Auburn University

Determining The Longevity and Service Life of Pavement Marking Materials

Literature Review and Annotated Bibliography

Highway Research Center
Harbert Engineering Center
Auburn University, Alabama 36849-5337

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Prepared by:
Brian L. Bowman
Highway Research Center
238 Harbert Engineering
Auburn University, AL 36849

INTRODUCTION

The longevity of pavement marking material has a direct impact on the cost of maintenance and user safety. The estimated cost of marking streets and highways in the U.S. each year is approximately $475 million. This cost consists of about $380 million for materials with the remaining $95 million expended on their application. The estimated quantity of marking materials consists of:

- 40 million gallons of traffic paint
- 200 million gallons of glass traffic beads
- 60 tons of thermoplastic materials
- $55 million worth of other materials such as preformed tapes, raised pavement markers, polyesters, epoxies and adhesives.

This is a significant amount of material representing not only a large monetary effort but also an extensive allocation of manpower and application equipment. Adequate pavement markings are, however, one of the highest payoff, lowest cost operational improvements that can be made to streets and highways. The FHWA Pavement Marking Demonstration Program of the 1970's demonstrated that improved transverse and longline pavement markings were effective in improving motorist safety. The improvement in safety was determined to be especially prevalent during nighttime and low visibility conditions when the pavement markings serve to delineate the required vehicle paths. The desirable delineation effect of pavement markings is accomplished by the principles of rectroreflectivity.

Glass beads have been used to make pavement markings reflective for approximately 50 years. Glass beads, if properly imbedded in a striping material, have the ability to collect incident light and reflect part of that light back to its source. It is this ability that makes spherical glass particles ideally suited in making pavement markings visible at night.

The performance of the glass beads is dependent upon their embedment depth, size and environmental conditions. Research conducted during the late 1960's indicated that the optimum embedment of the glass beads was 60 percent of the bead diametric. It was also noted that during periods of adverse weather, the small glass beads often became submerged in a film of water. Light from headlights bounced off this water surface and was lost. It was concluded that the rectroreflective capabilities of beads that functioned well when the roadway was dry were significantly reduced during rain and foggy or misty conditions. In addition, the type of marking material, which serves as a binder for the beads, had different effective service lives in their ability to hold the beads in place and thus retaining their rectroreflective properties.

Many changes have occurred in the pavement marking industry in the past 20 years; especially in the availability of polymeric nonshrink binders as durable striping materials. In addition to the advent of nonshrink polymeric binders has been the development of good water based paints with higher solids content than typical alkyd paint. Alkyd paints have also changed to comply with the requirement for short no-track time, affecting the final film thickness. The extended durability of these films, their greater thickness and recent enhancements to the glass bead surface to improve adhesion have resulted in the ability to use larger glass beads than was possible in the past.

The advantage of larger glass beads is that they break through the water film on the road surface, thereby reflecting the headlights and making the road markings more visible to the driver during adverse weather conditions. In addition, the use of large beads in conjunction with the enhanced binding properties and increased thickness of the new marking materials has the potential of providing increased effective service life. It is currently unknown, however, if this potential can be realized and which combinations of marking/binder types and bead size are the most advantageous.

PROJECT OBJECTIVE AND SCOPE

The objectives of this project are to:

1) Determine if larger glass bead sizes are effective in increasing wet pavement rectroreflectivity.

2) Determine the combination of pavement marker/binder and glass bead types which provide the longest effective service life.

3) Develop quantitative comparisons, including cost effectiveness on the rectroreflectivity levels and service lives between small bead and large bead pavement markings.

The advent of new binding materials and the recognition of nighttime wet pavement rectroreflectivity problems has resulted in efforts by researchers, material manufacturers, and governmental agencies to identify the most advantageous pavement marking types.

LITERATURE REVIEW SUMMARY

The primary purpose of this literature review is to identify recent and ongoing research into the night-time wet surface effectiveness, cost, and service life of various pavement marking types. A 1952 study by Pocock and Rhodes [16] is an early effort that was referenced by many subsequent studies. The study investigated the principles of glass bead reflectorization and studied the effects of application procedures, bead gradations and refractive index of the beads on retroreflectivity. This study indicated that an advantage of using smaller beads is they provide a larger reflective area per pound than large beads. The study , however, failed to consider the lower wet-night reflectivity resulting from the smaller beads being submerged by a film of water.

Dale [2], in a 1967 NCHRP report, investigated methods of improving roadway delineation under both wet and dry conditions. Emphasis was placed on the effectiveness of a silicone based surface layer. The silicone treatment resulted in reduction of both clogging of bead-dispensing equipment as well as over-embedment of beads into the pavement marking material. The study also determined that the optimum depth of bead embedment ranged from 55 to 60 percent of the bead diameter. Larger glass bead sizes, than those currently being used, were suggested as a way of overcoming the problem of loss of reflectivity during wet pavement conditions. However, it was also pointed out that the thickness of paint film would need to be increased in order to provide the necessary binding for the glass beads.

In a subsequent publication [3], Dale questioned the appropriateness of bead gradation used for drop-on application. Reference was made to the developments that had taken place in traffic marking paints, and the absence of change in bead size. This study illustrated that the use of a gradation of mixed sizes in a constant thickness of paint resulted in only a very small percentage of the beads operating efficiently on application. The rationale behind the use of a gradation of mixed sizes is that the pavement marking paint layer fails by abrasion resulting in smaller beads being exposed and thus providing sustained reflectivity. However, it was noted that paint often does not fail by abrasion but instead chips away. In this case, a lesser quantity of larger-sized beads would give higher retroreflectivity at a considerable overall cost saving.

A 1973 NCHRP synthesis study [13] evaluated various pavement marking materials and how the various methods of application affect their serviceability. Considerable attention was given to the selection of the paint-bead system. The authors discussed the difficulty in deciding the optimum bead gradation due to the wide variation in environmental conditions, application methods and control of materials. The theoretical considerations of film thickness and bead size must be adapted to the reality of stripe application and to the uncertainties of weather and of material control. In addition, the drying rate of the paint film affects the rate of bead settlement and hence their embedment depth. The results of a States' survey indicated that North Carolina and Ohio preferred the use of premixed beads in the paint due to the convenience of use and uniform distribution of beads in the paint film. However, 80 percent of State agencies used drop-on bead application due to the advantages of lower nozzle wear, faster drying, and the decreased need for paint agitation. The survey determined that the predominant bead gradation used by the states was 30 to 80 mesh.

Holman [10], in 1971, reported on Alabama's experience, during a national experimental program using traffic marking beads. Alabama used drop-on beads of gradation between U.S. Sieve #30 and #80, and premixed beads of gradations between U.S. Sieve #40 and #230. Test sections were installed at two locations in Montgomery, and monitored periodically for night visibility. It was concluded that test sections with high drop-on bead application rates had good night visibility but low durability as compared to premixed-bead sections.

A 1975 OECD Road Research report [15] summarized experience with road marking and delineation materials and devices. The report indicated conditions and factors that should be considered in the selection of appropriate materials for various circumstances. An optimum bead embedment of approximately 60 percent of the bead diameter for maximum reflectivity, and a bead gradation of between #40 and #80 mesh (between 0.42 and 0.177 mm) were suggested.

Ohio [6] substituted Visibeads (manufactured by Potters Industries) for standard-sized glass striping beads in a large glass bead testing project. A wide range of traffic volumes, roadway geometrics, and pavement conditions, were represented in this project. Preliminary results indicated that average reflectivities were well above the minimum acceptable levels. Joint sealing and snowplowing were two major causes of loss of reflectivity. It was estimated that 25 to 30% of the pavement markings were damaged by snowplowing, and another 5 to 10% by joint sealing.

Gillis [9] reported on a 1975 study by the Minnesota Department of Transportation that was conducted to evaluate epoxy, polyester, and thermoplastic resins as pavement marking materials. This project also developed a spray-on epoxy/glass bead system appropriate for both bituminous and concrete pavements. The study demonstrated that epoxy markings provide adequate delineation, for both day and night conditions, during an approximate 2 year period following installation. It was also found that epoxy provided better reflectivity compared to both paint and thermoplastic markings.

Fullerton [8], in the FHWA handbook on Roadway Delineation Practices, discussed delineation concepts, current practices, and introduced promising future techniques. This study reported that 85 percent of the State highway agencies used a bead gradation of #20 to #80 mesh sizes. The use of flotation beads, various application techniques, and volume of beads employed is also discussed in this report.

McGrath [12], reporting on a Durable Pavement Marking Materials Workshop, summarized presentations on the evaluation of six durable pavement marking materials. Beads with a gradation of #20 to #80 sieve were used in thermoplastic markings, giving excellent reflectivity on asphalt after 2 years, but with negligible reflectivity on concrete due to bond failure. Preformed materials performed satisfactorily for 4 years, epoxy for 2 years, polyester for up to 8 years, and epoflex performed exceptionally well even with high traffic volumes and warm climates. No specific information was given regarding traffic marking paint.

Dale [4], in another NCHRP Synthesis Report, described pavement marking needs, different types of pavement marking materials, and various methods of preparing the pavement surface prior to marking. This study investigated two types of paints (solvent-borne and water-borne), thermoplastics, thermosets (polyester and epoxy), and marking tapes. The cost-effectiveness of the different pavement marking types is discussed and life-expectancy curves provided for marking on both asphalt-concrete and PCC pavements.

