North Carolina for 6 to 8 years. Yellow thermoplastic provides at least 3 years of service, and longer in some cases.

Preformed tapes usually have very high initial retroreflectivity, but their retroreflectivity reduces very quickly in service. In an evaluation of the retroreflective behavior of five long-life preformed tapes, NCDOT (6) determined that the tapes provided an acceptable level of retroreflectivity for only 2 years.

Measuring Method

Evaluation and measurement of the visibility of pavement markings must be related to the visual requirements of the driver (46). Daytime reflection is usually measured under 45° (angle) illumination and 0° (angle) view (45/0 geometry) from the perpendicular to the road marking

according to ASTM E 97 (67). Retroreflectivity can be measured in a laboratory according to AASHTO T 257 (54) or Publication No. 54 of the International Commission on Illumination (69). The specific luminance or coefficient of retroreflected luminance ($\text{mcd/m}^2/\text{lx}$) is widely used as the measurement quantity for the retroreflectivity of marking stripes.

Retroreflective measuring instruments can be used for the evaluation of the visibility of pavement markings in both the field and the laboratory. In a research report on retroreflective measurement devices for pavement markings, Hoffman and Firth (26) divided the retroreflectometers into two classes, "fine" (geometry) and "coarse" (geometry). The fine geometry means that the light is incident at a fine angle approaching 0° , say 3.5° , with the horizontal surface, which is usually called 86.5° geometry (86.5° entrance angle to the normal). "Coarse" geometry means that the light is incident at a higher angle (say 15°) with the horizontal surface. Hoffman and Firth state that commercially manufactured instruments, such as the Ecolux, Erichsen, Optronik and Zehntner, all have a "fine" geometry and optical system to give a long, narrow light path, while instruments developed by, or for, state DOT's, such as Michigan, New York, Pennsylvania and Virginia, have a "coarse" geometry (with the exception of the Wallometer from Ohio). Analyses and repeated tests by Hoffman and Firth (26) affirmed that only the "fine" instruments can distinguish inadequate embedment of glass beads and are satisfactory for the purpose of accepting, or rejecting, newly laid markings. Hoffman and Firth also concluded that " 'coarse' instruments are adequate for the purpose of measuring the change in bead spacing as the paint deteriorates, but not for the purpose of determining the retroreflectivity level. However, it is statistically established that comparing different paint systems becomes unreliable as reflectivity decays: a State which procures paint by comparing life-to-failure would choose different paints if it used different instruments."

The Mirolux 12 is a portable "fine" (geometry) retroreflectometer which has been used for measuring retroreflectivity of pavement markings in many studies (6,7,29). *Better Roads* magazine (5) reported a new laser retroreflectometer developed by Potters Industries and Advanced Retro Technology, Inc. The laser retroreflectometer has a number of advantages: it allows mobile monitoring of pavement markings at highway speeds, including readings taken in the rain; use of the instrument provides much more accurate readings than earlier (primarily from hand-held) retroreflectometers; the cost is reasonable; and the method lets departments check on bead distribution and functionality during striping.

For the purpose of determining the retroreflectivity levels of markings, a subjective evaluation-rating is often applied along with objective measurements of retroreflectivity using retroreflectometers (23, 29). Usually, the rating levels are "less than acceptable", "acceptable", and "more than acceptable" (more rating levels can be added). The subjective rating level has been shown to be a logarithmic function of the retroreflectivity reading (26, 29).

2.5 Cost-Effectiveness

NCHRP Report 138 (19) gives a summary of the cost-effectiveness of various marking systems. It is stated that, "if a given pavement marking material is applied to a properly prepared pavement surface, using correct application procedure, its life expectancy will be a function of the type of pavement, the volume of traffic, the type of traffic, the environmentally induced factors including salt and sand, snowplowing, studded tires, and chains." In the report, the life expectancy of different types of marking materials is based on various sources, as divergent as California and New York and related to experience at different sites. The results are reproduced in Figs. 4 to 13. These figures show that, generally, 1) the life expectancy of markings is

inversely proportional to annual average daily traffic volume (AADT), 2) the amount of snowfall significantly reduces the marking service life due to snow removal, and 3) all surface markings, except epoxy markings, provide longer service life on asphaltic pavement than on portland cement concrete pavement.

Table 8 shows the life expectancy and the cost (in 1994 dollars) under 150-900 mm (6-36 in.) snowfall conditions on portland cement concrete pavement, as well as the cost-effectiveness factors (the ratio of cost to life expectancy) based on NCHRP Report 138 (19) and other sources (13, 35, 47). The results in Table 8 indicate that thermoplastic markings [3 mm (120 mil) thickness] are the most cost-effective marking systems among surface markings, with cost effectiveness factors in range of 0.07 to 0.12 for an AADT between 8000 and 16000. Epoxy markings are more cost-effective than preformed tapes. They are also more cost-effective than traffic paints under high traffic volume conditions (say above an AADT of 12000). The cost-effectiveness factors of epoxy markings are between 0.17 and 0.34 for an AADT from 8000 to 16000. Traffic paints are the cheapest marking material, with \$0.13 to \$0.23 per linear meter (\$0.04 to \$0.07 per linear foot), but they are only cost-effective under low traffic volume conditions. Preformed tapes [2.3 mm (90 mil) thickness] may provide the longest service life (say 4.7 to 3.5 years on concrete pavement with an AADT between 8000 and 16000). However, preformed tapes generally have highest cost-effectiveness factor (0.24 to 0.39).

2.6 Experience on PCPM

Material and performance

Most of the experience on PCPM over past 20 years has been obtained by the Washington State Department of Transportation (WSDOT). Anderson (4) investigated three backfilling

materials that were placed in 6 mm (1/4 in.) or 13 mm (1/2 in.) deep by 100 mm (4 in.) wide recesses in portland cement concrete pavement. The three materials were 1) white cement mortar with the mixture ratio varied from 1:1:2 to 2:1:2 to 2:1:3 for components of cement, glass beads, and sand, 2) Cleanosol thermoplastic from Sweden, and 3) Adhesive Engineering's Concreative 1064 (white), a two-component epoxy material containing reflective glass beads. Visual examinations showed that the durability of all three backfilling materials was outstanding over a three-year span. Only some hairline cracks were found on the marking surfaces, but no pop-outs or loss of material was observed. All three markings were more visible than the standard paint stripe under dry daytime conditions, and were the equal of paint under dry nighttime conditions. However, as Anderson observed that "all of the systems suffer in visibility under wet (daytime) conditions. The stripes virtually disappear when there is a water film over them. ... their visibility is only in the range of about 50 feet." None of the three systems provided adequate wet nighttime visibility. The Cleanosol stripe was the best one among the three systems for wet nighttime visibility, providing a visibility distance of about 50 feet.

In the mid 1980's, WSDOT (20) investigated three other inlaid stripe materials: Concreative 1170, a white pigmented epoxy supplied by Adhesive Engineering Company; Lafrentz System 400, a methyl methacrylate supplied by Lafrentz Road Service Ltd; and Norline hot thermoplastic supplied by Norris Paint Company. All three materials contained premixed glass beads, and drop-on glass beads were applied to all three systems. During the first year after the installation, the Concreative and Lafrentz systems showed very good adhesion and very little wear, and provided very good daytime visibility. However, both of the materials provided only marginal nighttime visibility because of a loss of glass beads. The top layer of glass beads were sheared off by snowplows, chains and studded tires. The Norline thermoplastic material suffered

considerable damage during its first six months of service: the stripes began to crack and spall out of the grooves almost immediately. The 60% of the material that remained in the grooves was worn just slightly. It was noted that the softness of the thermoplastic allowed the glass beads to wear off rather than shear off. This wear exposed more glass beads, which caused the nighttime visibility of the thermoplastic inlaid stripes to remain very good. However, the thermoplastic material did not provide as good a daytime visibility as the other two materials because of the loss of material. During installation, problems were encountered with the Concrete 1170 epoxy material: the glass beads in the mixture sank to the bottom of the stripes due to its low viscosity and long curing time; and the material flowed to down hill or to the lower side of the grooves, also due to low viscosity of the epoxy, necessitating retroweling of the stripe and reapplication of the drop-on glass beads.

Placing grooves

Making a groove is an important step for PCPM. Grooves can be placed into an existing pavement or during the initial paving operation. Diamond saws are commonly used to place grooves into existing portland cement concrete pavements. Investigators from WSDOT (4) investigated three procedures for grooving existing concrete pavements, using a diamond saw, a high-water jet, and a grinder. In that study, the diamond saw was found to be superior to the water jet and the grinder. More generally, concrete sawing equipment can be readily modified for making 4 in. wide grooves. There are at least two ways of using a diamond saw to make a wide groove (11).

- a) Diamond blades are stacked on a head with the required width and the pavement is cut vertically. The spaces between the blades are so small that grooves can be made directly. The disadvantage of this method is that it needs many diamond

saw blades to cut the required width and replacing inside damaged blades is not simple, requiring the removal of all blades from the head.

- b) A flatbottomed groove cut is made with a series of equal size horizontal cutting wheels. The cut is started by a short plunge cut with vertical blades. The grooves are cut horizontally and have a uniform depth and two circular arcs at ends.

In addition to diamond saws, there appears to be additional equipment worth considering. The Richland grinding machine (37), designed by Rick Younger and fabricated by Steel Engineers, Inc., is an option worth considering. This device has replaceable straps mounted on a rotating drum. Diamond segments are attached to sections of the strap, allowing damaged diamond segments to be easily replaced.

In the literature and patent search, no evidence was found that any attempts have been made to place grooves in portland cement concrete pavement as the pavement is being constructed. There are, however, several techniques that may be useful for this purpose: 1) using a special diamond saw to cut soft concrete (27); 2) rolling a cylinder or impressing plates in a soft concrete surface (38,45); and 3) using plates in conjunction with the slipforming operation.

CHAPTER 3

DISCUSSION OF PCPM

As described in the preceding chapter, the permanent pavement markings studied to date (4,20) have, in general, very good durability. However, like surface markings, the problem of insuring adequate visibility under wet conditions has not been solved. The initial cost of permanent markings is generally higher than that of other markings. Because of the rapid development of science and technology, however, a strong possibility exists for the development of a cost-effective PCPM system that will provide both long-term durability and adequate visibility throughout the service life. The following sections address the requirements of an effective PCPM system, including materials, installation, and cost. Since little research has been done on PCPM, many unknowns still exist, such as failure mode (durability failure or visibility failure), service life, and effects of thickness of PCPM, application of glass beads, and mixture design of backfilling material.

3.1 Basic Requirements

To date, no standard specifications for permanent pavement markings have been developed. Therefore, the following basic requirements are based on the ASTM, AASHTO, and KDOT standard specifications for surface pavement markings.

