Project No. 4-33

APPENDIX - RESEARCH LEADING TO THE DEVELOPMENT OF METHODOLOGY FOR DURABILITY ASSESSMENT OF DETECTABLE WARNING SYSTEMS

RECOMMENDED PROCEDURES FOR TESTING AND EVALUATING DETECTABLE WARNING SYSTEMS

FINAL REPORT

Prepared for
National Cooperative Highway Research Program (NCHRP)
Transportation Research Board
of
The National Academies

Thomas Rowe, Kimberly Steiner, John Lawler, and Jonah Kurth
Wiss, Janney, Elstner Associates, Inc.
Northbrook, IL
March 8, 2010

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INTRODUCTION

This appendix provides background on the methods that make up the recommended protocol for evaluating the durability of detectable warning systems. Each individual method, including the master method, is dealt with in a separate section of this appendix. Each section includes the following subsections:

- Need for Test/Exposure
- Basis for Method
    - Key Objectives
- Proposed Method
    - Summary Description of Method
    - Important Parameters of Method
    - Development Process
- Guidance in Use and Interpretation
    - Target result likely to coincide with acceptable performance

The background sections on the exposures and test methods describe physical phenomena likely to cause deterioration of detectable warning systems. Each section presents the state of practice regarding testing of detectable warning systems at the beginning of this project relative to the property considered. Each section explains the development of the method, discussing important decisions and findings during this process and presents the data collected to date using the newly developed method on a limited number of detectable warning system products. Each section also identifies key parameters that should be considered by anyone interested in performing these tests or modifying these methods. Finally, this document provides some guidance on the use of these methods and presents some preliminary discussion about the interpretation of results.

A key of objective of this project was to provide a framework for interpreting the results of testing with these methods, so that specifying agencies would be able to define benchmarks for desired performance. It is intended that the preliminary discussions about interpretation presented here form the initial step towards meeting that objective. However, the interpretations provided should be considered with care. The various mechanisms that may cause deterioration of detectable warning systems are complex and interact with one another to determine the overall durability of each product. As stated in nearly all of the discussions for each of these methods, little information is available about the performance of detectable warning systems in the field, and even less data is available relative to these newly developed test methods. For these reasons, the provided discussions should be considered as only a starting point for interpreting the results of these tests, and interpretations should be modified as experience and future knowledge permits.

With this caveat in mind, test results have been interpreted in terms of whether each test response is expected to exceed, meet, or fail to meet a criterion of “acceptable performance”. For the purposes of this project, “acceptable performance” is loosely defined as serviceable, functional and durable use within the environment represented by the selected exposure category for about five years or more.

MASTER

DURABILITY OF DETECTABLE WARNING SYSTEMS

Need for Test/Exposure

Detectable warning systems are commercially available in a wide variety of materials and are anchored in place by many different attachment mechanisms. Because of this wide variation and because some products have only been in use for short time, little information is currently available regarding the long-term durability of many systems. Any information that is available can be difficult to relate to in-place performance over the long term. Furthermore, this information has been collected using numerous different test methods, or field observation at varying locations for varying amounts of time, and the available results often do not permit unbiased comparisons between products.

For detectable warning systems to function and to serve as a safe walking surface, the following properties are essential: color contrast, slip resistance, mechanical integrity and dimensional stability. Environmental exposures and traffic-related forces may trigger a wide range of deterioration mechanisms that have a deleterious effect on these properties. These deterioration mechanisms are expected to interact, making in-service behavior difficult to predict.

Despite all these unknowns, state and municipal agencies must make selections among the available products. To support this decision, a controlled and repeatable testing method is needed to provide objective data than can be used to specify durable detectable warning systems.

Basis for Method

Much of the prior effort expended to evaluate detectable warning systems has employed one of two approaches. The first approach is based on field trials of systems installed in a setting where performance is monitored over a multi-year period. The second approach uses laboratory tests examining individual properties independently. This project was initiated to develop methods that could be implemented more quickly than field trials, would be applicable to the wide variety of detectable warning systems available, and also consider the influence of multiple properties of the systems simultaneously.

With the exception of the Evaluation of Detectable Warning Advisory Committee (EDWAC), few attempts have been made to develop laboratory testing programs to evaluate the overall performance of detectable warnings. The EDWAC program, initiated by the Division of the State Architect for the State of California, attempted to develop a laboratory test methodology to evaluate criteria specifically referenced in the state legislation (shape, colorfastness, confirmation, sound-on-cane acoustic quality, resilience, and attachment). The most recent draft of the testing protocol is incomplete, but the test methods, including conditioning regimes for outdoor and indoor use, have been developed conceptually (Evaluation of Detectable Warning Advisory Committee, 2006).

As part of separate effort, the research team participated in a laboratory study of detectable warning systems sponsored by Chicago Department of Transportation (CDOT). CDOT foresaw the need to understand long-term performance of detectable warning systems, and decided that laboratory testing could provide this information in a significantly shorter timeframe than field trials. While the report is not publicly available, the study has had a contributory role in the development of this test protocol.

Key Objectives

The key objectives in the development of the test protocol for detectable warning systems were: 1) to consider all the deterioration mechanisms significant to detectable warning systems, 2) to replicate the potential interaction of deterioration mechanisms, 3) to provide a universally-applicable method that could be used to compare all currently known product designs regardless of material or anchorage, and 4) to permit flexibility in the interpretation of the test results relative to local requirements and environmental conditions, as well as future findings. Since this test was developed to support comparisons of detectable warning system performance, repeatability of the test procedure is essential.

Proposed Method

Summary Description of Method

The protocol tests detectable warning systems installed in or applied to concrete slabs. Two types of test method are used. The first type of method is the evaluation test, which measures a specific property or quality. The evaluation tests are further characterized as non-destructive evaluation tests, which include visual and microscopic evaluation, color measurement, dome shape and geometry measurement, slip resistance; and destructive evaluation tests, which include system bond (no method finalized), coating and single dome bond, resistance to impact from a falling tup, wear resistance, and resistance to impact from a falling snow plow blade. The second type of method is the exposure regime, which simulates the effects of in-service exposure but do not include an evaluation phase. The evaluation tests are use to quantify the effects of the exposure regimes. The exposure regimes consist of freeze/thaw, high temperature thermal cycling, ultraviolet light exposure, and abrasion exposure.

The execution of the test protocol requires preparation of two detectable warning system/concrete slab specimens for each product in a manner that replicates the manufacturer's recommended procedures. The non-destructive evaluation tests are then performed on these unexposed samples. (Optionally, the destructive evaluation tests can also be performed on unexposed samples, but this requires additional slab specimens.) The samples are then subjected to four cycles of the exposure regimes, with each cycle consisting of one quarter of the full exposure duration. At the conclusion of the exposure cycles, all the evaluation tests are used to assess durability and performance of the detectable warning systems.

The details of exposure regimes are determined by the exposure category, which is selected by the user based on anticipated environmental conditions where the detectable warning system will be used. Two categories, designated "Hot" and "Cold", are available and are intended to represent the environmental extremes observed in the United States. For the Hot exposure category, the duration of the ultraviolet exposure is greater, the maximum temperature defining the high-temperature thermal cycling test is higher, and the freeze/thaw exposure and resistance to impact from simulated snow plow blade evaluation test are not included. The test methods for each exposure category are given in Table A1. The full exposure durations for each category are outlined in Table A2.

Table A1. Test methods for exposure categories

Test Method	Hot Exposure Category	Cold Exposure Category
Non-destructive Evaluation Test		
Visual and Microscopic Evaluation	Yes	Yes
Dome Shape and Geometry Measurement	Yes	Yes
Color Measurement	Yes	Yes
Slip Resistance	Yes	Yes
Destructive Evaluation Test		
Coating and Single Dome Bond	Yes	Yes
Resistance to Impact from Falling Tup	Yes	Yes
Wear Resistance	Yes	Yes
Resistance to Impact from Simulated Snow Plow Blade	No	Yes
System Bond	Yes*	Yes*
Exposure Regimes		
Freeze/Thaw	No	Yes
High-Temperature Thermal Cycling	Yes	Yes
Ultraviolet Light Exposure	Yes	Yes
Abrasion Exposure	Yes	Yes

* No method finalized

Table A2. Exposure duration for exposure categories

Exposure Regime	Hot Exposure Category	Cold Exposure Category
Freeze/Thaw	(None)	60 cycles
High-Temperature Thermal Cycling	60 cycles 25-93ºC (77–200°F)	60 cycles 25-77ºC (77–170°F)
Ultraviolet Light Exposure	1500 hrs	1000 hrs
Abrasion Exposure	16 passes	16 passes

This method has been designated Designation: Draft T4-33, Master *Recommended Method of Test for Durability of Detectable Warning Systems.*

Important Parameters of Method

The important parameters of the method include:

- Test of detectable warning/concrete performance - Since the durability of the detectable warning system sample is directly influenced by interactions with the substrate, it is essential that the system be attached to concrete in a manner representative of actual installations.
- Specimen size - Given that it is important to test the combination of the detectable warning system and concrete substrate, two other parameters must be considered:
    - Detectable warning dimensions - Aside from paver-based systems, which may consist of units as small in area as 30 x 30 cm (1 x 1 ft), the typical dimensions of the smallest commercially available unit of detectable warning system is 61 x 61 cm (2 x 2 ft). Each of these units forms a complete system, and often include: 1) anchorage features that combine to fix the system to the substrate and 2) edge feature around of the perimeter,

such as edges that project down into the concrete substrate or taper to a sealant joint. To evaluate the effect, which may be significant, that the anchorage and perimeter edge may have on the performance, it is important that the systems be tested intact, as supplied by the manufacturer, rather than cut to size. This size also provides sufficient surface area for suitable testing.

