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16. Abstract

This report documents the results of field testing seventeen types of retroreflective raised pavement markers (RRPMs) installed in August 1992 at four interstate locations around San Antonio, Texas. Reflectivity measurements were taken periodically at each site using a portable retroreflectometer. These data were supplemented with laboratory reflectivity measurements from RRPMs taken from each site and sent to the TxDOT Materials and Testing Laboratory in Austin, Texas.

Study results indicate that most of the RRPMs experienced significant losses in reflectivity over short periods of time. Under the range of traffic conditions examined, many RRPMs dropped below approximate minimum reflectivity thresholds after less than six months in the field. Certain RRPM designs did perform considerably better than others. In general, RRPM reflectivity was related to the cumulative vehicular exposure since installation. Using approximate RRPM purchase and installation cost data from TxDOT, it appears that the more durable (and expensive) RRPMs can be justified from a cost-effectiveness perspective once AADT levels on the roadway reach 10,000 vehicles per lane per day.

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RETROREFLECTIVE RAISED PAVEMENT MARKERS: A TWO-YEAR FIELD EVALUATION IN TEXAS

by

Gerald L. Ullman, P.E.

Research Report 1946-3F
Research Study Number 7-1946
Research Study Title: Raised Pavement Marking Field Testing

Sponsored by the

Texas Department of Transportation

October 1994

TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
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IMPLEMENTATION STATEMENT

The contents of the report should be useful to the Texas Department of Transportation in assessing the reflectivity performance of the many different types of retroreflective raised pavement markers being sold, particularly with respect to the effect of differing levels of traffic demand upon reflectivity retention. These data also provide the Department useful information upon which to evaluate current purchasing specifications for RRPMs. As a result of this research, the Department may wish to encourage the use of more durable RRPMs on high-volume facilities. This would reduce the frequency of RRPM replacement on such facilities, and promote adequate nighttime and wet-weather roadway delineation over longer periods of time. Based on the assumptions and available cost data, these RRPMs can be justified from a cost-effectiveness perspective once AADTs on the roadway reach 10,000 vehicles per lane per day.

DISCLAIMER

The contents of this report reflect the views of the author who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes. The engineer in charge of the project was Mr. Gerald L. Ullman (Texas P.E. registration #66876).

ACKNOWLEDGMENT

The study was designed and managed by Mr. Lewis Rhodes, P.E. of TxDOT. The guidance provided by Mr. Rhodes and by Messrs. John Bassett and Arthur Barrow, P.E., of the TxDOT Testing and Materials Division are gratefully acknowledged. Also, this study was made possible by the participation of product suppliers of six different retroreflective pavement marker manufacturers, namely; Apex, Batterson, Empco, Ray-O-Lite, Stimsonite, and Swareflex. Finally, the Maintenance section of the San Antonio District Office of TxDOT installed the RRPMs at the four test locations and provided traffic control support during each of the return visits for reflectivity measurements. Their assistance with this study is gratefully acknowledged.

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SUMMARY

This report summarizes the data collected during the two year field test of 17 types of RRPMs at four freeway locations around San Antonio, Texas. In total, researchers collected over 4,500 reflectivity readings among the four sites using a portable retroreflectometer designed to measure RRPM SI values in place on the roadway pavement. Over 900 RRPMs removed from the sites and taken to the TxDOT Materials and Testing Laboratory in Austin, Texas validated these readings. Researchers sampled traffic data at each study site periodically over the two-year period as well.

The results of the test show that many of the RRPMs failed to provide adequate levels of reflectivity after as little as six months exposure on high-volume facilities. For some of the RRPMs, high traffic demands quickly abraded the reflective lens and diminished reflectivity; for others designed to avoid tire abrasions, an accumulation of dirt residue on the lens that was not scrubbed off by tire-RRPM interactions led to the reduced reflectivity levels. A few RRPM designs did retain reflectivity somewhat longer, depending on the traffic characteristics of each site. Non-linear regression analyses indicate that RRPM reflectivity retention tends to be most dependent upon cumulative vehicular exposure since the time of installation. Modeling reflectivity retention as a function of cumulative truck exposure proved to be slightly less accurate overall, although this measure was a better predictor of RRPM reflectivity for a few of the RRPM types.

Using typical RRPM purchase and installation cost values and the results of the non-linear regression models, researchers found the more durable and expensive RRPMs to become cost-effective alternatives once AADT levels reach 10,000 vehicles per day (vpd) per lane. The reader is cautioned that the results of this test, particularly the reflectivity retention values over time for the various RRPMs, are only representative of the conditions evaluated; specifically, freeway facilities in central Texas having AADTs less than 120,000 vpd and truck usage between 3 and 15 percent of the AADT. Roadway and environmental conditions other than those evaluated in this test may yield different RRPM performance curves.

INTRODUCTION

BACKGROUND

Retroreflective raised pavement markers (RRPMs) are used extensively throughout Texas and other states for delineating lanes, freeway gore areas, narrow bridge approaches, and other geometric situations in both rural and urban areas (*1-4*). Researchers have documented the advantages of RRPMs for providing both short-range and long-range delineation (*5*, *6*). However, it is also well known that RRPMs experience significant losses in reflectivity over time. Over the past several years, the Texas Department of Transportation (TxDOT) has sponsored several studies to assess exactly how quickly RRPMs lose their reflectivity, and to identify what factors influence the loss of reflectivity (*7-9*). The results of that and other research indicate that sunlight, dirt accumulation and tire abrasions on the reflective lens of the RRPM all contribute to the loss of reflectivity. The loss rate differed somewhat depending on the type of RRPM used, the location where it was installed, etc. Unfortunately, the interaction between the factors affecting reflectivity loss made it extremely difficult to quantify their impacts upon the reflectivity of a given type of RRPM. Also, different roadway types and geographical areas produced different types of dirt and grit which themselves vary in terms of their abrasive properties.

In response to the need for better data regarding the loss rate of RRPM reflectivity in Texas, TxDOT initiated a two-year field test in August 1992 of seventeen different RRPMs. Researchers installed RRPMs at four different interstate locations near San Antonio, Texas. This report documents the final results of that evaluation.

STUDY OBJECTIVES

The primary objective of this two-year evaluation was to measure the reflectivity retention rate of various RRPM designs over time on freeway facilities in central Texas and to determine the effect of roadway volume, percent of large trucks, and frequency of lane-changing across the RRPMs upon this retention. As a secondary objective, researchers explored the accuracy of a portable retroreflectometer for measuring RRPM reflectivity while still in place on the roadway pavement. Previous RRPM evaluations have been hampered by the need to remove RRPMs from test sites for detailed laboratory analysis in order to assess reflectivity retention rates over time. An accurate field measurement device would allow more data to be collected cheaper and facilitate an improved understanding of RRPM reflectivity retention over time for different roadway and traffic conditions.

RRPMS EVALUATED

Since the results of the study were intended for informative purposes only and not as a TxDOT prequalification evaluation, both RRPMs currently available and those under development and/or undergoing field validation were included in the test. In June 1992, TxDOT contacted a number of RRPM manufacturers to solicit participation in the field test. Each manufacturer was allowed to submit up to six different types of markers for testing. A total of six manufacturers responded, furnishing seventeen different markers. Table 1 provides a summary of the general characteristics of each marker incorporated into the test (manufacturer, model number, marker dimensions, type of reflective surface, and specific intensity). Appendix A provides photographs of each RRPM.

The majority of the markers were a 10.2 cm (4-in) square design made of molded plastic, with either a single clear reflective lens or opposing clear/red lenses. The exceptions to this design included the following:

- Apex models 807 and 817 (constructed of ceramic),
- Batterson and Empco round plastic reflective buttons,
- Ray-O-Lite models 2002 and 2003 (rectangular low-profile prototype designs), and
- Stimsonite models 948 and 953 (also rectangular low-profile designs).

All but two of the markers rely on prismatic cube-corner lenses for reflectivity. The Batterson marker provided reflectivity by a strip of microprism high-intensity sheeting glued to a portion of the button milled perpendicular to its top. The Swareflex marker uses three rows of small, 3.2 mm (⅛ inch) glass beads embedded in the face of the marker for reflectivity. The Stimsonite models 911, 948, and 953 have a thin layer of glass attached over the acrylic prismatic lens to improve the durability of the reflective face. Finally, the Ray-O-Lite models 2002 and 2003 have a special chemical applied to their surfaces to resist dirt and abrasion. TxDOT has prequalified several of these markers for use on Texas highways. These are noted by an asterisk (*) in Table 1.

Table 1. RRPM Characteristics

Manufacturer	Model	Dimensions	Reflective Surface	Ave. SI
Apex	921	9.7 cm x 10.2 cm x 1.8 cm	acrylic cube-corner	3.5
Apex*	918	10.2 cm x 10.2 cm x 1.8 cm	acrylic cube-corner	4.2
Apex	928	10.2 cm x 10.2 cm x 1.8 cm	acrylic cube-corner	2.9
Apex	807	10.2 cm x 10.2 cm x 2.3 cm	acrylic cube-corner	2.4
Apex	817	10.2 cm x 12.2 cm x 2.3 cm	acrylic cube-corner	1.0
Batterson	Reflective Button	10.2 cm dia x 2.0 cm	microprism high-intensity sheeting	5.2
Empco	901	10.2 cm dia x 2.0 cm	acrylic cube-corner	1.8
Ray-O-Lite	8704 (S)[a]	10.2 cm x 10.2 cm x 1.8 cm	acrylic cube-corner	5.3
Ray-O-Lite	8704 (R)[b]	10.2 cm x 10.2 cm x 1.8 cm	acrylic cube-corner	5.3
Ray-O-Lite*	9704	10.2 cm x 10.2 cm x 1.8 cm	acrylic cube-corner	6.4
Ray-O-Lite	2002	6.1 cm x 12.2 cm x 1.3 cm	acrylic cube-corner	6.3
Ray-O-Lite	2003	5.1 cm x 14.7 x 1.0 cm	acrylic cube-corner	6.9
Stimsonite*	88	10.2 cm x 10.2 cm x 1.8 cm	acrylic cube-corner	7.4
Stimsonite*	911	10.2 cm x 10.2 cm x 1.8 cm	glass layer over acrylic cube-corner	9.2
Stimsonite*	948	5.8 cm x 11.9 cm x 1.3 cm	glass layer over acrylic cube-corner	8.0
Stimsonite	953	7.1 cm x 11.4 cm x 1.5 cm	glass layer over acrylic cube-corner	8.7
Swareflex	---	10.2 cm x 10.2 cm x 1.8 cm	0.3 cm glass beads	5.5

* RRPM prequalified by TxDOT
SI = Specific Intensity
Note: 1 cm = 0.39 in

[a] (S) = square-shouldered marker
[b] (R) = round-shouldered marker

The final column in Table 1 summarizes the initial laboratory reflectivity test results on each type of RRPM. These values represent the average specific intensity (SI) of five of each type of RRPM, drawn randomly from those submitted by the manufacturers for installation at the test sites. These initial measurements were conducted at the TxDOT Laboratory using an entrance angle of 4° and observation angle of 0.2°. An SI value relates a given luminance intensity of the retroreflector to the luminance intensity falling upon the reflective surface, with units of candela/lux (candela/foot-candle). However, previous research *(9)* has demonstrated that the TxDOT RRPM testing procedure differs slightly from that specified by the American Society for Testing and Materials (ASTM) and so has slightly different units (ft^2·ft-Lambert/ft-candle). Fortunately, SI values obtained via the TxDOT procedure need only to be divided by π to convert them into the ASTM units *(9)*. All SI values reported herein are based on the TxDOT procedure, and the conversion to ASTM units is left to the reader. The average SI values for the RRPMs tested in the study range from a low of 1.0 for the Apex model 817, to a high of 9.2 for the Stimsonite model 911.

The manufacturers participating in the field tests provided a minimum of 180 markers per model to be evaluated, yielding a total of slightly more than 3,000 markers for the entire study. These were divided into four lots of 45 of each type of RRPM, and were each installed at four interstate locations (four-lane and six-lane facilities) near San Antonio, Texas. The sequence of markers was randomized at each site, and were installed at 6.1 m (20-ft) spacings over a total distance of approximately 4.7 km (2.9 mi). On four-lane facilities, the RRPMs were installed between the inside and outside travel lanes. On six-lane facilities, researchers installed the RRPMs only on the lane line separating the inside and middle travel lanes. Researchers did this to minimize the impact of lane-changing activity upon RRPM performance. The markers were installed using bitumen adhesive as per standard TxDOT procedures.

DESCRIPTION OF STUDY SITES

Figure 1 identifies the relative locations of the four study sites near San Antonio. Table 2 summarizes the basic roadway and traffic characteristics of each site measured in July 1992, June 1993, and July 1994. Researchers chose the sites to expose the RRPMs to a wide range of daily traffic volumes in the test conditions. Site 1, located in the northbound direction of I-410 on the west side of San Antonio, carries the greatest amount of traffic daily. The second-most heavily traveled test site was located in the northbound direction of US-281 immediately adjacent to the San Antonio

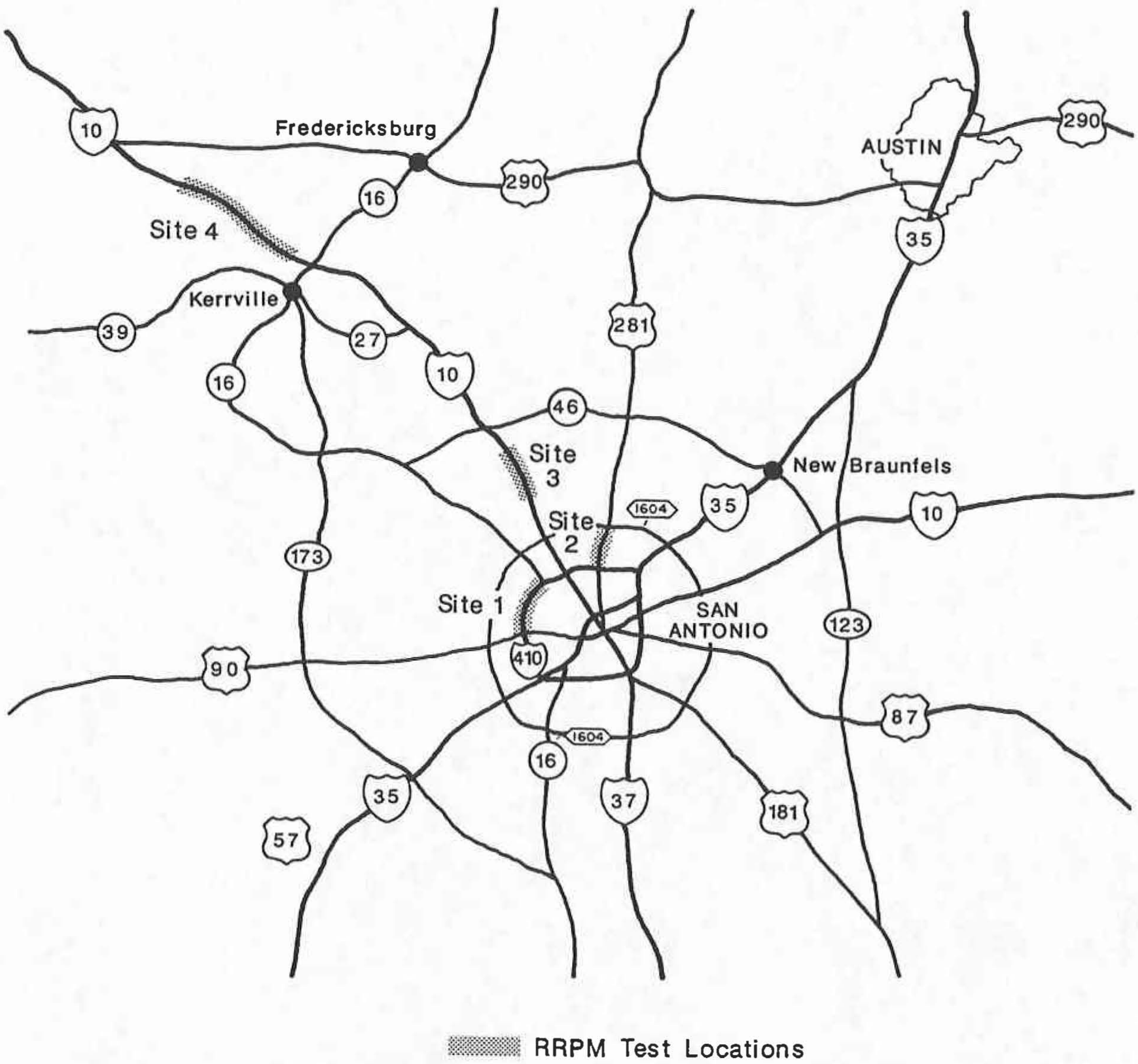


Figure 1. Study Site Locations

airport. Site 3 was located in the westbound direction of I-10 near Leon Springs. Site 4, located in the westbound direction of I-10 near Kerrville, was the lowest volume site. Because they were located in more urban surroundings, Sites 1 and 2 carried a lower percentage of heavy trucks than did Sites 3 and 4. As the table illustrates, volumes over the two years increased only slightly at Site 1, but more substantially at Sites 2 and 4. The number of heavy trucks also monitored during these studies remained fairly consistent over the two-year period.

Table 2. General Characteristics of the Study Sites

Site	Location	Lanes Per Direction	Traffic Volumes, vpd[a]			Percent Trucks[b]
			July 1992	June 1993	July 1994	
1	NB I-410	3	36,700 - 58,900[c]	33,000-61,700	33,000-63,200	3 - 6
2	NB US-281	3	21,200 - 21,400[c]	24,200[d]	25,300[d]	3 - 8
3	WB I-10	2	18,600[e]	18,200	---[f]	6 - 10
4	WB I-10	2	3,300[e]	4,600	4,500	10 - 15

a vpd = vehicles per day measured in one direction of travel
b peak and off-peak percentages, respectively
c volumes measured on the southern and northern ends of the test sections, respectively
d measured at the southern end of the section only
e volume measured in the middle of the test section
f researchers terminated data collection at Site 3 due to pavement resurfacing during 1993.

Researchers installed RRPMs at Sites 1 and 2 only between the inside and middle travel lanes. Consequently, they were subjected to traffic demands somewhat less than the total 24-hour volume counts across all travel lanes documented in Table 2. To estimate the amount of traffic actually passing next to the RRPMs at each site, researchers used lane distribution data collected during the studies. Researchers also used these estimates to compute normalized truck traffic demand volumes adjacent to the RRPMs at the four sites. Table 3 summarizes these rates. From this table, it can be seen that RRPMs at Site 1 were subjected to the greatest amount of daily traffic adjacent to the

RRPMs. However, although the overall traffic volumes at Site 2 were higher than at Site 3, the volume actually passing next to the RRPMs was lower. In fact, the truck volume passing next to the RRPMs at Site 3 was even higher than at Site 1. Meanwhile, Site 4 experienced the lowest total and truck traffic volume.