O'Brien [14] performed a laboratory investigation of the embedment characteristics of drop-on moisture-proofed and uncoated glass beads, and their retroreflectivity in combination with various types of hot-applied thermoplastic markings. He concluded that moisture-proofed drop-on beads give excellent retroflectivity. The study also showed that the retroreflectivity of the standard bead gradation was enhanced by increasing the proportion of the larger-sized beads.

Kalchbrenner [11], in a 1989 publication, described one of the most recent tests of large glass beads in pavement markings. Potters Industries, one of the pioneers of glass bead manufacture, experimented with large glass beads, in the laboratory as well as at a field test site in New Jersey, in 1984. Demonstration projects were set up in 25 States, encompassing 7 geographical areas. A variety of binders, road types, geographical areas, pavement types, and application methods were investigated in this study. The laboratory tests concluded that the optimum bead size for good wet night reflectivity ranged from #10 to #20 mesh, depending on the binder. The field test and demonstration projects showed that larger glass beads provided significantly superior retroreflectivity compared to standard bead sizes, for a variety of binders - thin film as well as thick film. This study also suggested bead gradation specifications for single- as well as dual-drop marking systems.

DeJaiffe [5], Schwab and Capelle [17], Bryden et al [1], Ethen and Woltman [7] and Van Gorkum [18], addressed the need for wet night delineation and different methods or instruments to measure the retroflectivity of markings. These studies did not, however, go into any detail on bead gradations for pavement markings.

PAVEMENT MARKING TYPES

Prior studies have demonstrated that in addition to the service life or durability of the binder, its applicability is determined by the ability of the binder to retain the retroreflective material over an acceptable period of time. Determining the most appropriate binder, therefore, requires consideration of the type of application (i.e. long line or transverse), glass bead retention ability, traffic volumes, pavement surface type, and total cost over its service life. This section of the report categorizes available information on the following types of binders. The following advantages, disadvantages and costs were identified by a 1981 FHWA report[12] on durable pavement marking materials.

TRAFFIC PAINT

Traffic paints have been the most widely used pavement marking material since their introduction in the early 1920's. Paints are classified by drying time: instant dry (less than 30 sec), quick-dry (30 to 120 sec), fast-dry (2 to 7 min), and conventional (over 7 min). Traffic paints are comprised of a paint vehicle (alkyd, modified alkyd, chlorinated rubber, or water-base), a solvent, a pigment, and glass beads. The drying time is determined by a paint's specific ingredients.

- Durability: Although the material, weather, application techniques, and traffic density affect the performance of pavement markings, their durability primarily depends on the type and condition of the surface when they are applied. If existing markings are not adhering well, or if the new paint has a solvent which acts as a paint remover, applications over existing markings will not be successful. Bonding problems common to both Portland concrete cement (PCC) and asphalt are caused by surface contamination and the substrate's moisture content. The use of water-soluble solvents and high temperatures can sometimes counteract problems related to moisture, but a paint's ability to penetrate surface dirt and oil depends on its composition and the length of time it remains wet before turning viscous. Solvents that require prolonged contact can soften the pavement surface and cause "bleeding", resulting in discoloration of the paint. Although this tendency is reduced by using fast drying paints on asphalt surfaces, adhesion can be adversely affected if solvents evaporate too rapidly and trap air between the paint and the pavement, a problem known as "bridging."

- Reflectivity: Paints provide good visibility under dry conditions, but tend to be obscured by water films.

- Advantages: The relatively low initial cost, well-established technology, ease of installation and readily available application equipment ensures continued widespread use of traffic paints. They provide good dry-night visibility, a choice of drying times, and are relatively safe to handle. The reduced drying time decreases traffic delays and potential accidents related to installation in addition to reduced labor costs.

- Disadvantages: Paints have the shortest life of all marking materials and offer poor wet-night visibility. Year-round delineation with one annual application is difficult to achieve in severe winter climates, particularly on high volume roadways. Paints with accelerated drying times also require more expensive striping equipment and cleaner pavement surfaces for successful adhesion and durability than their longer drying counterparts.

- Range of Costs (1981 Costs): Paint materials cost approximately $5 to $10/gal ($1.31 to $2.63/liter) and installation costs range from $0.30 to $0.06/ft ($0.09 to $0.18/m) for a 15-mils, 4-in. (10.2 cm) line. While the cost per installed foot for traffic paint is reasonable, the apparent cost savings are often lost due to the required frequency of application.

THERMOPLASTICS

Hot-applied thermoplastics are thick pavement marking materials consisting of a resin binder, reflective glass beads, coloring agents, and an inorganic filler. Proportioned and mixed in a factory, thermoplastics can be transported to job sites as solid slabs and blocks, or as granular powder. New York highway officials describe thermoplastics as a "generally good" but "variable" durable material which provides good year-round delineation under severe conditions. The performance of a thermoplastic material is affected by its particular composition [20]. Most commercial thermoplastics today use a blend of synthetic hydrocarbon resins, although alkyds may become more widespread as the price difference decreases.

- Durability: Southern States have reported an average thermoplastic service life of 10 years [21]. Some thermoplastic markings were observed to last the life of the pavement while other applications did not last 1 year under very heavy traffic in northern climates. Thermoplastic durability is considerably better on asphalt than on concrete pavement. The most common foes to durability in northern climates are abrasion, shaving, and bond failure. Abrasion and shaving are caused principally by snow and ice removal equipment. Since these failures are not inherent in the material, the apparent solutions are to change plowing procedures or to use a thinner marking material. Bond failure, on the other hand, results from improper installation (low temperature or dirty, oily, or cold pavement) and is common on concrete. On asphalt, abrasion is related to the volume of traffic and the incidence of abrasive materials and studded tires. Poor performance of longitudinal markings is usually attributable to dirty or deteriorating pavement at application.

- Reflectivity: Thermoplastics form a relatively durable reflectorized marking. Its initial appearance is generally excellent and reflectivity is sustained throughout service life. Delineation is good even after two winter seasons. The reflectivity of Thermoplastics is generally equivalent to beaded paint, but has greater visibility during rain. The crucial factor in its effectiveness is the application rate of beads, although reflectivity can be diminished by dirt built-up and plow damage. In a study conducted by the Texas Transportation Institute, reflectivity (on skip lines, with or without primer) was excellent on asphalt after 2 years, but was negligible on concrete because of bond failure.

- Advantages: Thermoplastics are capable of providing long lasting pavement markings with good night visibility when requirements are met for proper equipment, composition, and installation. Thermoplastics have an advantage over paints where year-round painting is not possible and where wet-night visibility is important.

- Disadvantages: Thermoplastics are a poor choice for transverse lines in areas with high volumes of traffic and for longitudinal lines where turning traffic is common. Because of their thickness, thermoplastic markings are not suitable in severe winter conditions because of their susceptibility to snowplow damage. Successful performance depends on following specific application instructions very carefully.

- Range of Costs (1981 Costs): The cost of thermoplastics, using the 1979-80 contract price paid by New York/DOT of \$0.40/ft (\$1.22/m) for a 4-in. (10.2 cm) line, is five to ten times higher than paint because of material and installation costs.

PREFORMED MATERIALS

Preformed pavement markings are retroreflective films comprising high quality plastic, pigments, and glass beads. The beads are uniformly distributed throughout the film and form a firmly bonded layer on the surface. These materials are purchased in rolls and applied to the surface either by pressure or by the application of heat to the material.

- Durability: A study conducted by the Kentucky Department of Transportation]19] reported a 4-year average useful life for preformed materials, although manufacturers will guarantee only 2 years for inlaid and 1 year for overlaid markings in snowbelt regions. After 2 years, preformed markings in Virginia had retained satisfactory appearance and lasted very well at several urban intersections, on a section of an interstate highway where the tapes had been applied during resurfacing and on a highway of 25,000 AADT and a high volume of turning traffic. For evaluation purposes, the Research Council of the Virginia Department of Highways and Transportation placed transverse lines across one lane with a volume of more than 15,000 vehicles and determined that the preformed markings had held up well. State officials consider 3 years to be a conservative estimate for preformed materials and have predicted an 8-year life for at least one area.

  The durability of preformed tapes and pavement messages relate most to the condition of the pavement and the number of pieces of tape used. Durability is poor on old and deteriorating pavements, especially concrete. Furthermore, since these materials can slide or shift, enhanced performance is obtained by minimizing the number of pieces of preformed tape.

- Reflectivity: Preformed tapes have been rated as five or six times brighter than paint when first placed and still brighter than new paint even when worn. The Kentucky study reported that preformed materials lost their reflectivity in less than 1 year [19]. This contradicts comparative visual evaluations conducted in Virginia. The Virginia study determined that some brands of preformed markings which were highly reflective when new, dropped in brightness slightly as the top beads wore off, but increased again after the surface wore and the beads inside appeared. Other brands had consistent reflectivity.