  - Concrete slab - It is vital that the concrete slab supporting the detectable warning be large enough so that the interaction of the system with the substrate is representative of systems installed in or on sidewalks. The sample must also be sufficiently sized so that sample fabrication closely replicates the field installation process. However, larger slabs are more cumbersome to work with and may require hoists or forklifts to move. The size selected (86 x 86 cm by 14 cm deep [34 x 34 inches in size by 5½ inches deep]) was chosen to allow the typical unit to be installed without protruding features of the detectable warning systems, such as anchors, contacting the bottom of the forms and without requiring consolidation processes not typically used for sidewalk construction.
- Deterioration mechanisms considered - Many things can limit the durability of detectable warning systems. It was a key goal of this protocol to represent the primary deterioration mechanisms thought to be significant to the durability of the systems, and an agency survey and extensive literature reviews were conducted to identify the mechanisms to be included. However, if, in the future, a greater understanding of the relevant mechanisms is achieved, then any newly identified mechanisms should be added to this protocol.
- Represented Environmental Conditions - Detectable warning systems can be exposed to a wide range in environmental, traffic and service conditions throughout the United States.
- Uniformity of test protocol for all detectable warning system types - During the testing methodology development, the many variations of materials, textures and attachment mechanisms as well as the potential variety of exposure conditions were considered. The test protocol was developed to be capable of providing universally applicable information about the durability of any detectable warning system product. This protocol is also highly adaptable, since great flexibility in the interpretation of the test results is possible.
- Combined Exposure Parameters - Three parameters must be considered when defining how the exposure test methods are combined:
  - Cycling process - The exposure regimes are cycled in the protocol to simulate field conditions where different types of exposures occur simultaneously or in sequence. A large number of cycles of each exposure would more closely represent simultaneous exposure but would require frequent handling of the large samples. In an attempt to limit the amount of handling required, four cycles have been selected for use.
  - Order of testing - It is uncertain whether the order of the exposure regimes will have a significant effect on sample response, though such an effect could be envisioned. For example, the first exposure regime will act on samples that have seen the other exposure regimes only three times, while the last will act on samples that have seen all the other regimes four times. Therefore, while the order of testing was selected arbitrarily for this protocol because the effect of the cycle order is unknown, the order specified in the method should be conscientiously followed.
  - Duration of Exposures - The severity of the exposure tests are governed by their duration. The durations selected must balance the needs to complete testing in a finite amount of

time and to adequately simulate field conditions. It is also important that the exposure duration represents realistic expectations regarding the anticipated service life of these systems.

Development Process

The testing protocol consists of numerous individual test methods, and the development process for each of those is discussed separately in the other sections of this appendix. This discussion provided here reviews the development process related to combining these methods.

The test protocol concept to incorporate cyclic exposure regimes followed by evaluation tests was conceived based on the key objectives outlined above and considering the input of specifying agencies and the progress made previously by the research team and others towards laboratory testing of detectable warning systems. This protocol was further refined based on testing conducted during this project.

The climatic conditions that detectable warnings might see throughout the United States were reviewed. Because the applicable degradation mechanisms vary with climate, two generalized climate exposure categories were identified: Hot and Cold. The conditions represented by the hot and cold exposure categories are presented in Table A3. These exposure categories are not intended to specifically represent the climate in any one area, rather they are intended to divide the exposures among areas experiencing frequent freezing and snowfall from those that experience only infrequent freezing but higher maximum temperatures.

Table A3. Climatic exposure categories and conditions

Climatic property	Cold	Hot
Winter freezing and snowfall	frequent	rare
Summer high temperatures	27 - 38 ºC (80 - 100°F)	>38 ºC (>100°F)
UV intensity	moderate	high

This testing conducted during protocol development was focused on concrete test slabs with detectable warning systems installed or applied to them. These slabs were then used to refine the exposure regimes and evaluation tests. Seven detectable warning systems were selected for inclusion (see Table A4) to represent the variety of types of systems commonly specified, as well as the breadth of system types commercially available. Various detectable warning systems have been selected to ensure that the testing protocol is broad enough to meet future changes in material or system availability.

Table A4. Specimen types

Material Type	Installation Method
Rigid polymer composite panel	Cast-in-place
Rigid polymer composite panel	Surface applied
Flexible polymer panel	Surface applied
Metal panel	Cast-in-place
Polymer concrete panel	Cast-in-place
Single domes	Surface applied
Precast concrete paver	Paver--thin set mortar

The concrete slabs were 86 x 86 cm by 14 cm deep (34 x 34 inches in size by 5½ inches deep). The concrete was reinforced with wire mesh near the bottom and rebar along the sides to maintain integrity. The concrete mixture was based on the local state agency’s mix for sidewalks (IDOT 1020 SI class) and contained 359 kg cement/m^3 (605 lbs. cement/yd^3), was air entrained, and had a specified strength of 24.1 MPa (3500 psi) at 14 days. The measured properties of the two batches of concrete used to fabricate the specimens are given in Table A5.

Table A5. Properties of Concrete Mixture

Tested Property	Test Method	Measured Property: Batch 1 / Batch 2
Slump, mm (in)	ASTM C143	100/125 (4/5)
Temperature, ºC (°F)	ASTM C1064	19/24 (66/75)
Air content, %	ASTM C231	8.2/6.0
Unit Weight, kg/m^3 (lbs/ft^3)	ASTM C138	2238/2300 (139.4/143.3)
Strength at 7 days , MPa (psi)	ASTM C39	27.4/34.5 (3970/5010)
Strength at 14 days , MPa (psi)	ASTM C39	31.0/38.0 (4500/5510)
Strength at 28 days , MPa (psi)	ASTM C39	32.8/39.4 (4760/5710)

Cast-in-place samples were installed into fresh concrete in the forms. For the pavers, a recess was formed in the concrete, and the pavers were adhered with a thin-set mortar after the concrete cured. For the surface applied systems, bare slabs were fabricated, the concrete was allowed to cure, and then the surface was prepared and the detectable warning system applied according to the manufacturer's instructions. Because several exposure and performance evaluation test methods require measurement of temperature, thermocouples were embedded in the slab. Manufacturer's representatives were invited to provide supervision of the installation process. One manufacturer's representative was unable to attend because of a scheduling conflict, but provided email feedback and written instructions.

Photographs of the casting process are provided in Figure A1 and Figure A2. Figure A3 and Figure A4 are photographs showing the process of installing two surface applied systems. Slabs with a nominally 50 mm (2-inch) deep void blocked out in the center were fabricated for the pavers. The pavers were installed after the concrete was cured for 28 days (Figure A5).

Subsequent to the slab sample preparation, these samples were used for development of the individual exposure regimes and evaluation tests. Each of these tests for which a standard method is recommended, and one test for which no method was finalized (system bond), is discussed separately in this Appendix. However, evaluation tests of number of other properties were considered and ultimately discarded. These were: chemical resistance, cyclic concentrated loading, condensation, water absorption, hardness, flame spread, flexural strength, compressive strength, coefficient of restitution, and acoustic quality. Of these methods, only the chemical resistance test was attempted as an evaluation test during this project. Chemical resistance testing was abandoned because no noticeable deterioration resulted from exposure to the group of chemicals identified for this test as being possible contaminants in sidewalk applications. The other tests were rejected for a number of reasons, including because these tests are component rather than system tests, because the properties indicated are considered more completely by the test methods that have been adopted, because the tested property is not relevant to the performance of the detectable warning system, or because the test for evaluating that property is not valuable for comparing detectable warning products.

Guidance in Use and Interpretation

A procedure for determining an overall rating of the detectable warning system performance was developed. This procedure is based on calculating the geometric mean of ratings for each evaluation test result based on whether that response is expected to meet a criterion of "acceptable performance". The geometric mean was selected over the arithmetic mean because a rating of "not likely to produce acceptable performance" for any test would eliminate that particular product from consideration. No industry-accepted or time-proven guidance has been developed for the interpretation of test results and prediction of in-service performance. The research team has applied judgment in evaluating the absolute and relative test data to determine these ratings. It is emphasized that the accuracy of the research team's judgment must be considered highly approximate, since these test methods are newly developed and this protocol has not been compared to a systematic study of the performance of detectable warnings in service.

A primary objective of this development process was a universally applicable set of methods that would provide sufficient, objective, and valuable information to allow the test protocol results to be interpreted relative to the needs of each agency. It is envisioned that raw test results (without interpretation) obtained during testing programs conducted at the direction of product suppliers could be shared among multiple agencies. However, for the test data to have universal application, it is important that the test protocols be strictly reproduced. Furthermore, to allow each agency to consider their own needs, the interpretation of the test results for a given product should be modified by that agency to suit the intended application.

Target result likely to coincide with acceptable performance

No definition of acceptable performance is possible, based on the proposed combination scheme. Instead, a determination of acceptable performance must be made based on the results of the individual test methods.