Table 3. Daily Traffic Adjacent to Test RRPMS at Each Site

Site	Traffic Characteristic					
	Vehicles Per Day			Trucks Per Day		
	July 1992	June 1993	July 1994	July 1992	June 1993	July 1994
1[a]	25,100 - 40,300	22,570-42,200	22,770-43,220	880-1,420	790-1,480	800-1,480
2[a]	13,800-14,000	15,750	16,470	940-950	1,070	1,120
3	18,600	18,200	---[b]	1,650	1,610	---[b]
4	3,300	4,600	4,500	500	700	680

[a] rates represent the data collected at the southern and northern ends of the study sites, respectively on lanes immediately adjacent to the test RRPMs.

[b] researchers terminated data collection at Site 3 due to pavement resurfacing that occurred in 1993.

Researchers also attempted to measure lane-changing activity across the RRPMs during each of the traffic studies. Upon review of these data from the three years at each site, however, it became apparent that this statistic is extremely sensitive to the location where it is measured, the prevailing traffic volume at the time of study, and other extraneous factors not accounted for in the data collection scheme. Consequently, these data are not reported here and were not used in the regression analyses of RRPM retention rates described later in this report. Those interested in the lane-changing rates that were recorded during the first two traffic studies should consult one of the earlier reports for this project (*10*, *11*).

DATA COLLECTION SCHEDULE

Several times throughout the two-year study, researchers sampled reflectivity of each type of RRPM on the roadway at each site using portable retroreflectometer equipment. Following the field measurements, TxDOT maintenance personnel then removed one to three of each type of RRPM from each site to be taken to the TxDOT Materials and Testing Laboratory in Austin. TxDOT laboratory personnel then measured the reflectivity of each RRPM in a dry, unwashed state and after washing the road grime from the reflective face of the RRPM.

Table 4 summarizes the planned and actual data collection schedule for the field study. Researchers scheduled measurements close together early in the study, when they anticipated most of the RRPM reflectivity loss to occur. In general, the actual data collection schedule coincided very closely with the planned schedule for the first 12 weeks of the study. The schedule then had to be modified slightly because of weather problems. Incomplete data were available for the 12-week and 23-week evaluations. Researchers did not remove any RRPMs at the 12-week evaluation for laboratory testing. Conversely, problems encountered with the portable reflectometer precluded field data from being collected at the 23-week evaluation (only laboratory data were obtained).

Table 4. Planned and Actual Data Collection Schedule

Time after installation of RRPMs	
Planned	Actual
at installation	at installation
2 weeks	2 weeks
4 weeks	4 weeks
6 weeks	6 weeks
8 weeks	9 weeks
12 weeks	12 weeks
20 weeks	23 weeks
28 weeks	32 weeks
36 weeks	48 weeks
52 weeks	54 weeks
78 weeks	82 weeks
104 weeks	106 weeks

PORTABLE RETROREFLECTOMETER PERFORMANCE

DESCRIPTION AND USE OF THE DEVICE

Advanced Retro Technology, Inc. manufactured and supplied a prototype portable retroreflectometer (model 1200C) to use during this field test. This rectangular unit (45.7cm x 15 cm x 25 cm) is self-contained with an internal rechargeable battery, calibrated light source, and photopically corrected solid-state light detector designed to measure light reflected from an RRPM at a 0.2° observation angle. The light source projects onto a collimating mirror that transforms the divergent light rays to parallel rays falling upon the RRPM at an angle analogous to simulated driving conditions.

A two-step process is required to calibrate the retroreflectometer. The user first sets the device down, illuminates the pavement on which the RRPMs are attached, and sets the light detector display reading on the device to zero. This factors out the normal reflectivity of the pavement. Next, the user places an RRPM for which the SI value has already been measured in the laboratory (i.e., a calibration marker) under the measuring window (approximately 3 cm x 14 cm) and illuminates it with the light source. The user adjusts the retroreflectometer reading to coincide with the laboratory-measured specific intensity (SI) value for that RRPM. Finally, the user places the retroreflectometer over the RRPMs of interest to obtain a calibrated SI value for each.

CORRELATION TO LABORATORY-MEASURED REFLECTIVITY

TTI researchers compared laboratory-measured SI values to SI values obtained via the portable retroreflectometer for over 900 RRPMs used in this field evaluation. Generally speaking, RRPM readings with the retroreflectometer at each study site have correlated quite well with the laboratory readings of those same RRPMs throughout this test. The Pearson Correlation Coefficient computed between the retroreflectometer and laboratory readings consistently exceeded 0.90 (*12*). Each of the different types of RRPMs tested maintained this high degree of correlation, suggesting that the portable device provides a reasonably accurate means of monitoring RRPM reflectivity performance over time.

Although generally good agreement existed between retroreflectometer SI values and SI values obtained in the laboratory, it is worth noting that the correlation is highest when the SI values

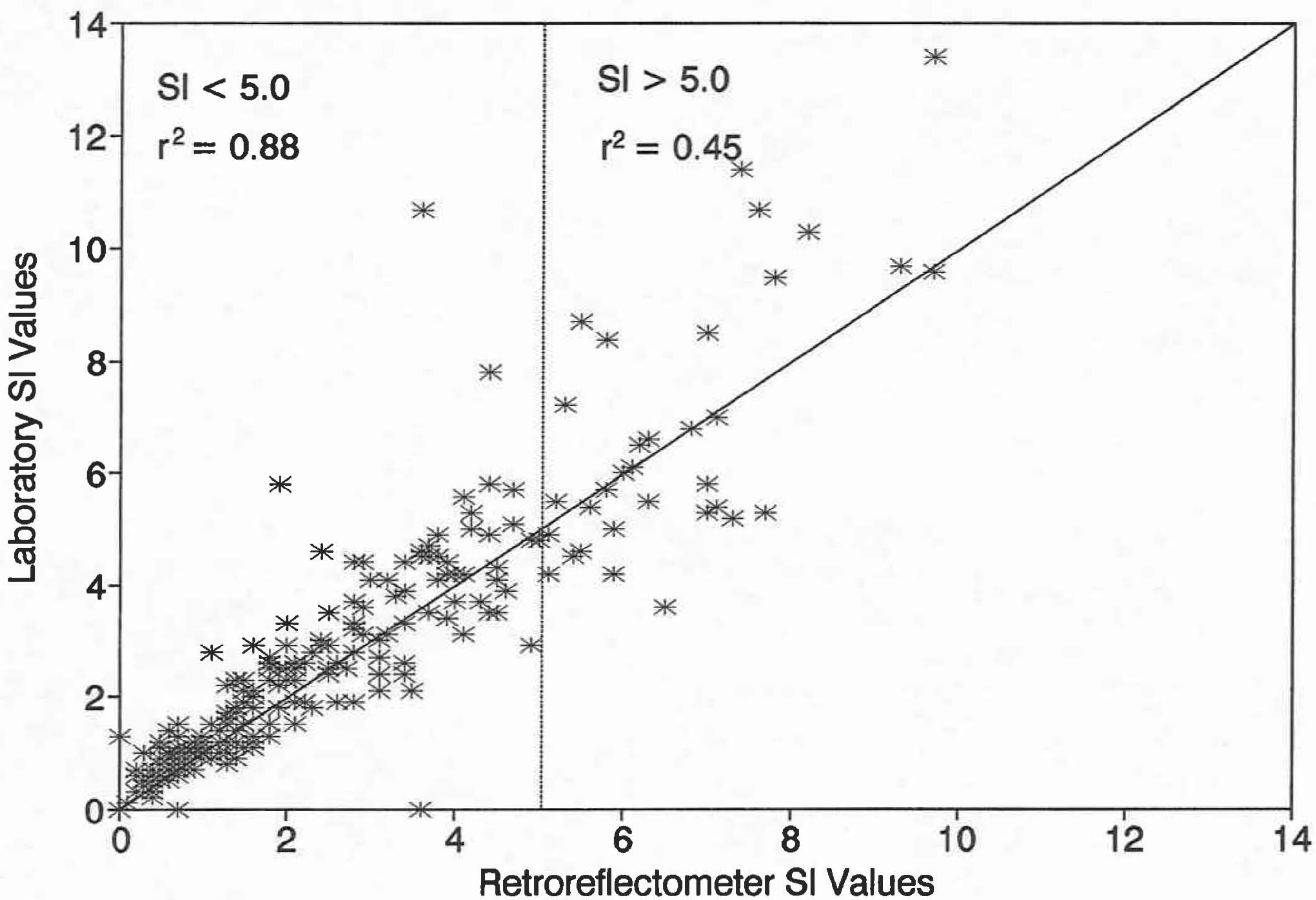


Figure 2. Correlation Between Retroreflectometer and Laboratory SI Measurements

of the RRPM are not particularly high. Figure 2 presents a graph of SI values measured with the retroreflectometer versus laboratory-measured SI values for all RRPMs removed from all sites during the August 16, 1992 and August 30,1992 evaluations (when both high and low SI value RRPMs existed at each site). As the figure illustrates, slightly larger discrepancies are evident at higher SI values. Researchers segregated the study sample depending on whether the laboratory SI value of the RRPM was greater than or less than 5.0. Researchers computed separate correlation coefficients for each group, the results of which are also shown in Figure 2. Whereas, comparison of the portable retroreflectometer and laboratory measurements yielded a correlation coefficient of 0.88 when the laboratory SI value was less than 5.0, the correlation coefficient for RRPMs with laboratory SI values greater than 5.0 was only 0.45.

LESSONS LEARNED

Throughout this field test, researchers learned a number of lessons about the operation of the portable retroreflectometer and its field implementation. The following is a list of some key points concerning the use of the retroreflectometer for field measurements:

- Overall, the retroreflectometer is not overly sensitive to the angle of alignment of the RRPM within the measuring window. Ideally, the reflective face of the RRPM should be aligned perfectly perpendicular with the long dimension of the retroreflectometer (i.e., parallel to the mirror located within the measuring window). Small departures from this ideal situation do not dramatically affect the SI value obtained. However, larger deviations do yield SI values that are substantially lower than the "true" value of the RRPM (as would be expected).
- Researchers found that SI values obtained with the retroreflectometer were somewhat sensitive to pavement temperature. Frequent recalibration is necessary when using the retroreflectometer during times of the day and seasons when the temperature changes substantially (such as in the early morning hours).
- Related to the previous topic, users must take care to acclimate the retroreflectometer to ambient temperature and humidity levels before attempting to utilize the device. On at least one occasion, fog developed on the reflective mirror within the retroreflectometer when it

was taken from an air-conditioned room into the field with a higher temperature and humidity level.

- The reflecting mirror did come loose during one data collection study and had to be reset. Other than that one instance, researchers noted no particular difficulties with respect to the durability of the device.
- Researchers using the retroreflectometer did notice that measured SI values of a given RRPM differed depending on whether the fan vents on the side of the device were open or were covered with a black cloth. It seems that some stray light can enter into the device through these vents, and future modifications to the device should include a baffle or shroud to limit this stray light and improve the precision of the measurements.

RRPM PERFORMANCE OVER TIME

AVERAGE SI VALUES BY TYPE OF RRPM

Appendix B provides average SI values recorded for each RRPM by site and by data collection dates corresponding to the schedule in Table 4. Researchers report both the data recorded using the portable retroreflectometer, and that recorded from RRPMs removed from each site and taken to the TxDOT laboratory. TxDOT laboratory personnel measured the SI value of each RRPM in the condition that it was in when removed from the test site, and then again after the RRPM had been washed to clean off the road film that had accumulated on the lens face. A comparison between the "as-removed" and "cleaned" RRPM conditions illustrates the effect that dirt accumulation on the reflective lens has upon overall reflectivity. Previous study reports document more fully the influence of this dirt accumulation on RRPM reflectivity (*10, 11*).

As a summary, Tables 5 through 8 present the average SI values of each type of RRPM measured at each site with the portable retroreflectometer. From these tables, consistent trends are evident for all of the RRPMs on a site-by-site basis, with RRPM SI values decreasing fastest at Site 1 and slowest at Site 4. Comparing the results from each site, one can group the various RRPMs into one of three performance categories: low, moderate, and high. The low performance category consisted of those RRPMs that did not initially meet the TxDOT minimum 3.0 SI value for prequalification purposes. In general, these RRPMs did not maintain even minimal levels of reflectivity (assumed to be 0.5 SI as defined in the previous report (*11*)) beyond six weeks of use at any of the sites. Included in this low category were the Apex models 807 and 817, and the Empco model 901.

Next, the majority of the RRPM types fall into a moderate performance category. These included the Apex models 921, 918, and 928; the Batterson button; the Ray-O-Lite models 8704 (S) and 8704 (R); and the Stimsonite model 88. As a group, these RRPMs performed reasonably well under the lower volume exposure at Site 4, maintaining at least a minimal degree of reflectivity over the first year of the evaluation. However, when exposed to the higher volume conditions at the other sites (especially Site 1), the reflectivity of these RRPMs quickly degraded to below an SI value of 0.5 by the time they had been in place for 32 weeks (approximately 7 months).

Table 5. SI Values Over Time: Site 1

RRPM	Time After RRPM Installation					
	New	6 wks	32 wks	~1 yr	~1½ yrs	~ 2 yrs
Apex 921	4.4	0.6	0.1	0.2	0.1	0.2
Apex 918	3.5	0.6	0.1	0.1	0.1	0.2
Apex 928	4.0	0.7	0.1	0.2	0.1	0.2
Apex 807	1.4	0.3	0.1	0.1	0.1	0.2
Apex 817	1.7	0.3	0.1	0.2	0.1	0.1
Batterson	5.5	0.2	0.1	0.0	0.0	0.1
Empco 901	2.4	0.3	0.0	0.1	0.0	0.1
Ray-O-Lite 8704 (S)	7.1	0.9	0.2	0.4	0.2	0.3
Ray-O-Lite 8704 (R)	5.3	0.6	0.2	0.2	0.1	0.2
Ray-O-Lite 9704	9.1	1.0	0.1	0.3	0.1	0.3
Ray-O-Lite 2002	9.3	2.9	0.6	0.3	0.1	0.1
Ray-O-Lite 2003	9.5	2.1	0.5	0.4	0.1	0.1
Stimsonite 88	7.1	1.2	0.1	0.2	0.1	0.2
Stimsonite 911	9.1	4.1	3.6	2.1	0.7	0.4
Stimsonite 948	8.9	3.6	2.4	1.8	0.4	0.2
Stimsonite 953	7.3	3.3	3.3	1.4	0.5	0.3
Swareflex	5.4	0.4	0.6	0.2	0.1	0.2

Table 6. SI Values Over Time: Site 2

RRPM	Time After Installation					
	New	6 wks	32 wks	~1 yr	~1½ yrs	~ 2 yrs
Apex 921	4.4	1.5	0.2	0.3	0.1	0.1
Apex 918	3.5	0.7	0.2	0.2	0.1	0.1
Apex 928	4.0	1.4	0.2	0.3	0.1	0.1
Apex 807	1.4	0.5	0.1	0.3	0.1	0.1
Apex 817	1.7	0.7	0.1	0.3	0.1	0.1
Batterson	5.5	0.6	0.1	0.1	0.1	0.0
Empco 901	2.4	0.8	0.1	0.2	0.1	0.0
Ray-O-Lite 8704 (S)	7.1	2.4	0.3	0.5	0.2	0.2
Ray-O-Lite 8704 (R)	5.3	N.A.	0.2	0.3	0.1	0.1
Ray-O-Lite 9704	9.1	3.2	0.2	0.3	0.1	0.2
Ray-O-Lite 2002	9.3	5.9	1.6	1.0	0.4	0.1
Ray-O-Lite 2003	9.5	5.3	1.1	0.7	0.2	0.1
Stimsonite 88	7.1	2.9	0.2	0.3	0.1	0.2
Stimsonite 911	9.1	5.9	4.3	2.7	1.3	0.8
Stimsonite 948	8.9	5.6	3.0	2.7	1.0	0.8
Stimsonite 953	7.3	6.0	4.0	2.0	0.6	0.5
Swareflex	5.4	2.2	1.1	0.6	0.4	0.2

N.A. Data Not Available

Table 7. SI Values Over Time: Site 3

RRPM	Time After Installation					
	New	6 wks	32 wks	~1 yr	~1½ yrs	~ 2 yrs
Apex 921	4.4	1.4	0.3	0.3	N.A.	N.A.
Apex 918	3.5	1.1	0.3	0.3	N.A.	N.A.
Apex 928	4.0	1.8	0.4	0.3	N.A.	N.A.
Apex 807	1.4	0.6	0.1	0.1	N.A.	N.A.
Apex 817	1.7	0.6	0.2	0.2	N.A.	N.A.
Batterson	5.5	0.5	0.2	0.2	N.A.	N.A.
Empco 901	2.4	1.0	0.2	0.2	N.A.	N.A.
Ray-O-Lite 8704 (S)	7.1	N.A.	0.6	0.5	N.A.	N.A.
Ray-O-Lite 8704 (R)	5.3	1.8	0.3	0.3	N.A.	N.A.
Ray-O-Lite 9704	9.1	1.8	0.6	0.5	N.A.	N.A.
Ray-O-Lite 2002	9.3	2.4	1.8	1.4	N.A.	N.A.
Ray-O-Lite 2003	9.5	2.8	1.9	0.3	N.A.	N.A.
Stimsonite 88	7.1	2.3	0.5	0.3	N.A.	N.A.
Stimsonite 911	9.1	4.7	4.1	1.1	N.A.	N.A.
Stimsonite 948	8.9	2.9	3.6	0.6	N.A.	N.A.
Stimsonite 953	7.3	4.1	3.6	1.0	N.A.	N.A.
Swareflex	5.4	0.9	0.7	0.3	N.A.	N.A.