- Advantages: A summary of the advantages of preformed marking materials is presented below:

  - Its durability eliminates annual or semiannual maintenance even in snowbelt regions.
  - Installation - is simple, safe, and clean (no paint spills or tracing).
  - Their appearance and initial retroreflective qualities are rated five or six times better than paint.
  - Preformed tapes meet all requirements for color and conform to the "Manual on Uniform Traffic Control Devices for Streets and Highways" (MUTCD).
  - Preformed tapes conform to the surface and adhere well; especially when laid on new pavements.
  - Are easy to repair because pieces adhere well to each other.
  - Eliminate the need for major traffic disruption during installation (transverse markings can be placed while traffic is waiting for a red signal); and
  - Can often be installed using construction funds--with Federal participation--rather than maintenance funds.

- Disadvantages: The major disadvantage of preformed markings appears to be loss of reflectivity, although in some brands the reflectivity seems to increase slightly after wear as the premixed beads below the surface appear. Also, under heavy turning traffic, the markings have a tendency to move. Other disadvantages noted by the Kentucky study are related to poor pavement conditions and installation practices (e.g., when a primer is required but not used). Late-season installation may not adhere well.

- Range of Costs (1981 Costs): The use of preformed tapes for lane lines is too new to have produced good benefit-cost statistics. However, the latest nationwide cost figures range from \$0.54 to \$0.80/ft (\$1.65 to \$2.44/m). Virginia currently pays \$0.60/ft (\$1.83/m) for a 4-in. (10.2 cm) line and expects the price to continue decreasing. Based only on the cost of materials and installation, State officials have estimated that the preformed tape placed on a section of interstate highway must last approximately 8 years to offset the cost of traffic paint. Although cost has been reported as a disadvantage for preformed markings, it depends on what other marking system it is being compared with and if such considerations as installation time, ease in installation, availability of application equipment, the need for priming, as well as maintenance, adhesion, distortion and skid resistance have been included.

EPOXY

Epoxy is a 100 percent solid, two-component, chemically-reacted system. It is both safe to handle and apply since it has no solvents to evaporate, and uses low heat. Epoxy is abrasion resistant, durable and adheres well on both asphalt as well as concrete.

- Durability: Epoxy's durability has proved "good to excellent" based on several tests in Minnesota. In one test, epoxy lasted over 1 year on high AADT systems as compared to conventional traffic paint (3 months or less), and was effective even 5 years later. At present, durability for 3 years has been proved on low AADT systems. Failures occur when pavement surface conditions are poor, when larger volumes of crossing or weaving traffic exists and when the requirements for application or quality control of the product have not been followed properly. Failures associated with epoxy are most likely to be one of the following:
    - Chipping, whether slight, moderate, or total, is caused by surface contamination or poor temperature control and can be apparent within days.
    - Color change is caused by lack of pressure control, improper mixing, or improper bead application.
    - Wheel tracking results from incorrect bead application.
    - Dirty stripes occur if the "instant no track" procedure designed for high speed roadways is used in urban, low-speed situations.

- Reflectivity: Under low to medium AADT conditions, epoxy's reflectivity is excellent when new and still acceptable after 3 years. Although daytime delineation has been found to drop after 2 years, nighttime value was more than adequate after three northern winters. Based on actual reflectivity readings, the Minnesota/DOT found that epoxy outlasted other durable marking materials.

Table 1. Service Life Comparison (in days)

AADT	Epoxy	Paint	Thermoplastic	Polyester
5,000	730 d.	365 d.	180 d.	NA
5-15,000	730 d.	180 d.	180 d.	365 d.
70,000	365 d.	90 d.	180 d.	NA

- Advantages: Epoxy is safe to handle and apply, has good color and bead retention (best when placed in 15 mils), excellent retroreflectivity, good abrasion resistance and good adhesion on both asphalt and concrete. Epoxy can be applied on damp pavement, achieves instant no track and is applied like paints. In addition, epoxies:
    - Provide an effective 12-month traffic delineation system (through the winter).
    - Increase safety since application exposes striping crews to traffic only once instead of four to eight times in the same period.
    - Requires less energy and equipment to apply than paint in order to service the same number of miles.

- Disadvantages: The majority of the disadvantages associated with epoxy are related to installation procedures and equipment. These disadvantages are:
    - The material is unforgiving--there is no room for sloppy, inattentive, or careless workmanship.
    - Control of the pressure and volume for the pumping system is critical; with present formulation, the material's temperature control during application is also critical.
    - Placement in urban, low speed situations must be protected to prevent tracking.
    - Special equipment is required, although not as much as thermoplastics require.
    - Placement and drying times are slow.

- Range of Costs(1981 Costs): The initial cost of epoxy is six times higher than for paint, although an extended service life results in an equitable cost comparison. Based on a 4-year projected cost study under various traffic volume situations, the Minnesota/DOT found that an application of epoxy (15 mils) outlasted applications of paint, thermoplastic, and polyester materials by factors of two to eight. Application of epoxy at 4 to 10 mils thicknesses further justify its favorable comparison with these materials. New epoxy formulations and redesign of equipment in the future are expected to reduce costs. Although outdated, the following are recent bid prices for epoxy:

Minnesota (500,000 feet [166,667 m] applied):	$0.28/ft ($0.85/m) edge line $0.30/ft ($0.91/m) skip line
Arizona (130,000 feet [43,444 m] applied):	$0.30/ft ($0.91/m) edge line

POLYESTER

Polyester is a thermosetting durable material consisting of two components, a resin and a catalyst. The resin resembles standard traffic paint, and the catalyst is normally an organic peroxide (methyl ethyl ketone peroxide - MEKP). MEKP must be handled with care as it can cause burns and its fumes are dangerous. Polyester has a long drying time, but can be applied over old paint.

- Durability: In one study, polyester lines rated equally in color with painted lines after 3 years, although the paint has been applied three times. In another study, the polyester line on a highway with 20,000 AADT appeared grayer than paint in the daytime but was superior at night and only reached the end of its useful life after 8 years. Based on experience in Ohio, the following service life can be expected when polyester is applied on good bituminous pavement:

  - 3-4 years - center line, up to 10,000 AADT;
  - 1 year - center line, up to 10,000 AADT with heavy trucks and curves; and
  - 3-4 years - lane line, up to 24,000 AADT.

  Polyester has been successful when used for center lines and lane lines and has few reported problems when applied over old paint. Currently, Ohio is not using polyester on its concrete pavements because of adhesion problems. Tests show that polyester lines applied at thicknesses of 7-1/2 mils and 15 mils are equally durable.

The biggest problem for polyester markings is abrasion. In addition, bond failures can occur if polyester is applied over an emulsion seal as well as from tracking, poor weather conditions, an oily asphalt mix, an inexperienced crew, or poor equipment. The "swiss cheese" effect, which occurs on oily asphalt if polyester material is applied too soon after paving, can be avoided either by waiting approximately 2 weeks after paving is completed or by striping first with fast-dry paints.

- Reflectivity: Using 15-mils wet thickness and 16 to 20 pounds of standard drop-on beads per gallon (1.9 to 2.4 kilograms per liter), polyester material provided good reflectivity in one 3-year study; it has provided superior reflectivity in another study for 8 years. As Ohio expands its use, it continues to find that polyester provides excellent reflectivity.

- Advantages: In addition to performing consistently well for more than 3 years, polyester material does not require more care than standard traffic paint or a minimum application temperature for the pavement. It is low in cost and can be applied over old paint.

- Disadvantages: There are several disadvantages associated with the use of polyester: its poor performance on concrete, bond failures due to abrasion (related to improper application procedures), and its lengthy drying time. Also, since the correct mix ratio does not stabilize immediately, some time must be allotted for this before each striping session begins. Equipment can be troublesome, particularly the plumbing for the catalyst if an air-atomized system is used; the catalyst itself requires cautious handling and the use of protective goggles and gloves. For best results, the air temperature must be 50°F (10°C), ambient, and application must wait for 2 weeks after paving, unless a primer is applied first.

- Range of Costs (1981 Costs): The following bid prices for polyester markings (including materials) show how costs have compared in recent years:

	1980	1979
Center line:	$289/mi	$632/mi
Lane line:	$266/mi	$258/mi
Channel line (8-in.):	$0.62/ft	$0.85/ft

Polyester compares with other durable materials (per foot) as follows:

	Polyester	Fast-Dry Paints	Epoxy
Edge line:	$0.12	$0.03	NA
Lane line:	$0.15	$0.04	$0.40
Center line:	$0.20	$0.05	$0.50

The Ohio/DOT spent approximately $7,000 to convert an older hot-line paint striper to apply polyester; a similar one was manufactured for $8,000. It was also able to convert an existing hot-line hand striper for approximately $1,300.

EPOFLEX

Epoflex is an epoxy thermoplastic material consisting of a binder (60 percent solid and 40 percent liquid resins), pigment, a calcium carbonate filler, and an amount of premixed glass beads that provide continuous reflectivity as the material wears.

- Durability: In field trials on both asphalt and concrete pavements in California, Colorado, Minnesota, and Texas, Epoflex has provided very satisfactory durability. In most cases, it is many times more durable than paints and at least twice as good under the most severe conditions in which it was tested--27,000 AADT with a high volume of trucks and much studded tire traffic use. Epoflex that was applied over existing paint stood up as well as that on bare pavement. The following conclusions about Epoflex's service life were based on these tests:

- The service life of Epoflex is equivalent to 10 applications of paint on concrete and asphalt pavements in warm climates (no snowplowing), under both moderate and heavy traffic conditions.
- The service life of Epoflex on asphalt is twice its life on concrete in cold climates and with moderate traffic conditions.