Durability

- (a) As permanent markings, PCPM shall have a design service life equivalent to the design life of the pavement.
- (b) PCPM shall be resistant to salt, solvents, grease, oil, and fuel.

- (c) PCPM material shall be weather resistant and show no appreciable fading, spalling, or other loss during the normal service life of the material.
- (d) PCPM shall tolerate tire wear and snow removal operations, including the use of salt, sand, and snowplows (and where applicable studded tires and chains). The amount of loss of reflective materials shall not be greater than 50 percent over the service life.

Visibility

Daytime visibility

White: daylight reflectance at 45°-0° shall be a minimum of 75 percent based on the ASTM E 97 (67) test method; the daylight color of white striping material shall be no darker than Color No. 37778 of Federal Standard No. 595a (68).

Yellow: daylight reflectance at 45°-0° shall be a minimum of 45 percent based on the ASTM E 97 (67) test method; the color shall match Color No. 13538 of Federal Standard No. 595a (68).

Retroreflectivity

The retroreflectivity value of PCPM shall be at least 100 mcd/m²/lx under dry-nighttime conditions when measured at 86.5 degree (light) entrance angle (the angle from light entrance to the normal) and 1.0 degree observation angle (the angle from the direction of light entrance) using a "fine" retroreflectometer that has been properly calibrated based on Test Method ASTM D 4061(59). Or PCPM shall be readily visible under dry nighttime conditions when viewed with automobile head-lamps using high beams from a distance of at least 300 feet (72). The minimum acceptable retroreflectivity under wet nighttime conditions needs further study.

Glass beads

The glass beads shall meet the general requirements of AASHTO M 247 (49). The refractive index shall be at least 1.5.

Installation

- (a) The surface of the grooves to hold the PCPM material shall be dry and clean.
- (b) The working life of the material shall be long enough to insure adequate installation.
- (c) Premixed glass beads shall be uniformly distributed in the marking material. Drop-on glass beads shall be uniformly distributed over the surface of the marking. The drop-on glass beads shall be embedded 60 to 65 percent of the bead diameter.

3.2 Selection of Materials

Selection of materials is the key to making PCPM successful. The materials selected should meet the basic requirements described above and be cost-effective.

Portland cement based

Portland cement has good durability and is cheaper than the other durable materials. To obtain good color matching, white cement is recommended for use. A yellow color can be achieved by adding color-conditioning admixtures to the white cement. The mixture ratio of the components of cement, water, sand, and glass beads should ensure that the fluid material should have enough workability and suitable fluidity, and that there be enough glass beads to ensure long-term visibility. For the application of drop-on glass beads, pressure application may be needed for adequate embedment. To date, there have been no attempts to test glass bead retention and long-term performance in portland cement based PCPM. Glass beads for use with portland cement will have to be alkali resistant.

Polymer binder based

Generally, it is expected that the polymer binders that can be used for portland cement concrete overlays can be used as backfilling materials for PCPM. ACI Committee 548 recommends four kinds of polymer binders for thin polymer concrete overlays, epoxies, polyesters, methyl methacrylates, and polyurethanes (1). Of these materials, epoxies are recommended as the first choice for PCPM due to their superior durability and adhesive behavior, based on the experience of WSDOT (4, 20). Some thermoplastics may be used for PCPM with a careful check of their properties and limitations of application. Table 4 shows the properties of some polymer binders. For the selection of a polymer binder as the backfilling material for PCPM, the following properties require consideration:

- (a) The thermal expansion of polymers is several times higher than that of portland cement concrete. Therefore, a lower coefficient of thermal expansion is desirable for thermal compatibility and freeze-thaw resistance. Fillers could be used to reduce the coefficient of thermal expansion.
- (b) High tensile elongation and low modulus of elasticity are desirable to provide thermal stress relief and avoid bond failure or fracture at the bond interface.
- (c) High bond strength is desired.
- (d) Low curing shrinkage is desired. For high curing shrinkage (above 2 percent), the use of fillers may be necessary to avoid shrinkage cracking.
- (e) The polymer binder should have proper viscosity for both successful application of drop-on glass beads and workability in installation. Low viscosity is helpful for obtaining enough embedment of drop-on glass beads, but high fluidity of the backfilling material will result in the material flowing to down hill or to the lower

side of a groove.

- (f) According to the experience of WSDOT (20), a long set time may cause glass beads that are mixed in the polymer binder to sink to the bottom of the marking stripe. Therefore, a reasonably fast set time is desirable. The use of a polymer binder with a fast set time may overcome problems involved with high fluidity problems.

The use of fillers can improve the properties of polymer backfilling materials. However there is little information about mixture design for the backfilling material of PCPM. The question of suitable mixture designs and viscosity of binders remains open for PCPM.

3.3 Installation

Placing grooves

On existing concrete pavement, a diamond saw cutting machine is recommended. The cutting equipment should be self-propelled, be able to make straight-edge grooves with the required width and depth, and be able to remove the slurry produced by the process. Equipment combining cutting, cleaning, and drying functions is desirable.

For new concrete pavement, the use of groove plates in conjunction with slipforming appears to provide a useful option for forming solid stripes. However, cutting with multiple diamond saws on soft concrete appears to be the best choice for broken stripes.

Coloring techniques

Like integrally colored concrete, there are two basic methods for producing colored PCPM. One is by using colored marking materials directly and the other is by adding a coloring agent during the mixing process. For use with polymer materials, colored polymer binders are

available. Selection of the binder includes a check to insure that the resins have good stability in sunlight. Another option is the addition of a pigment or color conditioning admixture (in the case of cement), in which case transparent or white binder should be used to obtain the closed color matching.

Application of glass beads

Larger glass beads can be used with thicker markings. They can be especially important for improving visibility in wet nighttime conditions. Since PCPM will likely be in the range of 1/8 to 1/4 in. thick, the use of larger glass beads will be possible. For obtaining long-term wet nighttime visibility, it seems that both premixed and drop-on applications of glass beads are necessary. However, for PCPM, it is currently not known what the optimum size and application rate of glass beads will be and which application method will be best for durability and visibility, as well as cost effectiveness.

3.4 Cost Analysis

The main purpose of this project is to establish whether or not a cost-effective PCPM system can be developed. The initial cost of PCPM will generally be higher than other marking systems. However, if PCPM has the desired service life, it will be cost effective when compared with other systems. In this cost analysis, only epoxies and thermoplastics are considered. The estimation of the installed cost is based on the previous experience on PCPM (4), cutting grooves (22) and other sources (19, 35).

Placing grooves

Table 5 shows the estimated cost for cutting a 100 mm (4 in.) wide groove in a concrete pavement using a dedicated diamond blade machine specifically designed for the purpose of

making marking grooves, including cutting, water cooling, and vacuum slurry removal, and a two (2) person machine operation, amortized at \$200/hr and a diamond blade cost of \$425/each plus 25 percent overhead and profit (22). Based on experience, the cost of cutting a groove into new concrete is approximately the same to that into hardened concrete, depending only on the cut depth and aggregate. The estimated cost is in range of \$0.49 to \$3.38 per linear meter (LM) [\$0.15 to \$1.03 per linear foot (LF)], depending on cut depth and aggregate. For a depth of 6.4 mm (1/4 in.), the costs are \$0.98/LM (\$0.30/LF) and \$2.23/LM (\$0.68/LF) for limestone and traprock-granite aggregates, respectively. For a solid-stripe groove shaped during concrete slipforming operation, the cost of shaping the groove is estimated at approximately 25 percent of the cost of cutting the groove - \$0.13/LM (\$0.04/LF) to \$0.85/LM (\$0.26/LF).

The previous experience of WSDOT on PCPM (4) showed that the cost of cutting a 6.4 mm (1/4 in.) thick groove was about \$4.99/LM (\$1.52/LF) (1994 price), almost equal to the cost of the epoxy material. The high cost of cutting the groove is the reason why the cost of the previous PCPM systems was high. However, the cost of placing a groove using a dedicated cutting machine is about 50 percent less than that of WSDOT, while the cost of shaping a solid-stripe groove, placed during concrete slipforming, is at least 75 percent less. These comparisons indicate that the costs of placing the groove will be very important for producing low cost PCPM.

Installed material

The installed cost of the materials depends on the thickness of the markings, the material, and the installation method. Table 6 shows the estimated installed cost of epoxies and thermoplastics, including material, labor, equipment, and overhead and profit. The installed cost of the materials ranges from \$0.48 to \$2.06 for thicknesses between 3.2 mm (1/8 in.) and 9.5 mm (3/8 in.). For a 6.4 mm (1/4 in.) thickness, the installed costs of the materials are \$2.04/LF and

\$0.76/LF for epoxies and thermoplastics, respectively.

Cost-effectiveness for long-term service

Table 7 shows the total installed costs of PCPM systems based on the above cost analyses. For epoxy PCPM systems with thicknesses between 3.2 mm (1/8 in.) and 9.5 mm (3/8 in.), the total installed costs should be between \$2.99/LM (\$0.91/LF) and \$10.14/LM (\$3.09/LF) for solid stripes on existing concrete pavement and broken stripes on new or existing concrete pavement, and between \$2.62/LM (\$0.80/LF) and \$7.64/LM (\$2.33/LF) for solid stripes on new concrete pavement. For thermoplastic PCPM systems, the corresponding total installed costs should be in the range of \$2.07/LM (\$0.63/LF) to \$8.04/LM (\$2.45/LF) for solid stripes on existing concrete pavement and broken stripes on new or existing concrete pavement, and \$1.71/LM (\$0.52/LF) to \$5.58/LM (\$1.70/LF) for solid stripes on new concrete pavement.

Table 7 also shows the cost-effectiveness factors which represent the total installed cost divided by the estimated service life. The cost-effectiveness factors for epoxy PCPM with thickness of 3.2 mm (1/8 in.), 6.4 mm (1/4 in.) and 9.5 mm (3/8 in.) are, respectively, 0.08-0.11, 0.16-0.21, and 0.23-0.31 for a 10-year service life, and 0.04-0.05, 0.08-0.11, and 0.12-0.16 for a 20-year service life. The cost-effectiveness factors for thermoplastic PCPM with thicknesses in the range of 3.2 mm (1/8 in.) to 9.5 mm (3/8 in.) are between 0.08 and 0.23 for a 10-year service life, and between 0.04 to 0.09 for a 20-year service life. The results indicate that, the thermoplastic PCPM systems might be more cost-effective than the epoxy PCPM systems, if thermoplastics have no adhesive problems to portland cement concrete.

The cost-effectiveness factors of standard surface markings vary from 0.10 to 0.40, depending on the marking material and traffic volume (see Table 8). The comparisons indicate that all of the PCPM systems are cost competitive for a 20-year service life, when compared with

surface marking systems. Even, for a 10-year service life, PCPM systems with a 3.2 (1/8 in.) thickness should be very competitive based on cost.