N.A. Data Not Available (pavement resurfaced after first year)

Table 8. SI Values Over Time: Site 4

RRPM	Time After Installation					
	New	6 wks	32 wks	~1 yr	~1½ yrs	~ 2 yrs
Apex 921	4.4	3.1	0.5	0.5	0.4	0.3
Apex 918	3.5	1.6	0.4	0.4	0.3	0.3
Apex 928	4.0	2.3	0.6	0.6	0.4	0.5
Apex 807	1.4	0.6	0.1	0.3	0.2	0.1
Apex 817	1.7	0.6	0.2	0.3	0.2	0.2
Batterson	5.5	1.7	0.4	0.2	0.2	0.1
Empco 901	2.4	1.5	0.2	0.3	0.2	0.1
Ray-O-Lite 8704 (S)	7.1	1.5	0.2	0.3	0.3	0.3
Ray-O-Lite 8704 (R)	5.3	2.5	0.5	0.6	0.5	0.5
Ray-O-Lite 9704	9.1	4.4	0.8	0.8	0.8	0.8
Ray-O-Lite 2002	9.3	6.8	2.4	1.4	1.1	0.7
Ray-O-Lite 2003	9.5	6.4	2.3	1.0	0.8	0.5
Stimsonite 88	7.1	3.6	0.7	0.7	0.6	0.6
Stimsonite 911	9.1	7.9	6.4	2.6	2.6	1.2
Stimsonite 948	8.9	7.4	4.6	2.5	2.2	0.9
Stimsonite 953	7.3	7.0	6.0	2.4	1.6	0.9
Swareflex	5.4	3.6	2.3	1.1	2.0	N.A.

N.A. Data Not Available

The high performance category RRPMs included the Ray-O-Lite models 9704, 2002, and 2003; the Stimsonite models 911, 948, and 953; and the Swareflex model. These RRPMs provided at least minimal reflectivity at most of the sites for an entire year or more. In fact, several of these RRPMs were still providing fairly high levels of reflectivity at Site 4 even after two full years in the field. However, it should be noted that at Site 1, the highest volume location of this test, only the Stimsonite models out of this category maintained minimal reflectivity levels up to and beyond one year. Those particular Stimsonite RRPMs have a thin layer of glass epoxied over the reflective lens to improve reflective durability.

PREDICTING RRPM REFLECTIVITY RETENTION RATES

Tables 5 through 8 demonstrate significant variation in RRPM reflectivity from site to site at any given point in time. Presumably, this variation occurs primarily because of the different traffic characteristics present at each site (since locating the four sites within the same TxDOT District helped to reduce the influence of other extraneous variables such as differences in sunlight intensity and heat levels, type and amount of windblown dirt and grit, relative rainfall intensities, etc.). Because reflectivity levels have been measured periodically at each site along with estimates of certain traffic characteristics, researchers can compare RRPM reflectivity levels directly to the amount of traffic to which they have been exposed since their installation. Researchers utilized nonlinear regression techniques to explore potential relationships between the RRPM SI values and cumulative estimates of total vehicle exposure (number of vehicles passing the markers) and truck exposure (number of trucks passing the markers) since RRPM installation. Although lane-changing frequency was also measured at each site during the traffic studies, the data appeared to be highly variable and too dependent upon location of measurement and other factors to make it a useful predictor of reflectivity retention.

Researchers computed cumulative total traffic exposure and truck traffic exposure rates for each site for each date of reflectivity data collection using the following equations:

Total Exposure = (vpd)(AADT adj.)(7 days/week)(weeks after installation) (1)

Truck Exposure = (vpd)(% trucks)(AADT adj.)(7 days/week)(weeks after installation) (2)

The vpd is the average daily volume (Tuesday-Thursday) measured in the lanes adjacent to the test RRPMs at each site during the traffic studies. This value is multiplied by the average ratio between daily volumes typically measured in June and July on freeways in the San Antonio area to the Average Annual Daily Traffic (AADT) on those freeways. The remaining factors convert the daily AADT or truck AADT for each site to a total traffic exposure since RRPM installation.

Researchers interpolated between increases in traffic volumes measured from year to year (significant at Sites 2 and 4 only). Also, researchers decided not to include Site 3 in the regression analyses. As noted earlier, data were available only for the first year at that site. Also, previous reports for this study documented somewhat atypical RRPM reflectivity behavior during the first several weeks worth of reflectivity data at this site because of oil and tar residue that leeched from the newly resurfaced pavement when the RRPMs were first installed (*10, 11*).

The data examined over the two-year duration of this study showed quite explicitly that the RRPMs did not lose their reflectivity at a constant rate. Rather, there was an initial period where reflectivity values dropped fairly rapidly (although the actual rate differed from RRPM to RRPM). At some point, reflectivity values tended to level off or decrease at a much slower rate. Therefore, researchers selected a linear two-regime model, as depicted in Figure 3, for use.

Mathematically, the linear two-regime model is written as:

$$SI_X = IV - \beta_1(X) + \beta_2(X - K)I \qquad (3)$$

where,

SI_X	=	RRPM SI value after exposure level X
IV	=	initial RRPM SI value
X	=	cumulative traffic exposure (all vehicles or trucks only)
K	=	"knee" point in the linear relationship (where the slope of the line changes)
I	=	indicator variable: I=0 for $X < K$, I=1 for $X \geq K$.
β_1, β_2	=	regression coefficients

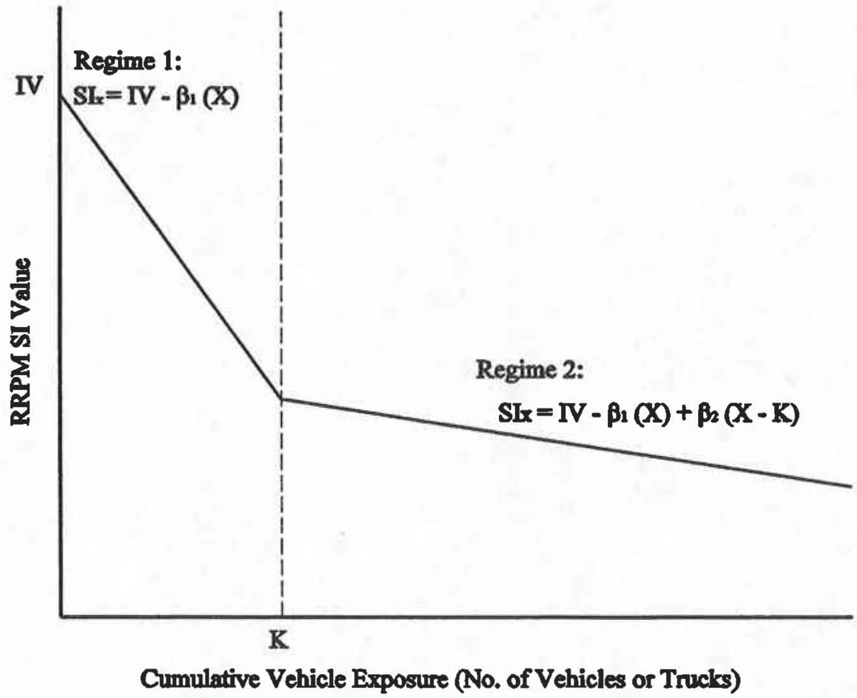


Figure 3. Characteristics of a Two-Regime Linear Regression Model

This particular model presents a difficulty in that the location of the "knee" in the relationship is not known, but rather must be estimated along with the parameters β_1 and β_2. Consequently, standard least-squares regression techniques cannot be used to determine the model parameters directly. Instead, one must employ nonlinear regression methods that use heuristic grid search patterns to estimate values of K, β_1, and β_2 together (*12*).

Researchers developed separate regression models of the form shown above for each of the 17 RRPM types. Models were first developed using the cumulative vehicle exposure estimates, and then again using only the cumulative truck exposure. For comparison purposes, a two-regime model was also developed for each RRPM based strictly on the time that the RRPMs had been in place (i.e., ignoring any site-by-site differences in reflectivity over time for each RRPM). Appendix C presents appropriate model parameters and summary statistics for each of these models for each RRPM type. Table 9 presents the resulting mean square error (MSE) values for each model. A smaller MSE value indicates a better "fit" between the reflectivity data and exposure variable (the lowest MSE value for each RRPM in Table 9 is identified with an asterisk).

Table 9. Comparison of Two-Regime Linear Exposure Models

RRPM Type	Mean Square Error (MSE)		
	Cumulative Time Model	Cumulative Vehicle Model	Cumulative Truck Model
Apex 921	1.241	1.056*	1.195
Apex 918	0.378	0.367*	0.368
Apex 928	0.519	0.479*	0.511
Apex 817	0.115*	0.123	0.121
Apex 807	1.124	1.095*	1.161
Batterson	0.236	0.245	0.212*
Empco 901	0.214	0.207*	0.241
Ray-O-Lite 8704 (S)	1.409	1.382*	1.422
Ray-O-Lite 8704 (R)	0.644	0.572*	0.716
Ray-O-Lite 9704	2.218	1.987*	2.221
Ray-O-Lite 2002	2.581	2.496	2.279*
Ray-O-Lite 2003	4.177	4.080	3.926*
Stimsonite 88	1.865	1.783*	1.901
Stimsonite 911	2.913	3.192	2.802*
Stimsonite 948	2.581	2.532	2.238*
Stimsonite 953	1.686	1.502*	1.656
Swareflex	0.682	0.510*	0.598

* represents the smallest MSE for that RRPM

As the table shows, models using the cumulative vehicle exposure variable provided the best description of reflectivity values for 11 of the 17 (65 percent) types of RRPMs tested. In five other cases, models using cumulative truck exposure provided the best fit to the reflectivity data. Exposure time provided the lowest MSE for only one of the RRPMs examined in this study.

Further review of the cumulative vehicle model regression parameters for each RRPM type uncovered a few interesting patterns. First, normalizing the regression parameters (dividing β_1 and β_2 by the initial RRPM SI value) yielded almost identical parameters for several of the RRPMs. These RRPMs included the Apex models 921, 918, and 928; the Ray-O-Lite models 8704 (S), 8704 (R), and 9704; the Stimsonite model 88, and the Swareflex model. Except for the Swareflex RRPM, each of these models has a fairly similar design and so would be expected to perform similarly under various traffic demands. Second, the three glass-covered Stimsonite RRPMs (models 911, 948, and 953) generated similar normalized parameter values. The two remaining Ray-O-Lite RRPMs (models 2002 and 2003) likewise generated normalized parameter values that were approximately equal to each other.

Once these basic RRPM categories were identified, researchers performed a second regression analysis by normalizing the reflectivity values recorded over time to the initial SI value and grouping the RRPMs by those three basic categories. Table 10 summarizes these relationships. As indicated by the coefficient of determination (r^2) values in Table 10, each of the regression models provided a fairly good representation of the reflectivity retention rates of the RRPMs in each group. Figure 4 presents each of the three regression equations plotted against cumulative vehicle exposure. A comparison of the β_1 regression parameter indicates that the Group 1 RRPMs initially lose reflectivity at a rate 2 times that of the Group 2 RRPMs and 7 times faster than the Group 3 RRPMs.

Table 10. Results of Normalized Regression Analyses by RRPM Group

RRPM Group	$SI_X/SI_I = 1 - \beta_1(X) + \beta_2[X - \text{knee}](I)$	r^2
Group 1 (Apex 921, 918, 928; Ray-O-Lite 8704 (S), 8704 (R), 9704; Stimsonite 88; Swareflex)	$SI_X/SI_I = 1 - 3.283(X) + 3.273(X - 0.2508)(I)$	0.84
Group 2 (Ray-O-Lite 2002, 2003)	$SI_X/SI_I = 1 - 1.679(X) + 1.664(X - 0.4521)(I)$	0.80
Group 3 (Stimsonite 911, 948, 953)	$SI_X/SI_I = 1 - 0.451(X) + 0.433(X - 1.436)(I)$	0.75

SIx = RRPM SI value after X amount of traffic exposure
SI_I = initial RRPM SI value
X = cumulative number of vehicles passing RRPMs (x 10^{-6})
knee = exposure level where linear model bends (cumulative # of vehicles x 10^{-6})
I = 0 if X < knee, 1 if X > knee

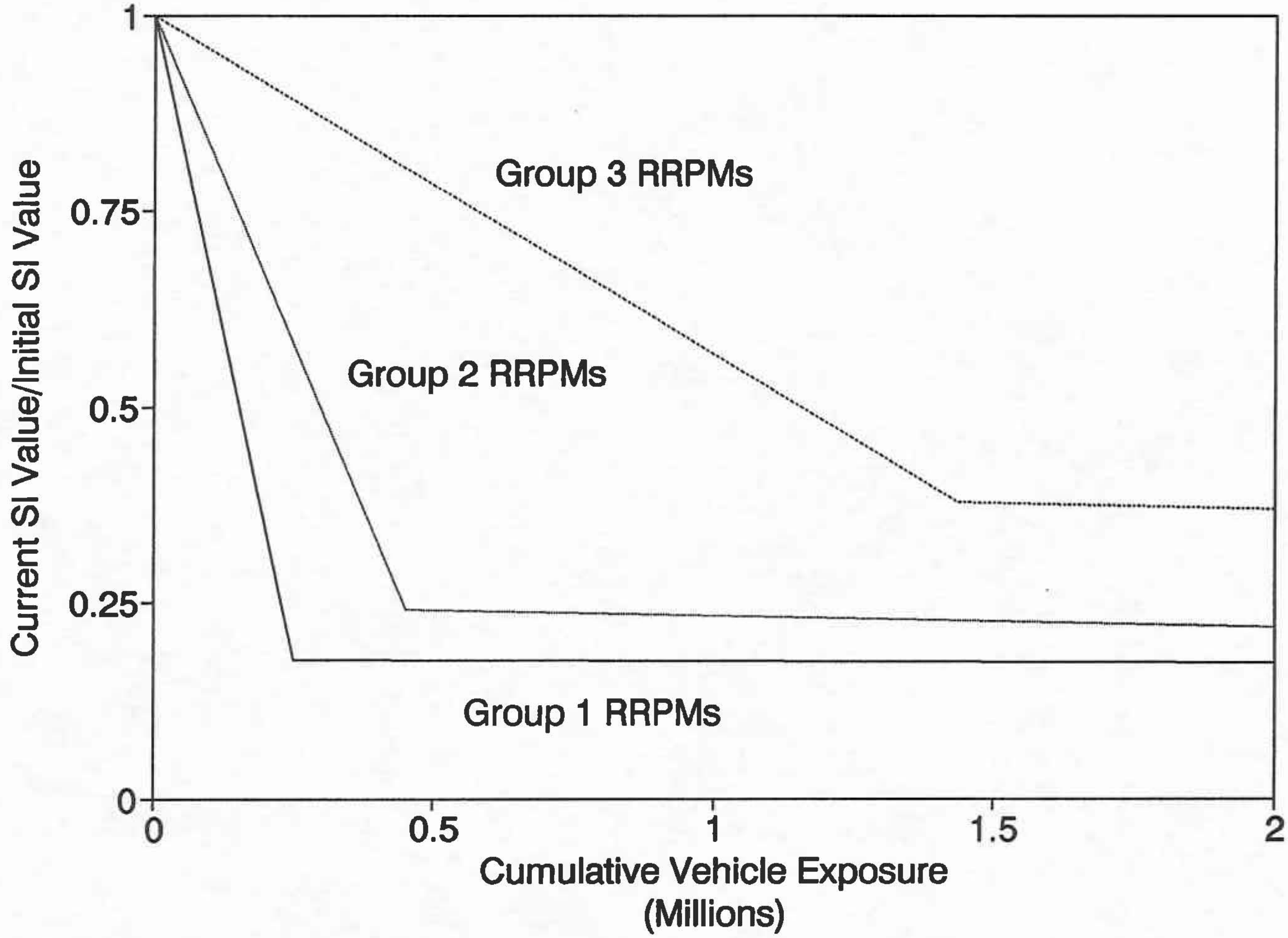


Figure 4. Two-Regime Regression Models by RRPM Group

RRPM DURABILITY

A secondary measure of RRPM performance is the extent to which they stand up to the repetitious pounding of vehicle tires (particularly large trucks) over time. During the final field evaluation, researchers identified those RRPMs that were cracked, delaminated (where all or part of the shell of the RRPM had separated from the base), missing a lens, etc. Researchers also noted any RRPMs missing at the time of this final evaluation. Table 11 summarizes the damage and loss rates of the various RRPMs, consolidated over Sites 1, 2, and 4 (no data could be collected at Site 3 because of pavement resurfacing that occurred in Fall 1993). The table shows damage and loss rates for each available site, consolidated over all of the RRPMs installed at that site.

Table 11. RRPM Durability and Retention

	Percent Damaged After Two Years	Percent Missing After Two Years
Overall	28.7	5.9
By Type of RRPM:		
Apex 921	29.6	6.9
Apex 918	31.0	0.0
Apex 928	25.8	0.0
Apex 807	55.6	3.6
Apex 817	55.6	0.0
Batterson	25.0	11.1
Empco 901	21.9	0.0
Ray-O-Lite 8704 (S)	13.8	3.3
Ray-O-Lite 8704 (R)	28.6	8.7
Ray-O-Lite 9704	32.3	0.0
Ray-O-Lite 2002	30.0	0.0
Ray-O-Lite 2003	50.0	0.0
Stimsonite 88	29.0	0.0
Stimsonite 911	14.8	0.0
Stimsonite 948	14.8	10.0
Stimsonite 953	14.8	3.6
Swareflex	0.0	55.2
By Site:		
Site 1	42.2	7.4
Site 2	17.7	0.0
Site 4	27.5	8.6

In general, the RRPM loss rate was fairly small, averaging slightly less than six percent. However, the Swareflex RRPM experienced a much higher loss rate. Averaged over the three sites for which data were available, over 50 percent of this particular RRPM were missing after two years. As shown in Figure 5, the bottom of the Swareflex RRPM is a waffle pattern intended to adhere better to the bitumen adhesive placed on the pavement, whereas all of the other RRPM have a smooth or lightly textured base. However, as vehicle tires impact this particular type of marker, it appears that this waffle pattern actually cuts into the adhesive and eventually separates itself from the adhesive and pavement entirely.