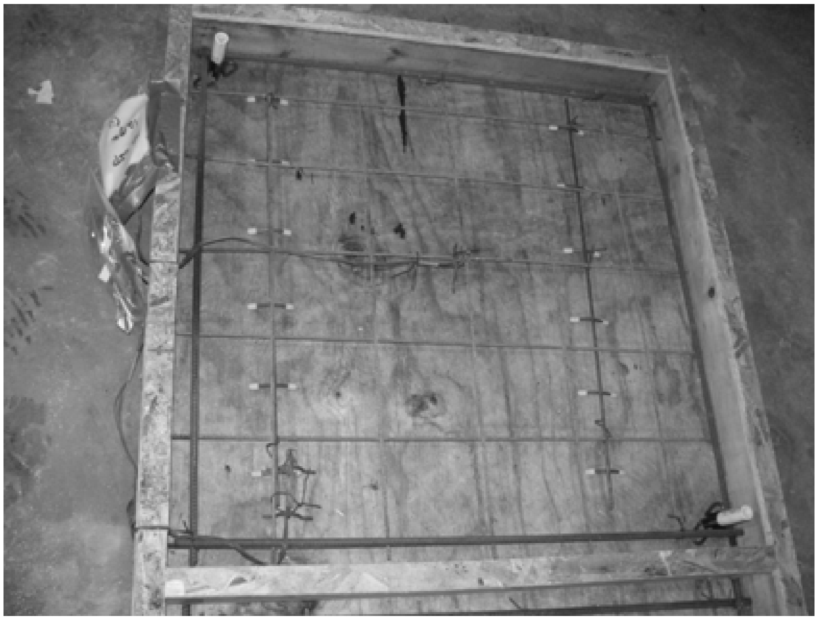


Figure A1. Form used for a cast-in-place specimen. Thermocouples have been placed in the forms.

Figure A2. Placing the cast-in-place metal samples.

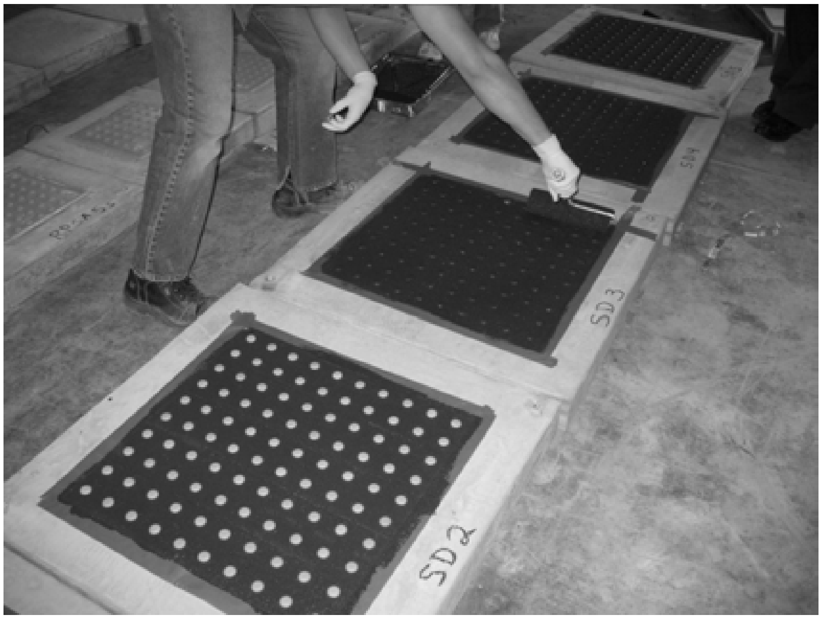


Figure A3. Installing the surface applied single domes.

Figure A4. Installing surface applied rigid polymer composite sample. Adhesive is being applied to the underside of the specimen

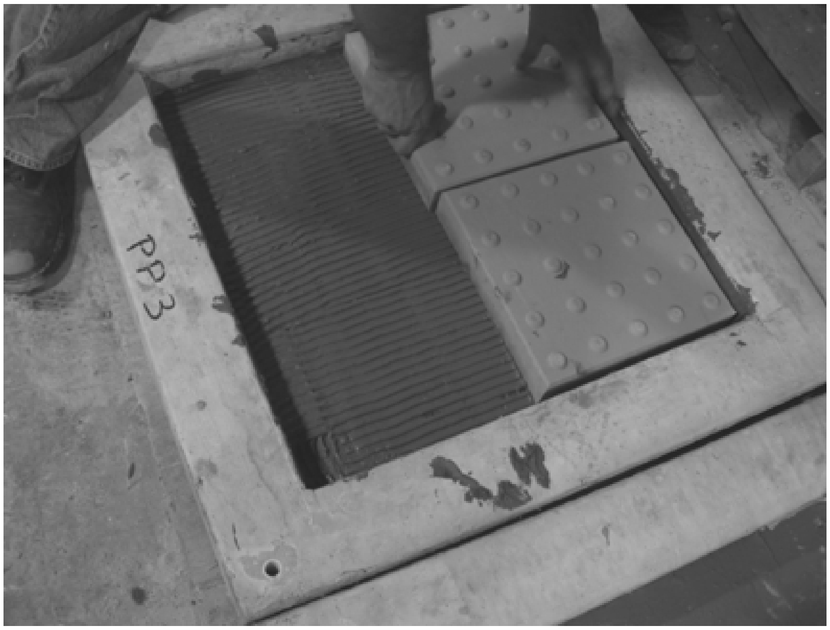


Figure A5. Installing precast concrete paver system. Concrete slab was blocked out to form the area for the pavers, which were applied with thin set mortar.

PART 1

FREEZE/THAW DURABILITY OF DETECTABLE WARNING SYSTEMS

Need for Test/Exposure

Freezing and thawing is of concern in much of the country, with the exception primarily southern locations. Freezing and thawing can have multiple effects on detectable warning systems.

Water goes through a volumetric expansion upon freezing, and water that penetrates into pores in detectable warning materials and subsequently freezes can cause cracking and degradation of the detectable warning system. Water that penetrates beneath the detectable warning system into any gaps or pockets between the concrete and the detectable warning system can disrupt anchorages, locally raise or jack the system, and cause other distress as the water expands upon freezing.

Different coefficients of thermal expansion of the detectable warning system materials and surrounding concrete can cause potential distress to both materials due to cyclic freezing and thawing. Because the detectable warning systems (with the exception of surface applied systems) are generally thinner and weaker than the constraining sidewalk concrete, it is expected that most damage related to defects of differential thermal movement will occur within the detectable warning systems.

In addition, ice and snow on sidewalks are often removed by the application of de-icing salts. This exposure to deicing salts can cause corrosion of metallic materials or distress in porous detectible warning system materials.

Basis for Method

Many standard test methods are available for testing freeze/thaw resistance of materials. Each method has been developed for a particular type of material, and each test is essentially a component, rather than system, test. Manufacturers of detectable warning systems reference some of these tests, but the test referenced depends on the type of material tested. The tests referenced in a survey of detectable warning system manufacturer’s product literature are:

- ASTM C666 *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing*
- ASTM C1262 *Standard Test Method for Evaluating the Freeze-Thaw Durability of Manufactured Concrete Masonry Units and Related Concrete Units*
- ASTM D1037 *Standard Test Method for Evaluating Properties of Wood-Base Fiber and Particle Panel Materials*
- ASTM C1026 *Standard Test Method for Measuring the Resistance of Ceramic Tile to Freeze-Thaw Cycling*
- ASTM C67 *Standard Test Method for Sampling and Testing Brick and Structural Clay Tile*
- ASTM D5860 *Standard Test method for Evaluation of the Effect of Water Repellent Treatments on Freeze-Thaw Resistance of Hydraulic Cement Mortar Specimens*
- ASTM C672 *Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals*

All of the existing standard tests used by detectable warning system manufacturers are component tests, i.e., tests focusing on representative samples of the material, rather than the material in combination with a substrate or surrounding material. While it is important that the components of the detectable warning systems withstand repeated freezing and thawing, an actual in situ system will be constrained by the anchorage to the sidewalk. For this reason, testing of the composite system consisting of the detectable warning system representatively installed within surrounding concrete is considered essential for the evaluation of detectable warning systems.

Key Objectives

The key objectives in the development of the freeze/thaw resistance test were: 1) to attempt to recreate conditions that occur in colder climates that might cause freeze/thaw damage in susceptible concrete/detectable warning systems, 2) to expose the samples to de-icing chemicals that might be used to clear snow and ice from sidewalks, and 3) to assure the test methodology is repeatable. Since this test protocol was developed to support comparisons of detectable warning system performance, repeatability of the test procedure is essential.

Proposed Method

Summary Description of Method

The proposed method consists of a freeze/thaw test where the concrete/detectable warning system samples are ponded or submerged in sodium chloride solution and subjected to repeated freezing and thawing cycles. The entire top surface of the specimen is ponded or submersed for the full duration of the test, to allow water to penetrate around any attachments, gaps, or cracks in the detectable warning system/concrete composite system. Water that freezes underneath the detectable warning system may lead to a phenomenon known as "freeze-jacking," whereby upheaval, cracking or distortion of the detectable warning system occurs as the water volume expands during the freezing process.

During the test, the system is held below freezing until the solution ponded on top of the detectable warning system has frozen completely. The samples are then held at a thawing temperature until the solution has completely thawed. This freeze/thaw cycle is repeated for a total of sixty times; fifteen times for each exposure cycle of in the test protocol.

This is an exposure, rather than evaluation test, so no evaluation protocol is required as part of the test method. Each detectable warning system type is tested in duplicate. The freeze/thaw resistance test is not intended to be conducted to evaluate performance in the Hot Exposure Category.

This method has been designated Draft T4-33, Part 1 *Recommended Method of Test for Freeze/Thaw Durability of Detectable Warning Systems*.

Important Parameters of Method

The important parameters of the method include:

- Test of detectable warning/concrete performance - Since the response of the system is critical to measuring freeze/thaw durability, this test is performed on the detectable warning system/concrete composite system only, not on individual components.
- Deicing salt solution - A 3 percent sodium chloride solution is described in the test method, in order to represent the most commonly used deicing salt. Exposure to chlorides will promote corrosion in some metallic systems. The use of a deicing salt, compared to plain tap water, depresses the freezing point of the water a few degrees, so this needs to be accounted for when setting the temperature of the freezing chamber.