The FHWA is encouraged about the possibility that Epoflex will be an excellent replacement for conventional traffic paints in almost any type of situation.

- Reflectivity: On a commuter route in Los Angeles (42,000 AADT), Epoflex demonstrated excellent bead retention and no discernable wear after 2 years, while lines of traffic paint showed very clear signs of deterioration. After a year in Minnesota, which included a severe winter, Epoflex was still providing very satisfactory day and night delineation and visibility. Glass beads are dropped on during application to provide initial reflectivity while the premixed beads ensure its continuance. Specially treated beads, which are more resistant to chemicals, provide better bead retention.

- Advantages: The major advantages of Epoflex are its no track time (less than 5 seconds), lack of volatile components, low cost and simplicity of formulation. It provides an extended service life and good reflectivity on both asphalt and concrete and can be applied at temperatures down to freezing.

- Disadvantages: Based on limited field experience, Epoflex has three major disadvantages: its high installation temperature, its incompatibility with existing striping equipment, and the timing of drop-on bead application.

- Range of Costs (1981 Costs): Epoflex is comparable to the low cost of traffic paint. The materials alone, without considering compounding into a finished product, cost approximately $7/gal ($1.85/liter) as compared to $4/gal ($1.06/liter) of traffic paint. A 4-in. (10.2 cm) line of Epoflex at 15-mils thickness costing $0.22/ft ($0.072/m) costs $0.005/ft ($0.016/m) more than paint (10 mils, dry). Since Epoflex has twice the service life of paint, however, it actually costs less in the long run. The cost of producing Epoflex from raw materials is expected to be small because of the simplicity of the formulation. Although the cost of converting stripers designed for paint will be significant, Epoflex's service life under almost any condition is expected to rapidly amortize this cost over a short time.

DIRECTION OF PROJECT ACTIVITIES:

The literature review revealed that previous studies have employed larger bead-size gradations resulting in improved wet-night retroreflectivity. However, specific information about the performance of particular bead-binder combinations was lacking. It is suggested that manufacturers of large glass beads be contacted to determine what is available, their associated cost, claimed service life and the product users. Potters Industries have been identified as being one of the pioneers in glass bead manufacture. Also, manufacturers of different binder types may be contacted to determine what binder-bead combinations could be optimally used.

More detailed reports of past large glass bead testing projects should be obtained. The literature review identified that the States of Ohio and Minnesota have conducted pavement marking test projects, with Ohio having specifically tested larger glass beads for pavement marking. Potters Industries also conducted field tests nationwide using larger beads at a test site in New Jersey and in subsequent demonstration projects in 7 geographic areas, encompassing 25 states.

It was noted that the level of precipitation that was considered to be heavy (1/2 inch/hr) [11], may not be appropriate for local conditions here in Alabama. It may be necessary to consider field testing of larger glass bead gradations under Alabama conditions and for the specific binder types prevalent in the State.

A further task that is suggested is to conduct a survey of the current state-of-the-practice. The survey would be directed primarily to State and local highway agencies identified through the literature review and would be used to determine which materials offer the best performance under actual roadway conditions.

Suggested Questions for State-of-the-Practice Survey

1. How many miles of roadway is your agency responsible for maintaining?

2. What types of pavement marking materials has your agency used, at least on an experimental basis?

Material Type	Surface Type and Application			
	Asphalt		Concrete	
	long lines	transverse	long lines	transverse
Paints Thermoplastics Preformed Markings Epoxy Polyester Epoflex				

3. What types of pavement marking material and reapplication schedule is currently used by your agency?

Material Type	Surface Type and Application			
	Asphalt		Concrete	
	long lines	transverse	long lines	transverse
Paints Thermoplastics Preformed Markings Epoxy Polyester Epoflex				

4. Please indicate any special problems that have been encountered by your agency in the use of following. (e.g. poor service-life, adhesion, checking, shifting etc.)

Material Type	Surface Type and Application			
	Asphalt		Concrete	
	long lines	transverse	long lines	transverse
Paints Thermoplastics Preformed Markings Epoxy Polyester Epoflex				

5. What size glass beads does your agency predominantly use?

6. Indicate if your agency has tried any large glass beads, the type of marking material and the performance.

Bead Size	Material		Rectroeflectivity		
			Performance		
	type	application thickness	Satisfied	Unsatisfied	Serviceable

7. What do you consider as being the most cost effective combination of marking material and glass bead size for the following?

	Material Type	Bead Size
Area/line type URBAN long line transverse RURAL long line transverse		

8. Are you aware of any study performed by your agency to determine the effectiveness and durability of different marking material types and large bead size?..

____ Yes Please provide a copy of study.

____ No

9. Would you like to receive a summary of the survey results? ____ Yes ____ No.

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1. Bryden, J.E., et. al., "Reflectivity and Durability of Epoxy Pavement Markings," Transportation Research Record 1086, Transportation Research Board, Washington, D.C.

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3. Dale, John M., "Traffic Marking Beads - Are the Gradations Right?", John M. Dale, Better Roads, January, 1969.

4. Dale, John M., "Pavement Markings: Materials and Application for Extended Service Life", NCHRP synthesis #138, TRB, Washington, D.C., June 1988.

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18. Van Gorkum, F. "Night-Time Visibility of Seven Road-Marking Materials", Traffic Engineering and Control, April, 1984.

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21. Bali, S.G., McGee, H.W. and Taylor, J.I., "State-of-the-Art on Roadway Delineation Systems", U.S. Department of Transportation, Federal Highway Administration, Report No. FHWA-RD-76-73, May 1976.

[1] Bryden, James E., et. al., "Reflectivity and Durability of Epoxy Pavement Markings." Transportation Research Record 1086, Transportation Research Board, Washington, D.C.

Epoxy pavement markings in New York were surveyed to determine their durability and reflectivity after up to 6 years of service. Study sites were identified by searching NYS DOT records to identify locations where epoxy markings were applied. Sixteen projects were identified, involving four contractors and three suppliers. A total of 145 samples were taken at these projects. Durability was rated as "good", "fair" or "poor" based on a subjective evaluation. Reflectivity was measured with a reflectometer patterned after one built by the Michigan Department of State Highways and Transportation. The instrument is equipped with a photocell and an internal light source and can provide a digital readout from examining a few inches of line.

Most projects appeared to be in good condition, however, some were performing poorly. No trends relating performance to the striping contractor or supplier were identified. More samples will be needed to identify the causes of the marking failures.

[2] Dale, John M., "Development of Improved Pavement Marking Material - Laboratory Phase", John M. Dale, NCHRP #45, Highway Research Board, 1967.

The objective of this project was to study ways of improving delineation of roadways under wet and dry conditions by either improving techniques that use existing materials or developing new materials and techniques.

The material presented regarding glass bead use in pavement markings is summarized below:

Physical Nature of Glass Beads

The effectiveness of glass beads is greatly reduced by their hygroscopic nature. This property leads to problems with clogging of bead-dispensing apparatus as well as over-embedment of beads into the pavement markings. A solution to this problem was silicone treatment of glass beads. Experiments were conducted to determine the duration of effectiveness of the treatment in the actual roadway environment.

Gradations of Beads

Typical gradation specifications for drop-on glass beads are presented, both for paint as well as for thermoplastic. Specifications for premixed glass beads call for a mixed gradation of beads of a smaller size than are called for in the drop-on application.

Retroreflective Characteristics of Glass Beads

Retroreflection is a function of bead embedment, binder orientation with the light source, mixed bead sizes in a constant-thickness binder, refractive index and shape. As well, the retroreflection is also a function of the thickness of water film submerging the beads.

Experiments were performed to illustrate the above variables' effects on retroreflection.

Interpretation of Results:

The optimum depth bead embedment for maximum retroreflection was found to range from 55 to 60 percent of the vertical height of the bead. Beads imbedded to less than half of their vertical height in ordinary binders have insufficient mechanical embedment to prevent them from being dislodged under traffic.

Bead orientation is largely due to the capillary action of the paint on the beads, regardless of the direction of application. However, vertical application of the beads from a moving machine resulted in a favorable orientation of the beads for one-way traffic. For more equal reflectance in both directions, it was suggested that angling the bead dispenser to the rear away from the machine could result in a favorable orientation of the beads.

Currently, the gradation being employed is that passing a No. 30 sieve and retained on a No. 50 sieve, giving an average diameter of approximately 17 mils. Also, current paint application film thickness range from 16 to 20 mils. It was suggested that the use of larger bead sizes could counteract the submerging effect of water films on wet days. However, if one is to use larger beads, it is necessary that the film thickness of wet paint be correspondingly increased. With the current application thickness of thermoplastic marking materials at approximately 125 mils, the opportunity to go to larger bead sizes is a simple, straightforward solution.

[3] Dale, John M., "Traffic Marking Beads - Are the Gradations Right?", John M. Dale, Better Roads, January, 1969.