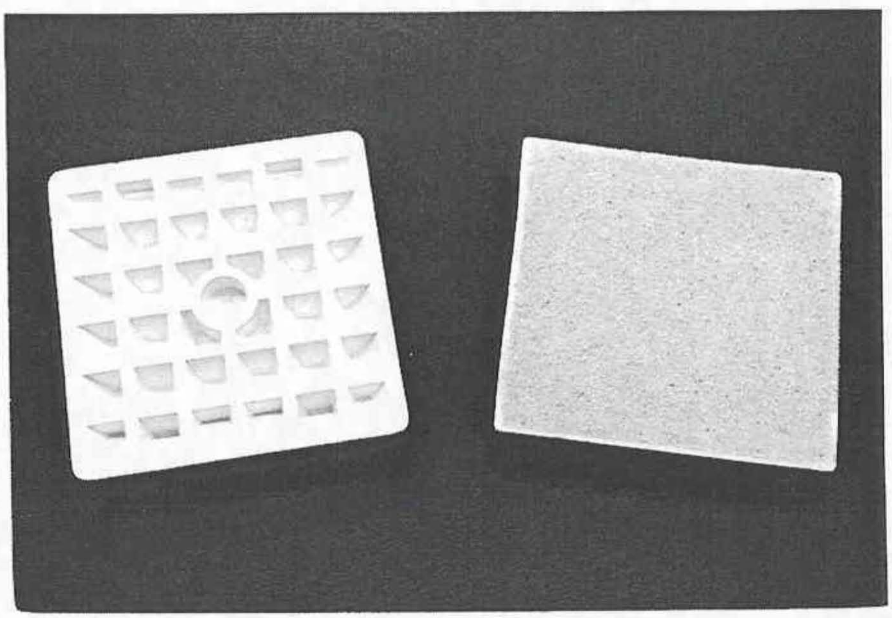


Figure 5. Base Designs for Swareflex and Apex RRPMs

Slightly more than one-fourth of the RRPMs tested in this study sustained damage during the two-year period of evaluation. Certain RRPM types were somewhat more susceptible to damage than others. As Table 11 illustrates, damage rates of the Apex models 817 and 807 and Ray-O-Lite model 2003 reached or exceeded 50 percent. For the Apex model RRPMs, it was the ceramic shell of the marker that was actually damaged (cracked, chipped, etc.). Although the shell condition was not inherently of great importance, the cracks and chips that occurred often caused the RRPM to lose its reflective lens as well. In contrast, the principal damage to the Ray-O-Lite 2003 RRPMs was that its plastic reflectorized shell tended to separate completely from its plastic base.

On a site-by-site basis, RRPMs at Site 2 were the least damaged of the three locations examined at the end of the two-year study. Presumably, the higher traffic volumes at Site 1 led to a greater damage and loss rate, whereas the higher speeds and greater number of large trucks at the more rural Site 4 location resulted in the damage and RRPM losses found there.

COMPARISON OF RRPM COST-EFFECTIVENESS

Using the aforementioned regression equations relating reflectivity retention to vehicular exposure, it is also possible to compare the cost-effectiveness of the various RRPM groupings. RRPMs that are able to retain their SI value over longer periods require less frequent replacement. However, more durable RRPMs are typically more expensive to purchase (installation costs are about equal) such that they are not necessarily appropriate for all types of roadway facilities.

The regression equations in Table 10 imply a relationship between roadway AADT and the service life of the three RRPM groupings. Figure 6 shows this relationship, based on assumptions that (1) the service life of an RRPM is reached once the SI value has dropped to 0.5, (2) the maximum service life possible for any of the RRPMs is 3 years, and (3) the initial SI value of an average Group 1 RRPM is approximately 5.0 as compared to an average SI value 9.0 for both Group 2 and 3 RRPMs. Of these assumptions, that of the maximum RRPM service life currently has the least data to support it at this time. However, the durability and loss data presented in Table 11 illustrate that RRPM damage and losses do accrue even under low volume conditions such as existed at Site 4. Therefore, an assumption that all RRPMs will require replacement after 3 years does not seem unreasonable.

As Figure 6 illustrates, the above assumptions and previous regression equations result in no differences in RRPM service lives until traffic volumes on the roadway reach approximately 5000 vpd

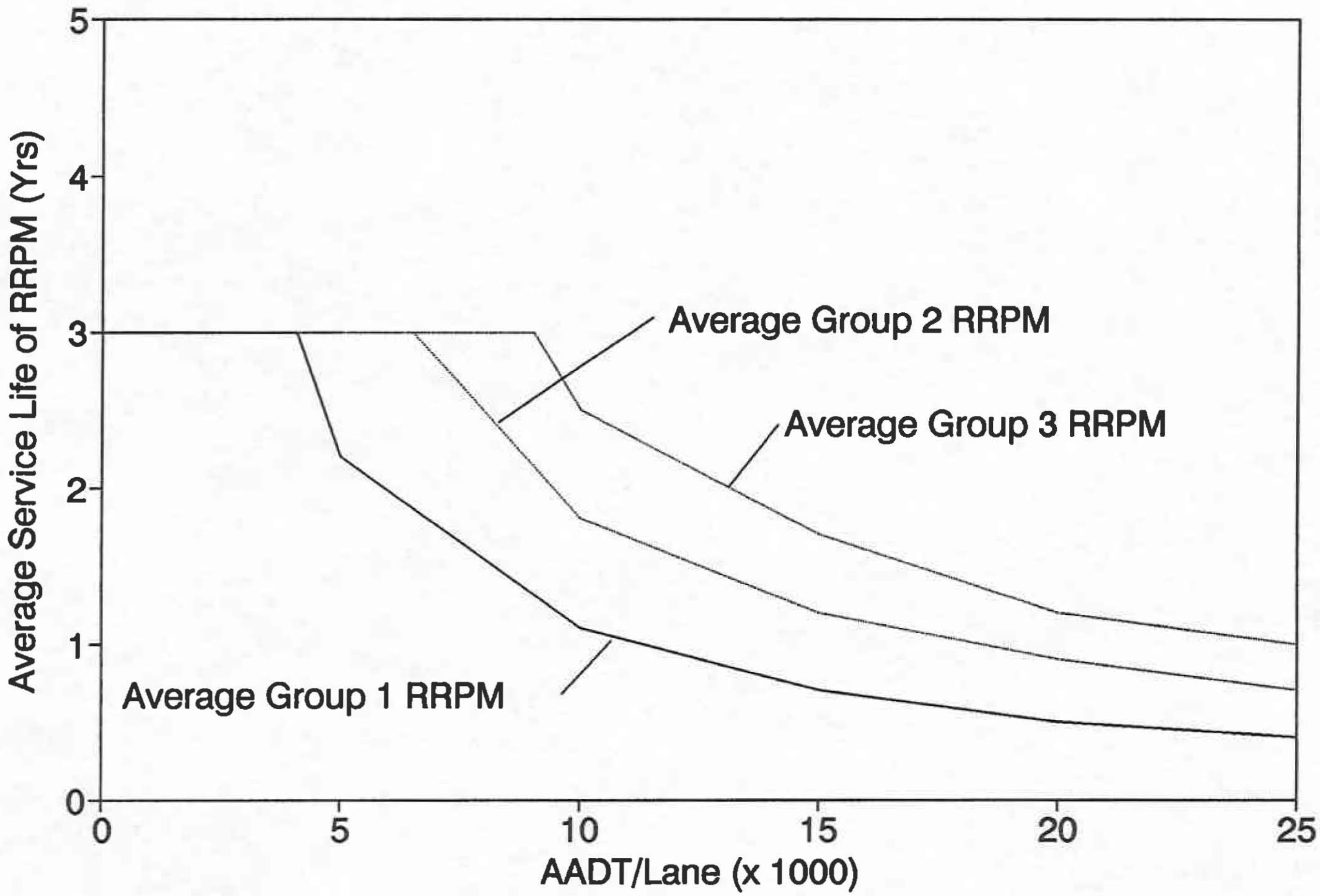


Figure 6. Estimated Service Lives of the RRPM Groups

per lane. However, once this volume is reached, significant differences by groupings become quite evident.

According to recent TxDOT estimates (*personal communication with Mr. Wade Odell, TxDOT, August 29, 1994)*, the average combined purchase and installation costs of RRPMs that are representative of Group 1 is about \$2.70. This value does vary somewhat depending on the number of RRPMs being installed as well as any other work included in the contract. However, it does reflect a reasonable statewide estimate of recent unit bid prices for RRPM installation. Meanwhile, the common RRPM spacing on a freeway lane line is 24 meters (80 feet), or about 42 per kilometer (km) (66 per mile). This spacing converts to a unit installation cost of \$113.40/km (\$178.20 per mile). Researchers combined this estimate with the relationship shown in Figure 6 to compute the cost-effectiveness of typical Group 1 RRPMs versus roadway AADT on a per lane basis. This relationship is shown in Figure 7.

Similar relationships exist for RRPMs in Groups 2 and 3 as well. According to recent approximate cost estimates provided by one of the RRPM manufacturers (*personal communication with Mr. Tom Boyce, Stimsonite Corporation, August 24, 1994)*, the RRPMs included in the Group 3 category average between \$0.43 and \$1.49 per RRPM more than Group 1 RRPMs. To be conservative in the analysis of these Group 3 RRPMs, researchers rounded these values up to the nearest dollar (i.e., an additional \$1.00 to \$2.00 per RRPM). Figure 7 presents the cost-effectiveness relationship for Group 3 RRPMs based on these conservative assumptions. Assuming that the RRPMs in Group 2 will likewise be \$1.00 higher than Group 1 RRPMs results in the final relationship shown in Figure 7. Figure 7 indicates that the more expensive Group 2 and 3 RRPMs do not become more cost-effective than the basic Group 1 RRPMs until AADTs approach 5,000 to 10,000 vpd/lane.

Of course, these relationships assume that the RRPMs will be replaced as soon as their reflectivity level drops below 0.5 SI. A lower SI threshold value or a delay replacement schedule will increase the break-even point on the AADT/lane axis, whereas higher threshold values (that may become necessary in the future as greater numbers of older drivers must travel at night) will decrease this break-even point. Likewise, RRPM price structures different than those assumed in this analysis will also yield different break-even points. Finally, the data upon which these values are computed reflect freeway facilities in central Texas only, and so caution must be used when applying these results to conditions other than those studied in this field test.

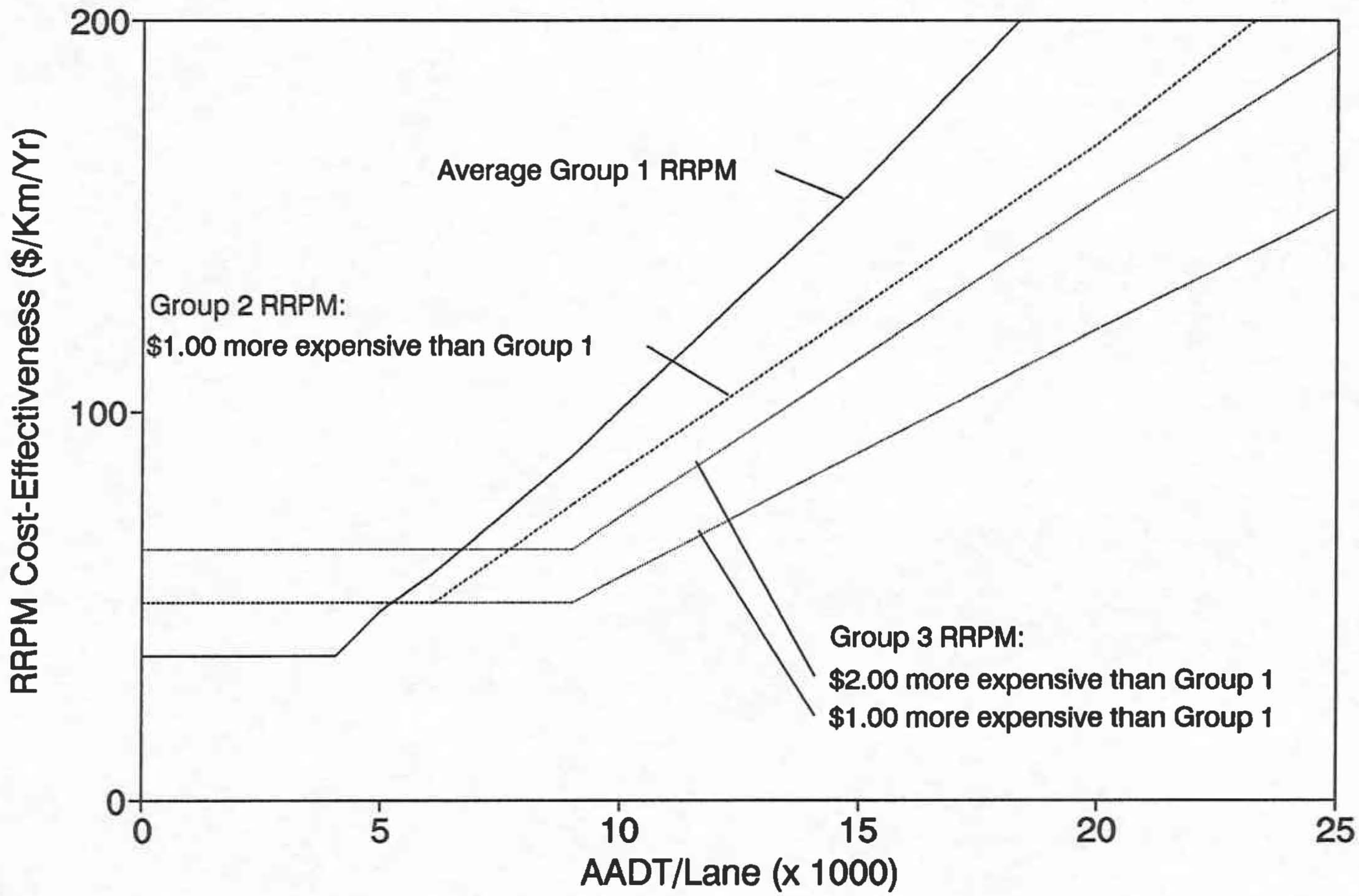


Figure 7. Cost-Effectiveness of Various RRPM Groups

SUMMARY AND CONCLUSIONS

This report summarizes reflectivity and traffic data collected during the two-year field test of 17 types of RRPMs at four freeway locations in and near San Antonio, Texas. In total, researchers collected over 4,500 reflectivity readings among the four sites using a portable retroreflectometer designed to measure RRPM SI values in place on the roadway pavement. These readings were validated by over 900 RRPMs removed from the sites and taken to the TxDOT Materials and Testing Laboratory in Austin, Texas. Researchers sampled traffic data at each study site periodically over the two-year period as well.

The results of the test show that many of the RRPMs failed to provide adequate levels of reflectivity after as little as six months exposure on high-volume facilities. For some of the RRPMs, high traffic demands quickly abraded the reflective lens and diminished reflectivity; for others designed to avoid tire abrasions, an accumulation of dirt residue on the lens that was not scrubbed off by tire-RRPM interactions led to the reduced reflectivity levels. A few specially-designed RRPMs did retain reflectivity somewhat longer, depending on the traffic characteristics of each site.

Specific findings and lessons learned during this two-year study include the following:

- The portable retroreflectometer provided an efficient and reasonably accurate estimate of RRPM reflectivity throughout the duration of the test. SI values obtained from the retroreflectometer and those measured in the TxDOT laboratory for the same RRPMs achieved a Pearson's Correlation Coefficient of between 0.85 and 0.95.
- Slight deviations in the measuring angle of the RRPM did not appear to significantly reduce the accuracy of the portable retroreflectometer. However, experiences suggest that some stray light does enter into the unit from the fan vents on the sides during measurements. It may be possible to modify the unit to eliminate this stray light, and the manufacturer should explore this suggestion in more detail.
- The field test results suggest the existence of three general performance classifications of RRPMs. Group 1 consists of most of the currently available RRPMs; Group 2 includes the Ray-O-Lite low-profile prototype models 2002 and 2003; and Group 3 includes the Stimsonite model 911, 948, and 953 that have glass layers epoxied over the reflective lens.

- Non-linear regression analyses indicate that RRPM reflectivity retention tends to be most dependent upon cumulative vehicular exposure since the time of installation. Modeling reflectivity retention as a function of cumulative truck exposure proved to be slightly less accurate overall, although this measure was a better predictor of RRPM reflectivity for a few of the RRPM types.
- Based on estimated typical RRPM purchase and installation cost values and the results of the non-linear regression models, the more expensive RRPMs comprising Groups 2 and 3 become cost-effective alternatives to the basic RRPMs in Group 1 once AADT levels reach 10,000 vpd/lane.

The reader is cautioned that the results of this test, particularly the reflectivity retention values over time for the various RRPMs, are only representative of the conditions evaluated; specifically, freeway facilities with AADTs less than 120,000 vpd in central Texas and with truck usage between 3 and 15 percent of the AADT. Roadway and environmental conditions other than those evaluated in this test may yield different RRPM performance curves. Therefore, researchers recommend additional RRPM testing under conditions other than those evaluated in this study.

REFERENCES

1. Niessner, C.W. *Raised Pavement Markers at Hazardous Locations.* Report No. FHWA-TS-84-215. Federal Highway Administration, Washington, D. C. December 1984.

2. Mathias, J.S. *Spacing of Raised Reflective Pavement Markers.* Report No. FHWA-AZ88-836. Center for Advanced Research in Transportation, Arizona State University, Tempe, Arizona. November 1988.

3. Kidd, S.Q. *An Evaluation of Reflective Markers.* Report No. MSHD-RD-90-67-4. Research and Development Division, Mississippi State Highway Department, Jackson, Mississippi. July 1990.

4. Bowman, B.L. *Inexpensive Accident Countermeasures at Narrow Bridges.* Report No. FHWA/RD-87/024. Federal Highway Administration, Washington, D. C. April 1987.

5. Allen, R.W., J.F. O'Hanlon, D.T. McRuer et al. *Driver's Visibility Requirements for Roadway Delineation: Volume 1, Effects of Contrast and Configuration on Driver Performance and Behavior.* Report No. FHWA-RD-77-165. Federal Highway Administration, Washington, D. C. November 1977.

6. Fullerton, I.J. *Roadway Delineation Practices Handbook.* Report No. DOT-I-82-36. Federal Highway Administration, Washington, D. C. September 1981.

7. Tielking, J.T. and J.S. Joel. *On the Retention of Reflective Raised Pavement Markers.* Report No. FHWA/TX-87/477-1F. Texas Transportation Institute, College Station, Texas. 1988.

8. McNees, R.W. and J.S. Noel. *Executive Summary, Significant Results and Assorted Tests and Procedures for Reflective Raised Pavement Markers.* Report No. FHWA/TX-86/13+322-4F. Texas Transportation Institute, College Station, Texas. 1986.