- Temperature - Complete freezing and thawing of the ponded solution is important for producing conditions which may lead to degradation of the detectable warning system/concrete system. If the ponded solution is kept frozen and thawed for at least 30 minutes, as outlined in the test method, any solution that penetrated to underneath the detectable warning system is expected also to freeze and thaw.

Development Process

The freeze/thaw resistance test is based on similar ponding and cyclic freezing tests commonly employed for other construction materials. One challenge was the development of a system to maintain a pond of the liquid salt solution on the surface of the detectable warning system/concrete composite system. Several schemes were trialed, and the research team ultimately constructed containers from plywood, and lined them with sheet rubber to form a water-impermeable system into which a full size detectible warning system/concrete specimen was placed. This method produced a suitable container, but occasional tears in the rubber liner produced some leaks. Fewer leaks would be anticipated with single-material water proof containers, such as plastic or stainless steel containers. In addition to optimizing containers, it was apparent that relatively tight-fitting lids were required to retard evaporation during the thaw cycles. Excessive evaporation can lead to reduced liquid levels in the sample, and possibly to corresponding changes in concentration of the salt solution, potentially affecting freezing point.

Selection of the optimum temperature conditions to ensure complete freezing and thawing, while keeping the cycle time as short as possible was another part of the development process. The research team used a large thermal cycling chamber to perform the freezing and thawing. The freezing temperature was optimized to an ambient temperature of -23ºC (-10°F), and the thawing temperature was optimized to an ambient temperature of 24ºC (75°F) (but not more than 29ºC [85°F]) in order to achieve freezing and thawing of the ponding solution in a reasonable amount of time (approximately 11 hours per cycle for the chamber used and the number of samples tested at one time). Temperature at the surface and within some concrete slabs was measured at various locations (1, 2, and 3 inches below the surface in the center of the slab, and 1, 2, and 3 inches below the surface about 2 to 3 inches from an edge) to assess temperature distributions during temperature cycling. As seen in Figure A6, the temperature difference between the center and side of the slab was less than 6ºC (10ºF) at all times. Therefore, the slab temperature ranged between approximately -7 and 7ºC (20 and 45°F). Temperature of the solution and concrete slab 2 inches below the top at the center was also measured to evaluate differences in concrete temperature and solution temperature (Figure A7). The temperature of the concrete slab (measured 2 inches from the top at the center) and the solution were similar, with the exception of a period of essentially isothermal behavior as the solution froze or thawed.

Sixty total freeze/thaw cycles was chosen based on previous experience with freeze/thaw testing of similar detectible warning systems, as well as optimizing the duration of the overall test. While additional cycles may provide a further assessment of durability, sixty cycles of hard freezing and thawing at the pavement level represents multiple years worth of cycles in many locations.

Guidance in Use and Interpretation

This test is an exposure test, and no evaluation is included in the method. Therefore, no guidance on interpretation is required.

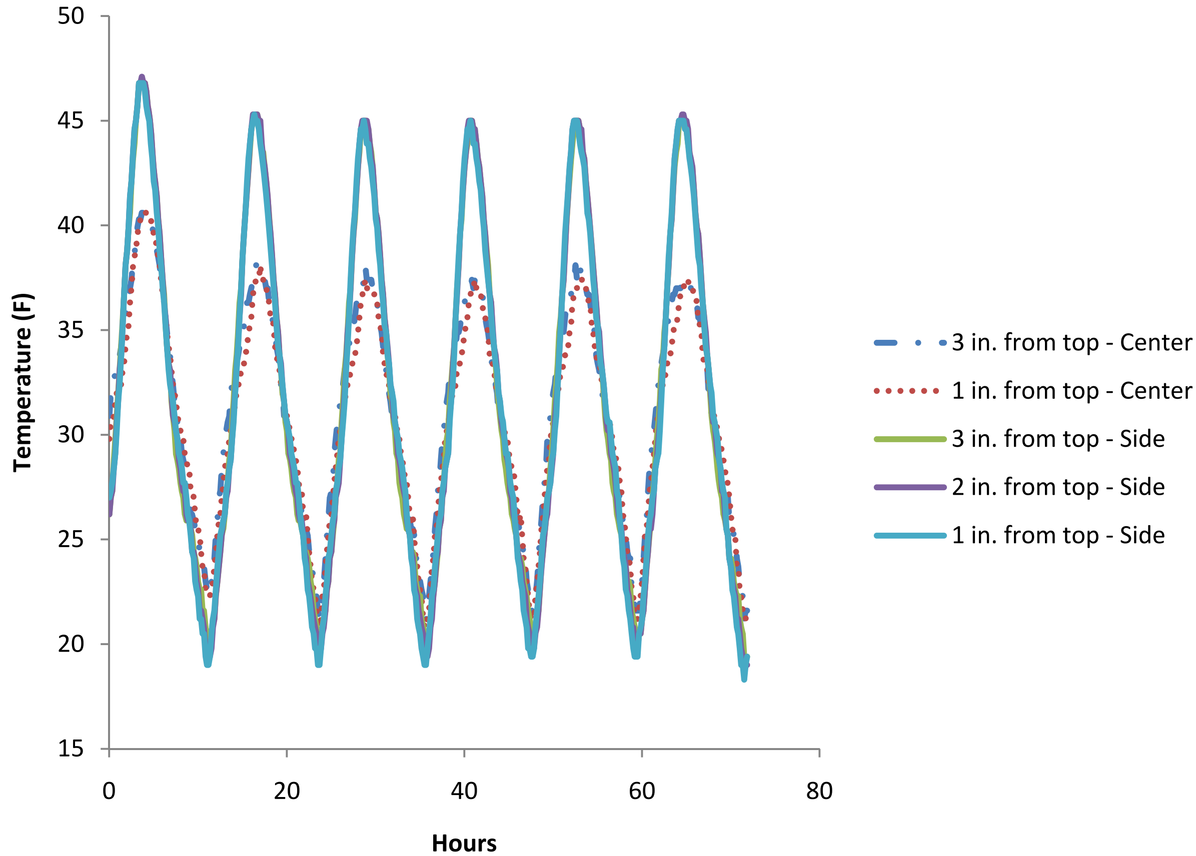


Figure A6. Plot of the internal temperature of the concrete slab at the center and near the side, indicating a temperature differential of fewer than ten degrees from the side to the center, and essentially no temperature difference through the thickness.

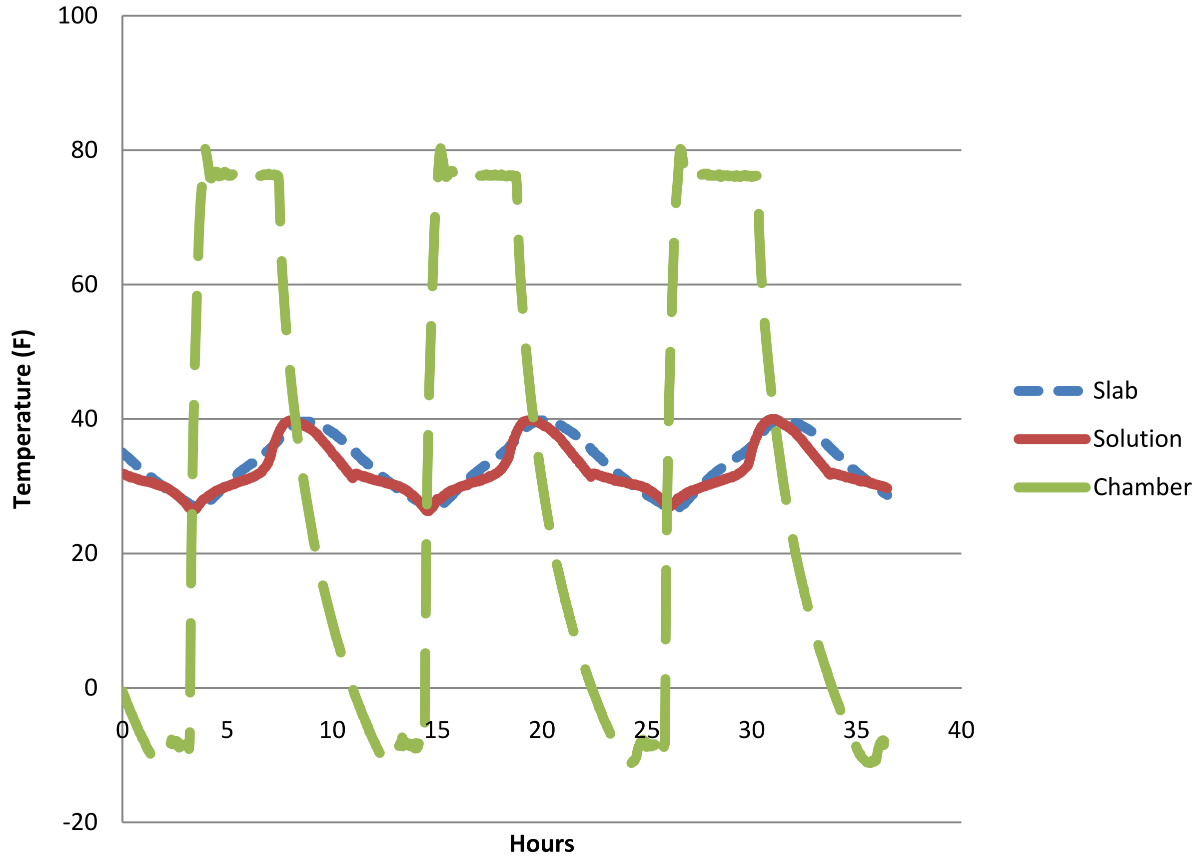


Figure A7. Plot of the internal temperature of the concrete slab, temperature of the ponding solution, and ambient temperature of the chamber.