The gradation specifications for glass beads used in reflectorizing traffic-marking materials are in large measure the gradations obtained in the bead-manufacturing processes and have an interesting but not fully appreciated relationship to their performance requirements. This paper examines the relationship above and gives a description of previous literature related to this topic and provides some interpretation of the work. This paper considers 'drop-on' beads exclusively.

Summary of Findings:

1. With the majority of the glass beads submerged in the paint, the predominant thought is that traffic marking paint fails by abrasion, and sooner or later all of the glass beads will become exposed and active. In actuality, this occurs only in very exceptional circumstances.

2. Glass-bead gradations have remained almost unchanged since the 1940's. However, there has been great change in paints since then. Since the performance of glass beads is necessarily linked to the performance of the paint or binder, a change in the type of paint and its performance should imply a change in bead gradations.

3. There is variation in the method of application of the drop-on beads, although similar bead-gradations exist between states - one state drops beads onto a wet-paint film

thickness of 0.015 inches, while another drops beads onto a wet-paint film thickness of 0.020 inches.

4. Bead gradations used are based on the fact that paint fails by abrasion. Yet large amounts of traffic paints are known to fail by chipping and flaking away. The ASTM has in fact developed a standard method entitled "Evaluating Degree of Resistance of Traffic Paint to Chipping" (D913-51).

5. On all but the smoothest textured pavement surfaces, the paint and beads on the uppermost protruding pieces of aggregate experience wear, whereas the bulk of the markings and beads lie in the valleys between the large pieces of aggregate. Here they are never exposed to wear.

6. To keep it simple, most authorities apply the same paint at the same thickness to city streets, curbs, gore areas, expressways etc. To keep it simple, they also apply the same bead gradation at all these locations. How efficient and how economical this proves to be is another question.

7. It was seen that the use of a gradation of mixed sizes in a constant thickness of paint results in only a very small percentage of the beads operating efficiently on application. If the material does not fail by abrasion, a lesser quantity of properly sized beads, though more costly per unit of weight, would give more retroreflection at a considerable overall cost savings.

[4] Dale, John M., "Pavement Markings: Materials and Application for Extended Service Life", NCHRP synthesis #138, TRB, June 1988.

This report describes the need for markings, preparation of the pavement surface, and the various types of paint, thermoplastics, and raised markers in current use.

The material relevant to the use of glass beads in various types of pavement markings - paints, thermoplastics, thermosets, and tapes is discussed below.

PAINTS:

Traffic paints are divided into two types:

Solvent Borne Paint

This paint contains approximately 25% by volume of pigment, extender, and filler. As well, 25% binder and 50% solvent are added. The favored pigments are titanium dioxide for white and lead chromate for the yellow paints. The binder portion of paint is actually a combination of as many as 10 ingredients.

Water-Borne Paint

California has developed a performance specification for water-borne paint. Water proof glass beads are used in this paint. California has concluded that water-borne paints;

1. Are proven alternatives to solvent-borne paints.
2. May be applied hot or cold depending on equipment and weather conditions.
3. Provide service life equal to or better than solvent-borne paints.
4. Provide bead retention superior to solvent-borne paints.

Bead Gradations for Drop-on Application:

Sieve		Openings	% Passing
Std.	Alt.	(in)	by Weight
600 µm	30	0.0234	100
250 µm	60	0.0098	40 - 70
180 µm	80	0.0070	15 - 35
106 µm	140	0.0041	0 - 5

Beads < 106 µm size are normally used as premix materials. However, some studies have questioned the gradation of the beads used.

THERMOPLASTICS:

Thermoplastic marking materials are a mixture of resins, glass beads, pigments, and fillers. A typical composition is as follows:

Materials	% by weight
Resin	18
Glass Beads	25
Pigment & Filler	57

Thermoplastic marking costs on the order of five to six times more than paint. However, thermoplastic marking applied at 60 to 120 mils (1.5 - 3 mm) in thickness project more easily through submerging water films and drain water more rapidly than thin film markings such as paint.

Epoflex, a thermoplastic epoxy marking material developed in the late 1970s, is a faster-setting, durable, low-profile marking material having
the following formulation:

Material	Parts by Weight	
	yellow	white
Solid epoxy resin	30	30
Liquid epoxy resin	20	20
Titanium Oxide (ASTM D476 Type II)	-	10
Lead Chromate	9.3	-
$CaCO_3$ (ASTMD 1199)	10	10
Premix Beads (ASTM 2205 Type I)	14	14

Drop-on, gradation-type traffic-marking beads are gravity dispensed onto the top of the molten Epoflex immediately behind the spray gun, where they embed themselves to just below their horizontal axis.

THERMOSETS:

Thermosetting materials have two different components that are brought together and a chemical reaction takes place that liberates heat. The two types of thermosetting materials considered here are Polyester and Epoxy.

Polyester:

Much of the original development and testing of polyester materials was done by the Ohio DOT and the Glidden Company during the 1970's.

Polyester pavement-marking materials are applied at a wet film thickness of approximately 0.4 mm and, because they contain no solvent, the hardened line retains its thickness. Glass beads of the type applied to conventional traffic paint at loadings of 12 lb/gal are applied to the polyester materials.

Epoxy:

Much of the developmental work on two-component, thermosetting epoxy pavement-marking materials was done by Minnesota DOT and the H.B. Fuller Company during the 1970s.

The epoxy marking materials are applied to Portland Cement concrete and asphaltic concrete pavements with success.

TAPES:

Tapes are fabricated as roll-sheet stock or cut-out legends in a factory. They are for the most part manufactured using polyvinyl chloride resin binders that are complemented in formulations with pigment, filler, and glass beads, used both in the premix and surface embedded forms.

There are two types of tape marking materials with the following specifications:

	Type I	Type II
Thickness	90 Mil	60 Mil
Composition (% by weight)		
Resins	40	20
Pigments & Filler	38	30
Glass Spheres	14	33

Cost Effectiveness:

With the exception of two-component internally mixed epoxy marking materials, almost all other pavement marking materials have been observed to fail more rapidly on PCC pavements than on asphaltic-concrete pavements. The most important reason for this is the loss of adhesion. The volume of traffic, type of traffic, and the environment are the most important factors affecting the life expectancy of the markings.

Given in this section are life expectancy curves of AADT per lane versus useful life for pavement markings on both asphaltic concrete and Portland Cement Concrete Pavements.

[5] DeJaiffe, Robert, "Measuring Wet-Night Delineation Reflectivity", Transportation Research Record 1149, Transportation Research Board, Washington, D.C., 1987.

Approximately 54 percent of fatal crashes occur at night; 14 percent occur when the road is wet. Pavement markings can lose their reflectivity, and visibility on dark rainy nights, when drivers actively look to them for guidance. Much research has been devoted to the issue of wet-night visibility. Potter's Industries Inc. (377 Route 17, Hasbrouck Heights, N.J. 07604) has been involved in numerous efforts to demonstrate the wet-night visibility effectiveness of various striping systems, particularly those using large glass beads. Rain, fog, and darkness can obscure vital visual communication from the road. Reflectorized pavement markings provide drivers with information about the roadway. Measurement of reflectivity accurately to obtain quantitative comparison for research purposes is a problem. This paper describes the two methods that have been used and the ways in which their deficiencies led to the development of a laser-illuminated retroreflectometer.

The two methods described are the Boppard System and Wood Research Center. The Boppard System uses luxmeter and telephotometer to measure reflectivity in artificially generated rain while the Wood Research Center uses a telephotomultiplier that can be adjusted to simulate the driver's visual perspective. However, quantitative and reproducible field measurements are not obtained. The laser reflectometer is able to measure retroreflectivity in real world tests. Three major benefits are listed. It can reject ambient light and reads luminance from the target area. This meter can be used in adverse environmental conditions. The need for both wet reflective systems and methods for measuring their performance has been noted in the report "Visual Aspects of Road Markings," from the Commission International De L' Eclairage.

[6] DePaulo, Donald, C., "Ohio Tests Large Glass Striping Beads", Better Roads, April 1990, pp. 42-46.

The Ohio Turnpike Commission, recognizing the fact that wet weather reflectivity at night is a serious problem, substituted standard-sized glass striping beads with Visibeads, made by Potters Industries, along the highway. Potters' Visibeads are three to four times larger than standard glass beads and are treated with a specialized coating to improve the embedment and adherence. Interviews conducted with the motoring public on a rainy night shortly after the project's completion yielded extremely favorable comments. The comparative cost for Visibeads is approximately 400% more per pound than that of the standard glass beads.

Polyester paint was used in the striping project, and the anticipated service life was two years. Sixteen test areas were established and readings taken every four months. The test areas represent a wide range of volumes and roadway geometrics, as well as pavement conditions. Nine readings were taken of both the white and yellow line at each location with a Mirolux Reflectometer. At the time this report was written, only four sets of data had been obtained, but all average reflectivities were above the acceptable level. In an 11 month period, the average reflectance decreased from 280 milli-candelas per square meter to 205 milli-candelas per square meter, with well over half of this drop occurring within the first three months following installation. Naturally, there was more loss of reflectivity in areas of higher traffic volumes. Also, in areas which were recently resurfaced, there was less loss of reflectivity than in areas which were in need of resurfacing.