CHAPTER 4

CONCLUSIONS

The following conclusions are based on the analyses presented in this report.

1. The development of a successful permanent concrete pavement marking (PCPM) system requires considerations of visibility, durability, and cost-effectiveness.
2. Generally, previous attempts at developing PCPM systems have produced systems with very good durability, but poor nighttime visibility.
3. Although unknowns, such as optimum depth, optimum mixture design, and glass bead application procedure, exist, there is a strong possibility that a cost-effective PCPM system can be developed.
4. Polymers, such as epoxies, are recommended as potentially the most effective backfilling materials for use in PCPM systems because of their superior durability and adhesion to concrete.
5. The application of larger glass beads will improve the wet nighttime visibility.
6. The cost of placing a groove is very important for developing a cost effective PCPM system. The cost of PCPM can be significantly reduced by using 1) a cutting machine designed specifically for grooving and 2) placing continuous grooves during the paving operation.
7. Epoxy and thermoplastic PCPM systems with a thickness of 9.5 mm (3/8 in.) or less will be generally cost effective for a 20-year service life, when compared with other marking systems. Systems with a thickness of 3.2 mm (1/8 in.) or less will be cost effective for a 10-year service life.

CHAPTER 5

STEPS REQUIRED FOR SUCCESSFUL IMPLEMENTATION OF PCPM

This report represents a summary of the background needed for the development of a successful permanent concrete pavement marking system. To implement such a system, however, will require a substantial research and development effort. The following steps will be required in that implementation effort:

1. Definition of failure of PCPM involving service life and failure model.
2. Determination of best combinations of depth and materials to provide adequate visibility and durability, as well as cost effectiveness, including a) optimum depth of PCPM with optimum combination of materials including binder and gradation (size) of glass beads, b) optimum mixture design of backfilling material (with or without fillers or glass beads and percentage of fillers and glass beads), and c) optimum glass bead application method and rate.
3. Development of a specification for PCPM.

REFERENCES

1. ACI Committee 548, "Guide for Polymer Concrete Overlays - ACI 548.5 R", *ACI Manual of Concrete Practice*, Part 5, American Concrete Institute, Detroit, MI, 1994.
2. Agent, Kenneth R. and Pigman, Jerry G., "Performance Evaluation of Experimental Paint-Stripe Beads," *Report No. FHWA/RD/KY-83/27*, Kentucky Transportation Research Program, College of Engineering, University of Kentucky, Lexington, Kentucky, 1983, 14 pp.
3. Allen, R. W., O'Hanlon, J. F., and Mckuer, D.T., "Driver's Visibility Requirements for Roadway Delineation," Vol. I, Effects of Contrast and Configuration on Drivers Performance and Behavior, *Report No. FHWA-RD-77-165*, System Technology, Inc, Hawthorne, California, 1977, 213 pp.
4. Anderson, K. W., "Permanent Lane Marking, (Recessed Lane Edge Stripe)," *Report No. WA-RD-46.1*, Washington State Department of Transportation, Olympia, WA, 1983, 23 pp.
5. Anon, "Quick way to measure marking reflection," *Better Roads*, Vol. 59, No. 12, 1989, pp. 40-41.
6. Attaway, R. W., "In-Service Evaluation of Thermoplastic and Tape Pavement Markings Using a Portable Retroreflectometer," *Transportation Research Record* 1230, TRB, National Research Council, Washington, D. C., 1989, pp. 45-55.
7. Attaway, R. W. and Adeleke-Sheidun, P. O., "Pavement Marking Materials Program," *Report No. FHWA/NC-89/005*, UNC Institute for Transportation Research and Education, Research Triangle Park, NC, 1990, 245 pp.
8. Baumann, Fred H., "Review of Traffic-Paint Research", *Pavement Marking Materials*, Highway Research Board Bulletin 57, National Research Council, 1952, pp. 23-31.
9. Blackwell, R. H., "Contrast Thresholds of The Human Eye," *Journal of the Optical Society of America*, Vol. 36, No. 11, 1946, pp. 624-643.
10. Blaauw, G. J., "Nighttime Visibility of Various Types of Road Markings: A Study on Durability, Including Conditions of Rain, Fog, and Dew," SAE Paper 820412, Detroit, 1982.
11. Bodenheimer, B. A., "Recessed Reflective Marker Feasibility Study," *Report No. FHWA/TS-86/207*, Bodenheimer (B. A.) and Co., Inc., Stanford, CT., 1985, 33 pp.

12. Bryden J. E. and Gurney, G. F., "Pavement-Marking Materials: New York's Experience," *Report No. FHWA/NY/RR-84/112*, New York State Department of Transportation, Albany, NY, 1984, 19 pp.
13. Bryden J. E., "Development of a Statewide Pavement-Marking Policy," *Report No. FHWA/NY/RR-88/143*, New York State Department of Transportation, Albany, NY, 1988, 28 pp.
14. "'Buttoning' The Streets Protects Chicago's Downtown Pedestrians," *Highway*, Vol. XVIII, No. 9, 1927, p. 247.
15. Chaiken, B., "Comparison of The Performance and Economy of Hot-Extruded Thermoplastic Highway Striping Materials and Conventional Paint Striping," *Public Roads*, Vol. 35, No. 6, 1969, pp. 135-156.
16. Culp, T., Yankovich, R., and Khan, M., "Polyester Markings," Durable Pavement Marking Materials Workshops, *Report No. FHWA-TS-81-221*, Federal Highway Administration, Washington, D. C., 1981.
17. Dale, J., "Development of Improved Pavement Marking Materials - Laboratory Phase," *NCHRP Report 45*, HRB, National Research Council, Washington, D. C., 1967, 24 pp.
18. Dale, J. M., "Pavement marking - Danish style," *Better Roads*, Vol. 4, No. 2, 1970, pp. 28-31.
19. Dale, J. M., "Pavement Markings: Materials and Application for Extended service Life," *NCHRP Report 138*, HRB, National Research Council, Washington, D. C., 1988, 45 pp.
20. Deer, R. and Mansfield, C., "Inlaid Traffic Lane Lines: I-90, Edgewick Road to Hyak," *Report No. WA-RD-184.1*, Washington State Department of Transportation, Olympia, WA, 1989, 36 pp.
21. "Edward N. Hines, Father of Center Traffic Line," *Roads and Streets*, Vol. 79, 1939, p. 52.
22. "Estimated Cost of Cutting Grooves," A Letter from the Allen Engineering Corporation, June 20, 1994.
23. Ethen, J. L.; and Woltman, H. L., "Minimum Retroreflectance for Nighttime Visibility of Pavement Markings," *Transportation Research Record 1093*, HRB, National Research Council, Washington, D. C., 1986, pp. 43-47.
24. Gillis, H. J., "Durable Pavement Marking Materials," *Transportation Research Report, 762* TRB, National Research Council, Washington, D. C., 1980, pp. 36-43.

25. Griffin, R. G., "Pavement Marking Materials," *Report No. CDOH-DTD-R-90-4*, Colorado State Department of Highways, Denver, 1990, 121 pp.
26. Hoffman, A. G. and Firth, B. W., "State-of-the-Practice Retroreflective Measurement Devices for Pavement Markings," *Report No. FHWA/TS-84/222*, Mobility System and Equipment Company, Los Angeles, 1985, 68 pp.
27. Johnston, R., "Saw cutting concrete flatwork," *Concrete Construction*, Vol. 39, No. 6, 1994, pp. 483-490.
28. Kalchbrenner, J., "Large Glass Beads for Pavement Markings," *Transportation Research Report 1230*, TRB, National Research Council, Washington, D. C., 1989, pp. 28-40.
29. King, L. E. and Graham, J. R., "Evaluation of Pavement Marking Materials for Wet Night Conditions," *Report No. FHWA/NC/003*, North Carolina University at Charlotte, Charlotte, 1989, 183 pp.
30. "Long Life Pavement Marking System," Poly-Carb Company, Cleveland, Ohio, 27 pp.
31. Lundkwis, S. O., "Study of Different Type of Road Markings as Related to Retroreflectivity and Wear," *Report No. VTI/MEDDELANDE-517A*, Statens Vaeg-och Trafikinstitut, Linkoeping, Sweden, 1989, 19 pp.
32. Lynch, L. N., "Pavement marking Types and Application," *Report No. GL-91-15*, Geotechnical Laboratory, US Army corps of Engineers, Vicksburg, MS, 1991, 35 pp.
33. Lysaght, M. J.; and Rich, T. R., "Epoxy Striping for Improved Durability," *Report No. FHWA-RD-78-156*, Amicon Corporation, Lexington, 1978, 140 pp.
34. Mattimore, H. S., "Highway Traffic Line (Zone) Paint," *Proceedings*, Highway Research Board, Vol. 5, Part 1, 1925, pp. 177-184.
35. "Means Heavy Construction Cost Data," R. S. Means Company, Inc., 8th Annual Edition, Kington, MA, 1994, 71 pp.
36. Meseberg, H. -H., "Retrometer zur Messung der Retroreflexion (Nacgtsuchtbarkeit) von Fahrbahnmarkierungen," *Straßenverkehrstechnik* 28, H. 2, S. 65-69, German, 1984.
37. "New Tools for Grooving or Grinding Pavements," *Concrete Construction*, Vol. 37, No. 7, 1992, pp. 561-563.
38. Novinson, T., "A Durable Airfield Marking System," *Report No. ESL-TR-84-59*, Engineering & Service Laboratory, Air Force Engineering & Service Center, Tyndall Air Force Base, Florida, 1985, 27 pp.

39. O'Brien, J., "Embedment and Retroreflectivity of Drop-on Glass Sphere in Thermoplastic Markings," *Transportation Research Report 1230*, TRB, National Research Council, Washington, D. C., 1989, pp. 37-44.
40. Pocock, B. W. and Rhodes, C. C., "Principles of Glass Bead Reflectorization," *Bulletin 57*, HRB, National Research Council, Washington, D. C., 1952, pp. 32-48.
41. Robertson, N., "Preformed Pavement Markings," Durable Pavement Marking Materials Workshops, *Report No. FHWA-TS-81-221*, Federal Highway Administration, Washington, D. C., 1981.
42. Robnett, Q. L. and Burrows, W. H., "Development of a Porous Lane Marking Systems," Office of Research & Development, Federal Highway Administration, Washington, D. C., 1977, 161 pp.
43. Sawyer, C. L., "White Brick form Permanent Centerline in Ohio County Road," *Engineering News-Record*, Vol. 93, 1924, p. 965.
44. Serres, A. M., "The Road Marking Visibility Relationship to the Contrast with the Road Surface, Requirements for Day Visibility and Night Visibility," International Symposium on Visual Aspects of Road Markings, Paris, May 1983.
45. Smith, A., "Pattern Rolling Instead of Stamping?," *Concrete Construction*, Vol. 36, No. 2, 1991, pp. 177-180.
46. "Visual Aspects of Road Markings," Joint Technical Report, International Association of Road Congresses, 1986, 53 pp.
47. Wagner, J. A., "Investigation of Possible Maintenance Procedures for Insuring Best Performance and Service Life of Thermoplastic Traffic Stripes," *Report No. FL/DOT/BMR-85-287*, Bureau of Materials and Research, Florida State Department of Transportation, Tallahassee, Florida, 1985, 50 pp.
48. "White Mortar Bands Mark Highway Traffic Lanes," *Engineering News-Record*, Vol. 109, No. 19, March 1932, pp. 553-555.