PART 2

HIGH TEMPERATURE THERMAL CYCLING OF DETECTABLE WARNING SYSTEMS

Need for Test/Exposure

Thermal cycling occurs during temperature fluctuations, such as from day to night or from seasonal variations. Detectable warning systems may be subjected to restraint-related cracking as a result of differential thermal expansion of the detectable warning system and the concrete sidewalk. High temperatures induced by radiant exposure can soften some polymeric materials, causing deformation or making them susceptible to other deterioration mechanisms. High temperatures can also cause degradation and softening of adhesives used on surface applied systems, leading to deformation. Repeated thermal stresses also have the potential to cause fatigue damage. For these reasons, it is important to evaluate the response of detectable warning systems fixed to a concrete substrate when subjected to thermal cycling.

Basis for Method

Various methods have been established to test material response to cyclical thermal changes. However, many of these methods relate to testing freezing and thawing durability. Freezing and thawing tests generally do not evaluate the effects of thermal cycling at elevated temperatures and rarely consider the interaction between a product and the substrate to which it is anchored. To evaluate the response of detectable warning systems to thermal cycling, consideration of the substrate is essential. A brief summary of the temperature range and number of heating and cooling cycles used by some ASTM methods is shown in Table A6. The test method developed for use in Draft T4-33, Master *Recommended Method of Test for Durability of Detectable Warning Systems* is intended to simulate degradation from fluctuations from surface temperatures above freezing to maximum surface temperatures that might occur on hot, sunny summer days.

Table A6. Existing cyclical thermal testing methods

Test method	Temperature range	Number of cycles
ASTM D 1037 *Standard Test Method for Evaluating Properties of Wood-Base Fiber and Particle Panel*	Freeze, thaw, and water steam	6
ASTM C 666 *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing*	-18 °C to 4 °C [0°F to 40°F]	300
ASTM C 1026 *Standard Test Method for Measuring the Resistance of Ceramic Tile to Freeze-Thaw Cycling*	-18 °C to 16 °C [0°F to 60°F]	15

Key Objectives

The key objective in the development of the high temperature thermal cycling test was to simulate the effects of cyclical variation in temperatures on detectable warning systems fixed to a concrete substrate in a laboratory setting using a control cycle defined independently of system characteristics. Since this test protocol was developed to support comparisons of detectable warning system performance, repeatability of the test procedure is essential.

Proposed Method

Summary Description of Method

Detectable warning systems are subjected to thermal cycling between specified temperatures, with the maximum temperature varied based on the exposure conditioning category. To produce conditions that may initiate deterioration, the durations and temperatures of the thermal cycle are designed to produce significant temperature differences between the detectable warning system and the concrete substrate. Specimens are irradiated with heat lamps to provide surface heating. The exposure is controlled based on insulated black panel thermometers, allowing the irradiation to be controlled independently of the detectable warning system properties. After the heating cycle, the specimens are cooled with flowing water, which produces a thermal shock and exposes the materials to moisture.

The basic test cycle, which is repeated a number of times based on the exposure conditioning category, consists of the following steps:

- Ramp - Heat the specimen until an insulated black panel thermometer placed on the surface of the specimen reaches the desired maximum temperature, which is 93°C (200°F) for the hot exposure category and 77°C (170°F) for the cold exposure category. This heating must be performed within a set time period.
- Soak - Maintain the temperature of the insulated black panel thermometer for a set time period.
- Cool - Cool the specimen until the central thermocouple embedded in the concrete reaches a baseline temperature of 25°C (77°F). After this temperature is reached, the cycle repeats.

Photos of test equipment are provided in Figure A8 through Figure A10.

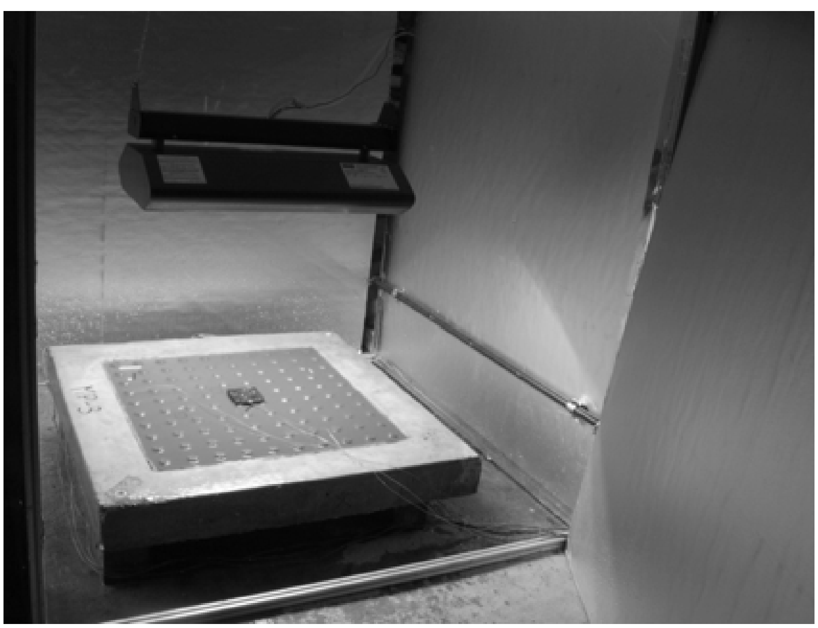


Figure A8. Enclosure and sample under heating (ramp) portion of test cycle.

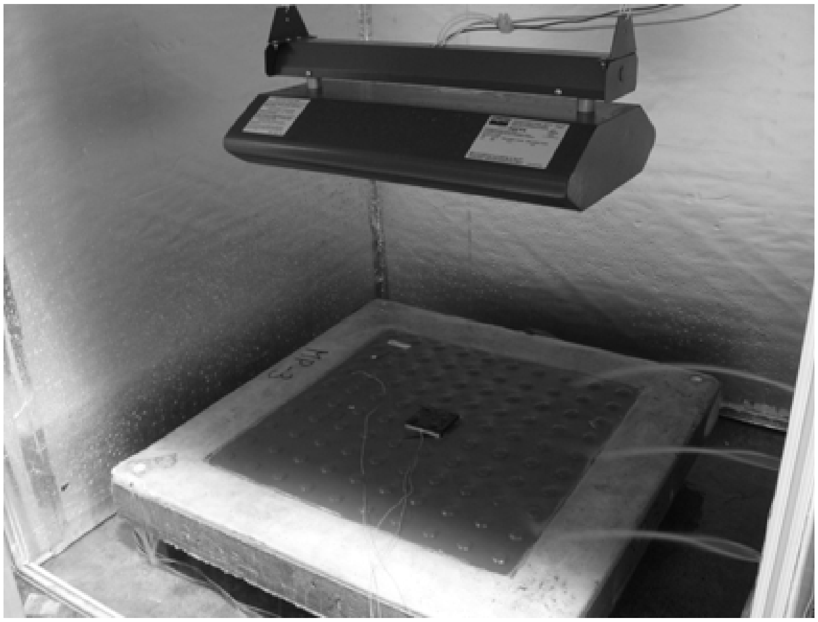


Figure A9. Enclosure and sample under cooling portion of test cycle. Note the sheet of water draining to the left on the sample surface.

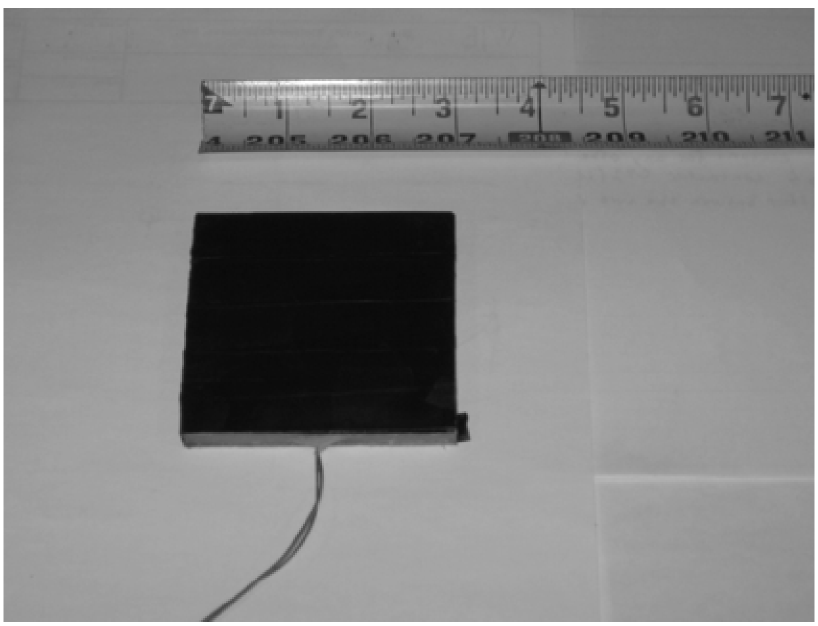


Figure A10. Insulated black panel thermometer used for surface temperature evaluation.