The two major causes to which the loss of reflectivity are attributed are joint sealing and snowplowing. The author estimated that 25 to 80% of the pavement markings along the length of the turnpike had been damaged and the level of reflectance lowered because of plow damage, with perhaps 5 to 10% of the markings being damaged by joint sealing. With regard to the 40% of the area in which the reflectance level has been reduced, the line was still there and remained much more visible than a fast-dry paint line with standard beads would have been under similar conditions.

[7] Ethen, J.L., and Woltman, H.L., "Minimum Retroreflectance for Night Time Visibility of Pavement Markings", Transportation Research Record 1093, Transportation Research Board, 1986.

Many studies have addressed questions related to pavement markings; few, however, have dealt with the subject of minimum and generally acceptable retroreflectance values for night-time visibility. Three studies that dealt with this subject were found, and they agreed closely on minimum and acceptable values, that is 100 and 300 $mcd/m^2/lx$ respectively.

Minimum retroreflectance depends on the retroreflective quality of the painted line, the quality of headlamp illuminance, the contrast between the line and the immediately adjacent road surface, and the presence or absence of roadway lighting.

This paper describes an experiment using markings with a broad range of retroreflectance on a level tangent roadway of weathered asphaltic concrete. A subjective rating system was employed, and the results correlated well with those of other studies.

The values of minimum and acceptable retroreflectance may be useful in establishing acceptance and service criteria for pavement markings.

The availability of portable instruments such as the Ecolux, which was used in this study, permits the assessment of pavements markings for conformance to the criteria of minimum and acceptable retroreflectance.

[8] I.J. Fullerton, "Roadway Delineation Practices Handbook", FHWA-IP-81-5, Federal Highway Administration, Washington, D.C., 1981.

This handbook provides fundamental concepts of delineation, current practices, and promising new techniques of the future. The handbook was developed using the experience of state, county, and city agencies and also summarizes future directions and developments as reported by research.

The material relevant to the use of glass beads in pavement marking is summarized below: Glass beads are mixed or dropped on paint, thermoplastic, polyester, and epoxy pavement markings to provide the necessary reflectivity. The amount of light reflected by glass beads is a function of three factors: refractive index; bead shape, size and surface characteristics; and the number of beads present and exposed to light rays.

Refractive Index:

Commonly, beads used in traffic paint have an RI of 1.50. There are some 1.65 beads used in thermoplastic and 1.90 beads used for airport markings. Each RI bead has a different density; the higher the RI the higher the density. However, despite the increased brightness gained with the higher RI, most state and local highway agencies use 1.50 RI beads. Some do use a mixture of 1.50 and 1.65 beads on highways, and a few supplement the 1.50 beads with 1.90 RI beads.

Bead Size or Gradation:

The standard gradation range used by 85% of the State highway agencies is 20 to 80 mesh. Some evidence suggests that uniform, smaller-sized beads (40 to 80 mesh) produce a brighter, more durable marking. However, this is not true under wet-pavement conditions.

Flotation Beads:

These are preferred by a number of agencies because of their superior embedment. Flotation beads are especially effective with a smaller, more uniform bead gradation and wet paint thickness of 11 mils. This may however require more frequent restriping and result in lower wet-night visibility.

Application Techniques:

Drop-on application of beads is the most commonly used technique. Smaller size beads are generally used in premix paint to avoid the bead settling problem in paint storage. Agencies using premix paint also apply drop-on beads (1 or 2 lbs/gal) to provide immediate reflectivity.

Volume of beads used:

The optimum amount of beads to be applied depends on paint thickness, size of beads, expected service life of marking, and the type of application and equipment. The normal application is 6 lbs/gal, but 4 lbs/gal has been reported to be effective.

[9] Gillis, Henry J., "Durable Pavement Marking Materials," Transportation Research Record 762, Transportation Research Board, Washington, DC 1980, pp. 36-45.

Objectives:

The purposes of this project were to evaluate epoxy, polyester and thermoplastic resins as pavement marking materials and to develop and evaluate a spray-on epoxy/glass bead system appropriate for both bituminous and concrete pavements. The study was conducted by the Minnesota Department of Transportation between 1975 and 1978 and was divided into two phases. During the first phase, in 1975 and 1976, 140 miles of epoxy skip line of varying film thickness and bead type was placed on high volume roadways in the Minneapolis area. Forty miles of polyester skip line was placed in 1976 to compare with the epoxy type. In the second phase, during 1977 and 1978, approximately 230 miles of thermoplastic and 150 miles of epoxy were placed statewide.

Phase I

One of the primary purposes of this phase was to develop and fabricate a fully production-capable machine to be used for heating, metering, mixing and spraying the two-component epoxy. The system developed is described.

In areas where the traffic volume was heavy, glass beads were poured on the epoxy stripe in an attempt to eliminate tracking of the epoxy. This worked so well that a free-fall system capable of flooding the epoxy stripes with glass beads at a rate of 20 to 25 lb/gal was developed. Three different types of beads were evaluated for reflectivity effectiveness. The Minnesota DOT specification beads reached the minimum acceptable reflectivity level within nine months after placement, while floating glass beads reached this level within 10.5 months. Chemically moisture-proofed beads were found to be acceptable for a period of approximately 14 months.

Observations showed that the epoxy provided adequate delineation in day and night conditions for 24 months following installation. During wet weather at night, the shiny enamel surface of the epoxy serves as a mirror and reflects the overhead lighting and the taillights of the vehicle ahead, serving to amplify the delineation system. A plot showing the retroreflective qualities versus time for a conventional traffic paint placed six times a year and for epoxy placed once in a two-year period is presented.

The following important information can be obtained from the chart:

- Epoxy has better reflectivity than conventional traffic paint 60.6 percent of the time.
- Paint has better reflectivity than epoxy 32 percent of the time.
- The reflectivity of paint is below the minimum acceptable level 51.7 percent of the time.

- No form of delineation exists 18.2 percent of the time when conventional traffic paints are used. Because of severe winter conditions, it was not possible to repaint the lines when such a point was reached.

Phase II

During this phase, bisymmetric glass beads were used on thermoplastic striping and chemically moisture-proofed beads were used on the two-component epoxy-resin system developed in the first phase of the study. Retroreflectivity readings were taken of test sections, with a failure being recorded for readings less than 30 percent of standard Minnesota DOT ERMA. The thermoplastic striping had a higher failure rate because it was either worn off or plowed off the pavement surface or because of the glass beads were removed and sheared off by snowplows as a result of the greater thickness of the material (30 mils). The epoxy failed due to adhesion problems caused by contamination of the pavement surface.

Material	No. Test Sections	Number of Months	Percent Failure
Thermoplastic	44	6	93
		12	77
		18	86
Epoxy	51	6	24
	25	12	8
	25	18	16

No specific information is given in this report as to the most appropriate size of glass beads to be used.

[10] Holman, F.L., "Glass Beads for Traffic Marking Paint", Alabama Highway Research, HPR Report #55, July 1971.

This report describes a study of glass beads in traffic marking paint done in Alabama under the "Traffic Marking Beads - National Experimental and Evaluation Program". This study included "premixed" beads as well as "drop-on" beads. In addition, a limited study of the effect of cleaning a new bituminous surface prior to painting was included.

Materials:

The reflective "drop-on" glass beads used were in accordance with the "Proposed Specifications for Reflective Glass Beads, Special Grade". Under this specification, beads with a refractive index of 1.50 and the gradation below were used:

Sieve	Total % Passing
30	100
40	90 - 100
80	0 - 10

The reflectorized white paint with premixed glass beads was in accordance with the Alabama Highway Department's Standard Specifications for Highways and Bridges. Under these specifications, a minimum of 4.20 lb/gal and a maximum of 4.90 lb/gal of beads were to be used, and the beads were to be of the following gradation:

Sieve	Minimum	Maximum
Retained #40		0
Passing #40 - Retained #60	0	5
Passing #60 - Retained #70	0	12
Passing #70 - Retained #80	0	15
Passing #80 - Retained #230	58	90
Passing #230	0	10

Test sections of centerline striping were installed on South Boulevard and the Atlanta Highway (US 80) in Montgomery. The roadways were subjected to traffic of approximately 26,000 vpd and 23,000 vpd for the two locations, respectively.

The test sections on South Boulevard were on a newly placed bituminous surface, while those on the Atlanta Highway were on a six lane concrete pavement which was about 8 years old. The stripes were periodically rated visually for appearance, durability, and night visibility on a scale of 0 to 10.

Conclusions:

The following conclusions were reached:

1. Test sections with very high "drop-on" bead application rates (9.9 and 17.4 lb/gal) had good night visibility but rated low in appearance and durability.
2. Early in the study, the paints with "drop-on" beads generally were rated the highest in durability. However, in the later stages, the test sections with premixed beads and no "drop-on" beads improved in standing.
3. Premixed beads with 2.2 lb/gal of "drop-on" beads and ordinary paints with 5.2 lb/gal of "drop-on" beads showed the best overall performance for asphalt pavements.
4. Premixed beads with 2.2 lb/gal of "drop-on" beads showed the best overall performance for concrete pavements.