Standards:

49. AASHTO Designation: M 247, Standard Specification for Glass Beads Used in Traffic Paint.
50. AASHTO Designation: M 248, Standard Specification for Ready-Mixed White and Yellow Traffic Paints.
51. AASHTO Designation: M 249, Standard Specification for White and Yellow Reflective Thermoplastic Striping Material (Solid Form).

52. AASHTO Designation: M 309, Standard Specification for White and Yellow Fast-Dry Traffic Paint.
53. AASHTO Designation: T 250, Standard Method of test for Thermoplastic Traffic Line Material.
54. AASHTO Designation: T 257, Standard Method of Test for Instrumental Photometric Measurements of retroreflective Materials and Retroreflective Devices.
55. ASTM Designation: D 713, Standard Practice for Conducting Road Service Tests on Fluid Traffic Marking Materials.
56. ASTM Designation: D 868, Standard Test Method for Evaluating Degree of Bleeding of Traffic Paints.
57. ASTM Designation: D 913, Standard Test Method for evaluating Degree of resistance to Wear of Traffic Paint.
58. ASTM Designation: D 969, Standard Test Method for Laboratory Evaluation of Degree of Bleeding of Traffic Paints.
59. ASTM Designation: D 4061, Standard Test Method for Retroreflectance of Horizontal Coatings.
60. ASTM Designation: D 4280, Standard Specification for Extended Life Type, Nonplowable, Prismatic, Raised, Retroreflective Pavement Markers.
61. ASTM Designation: D 4383, Standard Specification for Plowable, Raised, Prismatic, Reflective Pavement Markers.
62. ASTM Designation: D 4451, Standard Test Method for Pigment Content of Paint by Low-Temperature Furnace Ashing.
63. ASTM Designation: D 4505, Standard Specification for Preformed Plastic Pavement Marking Tape for Extended Service Life.
64. ASTM Designation: D 4592, Standard Specification for Preformed Plastic Pavement Marking Tape for Limited Service Life.
65. ASTM Designation: D 4797, Standard test Method for Chemical and Gravimetric Analysis of White and Yellow Thermoplastic Traffic Marking Containing Lead Chromate and Titanium.
66. ASTM Designation: D 4960, Standard test Method for Evaluation of Color for Thermoplastic Traffic marking Materials.

67. ASTM Designation: E 97, Standard Test Method for Directional Reflectance Factor, 45-deg 0-deg, of Opaque Specimens by Broad-Band Filter Reflectometry.
68. Federal Standard No. 595A, Colors.
69. "Retroreflection, Definition and Measurement," International Commission on Illumination Publication No. 54, 1982.
70. Standard Specification for State Road and Bridge Construction, Subsection 2204: Cold Plastic Pavement Marking Material, Kansas Department of Transportation, Edition 1990.
71. Standard Specification for State Road and Bridge Construction, Subsection 2205: Temporary Pavement Marking Tape, Kansas Department of Transportation, Edition 1990.
72. Standard Specification for State Road and Bridge Construction, Subsection 2206: Durable Pavement Marking Tape, Kansas Department of Transportation, Edition 1990.
73. Standard Specification for State Road and Bridge Construction, Subsection 2207: Thermoplastic Reflectorized Pavement Marking Materials, Kansas Department of Transportation, Edition 1990.
74. Special Provision to the Stand Specification: Epoxy Pavement Markings, Kansas Department of Transportation, Edition 1990.

Table 1: Minimum Nighttime Retroreflectivity Measured from Previous Studies

Condition	Retroreflectivity ($\text{mcd} / \text{m}^2 / \text{lx}$)				
	Allen (3) *	Ethen (23)	King (29)	Blaauw (10)	Serres (44) **
Dry Night	90	100	93	200	150
Wet Night	-	-	180	90	60

* Based on a marking contrast of 2 and road specific luminance of 30 $\text{mcd} / \text{m}^2 / \text{lx}$.

** The International Commission on Illumination believes that Serres's data represents the actual driving situation more closely than the Blaauw's data (46).

Table 2: Gradation of Glass Beads Used by Agent and Pigman (2)

	<u>Sieve Opening (mm)</u>	<u>US Sieve Number</u>	<u>Percent Passing</u>
Fine Size:	0.60	30	100
	0.25	60	40-70
	0.18	80	15-35
	0.15	100	0-5
Regular Size:	1.18	16	100
	0.60	30	45-95
	0.30	50	15-35
	0.15	100	0-5
Coarse Size:	1.18	16	100
	0.60	30	15-35
	0.30	50	5-15
	0.15	100	0-5

Table 3: Gradation Specifications for Large Glass Bead Systems (28)

Gradation of Standard Beads for Dual-Drop Application:

<u>Sieve Opening (mm)</u>	<u>US Sieve Number</u>	<u>Percent On</u>
0.85	20	0-5
0.60	30	5-20
0.30	50	30-75
0.18	80	9-32
0.15	100	0-5
-	PAN	0-2

Gradations for Thick-Film Binders (Thermoplastics and PMMA):

<u>Sieve Opening (mm)</u>	<u>US Sieve Number</u>	<u>Percent On</u>		
		<u>Sunbelt</u>	<u>Moderate</u>	<u>Northeast</u>
3.35	6	-	-	-
2.36	8	0-5	-	-
2.00	10	5 - 20	0-5	-
1.68	12	40-80	5 - 20	0-5
1.40	14	10 - 40	40-80	5 - 20
1.18	16	0-5	10 - 40	40-80
1.00	18	-	0-5	10 - 40
0.85	20	-	-	0-5
-	PAN	0-2	0-2	0-2

Note: Recommended gradations for thermoplastic vary depending on geographic location, with largest size used in Sunbelt locations. In all cases, the dual-drop system is used with thermoplastic. Application rate: Dual drop - 0.55 kg large and 0.55 kg standard beads/m² (12 lb large and 12 lb standard beads/100 ft²).
Coating: Binder specific.

Table 3 (continued)

Gradations for Durable 100 Percent Solid Thin-Film Materials:

Sieve Opening (mm)	US Sieve Number	Percent On		
		380 μm (15 mil) Single Drop	380 μm (15 mil) Dual Drop and 510 μm (20 mil) Single Drop	510 μm (20 mil) Dual Drop
2.36	8	-	-	-
2.00	10	-	-	0-5
1.68	12	-	0-5	5-20
1.40	14	0-5	5-20	40-80
1.18	16	5-20	40-80	10-40
1.00	18	40-80	10-40	0-5
0.85	20	10-40	0-5	-
0.71	25	0-5	-	-
-	PAN	0-2	0-2	0-2

Application rate: Single drop - epoxy, 2.9 kg/l (24 lb/gal); polyester, 1.45 kg/l (12 lb/gal).

Dual drop - epoxy, 1.45 kg large and 1.45 kg standard beads/l (12 lb large and 12 lb standard beads/gal); Polyester, 1.2 kg large and 1.2 kg standard beads/l (10 lb large and 10 lb standard beads/gal).

Coating: Binder specific.

Table 4: Typical Properties of Polymer Binders for PC Overlays (1)

Polymer Binder	Viscosity (centipoise)	Working Life (gel time) (minute)	Coefficient of Thermal Expansion (mm/mm/deg C) (in./in./deg F)	Bond Strength (MPa) (psi)	Tensile Strength (MPa) (psi)	Tensile Elongation (percent)	Modulus of Elasticity (MPa) (psi)	Curing Shrinkage (percent)
Epoxy	200-2000	10-60 **	$5-9 \times 10^{-5}$ ($3-5 \times 10^{-5}$)	Min. 7 (1000)	Min. 14 (2000)	Min. 30	$4.0-8.3 \times 10^2$ ($0.6-1.2 \times 10^5$)	0.02-0.08
Polyester	100-400	10-60 **	$36-90 \times 10^{-5}$ ($20-50 \times 10^{-5}$)	Min. 7 (1000)	Min. 14 (2000)	Min. 30	$2.4-6.2 \times 10$ ($3.5-9.0 \times 10^4$)	1-3
Methyl Methacrylate	1-50*	20-40 **	$22-54 \times 10^{-5}$ ($12-30 \times 10^{-5}$)	7-14 (1000-2000)	3-8 (500-1200)	100-200	Max. 7×10^2 GPa Max. 1×10^5 psi	1-2
Polyurethanes	1000-8000	15-60 **	***	***	6-10 (800-1500)	150-600	0.3-1 (50-200)	0.02-0.08

* Monomers: 1-50 centipoise; Polymer/monomer solutions: 250-1700 centipoise.

** Working life can be adjusted by varying the promoter and /or initiator.

*** Insufficient data available.

Table 5: Cost of Cutting Grooves in Portland Cement Concrete Pavement (22)

Cut Depth [mm (in.)]	Aggregate	
	Limestone [\$/LM (\$/LF)]*	Traprock-Granite [\$/LM (\$/LF)]
3.175 (1/8)	0.49 (0.15)	0.98 (0.30)
6.35 (1/4)	0.98 (0.30)	2.23 (0.68)
9.525 (3/8)	1.80 (0.55)	3.40 (1.03)
12.7 (1/2)	2.30 (0.70)	4.36 (1.33)

Note: The above costs are based on using a multiple diamond blade arbor driven cutting head self-propelled machine designed for cutting 100-mm (4-in.) wide grooves in portland cement concrete, with water cooling and vacuum water-slurry removal. The costs are based on a two (2) person machine operation, amortized at \$200/hr and a diamond blade cost of \$425/each. 25% overhead and profit has been included.

* \$/LM = dollars per linear meter;
 \$/LF = dollars per linear foot.

Table 6: Installed Material Cost of PCPM

Material	Installed Material Cost*		
	3.175-mm thick (1/8 in.)	6.35-mm thick (1/4 in.)	9.525-mm thick (3/8 in.)
	[\$/LM (\$/LF)]	[\$/LM (\$/LF)]	[\$/LM (\$/LF)]
Epoxy	2.49 (0.76)	4.79 (1.76)	6.76 (2.06)
Thermoplastic	1.57 (0.48)	3.15 (0.96)	4.72 (1.44)

* The installed material cost includes material cost and installation cost such as labor and equipment.