This method has been designated Draft T4-33, Part 2 *Recommended Method of Test for High Temperature Thermal Cycling of Detectable Warning Systems.*

Important Parameters of Method

The important parameters of the method include:

- Test of detectable warning/concrete performance - Since the response of the detectable warning system sample to the thermal cycling process is directly influenced by the manner by which it is fixed to the concrete substrate, it is essential that the system configuration be representative of actual installations.
- Infrared radiation flux (ramp) - The rate of heating influences the severity of the temperature gradient through the depth of the sample and dictates the amount of time that the specimen has to adjust to thermal strains, through creep and other mechanisms. More rapid heating is expected to produce greater deterioration. To ensure that heating rate is uniform across testing facilities, the temperature of the black panel thermometer should be raised to the test temperature within a controlled amount of time.
- Maximum test temperature (soak) - The maximum temperature of the insulated black panel thermometer during the test is designed to be representative of the temperature measured by an insulated black panel thermometer placed on a detectable warning system field installation at peak solar radiation in the climate represented by the exposure category. The difference in maximum temperature between the hot and cold exposure categories may impact both the type and severity of deterioration mechanisms. For example, an epoxy adhesive's glass transition temperature may be greater than the cold exposure maximum temperature but less than the hot exposure maximum temperature.
- Water flow rate (cool) - Like the rate of heating, the rate of cooling dictates the temperature gradient and the amount of time that the specimen has to adjust to thermal strains. More rapid cooling is expected to produce greater deterioration. The cooling consists of a uniform sheet of water flowing across the surface of the specimen in a controlled manner that does not result in water spray impacting the heating elements and is designed to produce a rapid and repeatable cooling process.
- Heat uniformity - Temperature at both the center and the corners of the detectable warning system are measured to ensure that the primary thermal differences occur between the detectable warning specimen and the substrate. A highly non-uniform heat distribution on the surface plane of the specimen would produce a less severe exposure and thermal stresses that are not likely to occur in installed systems. The heating gradient produced during this exposure is intended to be from the top to the bottom of the specimen.

Development Process

The exposure test was developed with the goal of creating a repeatable thermal cycle, simulating daily temperature fluctuations. The number of cycles for the test method was chosen to be consistent with the number of cycles typically used in cyclic freeze/thaw testing, another test in which conditions that may result in exposure-related deterioration are simulated. Each thermal cycle is split into ramp, soak, and cool phases. These phases are typical for digital controllers that are widely available for laboratory use. For this test method, a programmable logic controller was used.

The test method was designed to create consistent exposure conditions, independent of the characteristics of the detectable warning system. During development of the test chamber, temperatures were initially measured with thermocouples at eight locations. Three thermocouples at three depths in the slab were placed in both the corner and the center of the concrete substrate. Two measurements were taken initially by thermocouples taped on the specimen surface. Initial testing showed that the temperature readings of thermocouples on the sample surface varied between different detectable warning systems under the same exposure intensity and duration. This was due to the difference in detectable warning systems thermal emissivity, which varies for each product. Thermal emissivity describes the radiation or absorption quality of surfaces and is influenced by the surface's color and finish (dullness). To create an independent measure of surface temperature, insulated black panel thermometers, referenced in ASTM G 151-06 *Standard Practice for Exposing Nonmetallic Materials in Accelerated Test Devices that Use Laboratory Light Sources*, are used. The black panel thermometers allow the irradiation each sample receives, which defines the exposure, to be controlled at a consistent level regardless of the materials tested. While the actual surface temperature of the detectable warning system is expected to vary in this test, similar surface temperature variations would be expected in field installations depending on the characteristics of the detectable warning systems.

During the development of the test equipment, the duration for the ramp phase was determined by the power output of the heat source when in a constantly "on" condition and distance to the specimen surface. The most important parameters to obtaining uniform heating were determined to be the physical dimensions of the heat source and the distance from the heat source to the specimen surface. The digital controller used time-proportional control to produce the appropriate heat output to keep the reading of the black panel thermometers at the desired soak temperatures. A 3200 Watt (11,000 Btu/hr) infrared heater with quartz tube heating elements approximately 500 mm (20 inches) above the surface of the specimen provided an acceptable heat source for the test. In general, larger and more powerful heat sources provide quicker ramp durations and more uniform specimen heating.

The maximum temperature for the hot exposure category (93°C [200°F]) was chosen to heat the interface between the detectable warning system and concrete substrate to approximately 71°C [160°F]. This temperature is above the glass transition temperature of some adhesive epoxies. Previous research indicates that mid-summer temperatures can reach as high as 71°C [160°F] on the surface of asphalt parking lots in the southwestern United States (Celestian & Martin, 2004). The maximum test temperature of 93°C [200°F] was chosen because an insulated black panel temperature may be 3 to 12°C [5 to 22°F] higher than a high emissivity material subjected to the same irradiation. The soak duration was chosen based on the amount of time required for the concrete substrate to begin to warm to approximately 40°C [100°F].

The end of the cooling process is defined based on the temperature at the interior of the specimen. Interior temperatures are monitored by thermocouples placed both below the surface of the detectable warning system and in interior of the specimen. This effectively "resets" of detectable warning systems to the same temperature at the conclusion of each cycle. The cooling cycle is a based on a uniform sheet of water flowing over the surface of the specimen, without resulting in significant splashing or spray. Note that water spray contacting the hot heating elements could result in heating lamp failure. Tap water from a municipal supply provided a steady pressure and temperature for the test development.

Figure A11 shows three cycles of heating and cooling using this test method. Note the much more rapid increase in the surface temperature compared to the internal temperature during the ramp portion of the cycle. During the soak phase, the internal temperature of the concrete increases over time, even as the surface temperature of the specimen remains fairly constant. Also note the first cycle interior temperatures are slightly lower, because the specimen starts at a temperature less than 25°C [77°F].

Guidance in Use and Interpretation

This test is an exposure test, and no evaluation is included in the method. Therefore, no guidance on interpretation of results is provided.

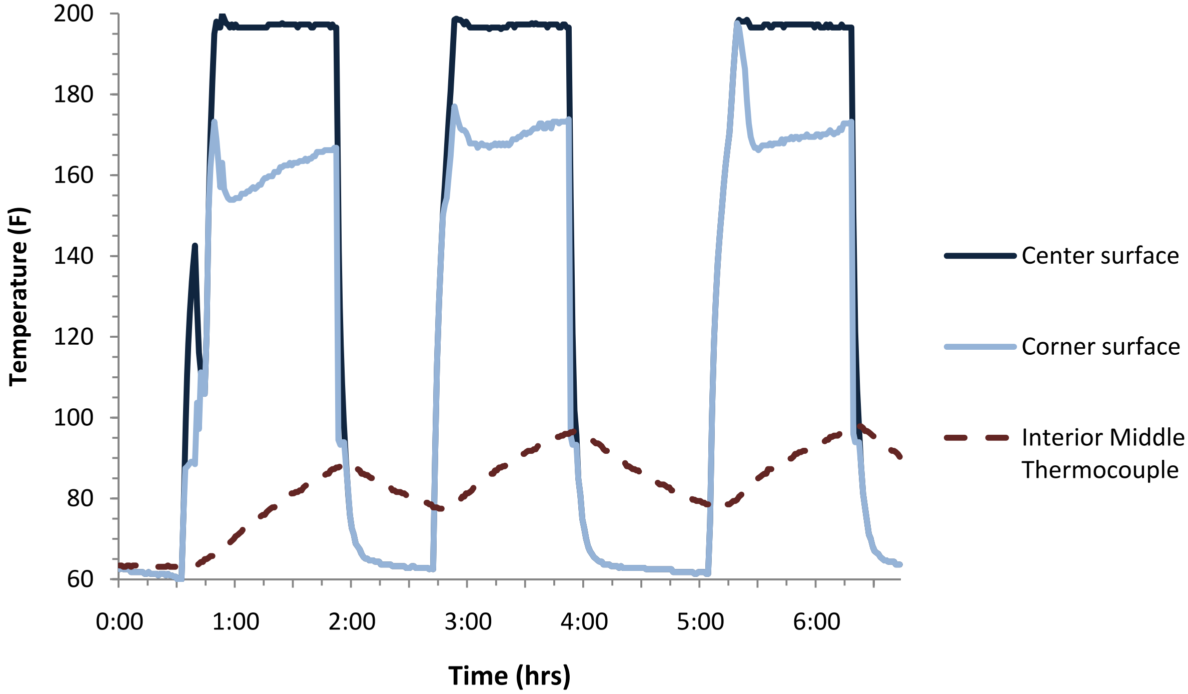


Figure A11. Sample high temperature thermal cycle readings. Note that the center surface temperature is near steady, because the digital control is based on this reading. The corner temperature tends to fluctuate slightly as the internal temperature, measured by the interior middle thermocouple, of the slab increases.

PART 3

ULTRAVIOLET LIGHT EXPOSURE OF DETECTABLE WARNING SYSTEMS

Need for Test/Exposure

Ultraviolet (UV) exposure occurs as the sun shines on a surface. UV intensity is greater in lower latitude and higher elevations of the country, and exposure duration is greater in areas with a high proportion of sunny to cloudy days. Polymeric systems are generally most sensitive to UV exposure. Polymeric systems include materials such as rigid polymer composites panels, flexible polymer mats, polymer concrete, polymeric coating systems, and polymeric additives to concrete. UV exposure is a primary cause of color fading, but may also cause surface cracking, making the material more susceptible to additional degradation. Many detectable warning systems have materials that are resistant to UV degradation, or have additives, often concentrated at the top surface, to reduce UV degradation. Abrasion exposure may remove this degradation-resistant layer, and the combined effects of cyclic exposure may be greater than would be obtained from UV exposure or abrasion exposure singly.