[11] Kalchbrenner, James, "Large Glass Beads for Pavement Markings", Transportation Research Record 1230, Transportation Research Board, Washington, D.C., 1989.

There have been many changes in the pavement marking industry in the past 20 years, particularly in the use of polymeric non-shrink binders (epoxy, polyester) as durable striping materials. It has become apparent that as striping line durability and wet line thickness increased, glass bead characteristics had to change. The extended durability of these films has shown the need for bead surface treatments that improve bead adherence to the binders. A need for larger-diameter glass beads is described, which also fits the theoretical requirement of bead embedment and binder thickness for optimum reflectivity.

Larger Glass Bead Development:

Potters Industries experimented with larger glass bead sizes both in the laboratory and at a field test site in New Jersey in 1984.

The laboratory tests under wet-night conditions indicated that larger glass bead sizes provided retroreflectivity levels 3 to 4 times higher than the minimum visibility requirements in rainfall rates up to 1/2 inch/hr - a level twice that considered to be heavy precipitation. When the rain stops, the large-bead pavement marking recover quickly to extremely high retroreflectivity values.

After different beads sizes had been tested, it was determined that properly embedded beads within the size range of 10 to 20 mesh, depending on binder, could overcome the water film effect and reflect light back even in rainfall rates of 1/2 inch/hr.

Initial field trials with large beads were conducted in West Milford, N.J. Both thin film materials of less than 20 mils (epoxy, polyester), as well as thick film materials (thermoplastics, etc.) were used in order to optimize bead binder systems. Variations in binder-film thickness, bead size, and bead surface treatments were evaluated for reflectivity, durability, and wet pavement/night-time performance.

Field Performance:

During the 3 years prior to this report, Potters Industries worked together with State and local jurisdictions across the U.S. to demonstrate the effectiveness of the large-bead system. Demonstrations using existing durable binders were initiated in 7 geographic areas covering 25 states. The trials involved a variety of binders, road types, geographical areas, pavement types, and marking applications.

Discussion of Results:

The performance of larger beads is demonstrated to be significantly superior to that of smaller (standard) bead sizes for a variety of binders - thin film (epoxy, polyester) as well as thick film (thermoplastics).

Conclusions:

Gradation specifications are suggested for single and dual-drop marking systems.

TABLE 2 GRADATIONS FOR DURABLE 100 PERCENT SOLID THIN-FILM MATERIALS

15 Mils		15-Mil Dual Drop and 20-Mil Single Drop		20-Mil Dual Drop	
U.S. Sieve	Percent On	U.S. Sieve	Percent On	U.S. Sieve	Percent On
8	–	8	–	8	–
10	–	10	–	10	0–5
12	–	12	0–5	12	5–20
14	0–5	14	5–20	14	40–80
16	5–20	16	40–80	16	10–40
18	40–80	18	10–40	18	0–5
20	10–40	20	0–5	20	–
25	0–5	25	–	25	–
PAN	0–2	PAN	0–2	PAN	0–2

NOTE: Application rate: Single drop—epoxy, 24 lb/gal; polyester, 20 lb/gal. Dual drop—epoxy, 12 lb large + 12 lb std/gal; polyester, 10 lb large + 10 lb std/gal. Rounds: 75 percent per screen, 80 percent overall. Coating: binder specific.

TABLE 3 GRADATION OF STANDARD BEADS FOR DUAL-DROP APPLICATION

U.S. Sieve	Percent On
20	0–5
30	5–20
50	30–75
80	9–32
100	0–5
PAN	0–2

TABLE 4 GRADATIONS FOR THICK-FILM BINDERS (THERMOPLASTICS AND PMMA)

U.S. Sieve	Sunbelt	Moderate	Northeast
6	–	–	–
8	0–5	–	–
10	5–20	0–5	–
12	40–80	5–20	0–5
14	10–40	40–80	5–20
16	0–5	10–40	40–80
18	–	0–5	10–40
20	–	–	0–5
PAN	0–2	0–2	0–2

NOTE: Recommended specifications for thermoplastics vary depending on geographic location, with the largest size used in Sunbelt locations. In all cases the dual-drop system is used with thermoplastics.

Application rate: Dual drop—12 lb large + 12 lb std/100 ft^2. Rounds: 75 percent per screen, 80 percent overall. Coating: binder specific.

[12] McGrath, Marcia, A., Durable Pavement Marking Materials Workshop, FHWA-TS-81-221, Federal Highway Administration, Washington, D.C., 1981.

This publication summarized presentations on the evaluations of six durable pavement marking materials as reported at 1991 workshops. Pertinent information of each marking materials is given below:

Paints

No specific information if given regarding glass bead size and positioning.

Thermoplastics

The New York DOT now allows either alkyd of hydrocarbon resins, but specifies a minimum 17 percent binder content, plus 20 percent minimum glass beads, and a maximum 49 percent calcium carbonate and other fillers. A minimum RI of 1.50 is required for the glass beads, whether they are premixed or drop-ons. The beads are graded from a #20 to a #80 sieve and must have a moisture-proof coating. Southern states have reported average service lives of 10 years for thermoplastics. Reflectivity is generally equivalent to beaded paint, but holds the advantage during rain. In a study conducted by the Texas Transportation Institute, reflectivity was excellent on asphalt after 2 years, but was negligible on concrete because of bond failure.

Preformed Materials

The State of Virginia specifies a minimum of 20 percent glass beads, by weight, with 2 percent on the surface and an RI of 1.50. A study conducted by Kentucky DOT reported a four year average useful life for preformed materials, although in snowbelt regions, manufacturers will guarantee only 2 years for inlaid and 1 year for overlaid markings.

Epoxy

A free-fall glass bead dispenser, which actually places all the beads on the surface of the epoxy stripe, is necessary to achieve "instant no track". Standard bead guns in a series of two or three will not do. Epoxy markings were found to have an average effective service life of 2 years on roadways with an ADT less than 15,000 vpd and 1 year on roadways with an ADT of approximately 70,000 vpd, according to the Minnesota DOT.

Polyester

Glass beads are applied under pressure at a minimum rate of 15 pounds per gallon of polyester. Based on experience in Ohio, when applied on good bituminous pavement, polyester can be expected to have an effective service life of 3 to 4 years as a center line on roadways with an ADT of 10,000 vpd, or one year if there is a large percentage of heavy trucks and many curves. As a lane line, polyester will last 3 to 4 years on roadways with an ADT up to 24,000 vpd. Using 15 mils wet thickness and 16 to 20 pounds of standard drop-on beads per gallon, polyester material provided good reflectivity in one 3-year study; it has provided superior reflectivity for 8 years.

Epoflex

Glass beads are dropped on during application to provide initial reflectivity while the premixed beads ensure its continuance. Specially treated beads, which are more resistant to chemicals, provide better bead retention. The service life is equivalent to 10 applications of paint on concrete and asphalt pavements in warm climates under both moderate and heavy traffic conditions. In Los Angeles, Epoflex demonstrated excellent bead retention and no discernible wear after 2 years on a commuter route with an average ADT of 42,000 vpd.

[13] Pavement Traffic Marking: Materials and Application Affecting Serviceability, NCHRP Synthesis of Highway Practice 17, Highway Research Board, Washington, D.C., 1973.

The theoretical considerations of film thickness and bead size must be adapted to the reality of the operations of strip application and to the uncertainties of weather and control of materials. Also, the rate of drying of the paint film affects the rate of settlement of the beads into the paint film. Because the methods and time of failure of the paint-bead system is not pre-determined, it is difficult to choose the optimum bead gradation or to decide whether beads should be well distributed in the paint film or concentrated on its surface.

North Carolina and Ohio are presently large users of premix paint. Three or four pounds of fine-gradation beads per gallon of paint are generally premixed with the paint and two pounds of coarser beads per gallon are dropped on the wet paint line. Convenience of use and better distribution of the beads in the paint film are North Carolina's chief reasons for use of premix. Some 80 percent of state agencies use nonbeaded paint, however, because of the advantages of less nozzle wear, faster drying, and less paint agitation necessary. Instead, a drop-on system is used. A wet paint thickness of 15 mils and five pounds of beads per gallon of paint have been the most prevalent rates of materials application. Colorado changed from six pounds per gallon of 20 to 200 mesh non-floating beads to four pounds per gallon of 30 to 80 mesh floating beads, and reported superior brilliance and durability. A number of other states have decreased their wet paint thickness and the amount of beads applied.

There has been much discussion indicating that the gradation of the beads affects the brilliance of the stripe and that one gradation is superior to another. Because of the many factors, most of which are not economically controllable in the actual striping operation, a number of proposed bead gradation changes are not practical. When gravity-applied floating beads are used on unskinned paint film, it is possible to capitalize on a narrow range of bead sizes. However, floating beads lose this advantage if pneumatically applied and forced into the paint film.

When nonfloating beads are dropped on an unskinned paint film, the large beads sink first, followed by successively smaller beads. Fortunately, for better reflectivity, a great number of the small or intermediate sized beads interfere with the settlement of the larger beads and some of the larger beads remain partially embedded for immediate reflectivity. Greatest reflectivity to the driver's eye results when 40 to 45 percent of the volume of each bead is exposed to the light rays of the automobile headlights.