Table 7: Total Installed Cost and Cost-Effectiveness Factor of PCPM Systems

PCPM System	Thickness [mm (in.)]	Cost* [\$/LM (\$/LF)]	Cost-Effectiveness Factor ** Service Life ***	
			10 years	20 years
Solid**** Epoxy PCPM on Existing Pavement or Broken **** Epoxy PCPM on New or Existing Pavement	3.2 (1/8) 6.4 (1/4) 9.5 (3/8)	2.99-3.48 (0.91-1.06) 6.43-7.02 (1.76-2.14) 8.56-10.14 (2.61-3.09)	0.091-0.106 0.176-0.241 0.261-0.309	0.046-0.053 0.088-0.107 0.131-0.155
Solid Epoxy PCPM on New Pavement	3.2 (1/8) 6.4 (1/4) 9.5 (3/8)	2.62-2.76 (0.80-0.84) 5.05-5.35 (1.54-1.63) 7.22-7.64 (2.20-2.33)	0.080-0.084 0.154-0.163 0.22-0.233	0.040-0.042 0.077-0.082 0.110-0.117
Solid Thermoplastic PCPM on Existing Pavement or Broken Thermoplastic PCPM on New or Existing Pavement	3.2 (1/8) 6.4 (1/4) 9.5 (3/8)	2.07-2.56 (0.63-0.78) 4.13-5.38 (1.26-1.64) 6.53-8.04 (1.99-2.45)	0.063-0.078 0.126-0.164 0.199-0.245	0.032-0.039 0.063-0.082 0.100-0.123
Solid Thermoplastic PCPM on New Pavement	3.2 (1/8) 6.4 (1/4) 9.5 (3/8)	1.71-1.84 (0.52-0.56) 3.41-3.71 (1.04-1.13) 5.18-5.58 (1.58-1.70)	0.052-0.056 0.104-0.113 0.158-0.170	0.026-0.028 0.052-0.057 0.079-0.085

* In 1994 dollars.

** Cost effectiveness factor = Cost/Service life.

*** Assumed service life.

**** Solid = Continuous stripe; Broken = Broken or dashed stripe.

Table 8: Total Installed Cost and Cost-Effectiveness Factor of Surface Markings

Marking System	Cost* [\$/LM (\$/LF)]	Average Daily Traffic	Service life (year)	Cost-Effectiveness
				Factor
Traffic Paint [205 µm (8 mil)]	0.13-0.23 (0.04-0.07)** [0.62 (0.16)]***	8000	0.35	0.114-0.200
		12000	0.25	0.160-0.280
		16000	0.15	0.267-0.467
Epoxy [380 µm (15 mil)]	1.12 (0.34)	8000	2.00	0.170
		12000	1.50	0.226
		16000	1.00	0.340
Thermoplastic [3050 µm (120 mil)]	1.05-1.44 (0.32-0.44)	8000	4.50	0.071-0.098
		12000	4.10	0.078-0.107
		16000	3.70	0.086-0.119
Thermoplastic Epoxy [380 µm (15 mil)]	0.79 (0.24)	8000	3.20	0.075
		12000	2.25	0.107
		16000	1.30	0.185
Preformed Tapes [2290 µm (90 mil)]	3.77-4.49 (1.15-1.37)	8000	4.70	0.244-0.291
		12000	4.10	0.280-0.334
		16000	3.50	0.328-0.391

* In 1994 dollars.

** Based on NCHRP Report 138 (19).

*** Based on 1994 Means Heavy Construction Cost Data (35).

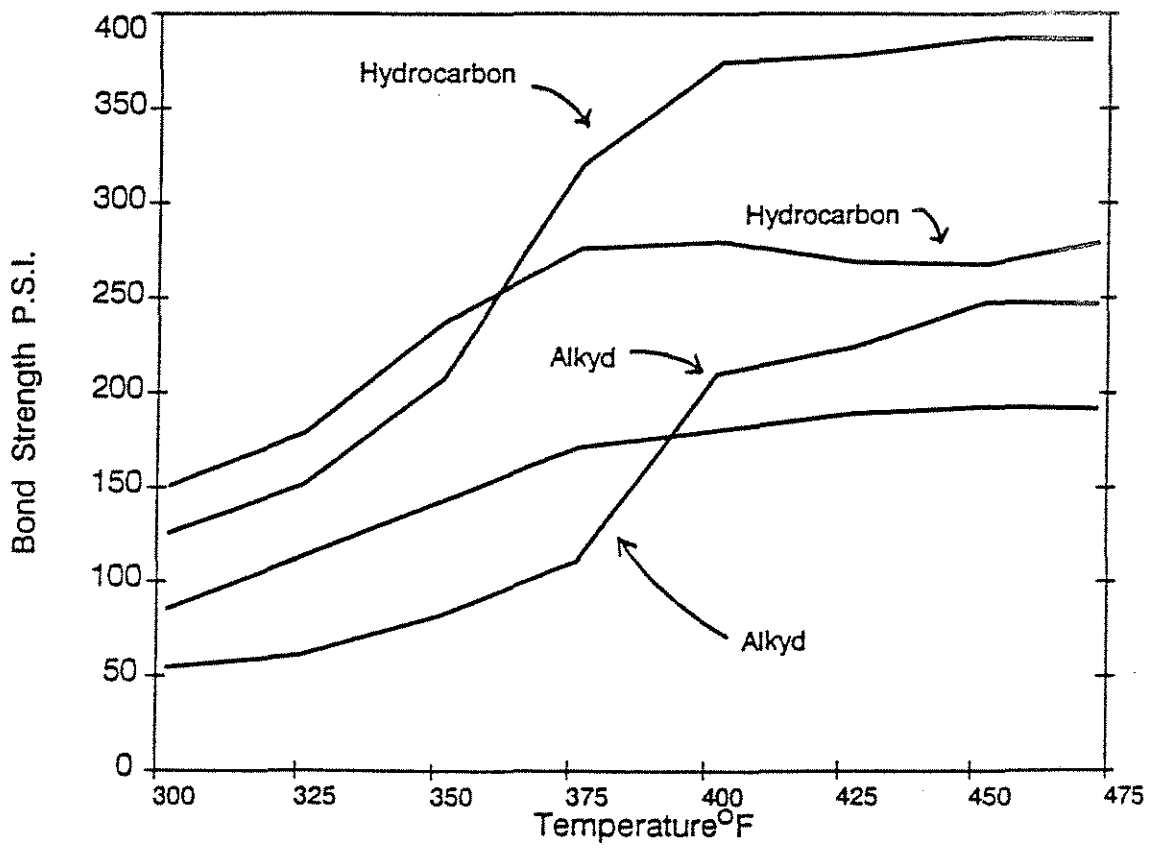
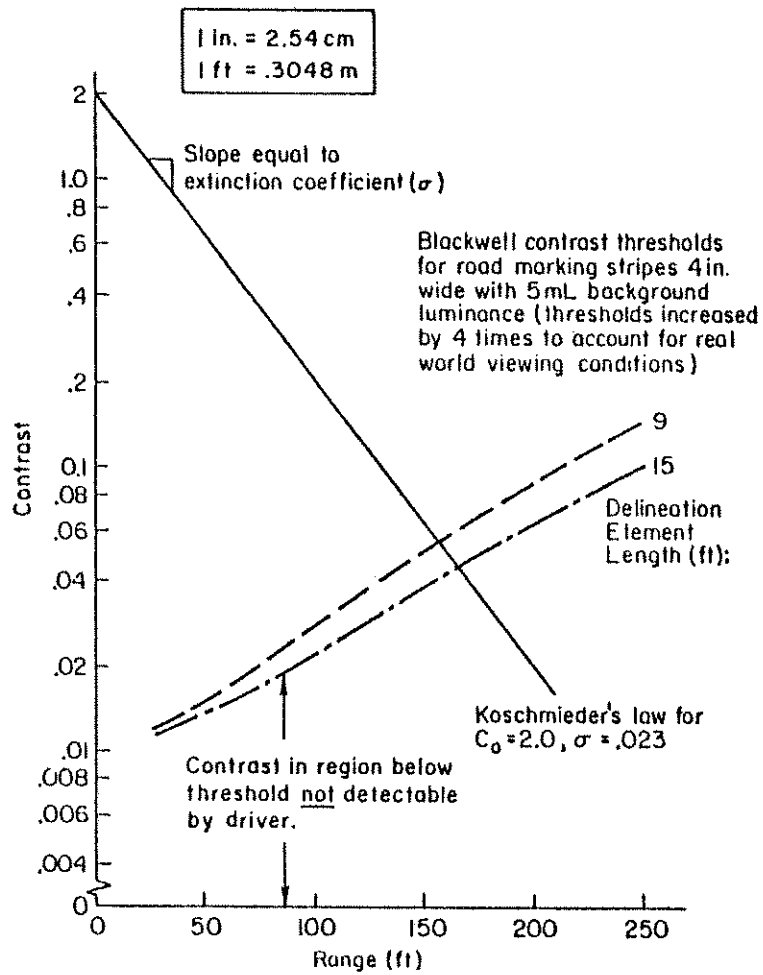
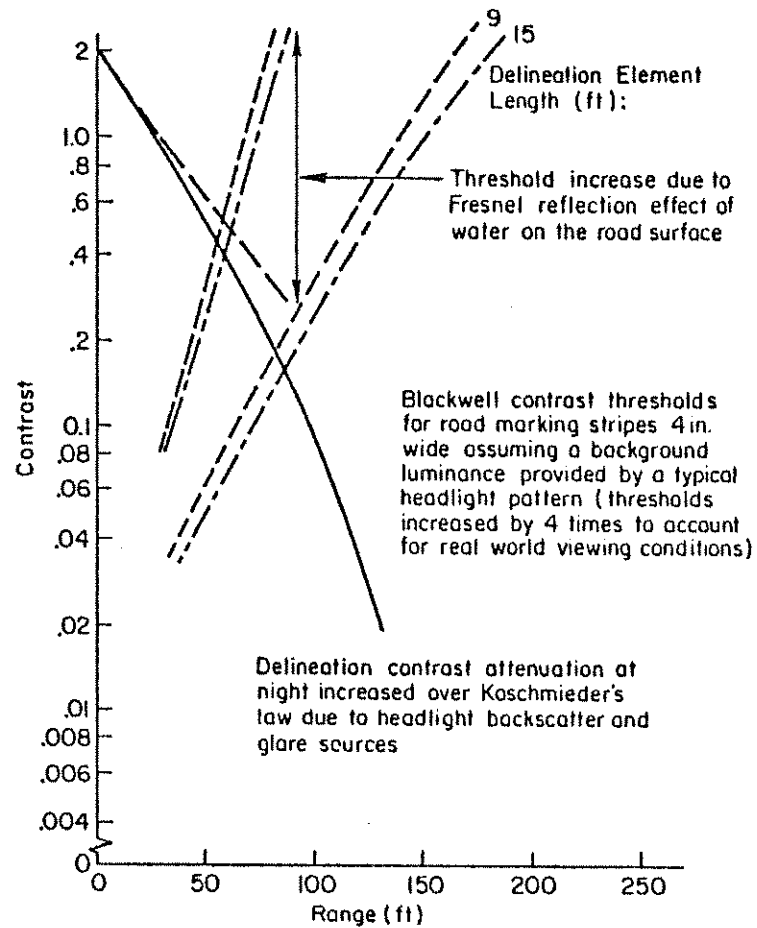