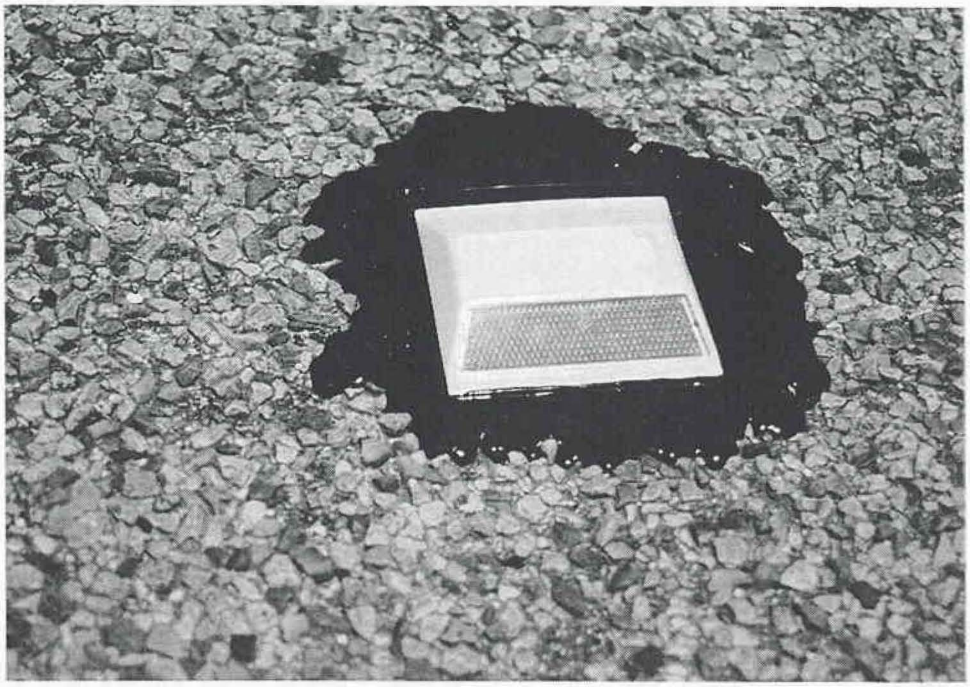
9. Pezoldt, V.J., R.J. Koppa, R.A. Zimmer, A.T. Perry, and H.W. Milsap. *Raised Pavement Marker Reflectivity.* Report No. TX-90/1151-1F. Texas Transportation Institute, College Station, Texas. 1990.

10. Ullman, G.L. *Retroreflective Raised Pavement Marker Field Testing: Initial Interim Report.* Report No. TX-92/1946-1. Texas Transportation Institute, College Station, Texas. 1992.

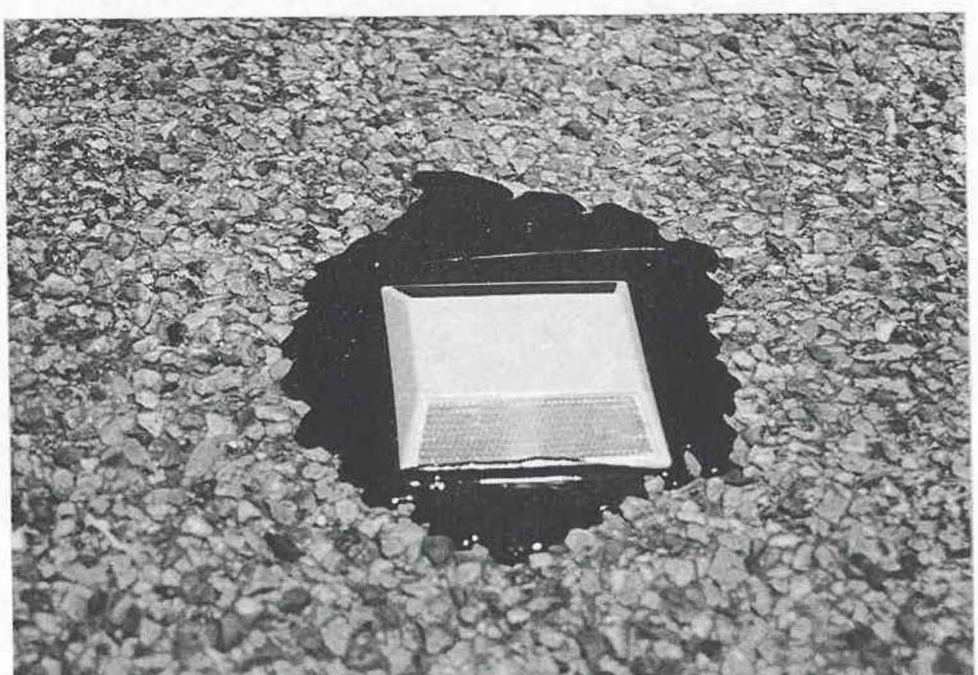
11. Ullman, G.L. *Retroreflective Raised Pavement Marker Field Testing: Results of the First-Year Evaluation.* Report No. TX-93/1946-2. Texas Transportation Institute, College Station, Texas. January 1994.

12. *SAS Procedure Guide for Personal Computers, Version 6 Edition*. SAS Institute, Inc., Cary, North Carolina. 1985.

APPENDIX A - RRPM PHOTOGRAPHS



Apex model 921



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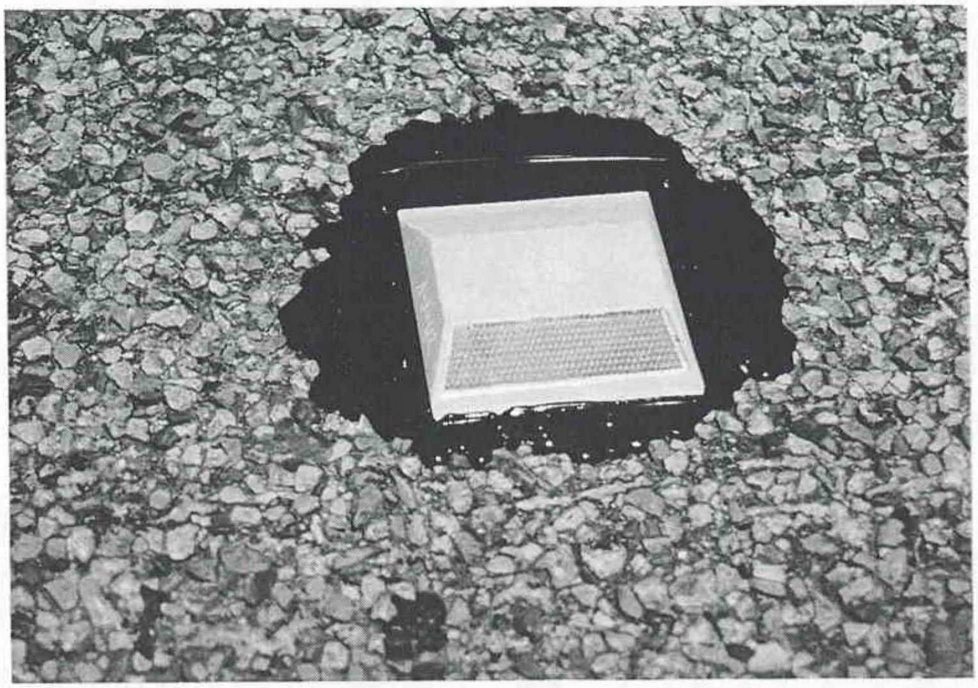
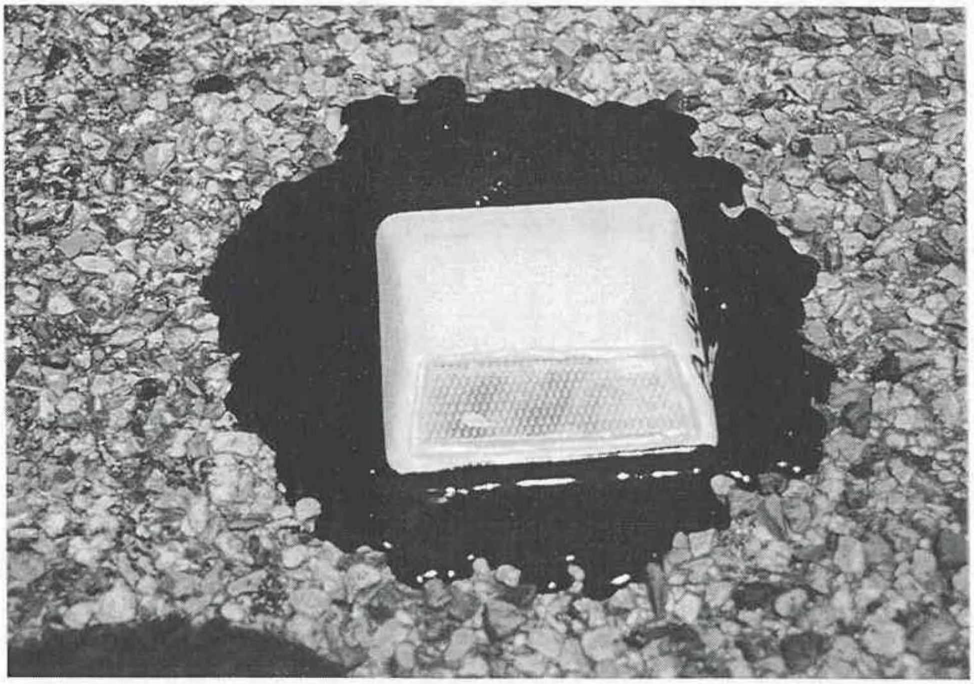
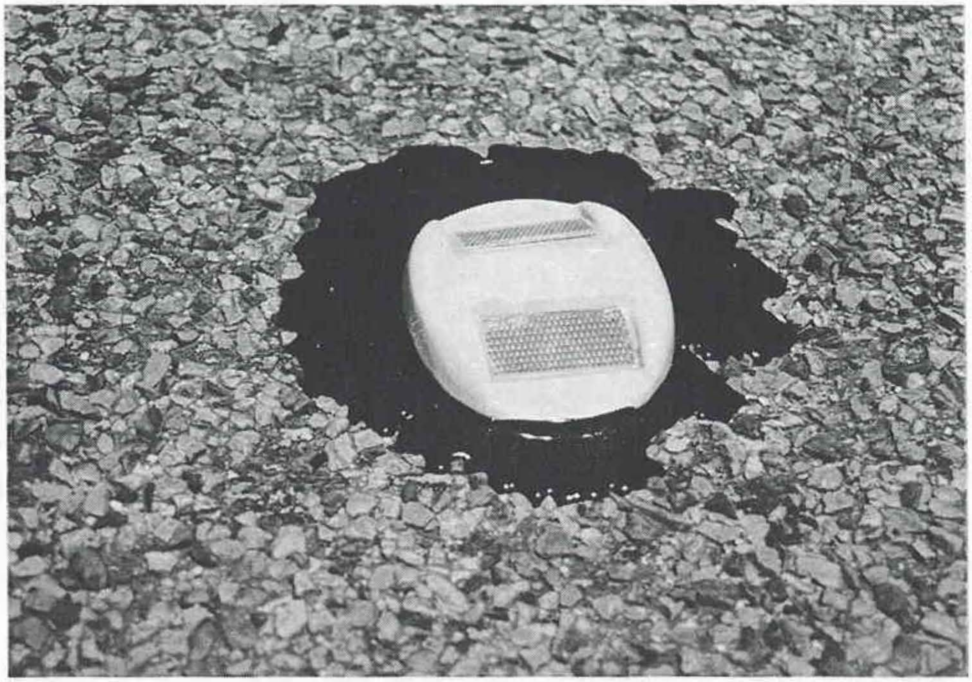