Basis for Method

Many manufacturers of polymeric detectable warning systems conduct UV exposure component tests. UV exposure tests generally consist of placing the material in an apparatus that provides radiation with UV light of a particular spectral distribution. Some apparatus cycle alternately between irradiation and water condensation, while other tests do not have a condensation component. Tests are generally conducted from 2000 to 5000 hours with approximately one half of these stated durations (1000 to 2500 hours) including actual UV radiation exposure. Evaluation of the effects of the UV exposure is generally not specified according to the test methods, but can consist of visual observation, color measurement, and strength testing. Tests methods referenced are standard practices for running the equipment, and often a specified testing regime is not referenced. Commonly used test methods are referenced below:

- ASTM G 151 *Standard Practice for Exposing Nonmetallic Materials in Accelerated Test Devices that Use Laboratory Light Sources*
- ASTM G 154 *Standard Practice for Operating Fluorescent Light Apparatus for UV Exposure of Nonmetallic Materials*
- ASTM G 155 *Standard Practice for Operating Xenon Arc Light Apparatus for Exposure of Non-Metallic Materials*
- ASTM G 23 *Practice for Operating Light-Exposure Apparatus (Carbon-Arc Type) With and Without Water for Exposure of Nonmetallic Materials* (withdrawn 2000)
- ASTM G 26 *Practice for Operating Light-Exposure Apparatus (Xenon-Arc Type) With and Without Water for Exposure of Nonmetallic Materials* (withdrawn 2000)
- ASTM G 53 *Practice for Operating Light- and Water-Exposure Apparatus (Fluorescent UV-Condensation Type) for Exposure of Nonmetallic Materials* (withdrawn 2000)
- ASTM G 90 S*tandard Practice for Performing Accelerated Outdoor Weathering of Nonmetallic Materials Using Concentrated Natural Sunlight*
- ASTM D 822 *Standard Practice for Filtered Open-Flame Carbon-Arc Exposures of Paint and Related Coatings*
- ASTM D 1501 *Recommended Practice for Exposure of Plastics to Fluorescent Sunlamp* (withdrawn 1990)

- ASTM D 2565 *Standard Practice for Xenon Arc Exposure of Plastics Intended for Outdoor Applications*

Because it is anticipated that the various exposure mechanisms may cause increased degradation when combined, UV exposure will be conducted on systems, rather than components. Because of the large size and weight of the proposed test samples a standard UV exposure cabinet could not be used. This test method was developed based primarily on ASTM G 151-06 and ASTM G 154-06.

Key Objectives

The UV exposure test development had two key objectives: first, develop a UV exposure chamber capable of testing entire detectable warning system specimens; second, set appropriate exposure parameters including irradiation intensity, duration, temperature, and moisture level. Repeatability of the test procedure is essential because this exposure was developed to support comparisons of detectable warning system performance.

Proposed Method

Summary Description of Method

UV exposure is conducted according to ASTM G 151-06 and ASTM G 154-06. UV lamps are positioned at a fixed distance above the detectable warning system surface. The lamps are UVA-340 fluorescent lamps that are intended simulate sun exposure in the UV-A region. These lamps are the same and the distance is similar to a conventional commercially available UV weathering cabinet. The systems are placed in a tent or other structure to protect worker's eyes from the UV radiation and maintain constant exposure conditions for the specimens. The duration of irradiation is different for the hot and cold exposure categories. The hot exposure category has a 50% longer duration of UV irradiation than the cold exposure category.

This method is designated Draft T4-33, Part 3 *Recommended Method of Test for Ultraviolet Exposure of Detectable Warning Systems.*

Important Parameters of Method

Comparisons based on cumulative energy of exposure alone are misleading, even for tests conducted under the same method, without controlling for variations in lamp spectrum, test temperature, or moisture exposure (Grossman, 1993). For this reason, lamp spectrum, test duration, moisture exposure, and test temperature are all specified to ensure repeatability and reproducibility. The important parameters of the method include:

- UV irradiation - For UVA-340 lamps, UV power levels are determined by measuring the irradiance at a wavelength of 340 nm over a narrow bandpass. The overall irradiance, as measured on the sample surface, can be adjusted by modifying the number of lamps, distance from lamps to specimen surface, and lamp power input.
- Test duration - The test duration greatly influences the degree of degradation. Increasing the test duration increases the amount of energy delivered to the specimen surface. Note that degradation in various materials often is not linearly related to linear test duration and is highly dependent on specimen material (Fedor & Brennan, 1996). However, it is anticipated that testing of multiple

detectable warning systems according to this method will provide results that can be used for comparison.

- Moisture - The addition of moisture to UV exposure has been shown to influence the rate and type of degradation for multiple types of materials. In some cases, the absence of moisture reduces the rate of measured degradation and does not result in all the same degradation mechanisms, such as chalking, as compared to outdoor exposure testing. In other cases, the dry UV exposure has been shown to increase the degradation or cause a color change opposite to those specimens testing with combined moisture and UV exposure (Fedor & Brennan, 1996). This test method does not include moisture exposure as part of the UV exposure, because this test is designed to be run as part of Draft Standard T4-33 in sequence with other exposure tests that include moisture exposure.
- Temperature - The test temperature also has the potential to influence degradation from UV exposure. The test temperature is elevated above standard laboratory temperatures, to reflect air temperatures likely to be seen during peak UV exposure in the field.
- Uniformity - Irradiation is measured over the surface of the detectable warning system in order to assure uniform response to exposure. The concrete edges on the top of the specimen, outside the detectable warning system area, are not included in the uniformity requirement.

Development Process

Two ASTM test methods were used as the basis for this test, G 151-06 and G 154-06. ASTM G 151-06 is a general standard practice for the exposure of nonmetallic materials to UV, which details requirements for UV exposure regardless of the UV source used. ASTM G 154-06 is specific to UV exposure by fluorescent lamps and dovetails with requirements of ASTM G 151-06. Because these methods are well established, this test development process had two main goals: develop a large scale chamber capable of testing entire detectable warning system specimens, and set appropriate exposure parameters.

The greatest difficulty in constructing a large test chamber to meet the requirements of ASTM G 151-06 and ASTM G 154-06 was ensuring that irradiance over the entire area of specimen exposure was at least 70% of the maximum irradiance.

Figure A12 shows the irradiation profile developed for specimen exposure. The lights were spaced wider in the center of the chamber and closer on the edges, in order to avoid over-irradiating the center of the specimen. Additionally, irradiation levels were adjusted by varying the distance from the specimen surface to lamps. The UVA-340 lamps used for this test were powered by commercially available F40 T12 electronic ballasts, which were not adjustable in power output.

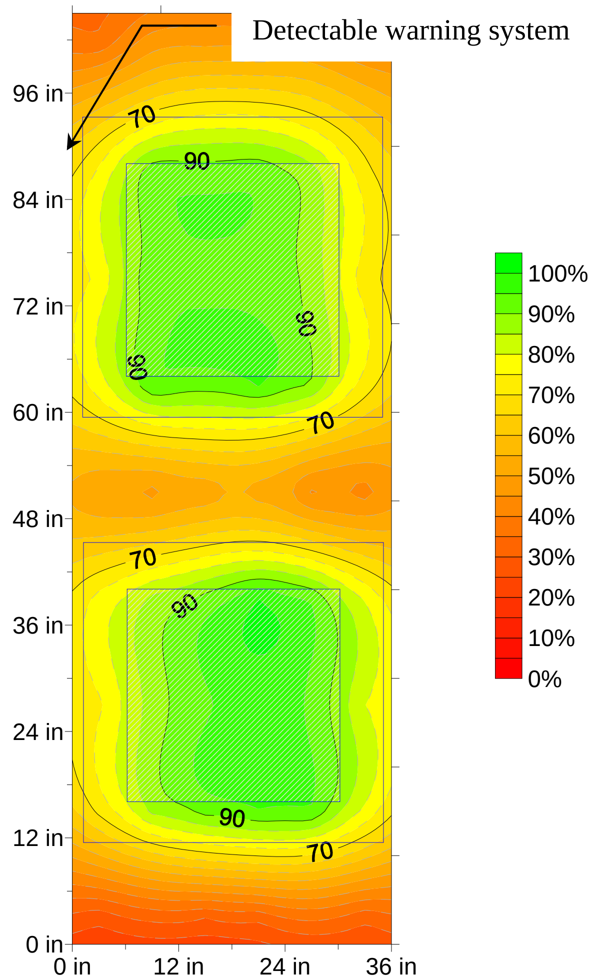


Figure A12. Sample contour plot of UV irradiance on the interior of a test chamber capable of irradiating two specimens. Measurements were taken on a regularly spaced grid at the surface level of the specimens. Contour lines are shown at 70% and 90% levels. The specimen surface is marked by the diagonal lines. Note that the entire specimen surface is irradiated at levels greater than 70% of the maximum set point.

The test parameters of duration, temperature, and moisture exposure were specified based on the researchers' experience with other UV testing. The specified UV duration is somewhat less than other test methods, due to the expected synergistic degradation from other exposure methods. Peak UV exposures coincide with summer months, with elevated air temperatures in the range of 30 °C [86 °F]. The specified test temperature was obtained using forced air circulation with two 18-cubic feet per minute fans and heat from the UVA-340 lamps. No moisture exposure was included, because other exposure methods performed in conjunction with this method will include cycles of moisture exposure and saturation.

Guidance in Use and Interpretation

This test is an exposure test, and no evaluation is included in the method. Therefore, no guidance on interpretation of test results is provided.

PART 4

ABRASION EXPOSURE OF DETECTABLE WARNING SYSTEMS

Need for Test/Exposure

Abrasion is a significant source of degradation of detectable warning systems. The primary source of abrasion is foot traffic, though wheeled traffic, such as wheelchairs, carts, bicycles, and small and large vehicles, that travel over detectable warning systems also provide a source of abrasion. Dirt, road debris, and sand used for traction in winter increases the abrasive effect of foot and other traffic. Abrasion can reduce overall dome height and alter the surface texture of detectable warning systems. Surface texture is often relied on to provide slip resistance, and abrasion-related decrease in texture of the surface can pose a hazard to pedestrians using the sidewalk. In addition, abrasion can make a detectable warning system more susceptible to other kinds of deterioration mechanisms, for example by removing the ultraviolet resistant surface layer that is present on some polymer systems. Similarly, other exposure regimes, such as ultraviolet, can lead to decreased abrasion resistance because of microcracking/degradation of the surface of polymeric materials.