Fig. 1 Temperature vs. Bond Strength, Alkyd and Hydrocarbon Thermoplastic (19)



a) Daylight Illumination



b) Headlight Illumination

Fig. 2 Delineation Visibility Under Natural (Daylight) and Night (Headlighting) Conditions (3)

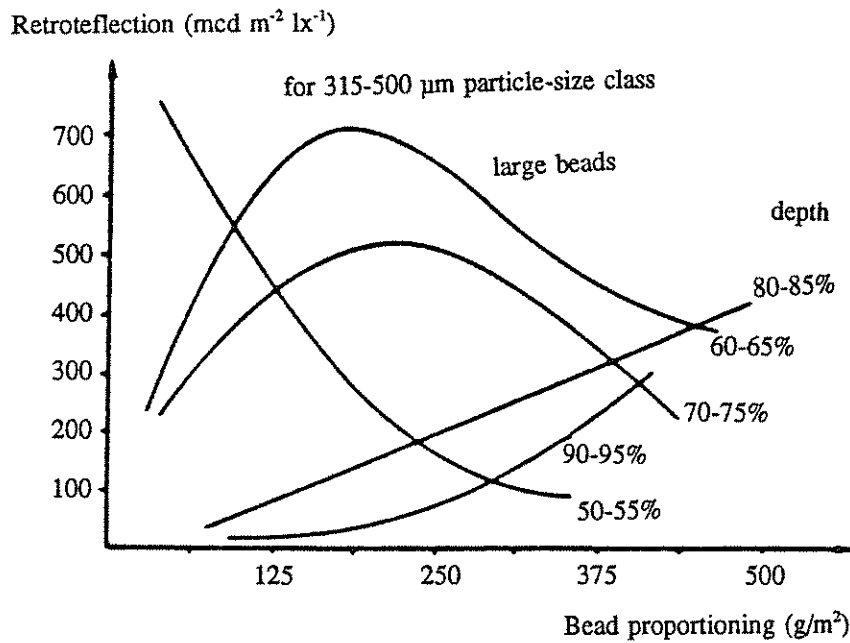
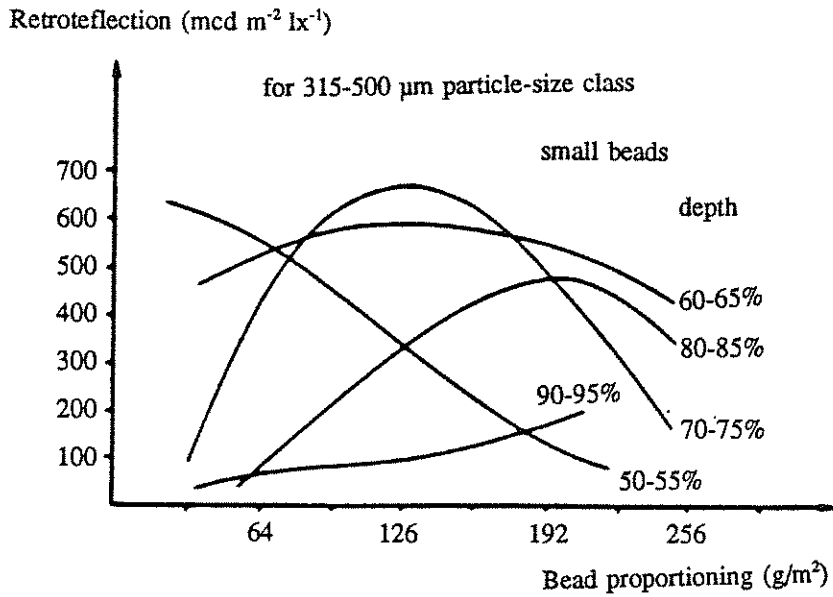


Fig. 3 Retroreflectivity ($\alpha_p=4.5^\circ$, $\epsilon_p=3.5^\circ$, $\beta_p=180^\circ$) as a Function of Application Rate and Embedment of Glass Beads (46)

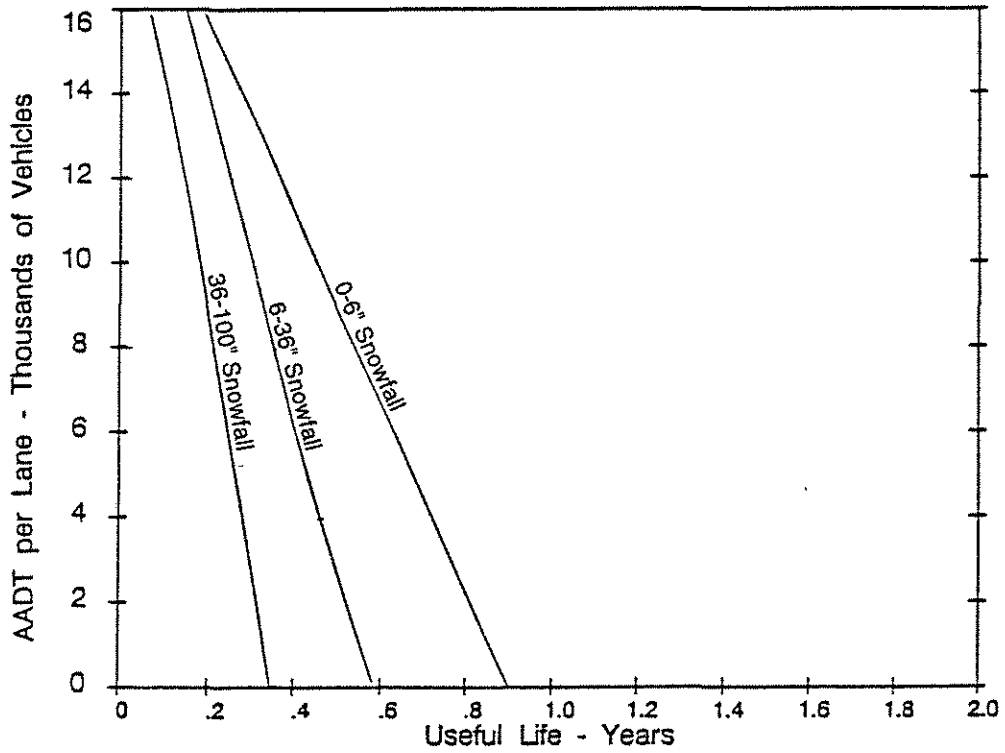


Fig. 4 Life Expectancy of Solvent-Borne Traffic-Marking Paint on Asphaltic Concrete (19)

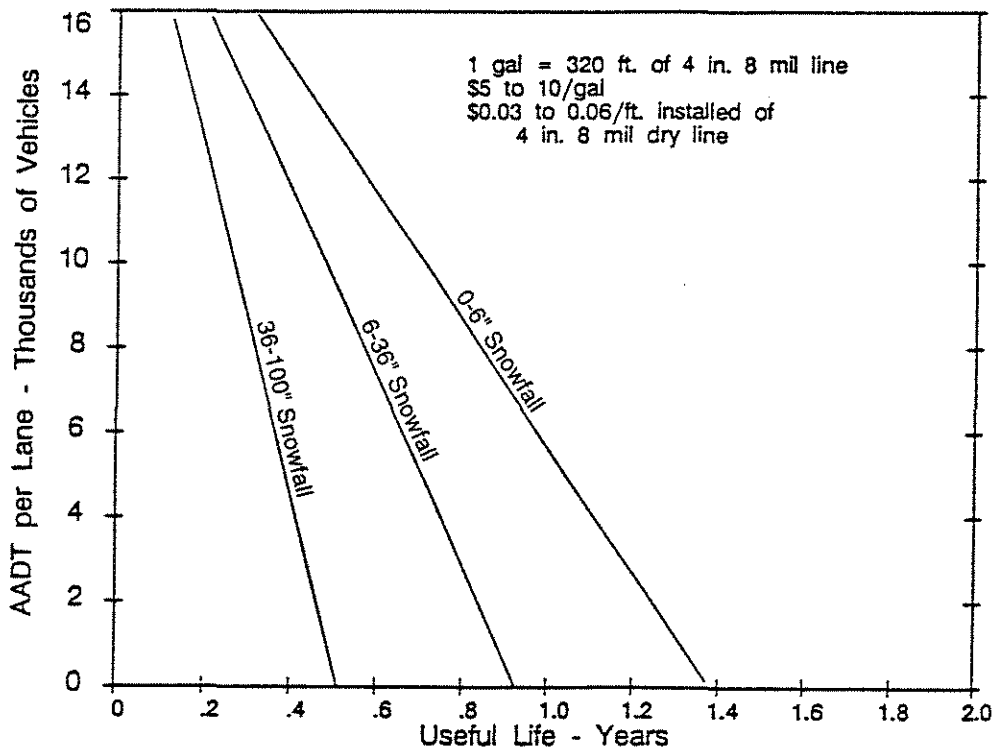


Fig. 5 Life Expectancy of Solvent-Borne Traffic-Marking Paint on Portland Cement Concrete (19)