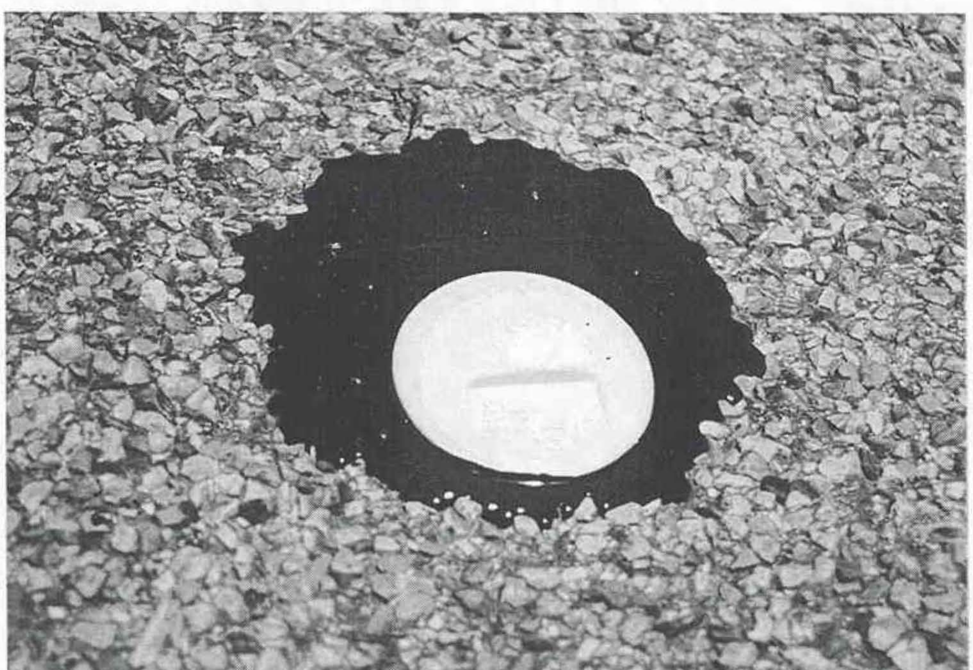
Apex model 928



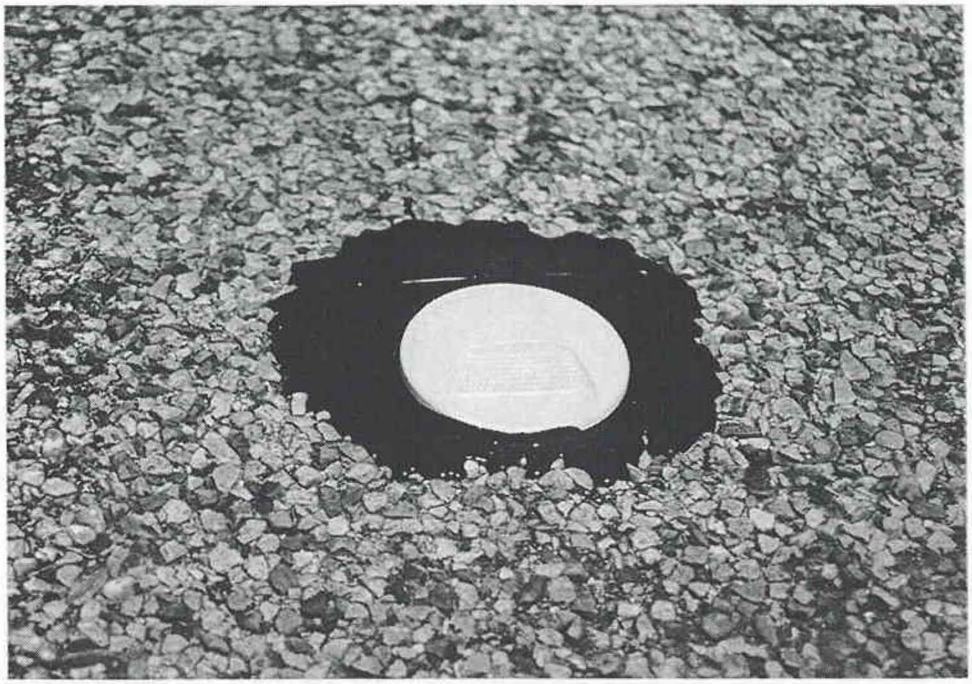
Apex model 807



Apex model 817

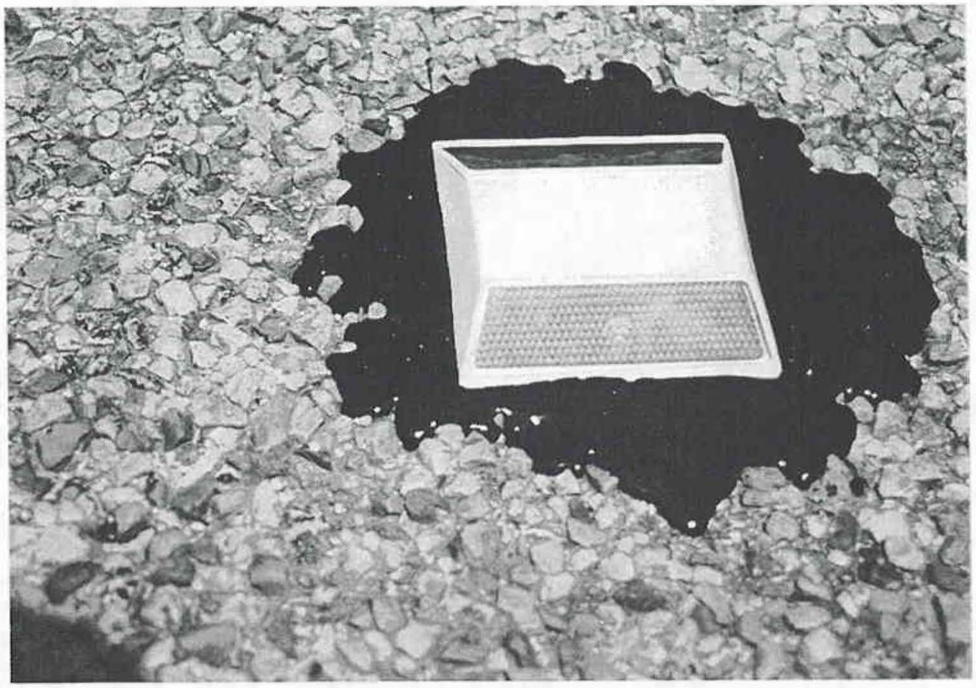


Batterson reflective button

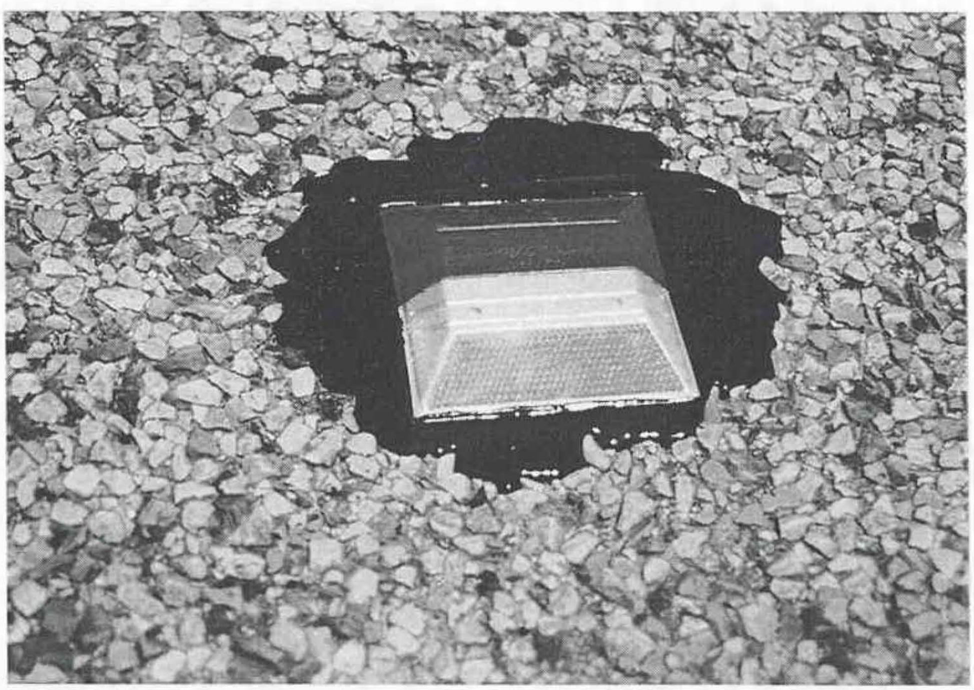


Empco model 901

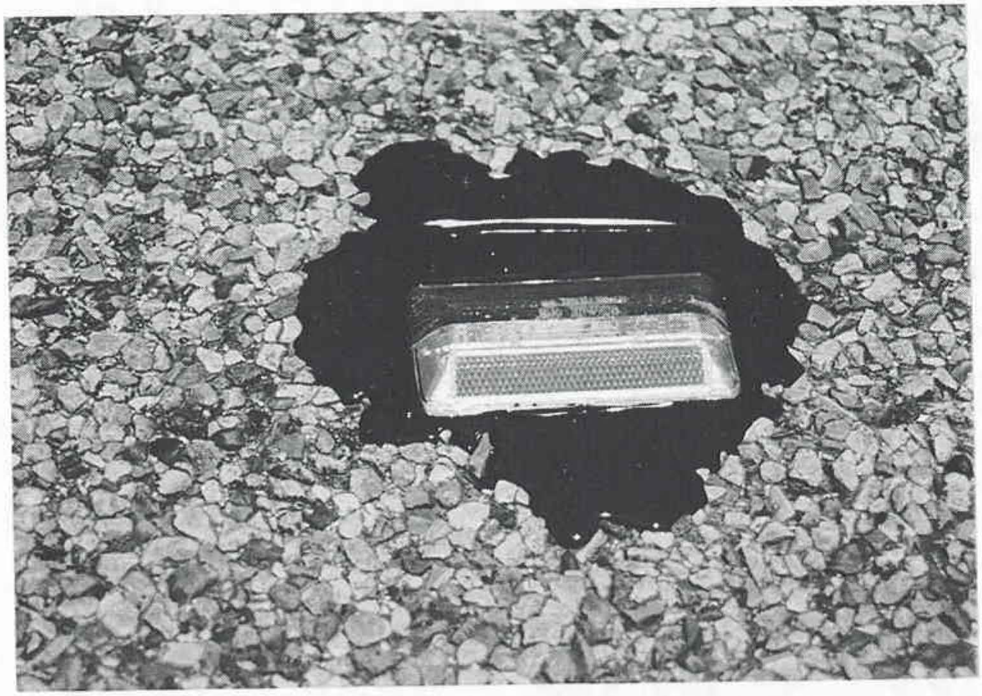
Ray-O-Lite model 8704 (S)



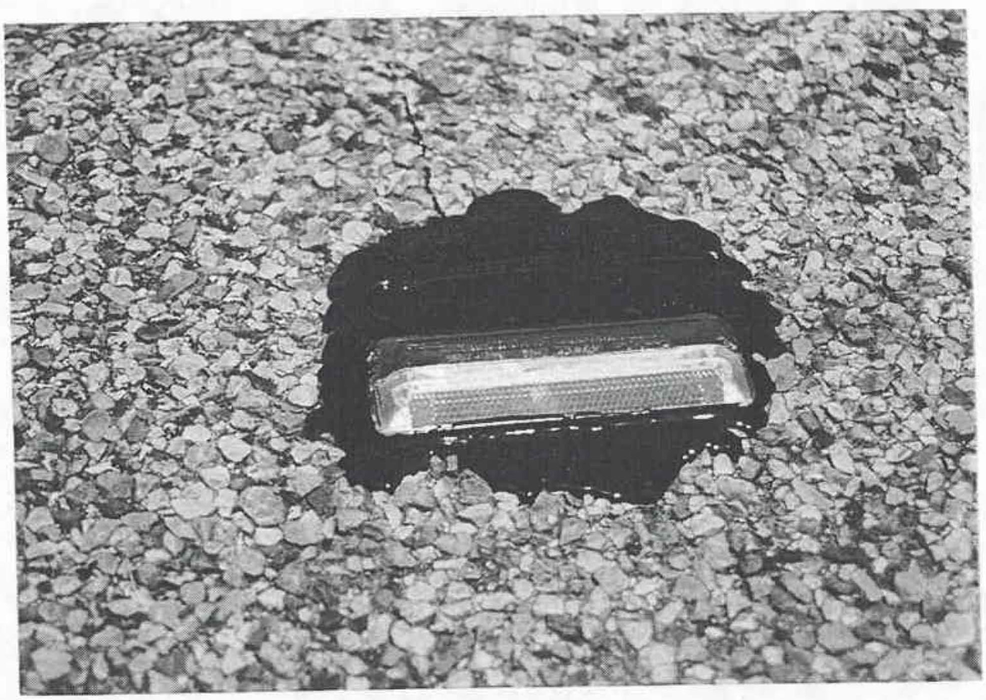
Ray-O-Lite model 8704 (R)



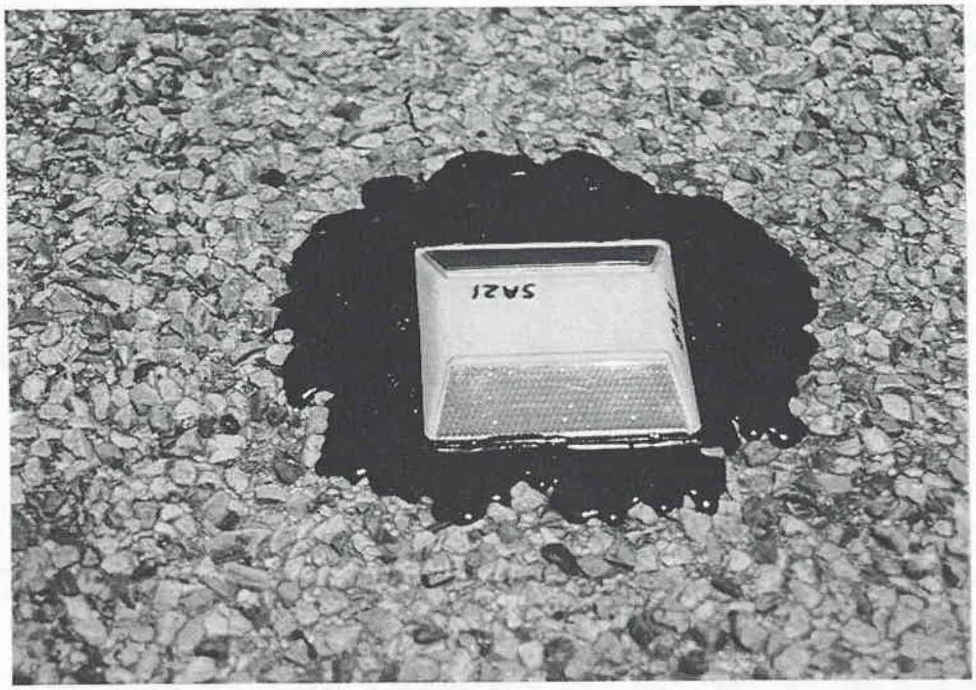
Ray-O-Lite model 9704



Ray-O-Lite model 2002

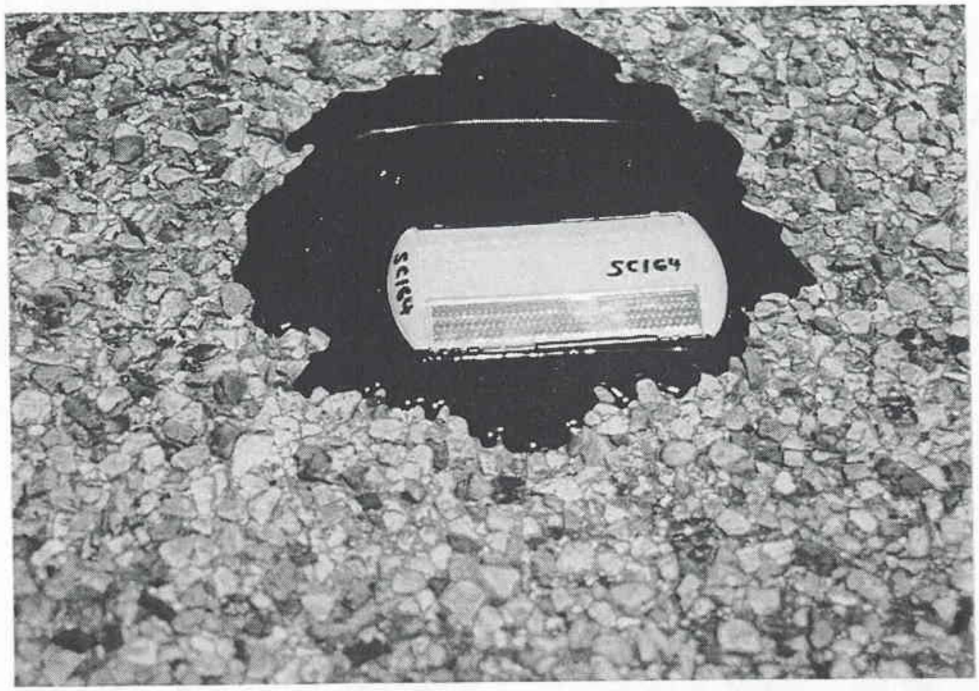


Ray-O-Lite model 2003

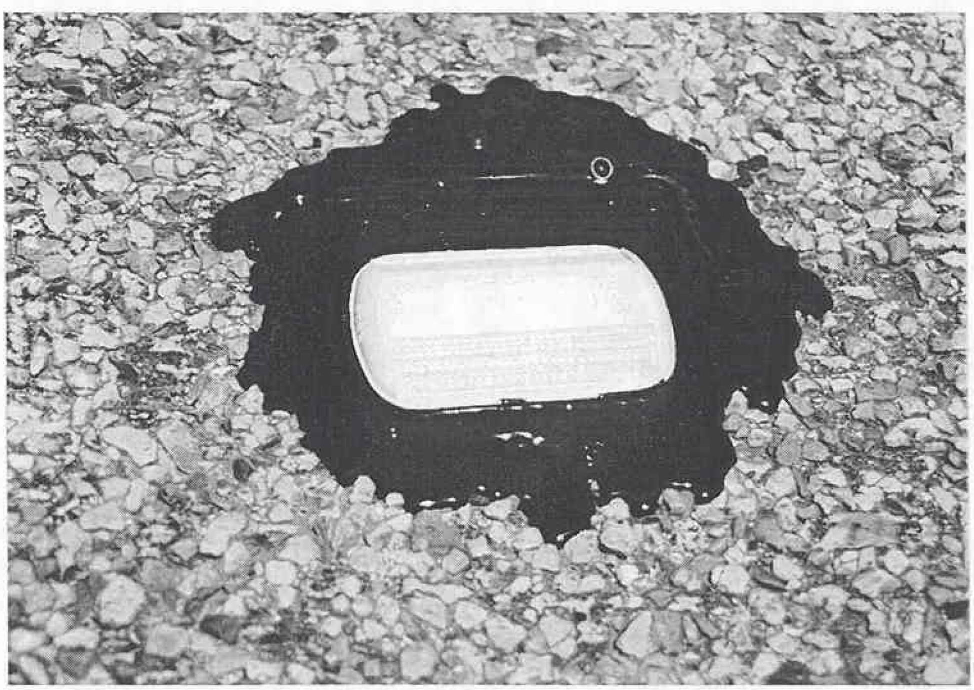


Stimsonite model 88

Stimsonite model 911



Stimsonite model 948



Stimsonite model 953

Swareflex

APPENDIX B - RETROREFLECTOMETER AND LABORATORY SI VALUES

Table B-1. Average Field and Laboratory SI Values: Apex 921

Weeks After Installation	Site 1			Site 2			Site 3			Site 4		
	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed
0	4.4 (1.9)	3.5	3.5	4.4 (1.9)	3.5	3.5	4.4 (1.9)	3.5	3.5	4.4 (1.9)	3.5	3.5
2	0.9 (0.8)	0.8	1.4	1.3 (0.2)	2.1	1.9	0.7 (0.4)	1.3	3.0	3.3 (1.6)	1.5	2.4
4	1.3 (0.2)	1.7	2.1	1.5 (1.2)	1.5	1.8	0.7 (0.1)	0.9	1.9	3.1 (1.0)	2.5	3.1
6	0.6 (0.2)	0.8	1.5	1.5 (0.8)	1.0	1.2	1.4 (0.9)	1.2	1.6	3.1 (0.5)	2.1	2.5
9	0.6 (0.1)	0.6	1.1	0.8 (0.6)	1.0	1.7	1.0 (1.0)	0.6	1.8	1.5 (0.3)	1.4	2.4
12	0.7 (0.2)	N.A	N.A	0.7 (0.3)	N.A	N.A	0.9 (0.6)	N.A	N.A	1.6 (0.8)	N.A	N.A
23	N.A	0.1	0.1	N.A	0.3	0.4	N.A	0.2	0.7	N.A	0.3	0.4
32	0.1 (0.2)	0.1	0.3	0.2 (0.1)	0.2	0.3	0.3 (0.1)	0.2	0.4	0.5 (0.3)	0.2	0.2
48	0.1 (0.0)	0.0	0.1	0.2 (0.0)	0.1	0.1	0.3 (0.1)	0.2	0.1	0.5 (0.2)	0.4	0.3
54	0.2 (0.0)	0.2	0.3	0.3 (0.1)	0.2	0.2	0.3 (0.2)	0.3	0.8	0.5 (0.3)	0.6	0.7
74	0.1 (0.1)	0.1	0.1	0.1 (0.1)	0.2	0.1	N.A.	N.A.	N.A.	0.4 (0.3)	0.5	0.2
106	0.2 (0.1)	0.1	0.2	0.1 (0.0)	0.1	0.2	N.A.	N.A.	N.A.	0.3 (0.3)	0.5	0.8

( ) Standard Deviation
N.A Data not available

Table B-2. Average Field and Laboratory SI Values: Apex 918

Weeks After Installation	Site 1			Site 2			Site 3			Site 4		
	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed
0	3.5 (1.1)	4.2	4.2	3.5 (1.1)	4.2	4.2	3.5 (1.1)	4.2	4.2	3.5 (1.1)	4.2	4.2
2	1.0 (0.5)	1.2	1.9	1.7 (0.5)	1.8	2.3	0.9 (0.3)	1.0	3.3	2.0 (0.7)	1.2	1.9
4	1.2 (0.2)	1.2	1.7	1.0 (0.2)	1.2	1.9	0.6 (0.2)	0.8	1.5	1.7 (0.6)	1.9	2.5
6	0.6 (0.2)	0.7	1.2	0.7 (0.2)	0.5	0.5	1.1 (0.3)	1.0	1.7	1.6 (0.2)	1.4	1.3
9	0.7 (0.1)	0.7	1.0	0.5 (0.3)	0.5	0.7	0.6 (0.0)	0.9	1.8	1.0 (0.3)	1.2	1.7
12	0.5 (0.1)	N.A	N.A	0.7 (0.1)	N.A	N.A	0.7 (0.3)	N.A	N.A	1.2 (0.4)	N.A	N.A
23	N.A	N.A	N.A	N.A	0.1	0.2	N.A	0.2	0.4	N.A	0.4	0.6
32	0.1 (0.0)	0.1	0.1	0.2 (0.1)	0.1	0.1	0.3 (0.1)	0.2	0.4	0.4 (0.2)	0.1	0.1
48	0.1 (0.0)	0.0	0.1	0.2 (0.0)	0.1	0.1	0.3 (0.1)	0.3	0.4	0.4 (0.1)	0.4	0.3
54	0.1 (0.1)	0.3	0.4	0.2 (0.1)	0.2	0.4	0.3 (0.1)	0.2	0.6	0.4 (0.1)	0.5	0.6
74	0.1 (0.0)	0.1	0.1	0.1 (0.1)	0.1	0.1	N.A	N.A	N.A	0.3 (0.2)	N.A	N.A
106	0.2 (0.1)	N.A	N.A	0.1 (0.1)	0.1	0.2	N.A	N.A	N.A	0.3 (0.1)	N.A	N.A

( ) Standard Deviation
N.A Data not available

Table B-3. Average Field and Laboratory SI Values: Apex 928

Weeks After Installation	Site 1			Site 2			Site 3			Site 4		
	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed
0	4.0 (1.1)	2.9	2.9	4.0 (1.1)	2.9	2.9	4.0 (1.1)	2.9	2.9	4.0 (1.1)	2.9	2.9
2	1.5 (0.1)	1.5	2.1	2.5 (0.3)	4.4	4.7	1.0 (0.4)	0.7	1.2	2.0 (0.5)	2.5	3.7
4	1.0 (0.1)	1.0	1.2	1.3 (0.4)	1.0	1.4	1.6 (0.6)	1.7	3.3	1.9 (0.9)	1.2	1.5
6	0.7 (0.2)	0.7	1.2	1.4 (0.3)	1.0	1.1	1.8 (0.8)	1.8	2.7	2.3 (0.8)	1.5	1.6
9	0.8 (0.2)	0.5	1.3	1.1 (0.2)	1.1	1.9	1.2 (0.2)	0.5	0.6	2.3 (0.7)	2.1	3.0
12	0.7 (0.1)	N.A	N.A	1.1 (0.2)	N.A	N.A	1.0 (0.3)	N.A	N.A	1.7 (0.6)	N.A	N.A
23	N.A	0.1	0.2	N.A	0.3	0.3	N.A	0.3	0.4	N.A	N.A	N.A
32	0.1 (0.1)	0.1	0.1	0.2 (0.1)	0.2	0.2	0.4 (0.2)	0.5	0.9	0.6 (0.3)	0.2	0.2
48	0.1 (0.0)	0.0	0.1	0.2 (0.0)	0.0	0.1	0.3 (0.1)	0.4	0.4	0.6 (0.1)	0.3	0.4
54	0.2 (0.1)	0.3	0.3	0.3 (0.1)	0.3	0.3	0.3 (0.1)	0.3	0.6	0.6 (0.1)	0.9	1.0
74	0.1 (0.0)	0.1	0.1	0.1 (0.1)	0.1	0.2	N.A	N.A	N.A	0.4 (0.2)	0.3	0.8
106	0.2 (0.2)	0.3	0.3	0.1 (0.1)	0.1	0.3	N.A	N.A	N.A	0.5 (0.2)	N.A	N.A