[14] O'Brien, Jim, "Embedment and Retroreflectivity of Drop-On Glass Spheres in Thermoplastic Markings", Transportation Research Record 1230, Transportation Research Board, Washington D.C., 1989.

In this paper, the embedment characteristics of drop-on moisture proofed and uncoated glass spheres and their subsequent retroreflectivity are discussed. The above properties were evaluated subjectively in various types of hot-applied thermoplastic traffic markings by illuminating test panels in a dark room.

It was found that, in all of the hot-applied thermoplastic traffic marking types tested, uncoated drop-on spheres were generally over-embedded because of positive wetting of the spheres by the thermoplastic traffic marking, and their retroreflectivity varied.

The use of moisture proofed drop-on spheres in various thermoplastic traffic marking types resulted in optimal bead embedment with subsequent excellent retroreflectivity. The optimal rate of glass sphere application in all of the thermoplastic marking types was found to be 10 lb of moisture-proofed glass spheres per 100 ft^2. This rate enhanced retroreflectivity, bead embedment, and coverage.

It was concluded that the retroreflectivity of the standard gradation of glass spheres may be enhanced in all of the thermoplastic types by increasing the percentage of spheres retained on U.S. Sieves 30, 40, and 50 and by increasing the overall rounds from 70 percent to 80 percent.

[15] "Road Marking and Delineation", OECD Road Research Group Report, Feb 1975.

This report summarizes the experience gained with road marking and delineation materials and devices. The advantages and drawbacks, as well as the specific properties of pavement markings, raised markers and delineators, and of the various materials used are evaluated. The report indicates the conditions and factors to be considered in the selection of suitable systems and materials for any given circumstance.

The material relevant to glass bead retroreflectivity, is summarized below:

Factors which improve the degree of retroreflection of glass beads include:

(a) Depth of embedment (the bead should be embedded to approximately 60% of its vertical height for optimum reflection). This depth also gives good bead retention properties in the binder.

(b) The refractive index of bead material should be as high as possible. However, studies have shown that beads with higher R.I.'s of up to 1.9 do not give significantly better reflectivity from the driver's point of view compared to beads of R.I. of 1.5. However, high R.I. glass beads are not suitable from a durability point of view, as the durability diminishes with increasing refractive index.

(c) A rate of application should be utilized such that beads do not optically interfere with one another and should be spaced to allow water films to drain from the exposed surface.

(d) The grading of beads is also important. Beads which are too small tend to be submerged in the marking film while large beads would not have sufficient embedment to be retained under traffic. It is considered that the gradation of beads should be between ASTM No. 40 (0.42 mm) and No. 80 (0.177 mm) mesh.

The life span of markings is largely determined by the thickness, type of marking, and traffic volume. Deterioration of the marking is also caused by mechanical stresses or climatic effects. Finally, the wear resistance is dependent on the type and amount of binder present in the material, the type of pigments and the thickness of application.

Adhesion between the marking material and substrate is dependent on good bonding at the marking/pavement interface. Adhesion problems are associated more with concrete than with bituminous pavements. The presence of curing compounds, the tendency of water to migrate to the surface, etc., are some of the situations whereby pavement marking failure occurs due to poor adhesion on concrete pavements. Failure on bituminous pavement is less common, but may occur on newly laid areas due to the presence of excess bituminous binders on the surface, and on older surfaces due to the polishing of aggregates.

Factors considered in providing specifications for glass beads are:

- refractive index of the glass.
- bead size distribution.
- percentage of defects.
- chemical resistance to $CaCl_2$, water etc.
- water-repellent characteristics.

No unanimity exists as to the preferred bead size distribution. Countries have three categories of glass bead: for mixed-in beads for paint, for drop-on beads, and for thermoplastics.

Mixed-in Beads:

France, U.S. - Diameters from 60 to 200 μ

Belgium, Netherlands - Diameters up to 420 μ

Thermoplastics:

U.K. - 400 to 1,600 μ

Belgium - 150 to 850 μ

ASTM (U.S.) - 180 to 420 μ

Spray-on Beads:

Specifications vary.

Several studies have been conducted with the aim of improving visibility in wet weather. They include: (a) Dressing with 8/12 mm grains before marking, in order to obtain a granular surface standing clear of the water film; (b) use of large glass beads (6 mm ϕ); (c) use of grains (4/8 mm) precoated with a binder containing microbeads.

Other studies were aimed at improving the effectiveness of the application process by using floating beads. An example of this type of study, "Reflective Traffic Bead Study-Final Report, May 1970", was conducted by the Colorado Department of Highways.

[16] Pocock, B.W. and Rhodes, C.C., "Principles of Glass Bead Reflectorization," Highway Research Bulletin 57, Highway Research Board, Washington, D.C., 1952, pp. 32-48.

Effect of Composition on Density and Refractive Index

The density of a glass bead is of interest for three reasons: (1) it determines the relative amount of reflective surface furnished per pound of beads of a given size; (2) it affects application procedures through its effect on the sedimentation rate of beads in paint; and (3) it is related closely to the refractive index, which increases as the density increases. Silica and boric oxide are the lowest in density, followed by the oxides of aluminum, sodium, potassium, magnesium, iron, calcium, zinc, barium, and lead.

Effect of Refractive Index on Distribution of Reflected Light

When light is incident on an interface of two transparent media, part of the light will be reflected from the surface of the second medium, part will be transmitted, and the remainder will be absorbed. The proportion of light reflected at the boundary surface can be determined from the equation:

$$R = 0.5(\sin^2(i-r)/\sin^2(i+r)) + (\tan^2(i-r)/\tan^2(i+r))]$$

where

R = fraction of incident light reflected

i = angle of incidence

r = angle of refraction

When one medium is air, the reflection at normal incidence is:

$$R = (n-1)^2/(n+1)^2$$

where

n = ratio of the refractive index of the second material to that of the first

An increase in the refractive index of glass from 1.50 to 2.00 will result in a tripling of the percentage of reflected light at normal incidence, from around 4% to approximately 12%. Maximum efficiency in the conservation of reflected light is achieved when this index is about 1.90, which brings parallel rays to an approximate focus at the rear surface of the bead.

Interrelation of Beads and Paint in Reflex Refraction

When a beam of light strikes the interface between a glass bead and the vehicle in which the finely divided paint pigment particles are suspended, the portion of light reflected is determined by the refraction indices of the glass and vehicle. The remainder, with some loss by absorption, is transmitted through the vehicle to the pigment particles where some of it is absorbed, some transmitted and the balance diffusely reflected. The amount of light reflected by the pigment particles is a function of their refractive index in relation to that of the vehicle, and the amount transmitted through them depends on their absorption characteristics.

Glass Bead Gradations

There are several advantages to the use of beads of smaller maximum size. Other things equal, the projected reflecting area per pound of beads is greatly increased as the average diameter is decreased. Since beads are sold by weight, which is proportional to volume, a dollar will buy more reflection in the smaller beads. Pound for pound, small beads maintain useful reflection longer because of their greater surface to mass ratio. In addition, smaller beads can be more easily premixed with the paint, will reduce drying time and the effect of relative humidity on drying time, and will lower the loss by rebound when bead-paint mixtures are sprayed on the pavement. The percentage of irregular and fragmentary particles is also noticeably lower in beads of smaller size.

Principles of Application

Beads mixed in traffic-marking paint and subjected to the usual pressures of spray application will undergo considerable loss through rebound from the pavement surface if they are larger than No. 60 sieve opening (0.0098 inch).

For beads with a refractive index of around 2.0, the efficiency of light return becomes very small under the conditions of illumination ordinarily encountered in driving, when the beads are embedded to a depth of half their diameters. Where beads are embedded less than 50 percent, the vertical aperture for reflex reflection is correspondingly greater, but this advantage is offset to some extent by the likelihood of poor bead retention. At the small angles of illumination usually involved, beads have to be embedded only slightly over 50 percent to lose the property of reflex reflection altogether.

To prevent beads which are in direct alignment with the light source from partially eclipsing each other, the following critical separation distance should be used:

Bead Diameter (in).	Corresponding Sieve	Critical Separation Distance At 500 Feet (in.)	Critical Separation Distance At 50 Feet (in.)
0.0165	40	1.55	0.16
0.0117	50	1.10	0.12
0.0059	100	0.55	0.06

[17] Schwab, Richard N. and Capella, Donald G., "Is Delineation Needed?", Public Roads, December 1979.

Delineation provides guidance and regulatory or warning information to a driver. Delineation shows the motorist the proper path to follow. This article compares three delineation treatments -stripes, raised pavement markers and post mounted delineators. Where, when, and how much delineation is required for safe and effective driving is discussed. The research involved a driving simulator that used computer-generated images projected on a screen in front of a real vehicle passenger compartment. Color identification under daytime and night-time illumination was also studied.

Striping reduced accidents approximately 30 percent. A mixture of 50% white pigment to 50% yellow pigment, by weight, will not decrease color identification. The traffic performance study found little difference in driver performance for a 1:3 strip-to-gap ratio in dry weather and in wet weather.

Raised pavement markers are cost beneficial at an ADT volume of 3,000 vpd. Accident analysis studies showed that when painted centerlines are replaced with raised pavement