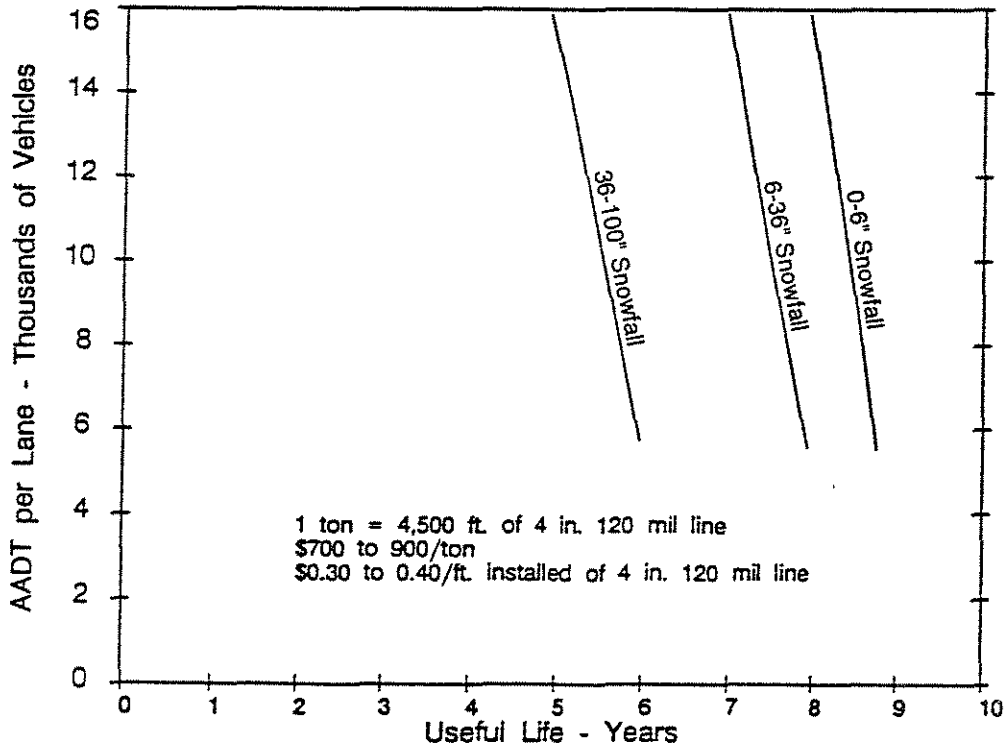


Fig. 6 Life Expectancy of Thermoplastic on Asphaltic Concrete (19)

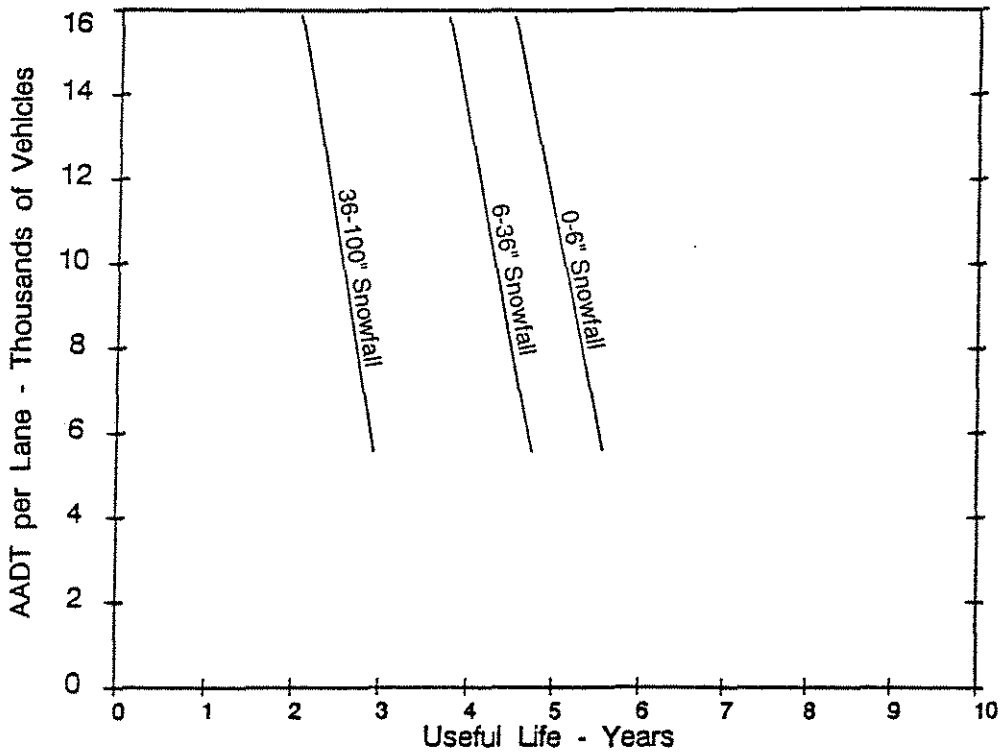


Fig. 7 Life Expectancy of Thermoplastic on Portland Cement Concrete (19)

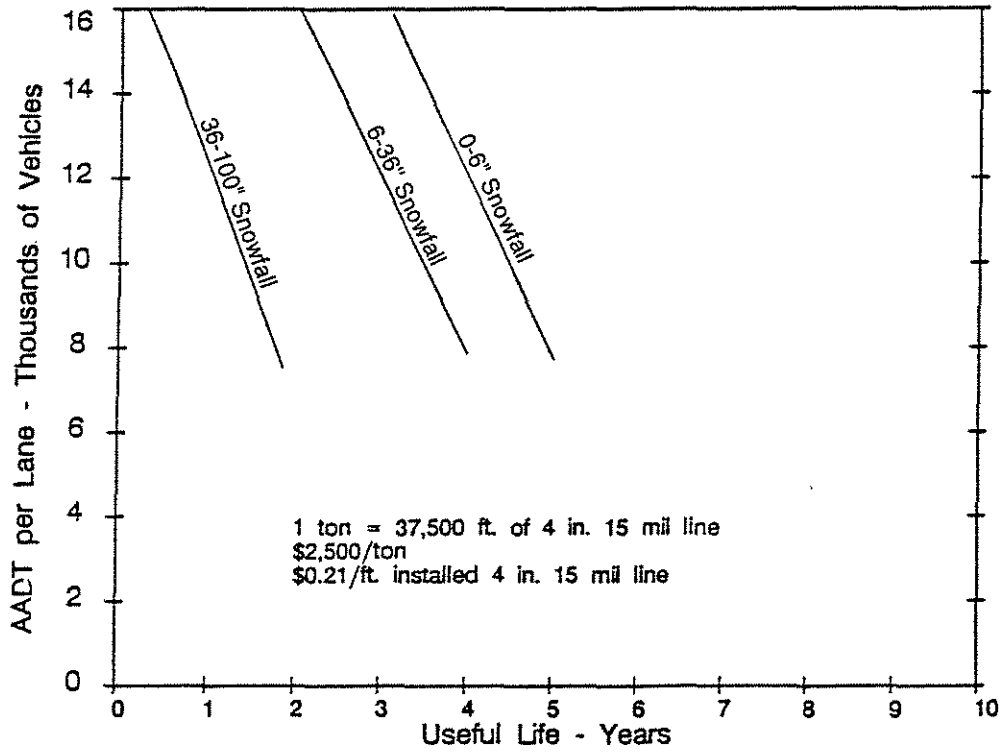


Fig. 8 Life Expectancy of Thermoplastic Epoxy (Epoflex) on Asphaltic Concrete (19)

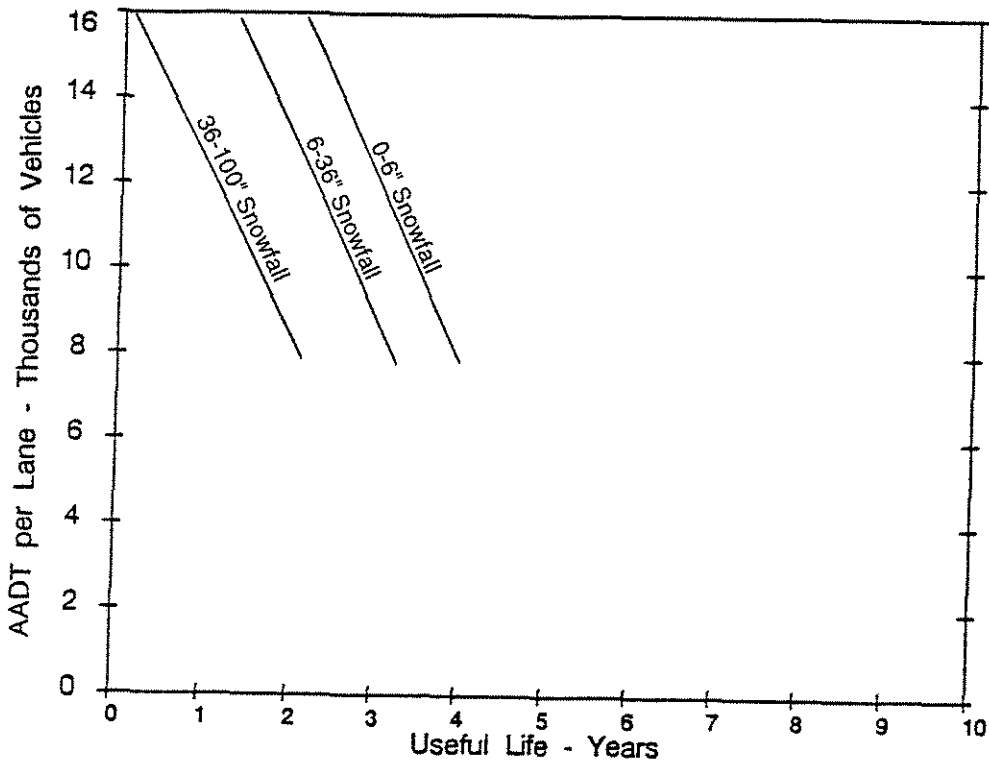


Fig. 9 Life Expectancy of Thermoplastic Epoxy (Epoflex) on Portland Cement Concrete (19)

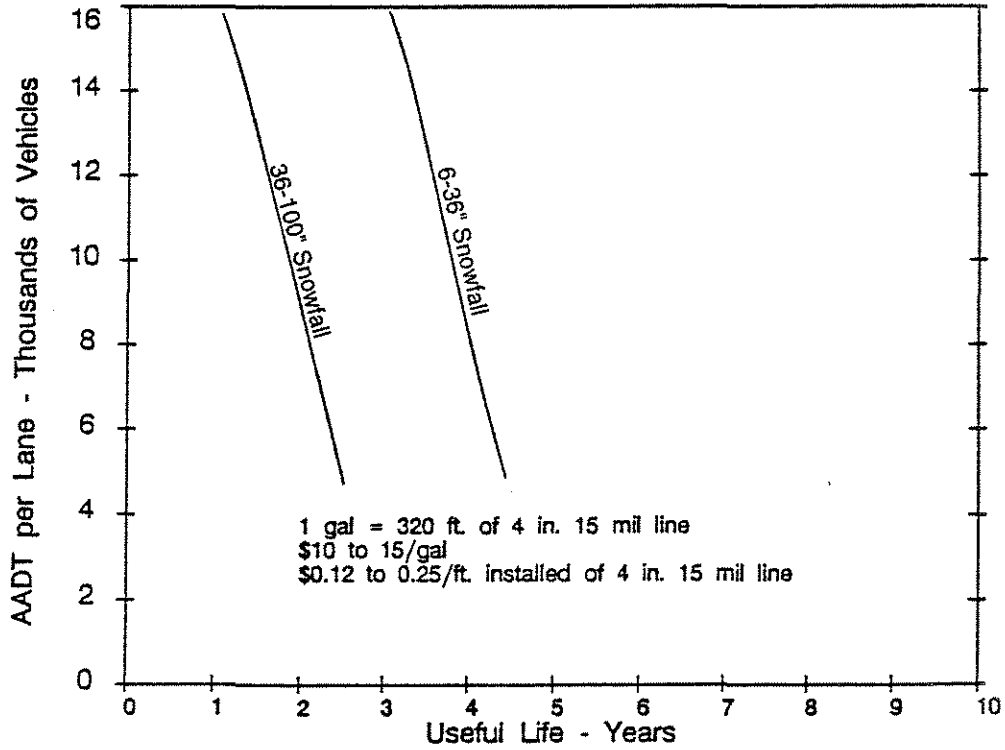


Fig. 10 Life Expectancy of Polyester on Asphaltic Concrete (19)