( ) Standard Deviation
N.A Data not available

Table B-4. Average Field and Laboratory SI Values: Apex 807

Weeks After Installation	Site 1			Site 2			Site 3			Site 4		
	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed
0	1.4 (0.8)	2.4	2.4	1.4 (0.8)	2.4	2.4	1.4 (0.8)	2.4	2.4	1.4 (0.8)	2.4	2.4
2	0.5 (0.1)	0.7	1.0	0.7 (0.4)	1.0	1.5	0.3 (0.3)	0.4	0.7	0.6 (0.4)	1.0	1.2
4	0.4 (0.2)	0.5	0.6	0.4 (0.3)	0.7	0.7	0.4 (0.3)	1.0	1.4	0.5 (0.2)	0.9	0.9
6	0.3 (0.1)	0.4	0.4	0.5 (0.2)	0.6	0.5	0.6 (0.2)	0.8	0.4	0.6 (0.2)	0.6	0.6
9	0.3 (0.1)	0.3	0.3	0.3 (0.2)	0.3	0.3	0.5 (0.1)	0.8	1.0	0.5 (0.2)	0.8	1.0
12	0.4 (0.1)	N.A	N.A	0.3 (0.1)	N.A	N.A	0.5 (0.3)	N.A	N.A	0.8 (0.3)	N.A	N.A
23	N.A	0.1	0.1	N.A	0.1	0.1	N.A	0.1	0.1	N.A	0.1	0.1
32	0.1 (0.1)	0.1	0.1	0.1 (0.0)	0.1	0.1	0.1 (0.1)	0.3	0.2	0.1 (0.1)	0.2	0.1
48	0.1 (0.0)	N.A	N.A	0.2 (0.0)	0.0	0.1	0.1 (0.1)	0.0	0.0	0.2 (0.2)	0.0	0.1
54	0.1 (0.1)	N.A	N.A	0.3 (0.2)	0.2	0.1	0.1 (0.1)	0.2	0.2	0.3 (0.2)	0.2	0.2
74	0.1 (0.1)	0.1	0.0	0.1 (0.1)	0.1	0.1	N.A	N.A	N.A	0.2 (0.2)	0.1	0.1
106	0.2 (0.2)	0.1	0.1	0.1 (0.1)	0.2	0.2	N.A.	N.A.	N.A.	0.1 (0.1)	0.2	0.2

( ) Standard Deviation
N.A Data not available

Table B-5. Average Field and Laboratory SI Values: Apex 817

Weeks After Installation	Site 1			Site 2			Site 3			Site 4		
	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed
0	1.7 (0.9)	1.0	1.0	1.7 (0.9)	1.0	1.0	1.7 (0.9)	1.0	1.0	1.7 (0.9)	1.0	1.0
2	0.7 (0.2)	1.0	1.2	0.8 (0.7)	0.8	1.0	0.5 (0.3)	0.4	0.8	1.0 (0.5)	0.9	1.3
4	0.6 (0.2)	0.9	1.3	0.4 (0.4)	0.3	0.5	0.4 (0.1)	0.7	0.9	0.6 (0.2)	1.5	1.4
6	0.3 (0.2)	0.8	0.9	0.7 (0.2)	1.2	1.6	0.6 (0.1)	0.6	0.6	0.6 (0.1)	1.0	0.9
9	0.4 (0.2)	0.6	0.7	0.5 (0.2)	1.3	1.5	0.5 (0.2)	N.A	N.A	0.5 (0.1)	0.6	0.8
12	0.4 (0.2)	N.A	N.A	0.4 (0.2)	N.A	N.A	0.5 (0.3)	N.A	N.A	1.6 (3.2)	N.A	N.A
23	N.A	0.1	0.1	N.A	N.A	N.A	N.A	0.2	0.1	N.A	0.1	0.1
32	0.1 (0.1)	0.2	0.1	0.1 (0.1)	0.1	0.1	0.2 (0.1)	0.7	0.5	0.2 (0.1)	0.2	0.1
48	0.1 (0.0)	0.0	0.1	0.1 (0.1)	0.2	0.2	0.2 (0.1)	0.5	0.7	0.2 (0.1)	0.2	0.2
54	0.2 (0.1)	0.3	0.5	0.3 (0.2)	0.2	0.3	0.2 (0.1)	0.4	0.4	0.3 (0.1)	0.2	0.3
74	0.1 (0.0)	0.1	0.1	0.1 (0.1)	0.3	0.2	N.A	N.A	N.A	0.2 (0.1)	0.7	0.4
106	0.2 (0.2)	N.A.	N.A.	0.1 (0.1)	0.2	0.2	N.A.	N.A.	N.A.	0.2 (0.2)	0.3	0.2

( ) Standard Deviation
N.A Data not available

Table B-6. Average Field and Laboratory SI Values: Batterson

Weeks After Installation	Site 1			Site 2			Site 3			Site 4		
	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed
0	5.5 (1.0)	5.2	5.2	5.5 (1.0)	5.2	5.2	5.5 (1.0)	5.2	5.2	5.5 (1.0)	5.2	5.2
2	0.6 (0.2)	1.0	4.4	1.4 (0.1)	1.7	3.8	1.0 (0.3)	1.4	5.1	2.6 (0.8)	3.5	4.6
4	0.3 (0.1)	0.4	2.6	0.4 (0.1)	0.5	2.2	0.5 (0.2)	0.4	3.7	1.6 (0.2)	2.3	4.8
6	0.2 (0.2)	0.7	2.1	0.6 (0.0)	0.7	3.0	0.5 (0.2)	0.6	3.9	1.7 (0.3)	2.0	4.4
9	0.6 (0.3)	0.7	1.4	0.3 (0.1)	0.3	2.5	0.4 (0.2)	0.3	4.8	1.2 (0.2)	1.3	3.6
12	0.2 (0.1)	N.A	N.A	0.2 (0.1)	N.A	N.A	0.2 (0.1)	N.A	N.A	0.4 (0.1)	N.A	N.A
23	N.A	0.1	1.4	N.A	0.1	1.2	N.A	0.3	3.4	N.A	0.6	1.4
32	0.1 (0.1)	0.2	1.1	0.1 (0.1)	0.1	1.2	0.2 (0.1)	0.1	2.7	0.4 (0.2)	0.3	1.0
48	0.1 (0.0)	0.1	0.7	0.1 (0.0)	0.1	0.4	0.2 (0.1)	0.3	1.9	0.4 (0.1)	0.2	0.8
54	0.1 (0.0)	0.1	0.1	0.1 (0.1)	0.1	0.4	0.2 (0.1)	0.1	0.4	0.2 (0.1)	0.2	1.2
74	0.0 (0.0)	0.1	0.5	0.1 (0.1)	0.1	0.9	N.A	N.A	N.A	0.2 (0.1)	0.2	0.8
106	0.1 (0.1)	N.A.	N.A.	0.0 (0.0)	0.0	1.0	N.A.	N.A.	N.A.	0.1 (0.0)	0.2	0.5

( ) Standard Deviation
N.A Data not available

Table B-7. Average Field and Laboratory SI Values: Empco 901

Weeks After Installation	Site 1			Site 2			Site 3			Site 4		
	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed
0	2.4 (1.0)	1.8	1.8	2.4 (1.0)	1.8	1.8	2.4 (1.0)	1.8	1.8	2.4 (1.0)	1.8	1.8
2	0.6 (0.1)	0.8	1.1	1.0 (0.1)	1.1	1.1	0.8 (0.4)	1.2	2.0	1.0 (0.3)	1.7	1.7
4	0.4 (0.1)	0.4	0.7	0.5 (0.2)	0.6	0.9	0.9 (0.0)	N.A	N.A	1.2 (0.8)	1.0	0.9
6	0.3 (0.1)	0.3	0.7	0.8 (0.1)	1.1	1.4	1.0 (0.2)	1.1	1.3	1.5 (0.5)	0.9	1.0
9	0.4 (0.1)	0.2	0.8	0.6 (0.2)	0.7	0.9	1.0 (0.1)	1.0	1.5	1.3 (0.1)	1.2	1.7
12	0.3 (0.2)	N.A	N.A	0.4 (0.1)	N.A	N.A	0.4 (0.2)	N.A	N.A	0.9 (0.2)	N.A	N.A
23	N.A	0.1	0.2	N.A	0.1	0.4	N.A	0.3	0.4	N.A	0.4	0.4
32	0.0 (0.0)	0.1	0.1	0.1 (0.0)	0.1	0.2	0.2 (0.1)	0.1	0.2	0.2 (0.2)	0.1	0.1
48	0.1 (0.0)	0.1	0.2	0.2 (0.1)	0.1	0.1	0.2 (0.1)	0.1	0.2	0.3 (0.1)	0.2	0.1
54	0.1 (0.1)	N.A	N.A	0.2 (0.1)	0.1	0.2	0.2 (0.1)	0.1	0.3	0.3 (0.1)	0.3	0.4
74	0.0 (0.0)	0.1	0.1	0.1 (0.1)	0.1	0.2	N.A	N.A	N.A	0.2 (0.1)	0.3	0.3
106	0.1 (0.1)	0.1	0.2	0.1 (0.1)	0.1	0.1	N.A.	N.A.	N.A.	0.1 (0.1)	N.A.	N.A.

( ) Standard Deviation
N.A Data not available

Table B-8. Average Field and Laboratory SI Values: Ray-O-Lite 8704(S)

Weeks After Installation	Site 1			Site 2			Site 3			Site 4		
	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed
0	7.1 (1.5)	5.3	5.3	7.1 (1.5)	5.3	5.3	7.1 (1.5)	5.3	5.3	7.1 (1.5)	5.3	5.3
2	2.4 (0.4)	2.1	4.1	2.9 (0.8)	3.8	6.4	N.A	N.A	N.A	1.0 (0.3)	1.7	1.7
4	1.9 (0.2)	2.3	2.9	1.7 (0.3)	2.0	3.0	N.A	N.A	N.A	1.2 (0.8)	1.0	0.9
6	0.9 (0.6)	0.1	0.4	2.4 (0.7)	2.0	2.9	N.A	N.A	N.A	1.5 (0.5)	0.9	1.0
9	1.0 (0.1)	1.5	2.5	1.6 (0.4)	1.3	1.9	N.A	N.A	N.A	1.3 (0.1)	1.2	1.7
12	1.1 (0.2)	N.A	N.A	1.4 (0.4)	N.A	N.A	1.6 (0.4)	N.A	N.A	0.9 (0.2)	N.A	N.A
23	N.A	0.1	0.4	N.A	0.3	0.7	N.A	N.A	N.A	N.A	0.4	0.4
32	0.2 (0.1)	0.2	0.5	0.3 (0.1)	0.3	0.6	0.6 (0.2)	N.A	N.A	0.2 (0.2)	0.1	0.1
48	0.1 (0.0)	0.1	0.2	0.2 (0.1)	0.2	0.2	0.6 (0.1)	0.5	0.5	0.3 (0.1)	0.2	0.1
54	0.4 (0.1)	0.4	0.4	0.5 (0.1)	0.3	0.4	0.5 (0.1)	0.5	1.2	0.3 (0.1)	0.3	0.4
74	0.2 (0.0)	0.2	0.2	0.2 (0.1)	0.2	0.2	N.A	N.A	N.A	0.2 (0.1)	0.3	0.3
106	0.3 (0.2)	0.3	0.5	0.2 (0.1)	0.3	0.4	N.A.	N.A.	N.A.	0.1 (0.1)	N.A.	N.A.

( ) Standard Deviation
N.A Data not available

Table B-9. Average Field and Laboratory SI Values: Ray-O-Lite 8704(R)

Weeks After Installation	Site 1			Site 2			Site 3			Site 4		
	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed
0	5.3 (1.3)	5.3	5.3	5.3 (1.3)	5.3	5.3	5.3 (1.3)	5.3	5.3	5.3 (1.3)	5.3	5.3
2	1.2 (0.1)	1.5	3.6	N.A	N.A	N.A	1.1 (0.3)	1.8	3.2	3.3 (0.3)	3.0	3.9
4	1.0 (0.2)	2.2	2.4	N.A	N.A	N.A	1.5 (0.1)	1.8	3.6	2.6 (0.5)	2.7	3.7
6	0.6 (0.3)	0.6	1.9	N.A	N.A	N.A	1.8 (0.2)	2.2	3.7	2.5 (0.4)	3.3	3.8
9	0.7 (0.0)	0.9	2.1	N.A	N.A	N.A	1.5 (0.3)	2.5	3.9	2.0 (0.2)	2.9	3.8
12	1.2 (1.2)	N.A	N.A	1.6 (---)	N.A	N.A	1.2 (0.1)	N.A	N.A	1.8 (0.3)	N.A	N.A
23	N.A	0.1	0.2	N.A	N.A	N.A	N.A	0.3	0.6	N.A	0.5	0.6
32	0.2 (0.3)	0.1	0.4	0.2 (---)	N.A	N.A	0.3 (0.1)	0.4	0.7	0.5 (0.3)	0.2	0.2
48	0.1 (0.1)	0.4	0.4	0.2 (---)	N.A	N.A	0.5 (0.3)	N.A	N.A	0.6 (0.2)	0.4	0.4
54	0.2 (0.1)	0.4	0.5	0.3 (---)	N.A	N.A	0.3 (0.1)	0.3	1.2	0.6 (0.1)	0.5	0.9
74	0.1 (0.0)	0.1	0.2	0.1 (---)	N.A	N.A	N.A	N.A	N.A	0.5 (0.1)	0.6	0.3
106	0.2 (0.1)	0.2	0.3	0.1 (0.0)	0.2	0.2	N.A.	N.A.	N.A.	0.5 (0.2)	0.4	0.6

( ) Standard Deviation (---) No Standard Deviation Available
N.A Data not available
--- No standard deviation (only one data point obtained)

Table B-10. Average Field and Laboratory SI Values: Ray-O-Lite 9704

Weeks After Installation	Site 1			Site 2			Site 3			Site 4		
	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed
0	9.1 (2.2)	6.4	6.4	9.1 (2.2)	6.4	6.4	9.1 (2.2)	6.4	6.4	9.1 (2.2)	6.4	6.4
2	2.5 (0.8)	2.8	5.8	5.1 (0.8)	4.8	5.4	1.6 (0.6)	1.2	3.0	6.2 (0.3)	5.0	5.8
4	2.0 (0.4)	2.9	3.4	2.7 (1.1)	3.1	3.7	2.4 (0.5)	2.7	5.7	4.7 (0.8)	3.5	3.8
6	1.0 (0.3)	1.0	2.1	3.2 (0.8)	3.0	3.5	1.8 (0.7)	1.2	2.8	4.4 (0.8)	4.2	5.8
9	1.2 (0.2)	1.4	2.6	2.0 (0.4)	1.9	2.9	2.7 (0.7)	3.0	8.5	3.5 (0.6)	3.8	5.5
12	1.1 (0.4)	N.A	N.A	2.0 (0.4)	N.A	N.A	2.2 (0.3)	N.A	N.A	2.9 (0.4)	N.A	N.A
23	N.A	0.1	0.7	N.A	0.3	1.3	N.A	0.4	1.7	N.A	0.9	1.6
32	0.1 (0.1)	0.1	0.6	0.2 (0.0)	0.2	0.5	0.6 (0.2)	0.7	1.1	0.8 (0.4)	0.2	0.4
48	0.1 (0.0)	0.1	0.2	0.2 (0.0)	0.2	0.4	0.5 (0.1)	0.5	1.5	0.8 (0.2)	0.6	0.7
54	0.3 (0.1)	0.2	0.2	0.3 (0.2)	0.3	0.4	0.5 (0.2)	0.3	1.5	0.8 (0.1)	0.7	1.4
74	0.1 (0.0)	0.1	0.2	0.1 (0.1)	0.1	0.2	N.A	N.A	N.A	0.8 (0.3)	0.6	0.7
106	0.3 (0.2)	0.4	0.5	0.2 (0.1)	0.2	0.6	N.A.	N.A.	N.A.	0.8 (0.2)	0.7	1.2

( ) Standard Deviation
N.A Data not available

Table B-11. Average Field and Laboratory SI Values: Ray-O-Lite 2002

Weeks After Installation	Site 1			Site 2			Site 3			Site 4		
	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed
0	9.3 (1.8)	6.3	6.3	9.3 (1.8)	6.3	6.3	9.3 (1.8)	6.3	6.3	9.3 (1.8)	6.3	6.3
2	4.0 (0.6)	4.1	4.9	5.0 (1.0)	3.1	5.9	1.6 (1.1)	2.7	5.9	6.4 (1.4)	3.6	5.6
4	3.4 (1.6)	3.7	7.0	3.6 (0.3)	3.8	5.9	1.8 (0.6)	0.8	2.9	6.4 (3.3)	4.2	6.1
6	2.9 (0.6)	1.8	4.2	5.9 (0.1)	N.A	N.A	2.4 (0.2)	1.6	5.0	6.8 (2.1)	3.1	4.0
9	3.3 (0.5)	4.4	6.0	4.6 (0.5)	5.1	6.3	3.3 (0.5)	3.8	7.7	5.1 (0.7)	5.9	6.7
12	3.3 (0.6)	N.A	N.A	4.0 (0.8)	N.A	N.A	2.5 (0.9)	N.A	N.A	6.0 (0.7)	N.A	N.A
23	N.A	0.2	2.1	N.A	0.8	2.8	N.A	0.1	1.5	N.A	3.0	3.6
32	0.7 (0.4)	0.7	2.1	1.6 (1.4)	2.0	2.4	1.8 (0.5)	2.3	2.3	2.4 (0.6)	2.0	2.1
48	0.4 (0.2)	0.5	1.5	1.1 (0.8)	1.2	1.8	1.6 (0.5)	1.1	2.6	1.9 (0.5)	1.8	1.7
54	0.3 (0.2)	N.A	N.A	1.0 (0.5)	1.0	1.7	0.4 (0.2)	0.6	4.0	1.4 (1.0)	2.0	3.2
74	0.1 (0.0)	0.2	0.4	0.4 (0.3)	0.6	1.1	N.A	N.A	N.A	1.1 (0.8)	0.7	1.3
106	0.1 (0.1)	0.2	0.3	0.1 (0.1)	0.2	0.3	N.A.	N.A.	N.A.	0.7 (0.5)	0.7	0.9

( ) Standard Deviation
N.A Data not available

Table B-12. Average Field and Laboratory SI Values: Ray-O-Lite 2003

Weeks After Installation	Site 1			Site 2			Site 3			Site 4		
	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed
0	9.5 (3.3)	6.9	6.9	9.5 (3.3)	6.9	6.9	9.5 (3.3)	6.9	6.9	9.5 (3.3)	6.9	6.9
2	3.8 (3.4)	4.6	6.1	3.5 (1.6)	4.5	4.7	2.1 (0.9)	2.9	5.1	7.2 (0.9)	6.5	6.1
4	2.9 (1.8)	2.5	3.2	3.6 (0.4)	3.7	7.0	1.9 (0.4)	1.3	6.3	5.7 (0.4)	5.5	6.7
6	2.1 (1.5)	4.1	8.9	5.3 (1.2)	4.5	7.5	2.8 (0.2)	2.6	7.1	6.4 (1.0)	6.6	8.0
9	1.4 (0.2)	1.2	4.0	4.0 (0.3)	4.2	4.7	2.7 (0.7)	4.3	7.8	3.7 (0.7)	4.2	6.4
12	3.0 (1.3)	N.A	N.A	4.9 (0.9)	N.A	N.A	2.3 (0.6)	N.A	N.A	5.7 (1.2)	N.A	N.A
23	N.A	0.1	1.8	N.A	1.3	2.8	N.A	1.2	1.9	N.A	3.6	3.5
32	0.5 (0.3)	0.3	1.0	1.1 (0.4)	1.5	1.9	1.9 (0.5)	1.5	4.1	2.3 (1.0)	0.6	0.6
48	0.5 (0.2)	0.6	1.3	1.0 (0.3)	0.6	0.8	1.7 (0.4)	0.9	2.9	1.7 (0.5)	1.1	1.5
54	0.4 (0.2)	0.4	0.5	0.7 (0.3)	0.9	1.3	0.7 (0.2)	1.0	4.5	1.0 (0.3)	N.A	N.A
74	0.1 (0.0)	0.3	0.7	0.2 (0.2)	0.5	0.8	N.A	N.A	N.A	0.8 (0.6)	0.7	0.8
106	0.1 (0.1)	0.1	0.2	0.1 (0.1)	0.2	0.4	N.A.	N.A.	N.A.	0.5 (0.4)	N.A.	N.A.