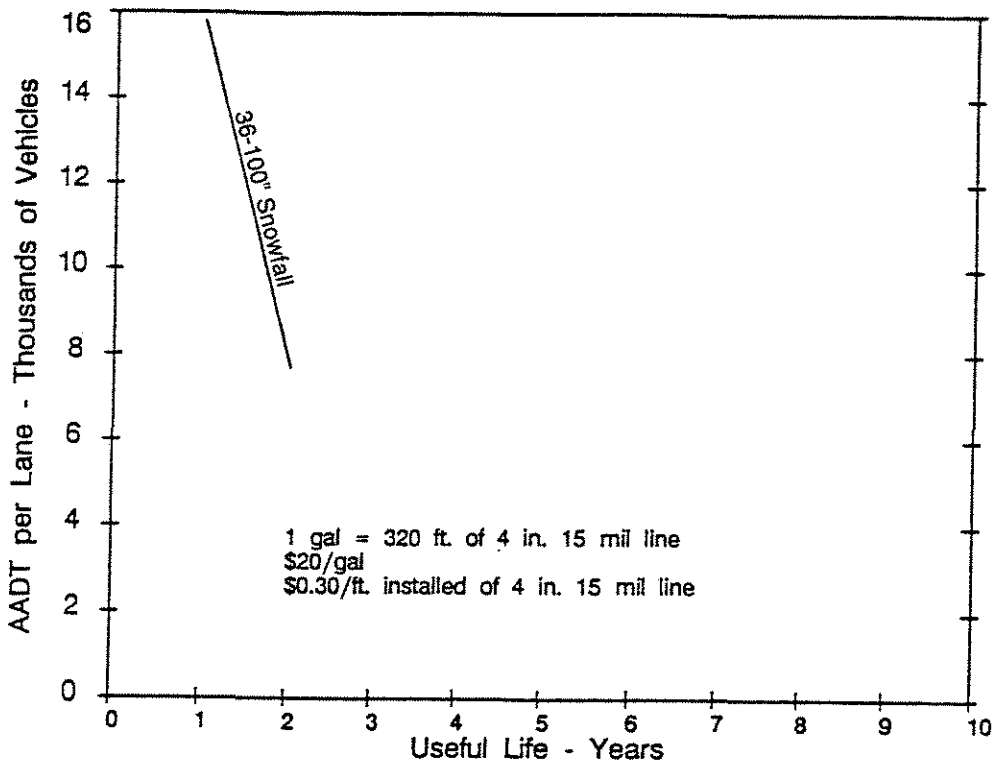


Fig. 11 Life Expectancy of Two-Component Epoxy on Asphaltic Concrete and Portland Cement Concrete (19)

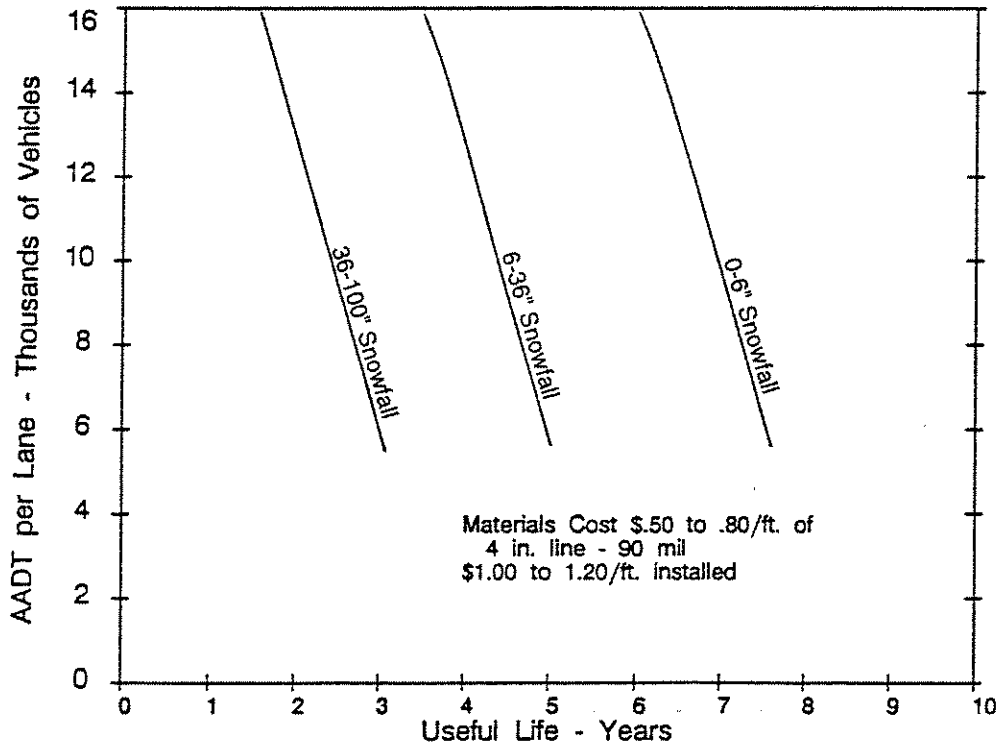


Fig. 12 Life Expectancy of Preformed Tape on Asphaltic Concrete and Portland Cement Concrete (19)

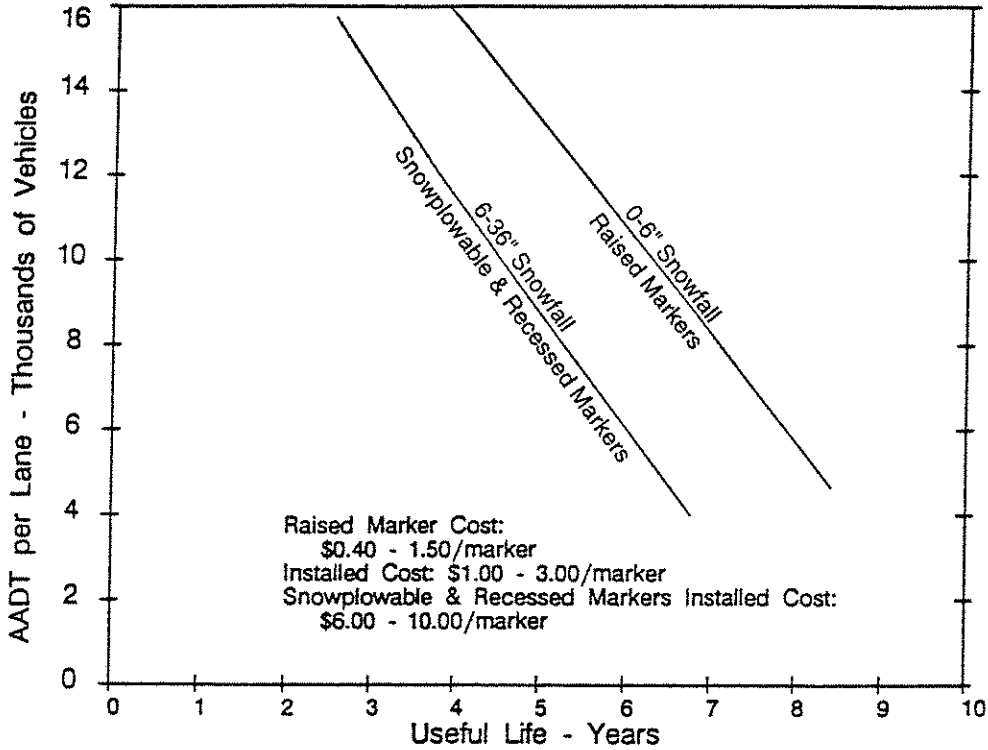


Fig. 13 Life Expectancy of Raised Markers, Snowplowable, and Recessed Markers on Cured Asphaltic Concrete and Portland Cement Concrete (19)

APPENDIX I

DEFINITIONS OF TERMS

Luminous Energy	Luminous energy is visually evaluated radiant energy traveling in the form of electromagnetic waves. The unit is the lumen-second (lm-s).
Solid Angle	Solid angle is the ratio of the sphere surface area enclosed to the square of the radius.
Luminous Flux	Luminous flux is the time rate of flow of luminous energy. The unit is lumen (1 lumen = 1 candela-steradian = 1 cd-sr).
Illuminance	Illuminance is the incident of luminous flux on a small surface per unit area of the surface. The unit is lux = lumen per square meter, lumen/m ² .
Luminous Intensity	Luminous intensity is the solid-angular luminous flux density in a given direction, which indicates the ability of a light source to produce illuminance in a given direction. The unit is lm/sr = candela, cd.
Luminance	Luminance is the luminous flux per unit of projected area per unit solid angle leaving a given point in a given direction, which used to be called brightness . Luminance can also be defined as the luminous intensity of a surface in a given direction per unit projected area as viewed from that direction. The unit is luminous intensity per square meter, cd/m ² .
Luminance Factor	Luminance factor is the ratio of the luminance of a surface to that of a perfect diffusing surface, when illuminated and viewed under the same geometric conditions.
Contrast	The contrast of pavement markings is the luminance (or luminance factor) difference between marking and background (pavement) divided by background luminance (or luminance factor).
Luminance Threshold	Luminance threshold of pavement markings is the luminance that is needed under certain conditions (illuminance and size of object) to make an object (marking stripe) just visible to the observer.
Contrast Threshold	The contrast threshold of pavement markings is the contrast of the pavement markings that is needed under certain conditions (illuminance and size of object) to make an object (marking stripe) just visible to the observer.
Visibility Distance	The visibility distance of pavement markings is the distance between the marking and the observer from which the marking is just visible to the observer.

- Specific Luminance** Specific luminance is the ratio of the luminous intensity of the projected surface to the normal illuminance at the surface on a plane normal to the incident light. The unit is candelas per square meter per lux, $\text{cd}/\text{m}^2/\text{lx}$. Millicandelas per square meter per lux is often used to avoid fractional values.
- Retroreflectivity** The retroreflectivity of pavement markings is the characteristic for which the marking surface reflects and returns a relatively high proportion of light in a direction close to the direction from which it comes.