( ) Standard Deviation
N.A Data not available

Table B-13. Average Field and Laboratory SI Values: Stimsonite 88

Weeks After Installation	Site 1			Site 2			Site 3			Site 4		
	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed
0	7.1 (2.1)	7.4	7.4	7.1 (2.1)	7.4	7.4	7.1 (2.1)	7.4	7.4	7.1 (2.1)	7.4	7.4
2	2.7 (0.6)	2.4	5.7	3.7 (1.0)	4.9	7.9	2.3 (1.3)	3.0	5.2	5.4 (2.2)	4.8	5.0
4	2.1 (0.7)	2.7	3.0	2.0 (0.6)	2.5	3.2	1.9 (0.8)	2.4	4.1	3.7 (1.9)	5.7	6.8
6	1.2 (0.2)	1.2	2.8	2.9 (0.2)	2.4	2.6	2.3 (0.8)	2.7	3.6	3.6 (0.7)	3.8	3.7
9	1.3 (0.4)	1.3	2.5	2.2 (0.3)	2.5	3.2	2.6 (0.8)	3.6	7.5	2.6 (0.6)	3.3	4.7
12	1.3 (0.3)	N.A	N.A	1.9 (0.4)	N.A	N.A	1.5 (0.6)	N.A	N.A	2.9 (0.6)	N.A	N.A
23	N.A	0.1	0.4	N.A	0.2	0.4	N.A	0.3	0.5	N.A	0.5	1.0
32	0.1 (0.1)	0.2	0.4	0.2 (0.1)	0.2	0.8	0.5 (0.1)	0.6	1.2	0.7 (0.4)	0.3	0.3
48	0.1 (0.0)	0.1	0.1	0.2 (0.0)	0.1	0.1	0.4 (0.1)	0.2	0.8	0.8 (0.2)	0.6	0.7
54	0.2 (0.0)	0.5	0.3	0.3 (0.1)	0.3	0.4	0.3 (0.1)	0.4	1.5	0.7 (0.2)	0.7	1.0
74	0.2 (0.0)	0.1	0.2	0.1 (0.1)	0.1	0.2	N.A	N.A	N.A	0.6 (0.2)	0.7	0.4
106	0.2 (0.1)	0.3	0.4	0.2 (0.1)	0.2	0.3	N.A.	N.A.	N.A.	0.6 (0.2)	0.6	0.7

( ) Standard Deviation
N.A Data not available

Table B-14. Average Field and Laboratory SI Values: Stimsonite 911

Weeks After Installation	Site 1			Site 2			Site 3			Site 4		
	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed
0	9.1 (2.5)	9.2	9.2	9.1 (2.5)	9.2	9.2	9.1 (2.5)	9.2	9.2	9.1 (2.5)	9.2	9.2
2	5.8 (0.4)	7.4	11.6	7.7 (2.0)	6.8	8.8	4.5 (1.8)	5.3	12.4	10.5 (1.8)	9.7	13.3
4	5.3 (1.0)	4.9	5.8	6.4 (2.3)	7.3	9.5	3.2 (1.1)	4.7	8.7	7.9 (2.2)	13.4	13.9
6	4.1 (1.2)	4.7	12.3	5.9 (1.2)	7.2	7.7	4.7 (1.3)	5.2	7.7	7.9 (1.9)	8.4	9.2
9	4.5 (0.8)	5.7	9.2	5.9 (1.3)	8.5	8.5	4.3 (1.2)	6.7	9.8	5.3 (1.4)	6.4	7.8
12	5.0 (1.2)	N.A	N.A	5.2 (0.9)	N.A	N.A	3.8 (1.1)	N.A	N.A	6.0 (1.6)	N.A	N.A
23	N.A	1.2	6.2	N.A	5.6	7.8	N.A	3.2	7.5	N.A	5.1	7.8
32	3.6 (1.1)	2.0	4.7	4.3 (0.8)	5.0	7.0	4.1 (1.1)	5.0	7.7	6.4 (1.5)	5.5	5.6
48	2.6 (0.5)	2.9	4.0	3.6 (0.7)	4.0	5.6	3.0 (0.7)	3.0	3.7	5.0 (1.3)	6.5	12.0
54	2.1 (0.4)	2.2	1.7	2.7 (0.6)	3.5	4.3	1.1 (0.5)	1.8	7.7	2.6 (0.7)	2.9	5.0
74	0.7 (0.3)	0.6	1.5	1.3 (0.5)	1.7	2.5	N.A	N.A	N.A	2.6 (1.2)	1.8	3.1
106	0.4 (0.2)	0.5	0.5	0.8 (0.2)	0.8	0.8	N.A.	N.A.	N.A.	1.2 (0.7)	1.1	1.4

( ) Standard Deviation
N.A Data not available

Table B-15. Average Field and Laboratory SI Values: Stimsonite 948

Weeks After Installation	Site 1			Site 2			Site 3			Site 4		
	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed
0	8.9 (2.4)	8.0	8.0	8.9 (2.4)	8.0	8.0	8.9 (2.4)	8.0	8.0	8.9 (2.4)	8.0	8.0
2	3.5 (1.0)	7.0	8.5	5.1 (2.7)	4.1	4.5	2.1 (0.7)	2.3	4.8	8.9 (2.5)	11.4	12.7
4	4.6 (1.0)	5.7	7.5	5.6 (1.8)	5.3	7.5	2.1 (0.5)	2.8	5.7	6.9 (1.3)	9.4	10.8
6	3.6 (1.9)	2.9	9.5	5.6 (1.4)	7.8	9.0	2.9 (1.2)	2.9	5.5	7.4 (2.1)	9.6	11.1
9	4.0 (1.6)	5.6	6.5	6.0 (1.7)	10.7	9.8	2.4 (0.3)	2.2	5.7	6.9 (0.8)	9.0	10.3
12	4.1 (1.3)	N.A	N.A	5.0 (1.3)	N.A	N.A	2.4 (0.8)	N.A	N.A	5.3 (1.3)	N.A	N.A
23	N.A	0.7	7.1	N.A	2.4	2.4	N.A	3.3	5.5	N.A	5.1	5.2
32	2.4 (0.8)	3.2	7.0	3.0 (0.8)	4.6	5.6	3.6 (1.4)	3.4	5.0	4.6 (1.3)	3.2	3.0
48	2.3 (0.6)	2.5	3.9	2.5 (1.1)	2.5	3.8	2.8 (0.6)	2.1	4.4	4.7 (1.5)	4.4	4.8
54	1.8 (0.5)	2.9	3.9	2.7 (1.0)	2.9	4.0	0.6 (0.3)	0.8	3.8	2.5 (1.0)	2.9	4.3
74	0.4 (0.1)	0.6	1.7	1.0 (0.3)	2.2	2.8	N.A	N.A	N.A	2.2 (1.7)	2.7	1.3
106	0.2 (0.2)	0.4	0.9	0.8 (0.4)	1.0	1.7	N.A.	N.A.	N.A.	0.9 (0.7)	0.7	0.9

( ) Standard Deviation
N.A Data not available

Table B-16. Average Field and Laboratory SI Values: Stimsonite 953

Weeks After Installation	Site 1			Site 2			Site 3			Site 4		
	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed
0	7.3 (1.4)	8.7	8.7	7.3 (1.4)	8.7	8.7	7.3 (1.4)	8.7	8.7	7.3 (1.4)	8.7	8.7
2	4.2 (1.4)	4.7	6.4	4.5 (2.4)	5.8	6.5	4.2 (2.1)	4.5	6.6	7.9 (0.3)	5.3	6.3
4	4.8 (0.2)	2.9	5.7	5.2 (1.6)	5.3	6.8	2.8 (0.7)	1.9	6.4	6.6 (0.8)	5.4	6.3
6	3.3 (1.0)	3.7	6.5	6.0 (0.4)	5.5	6.2	4.1 (0.9)	2.5	3.8	7.0 (0.4)	5.2	5.9
9	3.8 (0.9)	3.5	5.1	5.2 (0.4)	4.6	6.6	2.6 (0.3)	1.9	4.3	4.9 (1.1)	3.9	5.3
12	3.5 (1.2)	N.A	N.A	5.0 (0.9)	N.A	N.A	2.9 (0.4)	N.A	N.A	5.9 (1.3)	N.A	N.A
23	N.A	0.8	4.0	N.A	2.8	4.9	N.A	1.5	3.1	N.A	3.1	4.3
32	3.3 (1.2)	1.0	2.2	4.0 (1.0)	3.2	4.1	3.6 (0.7)	1.9	4.3	6.0 (1.4)	2.3	2.6
48	2.3 (0.6)	0.7	1.7	2.9 (0.8)	2.1	2.7	3.1 (0.6)	1.7	2.5	3.7 (1.6)	3.0	3.3
54	1.4 (0.4)	1.1	1.7	2.0 (0.6)	1.7	2.6	1.0 (0.3)	0.7	2.3	2.4 (0.9)	2.1	2.9
74	0.5 (0.2)	0.3	0.8	0.6 (0.3)	0.5	1.0	N.A	N.A	N.A	1.6 (0.9)	0.7	1.1
106	0.3 (0.2)	0.3	0.4	0.5 (0.3)	0.3	0.6	N.A.	N.A.	N.A.	0.9 (0.6)	0.3	0.3

( ) Standard Deviation
N.A Data not available

Table B-17. Average Field and Laboratory SI Values: Swareflex

Weeks After Installation	Site 1			Site 2			Site 3			Site 4		
	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed	Field	Lab Unwashed	Lab Washed
0	5.4 (1.0)	5.5	5.5	5.4 (1.0)	5.5	5.5	5.4 (1.0)	5.5	5.5	5.4 (1.0)	5.5	5.5
2	1.8 (0.7)	2.8	4.8	3.1 (0.8)	3.6	5.3	1.6 (0.7)	1.5	4.9	4.1 (1.8)	4.3	5.8
4	1.3 (0.2)	2.3	5.8	1.2 (0.3)	1.4	5.2	0.7 (0.2)	1.0	3.1	2.8 (0.6)	3.1	5.8
6	0.4 (0.1)	0.9	4.3	2.2 (0.1)	2.6	5.1	0.9 (0.3)	1.2	5.0	3.6 (0.5)	4.1	5.1
9	0.9 (0.1)	0.9	5.1	1.2 (0.6)	2.1	5.3	0.6 (0.2)	1.3	6.1	2.3 (0.6)	2.5	5.0
12	0.8 (0.3)	N.A	N.A	0.9 (0.2)	N.A	N.A	0.3 (0.2)	N.A	N.A	1.9 (0.4)	N.A	N.A
23	N.A	0.1	3.5	N.A	1.0	4.2	N.A	0.6	5.0	N.A	1.4	4.8
32	0.5 (0.1)	0.6	3.0	1.1 (0.4)	2.2	3.8	0.7 (0.2)	0.7	4.8	2.3 (0.6)	N.A	N.A
48	0.4 (0.1)	0.7	2.5	0.9 (0.3)	1.4	3.1	0.5 (0.1)	0.6	3.7	1.5 (0.6)	N.A	N.A
54	0.2 (0.1)	0.7	2.4	0.6 (0.2)	0.6	3.4	0.3 (0.1)	0.3	4.6	1.1 (0.6)	0.7	3.7
74	0.1 (0.0)	0.2	1.5	0.4 (0.2)	0.5	2.9	N.A	N.A	N.A	2.0 (1.0)	1.7	3.1
106	0.2 (0.0)	0.1	0.9	0.2 (0.1)	0.6	1.5	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.

( ) Standard Deviation
N.A Data not available

APPENDIX C - NON-LINEAR REGRESSION RESULTS

Table C-1. SI Value Versus Cumulative Vehicle Exposure by RRPM Type

RRPM Type	$SI = SI_{Initial} + \beta_1 Veh^a + \beta_2 (Veh - Knee^b) I^c$				
	$SI_{Initial}$	β_1	β_2	Knee	MSE
Apex 921	4.4	-74.82	74.60	0.051	1.056
Apex 918	3.5	-62.99	62.82	0.048	0.367
Apex 928	4.0	-56.06	55.83	0.059	0.479
Apex 807	1.4	-19.20	19.13	0.059	0.123
Apex 817	1.7	-4.51	4.44	0.166	1.095
Batterson	5.5	-163.25	163.15	0.032	0.245
Empco 901	2.4	-4.02	40.07	0.052	0.207
Ray-O-Lite 8704(S)	7.1	-107.47	107.06	0.056	1.382
Ray-O-Lite 8704(R)	5.3	-92.80	92.57	0.049	0.572
Ray-O-Lite 9704	9.1	-159.68	159.24	0.050	1.987
Ray-O-Lite 2002	9.3	-41.94	41.31	0.183	2.498
Ray-O-Lite 2003	9.5	-45.93	45.44	0.179	4.080
Stimsonite 88	7.1	-113.78	113.35	0.053	1.783
Stimsonite 911	9.1	-26.55	25.54	0.217	3.192
Stimsonite 948	8.9	-30.74	29.82	0.199	2.532
Stimsonite 953	7.3	-18.33	17.38	0.245	1.502
Swareflex	5.4	-88.13	87.60	0.047	0.510

[a] cumulative vehicle exposure (10^{-6})
[b] vehicle exposure level where relationship changes (10^{-6})
[c] indicator variable: I=0 if Veh < Knee, I=1 if Veh≥ Knee

Table C-2. SI Value Versus Cumulative Truck Exposure by RRPM Type

RRPM Type	$SI = SI_{Initial} + \beta_1 Trk^a + \beta_2(Trk - Knee^b) I^c$				
	$SI_{Initial}$	β_1	β_2	Knee	MSE
Apex 921	4.4	-535.80	531.20	0.007	1.195
Apex 918	3.5	-851.45	845.62	0.003	0.368
Apex 928	4.0	-856.29	847.43	0.004	0.511
Apex 807	1.4	-430.13	426.97	0.002	0.121
Apex 817	1.7	-42.97	42.39	0.019	1.191
Batterson	5.5	-2115.97	2111.72	0.002	0.212
Empco 901	2.4	-297.41	294.89	0.007	0.241
Ray-O-Lite 8704(S)	7.1	-2141.88	2131.94	0.003	1.422
Ray-O-Lite 8704(R)	5.3	-676.00	669.12	0.007	0.716
Ray-O-Lite 9704	9.1	-1155.06	1145.79	0.007	2.221
Ray-O-Lite 2002	9.3	-517.51	499.12	0.014	2.279
Ray-O-Lite 2003	9.5	-630.02	610.36	0.012	3.926
Stimsonite 88	7.1	-821.96	811.99	0.007	1.901
Stimsonite 911	9.1	-569.69	522.77	0.007	2.802
Stimsonite 948	8.9	-663.77	624.16	0.007	2.238
Stimsonite 953	7.3	-181.79	147.75	0.022	1.656
Swareflex	5.4	-1052.88	1040.82	0.004	0.598

[a] cumulative truck exposure (10^{-6})
[b] truck exposure level where relationship changes (10^{-6})
[c] indicator variable: I=0 if Trk < Knee, I=1 if Trk ≥ Knee

Table C-3. SI Value Versus Cumulative Time Exposure by RRPM Type

RRPM Type	$SI = SI_{Initial} + \beta_1 Tm^a + \beta_2 (Tm - Knee^b) I^c$				
	$SI_{Initial}$	β_1	β_2	Knee	MSE
Apex 921	4.4	-0.55	0.55	6.54	1.241
Apex 918	3.5	-0.63	0.62	4.50	0.378
Apex 928	4.0	-0.72	0.71	4.12	0.519
Apex 807	1.4	-0.40	0.40	2.48	0.115
Apex 817	1.7	-0.11	0.11	4.05	1.124
Batterson	5.5	-1.98	1.97	2.53	0.236
Empco 901	2.4	-0.77	0.76	2.45	0.214
Ray-O-Lite 8704(S)	7.1	-1.31	1.29	4.38	1.409
Ray-O-Lite 8704(R)	5.3	-1.53	1.51	2.64	0.644
Ray-O-Lite 9704	9.1	-1.65	1.63	4.47	2.218
Ray-O-Lite 2002	9.3	-0.47	0.45	16.02	2.581
Ray-O-Lite 2003	9.5	-0.52	0.50	15.66	4.177
Stimsonite 88	7.1	-1.21	1.20	4.49	1.865
Stimsonite 911	9.1	-0.55	0.50	6.36	2.913
Stimsonite 948	8.9	-0.38	0.34	13.28	2.581
Stimsonite 953	7.3	-0.24	0.19	9.97	1.686
Swareflex	5.4	-0.97	0.95	4.07	0.682

[a] cumulative time exposure (weeks since RRPM installation)
[b] time exposure level where relationship changes
[c] indicator variable: I=0 if Tm < Knee, I=1 if Tm ≥ Knee