Since both the ability of a system to resist wear and the effect that abrasion can have on overall durability are significant to the performance of detectable warning systems, the abrasion/wear mechanisms are considered in this detectable warning system testing protocol as both an exposure regime and as an evaluation test. To differentiate the two, the evaluation test considering abrasion will be referred to as the "wear resistance" test. The method discussed in this section is the abrasion exposure.

Basis for Method

Many tests for abrasion resistance exist. Several manufacturers test abrasion resistance of their detectable warning systems, generally using an abrasion test that is designed for their type of material. Because of this, the severity of the tests and interpretation of results are not consistent from test to test. The results of most abrasion tests cannot be correlated directly to an amount of foot traffic. The following ASTM methods were reviewed in the development of this method:

- ASTM C501 *Standard Test Method for Relative Resistance to Wear of Unglazed Ceramic Tile by the Taber Abraser*
- ASTM C418 *Standard Test Method for Abrasion Resistance of Concrete by Sandblasting*
- ASTM C241 *Standard Test Method for Abrasion Resistance of Stone Subjected to Foot Traffic*
- ASTM D4060 *Standard Test Method for Abrasion Resistance of Organic Coatings by the Taber Abraser*
- ASTM D2486 *Standard Test Methods for Scrub Resistance of Wall Paints*

The abrasion exposure regime will be carried out on the fabricated systems and is intended to simulate the effects of the actual abrasion process that might be encountered in use. The standard abrasion tests listed above were developed to rapidly assess wear resistance and do not test a large sample area. As a result, they are not applicable to producing an exposure regime for these detectable warning systems, nor are they suitable for the sample geometry. Therefore, an exposure method was developed to simulate the abrasive nature of foot traffic, but to do so in mildly aggressive manner in which the effects are distributed over the four cycles that make up the test protocol.

Key Objectives

The key objectives in the development of the abrasion exposure test were: 1) to simulate wear of the dome surface in a progressive and realistic way, so that other wear triggered exposure-related deterioration mechanisms may manifest themselves if the system is susceptible to those effects, and 2) to act on all domes in an essentially equal manner, so that the domes can be considered equivalent for subsequent evaluation tests on individual domes. Since this test protocol was developed to support comparisons of detectable warning system performance, repeatability of the test procedure is also essential.

Proposed Method

Summary Description of Method

The proposed test method consists of a laboratory-based exposure test where a fixed weight sled, consisting of aluminum oxide abrasive sand paper mounted against a sheet of compressible foam attached to a rigid plate, is dragged across the surface of the system by a hand-operated unit that relies on a cable to move the abrasive sled. The foam allows the sandpaper to conform somewhat to the tops of the domes. The tests apparatus is shown in Figure A13. This sled, which is sized to cover half of the width of a typical detectable warning system, is cycled back and forth over the surface of first one half of a system and then the other half. For informational purposes only, the effect of the abrasive action can be assessed by measuring the height of four domes before and after exposure.

This method has been designated Draft T4-33, Part 4 *Recommended Method of Test for Abrasion Exposure of Detectable Warning Systems*.

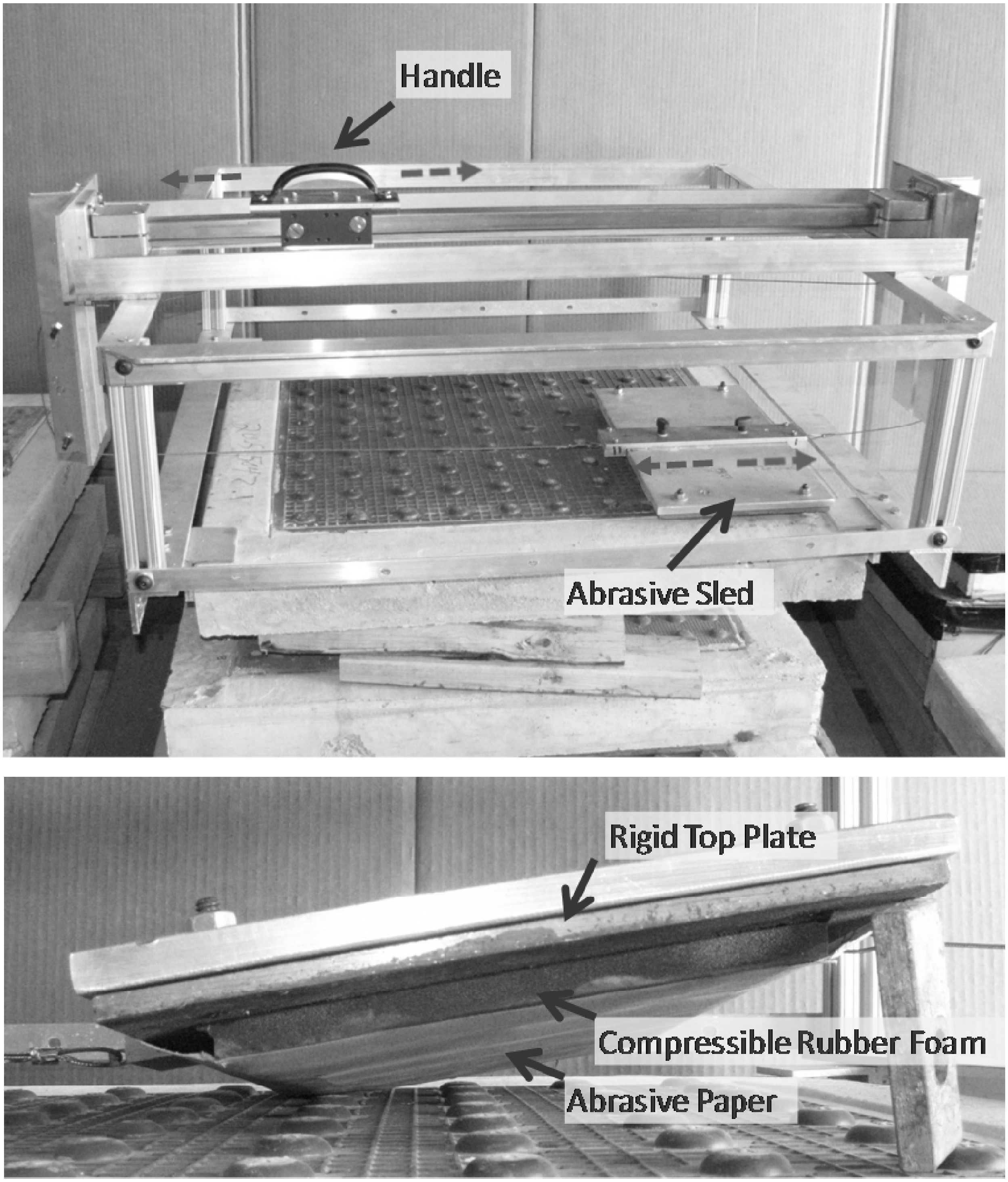


Figure A13. Abrasion Exposure Setup: A frame supporting a hand-activated wire and pulley system that translates the abrasive sled across the sample surface (top) and close up of the side of the abrasive sled showing rigid top plate, compressible foam and abrasive paper (bottom).

Important Parameters of Method

The important parameters of the method include:

- Pressure - The amount of wear experienced by the tops of the domes in the detectable warning system sample during this exposure is directly influenced by the pressure applied to the abrasive paper. This pressure is determined by the weight and size of sled, and it is essential that the sled configuration be faithfully reproduced for this testing.
- Abrasive paper - The nature of the abrasive will determine the severity of the wearing action, and the binding adhesive and paper used to hold this abrasive against the systems will determine the consistency of exposure during the test cycles. Specifying and achieving uniformity in the wearing action is important for the repeatability of this method.
- Rigidity of abrasive paper support - The compressibility of the foam and the stiffness of the paper will have an effect on the severity of the wearing action along the edges of the domes and the surface texture.
- Number of cycles - More cycles will result in more abrasive action.

Development Process

The development for the abrasion exposure initially focused on designing a system that could abrade a large area of the system surface in a repeatable manner. At first, methods for applying the abrasive media to detectible warning systems that did not rely on abrasive papers, such as submerging the samples in a slurry or covering the surface with loose particles of sand, were considered since there was concern that the paper would break down quickly and require frequent replacement. However, difficulties in controlling the distribution of the abrasive material, i.e. maintaining a uniform layer of abrasive on top of the domes, made such approaches impractical. Therefore, a high quality, durable and well-characterized 120-grit aluminum oxide abrasive paper was identified as the best choice for this application.

The second focus of the development was the design of a mechanism that could repeatedly cycle the abrasive sled over as large a portion of the surface of the sample as convenient. Originally, an automated mechanism that could produce as many as 100 abrasive cycles for each exposure was envisioned. A simple hand-operated mechanism for translating the sled was initially developed to support trials to evaluate the number of cycles needed. These trials were conducted on flexible polymer, metal panel, and polymer concrete systems and consisted of varying the number of abrasive cycles while visually comparing wear after each cycle. Based on the response of these detectable warning systems, it was quickly apparent that many fewer cycles than 100 were required to produce pronounced wear with the abrasive paper selected. Based on this work, the entire surface of each slab will be abraded for 16 total cycles, broken into four exposures of four cycles each. Figure A14 shows the condition of the some domes during this process. A hand-operated mechanism is sufficient to produce four cycles, and development of an automated mechanism was judged unnecessary. Additionally, the hand-operated mechanism is light weight and easily moved from sample to sample. The mechanism can be placed on the concrete surrounding the detectable warning system surface, and does not require additional anchoring.

Figure A14. Close-up of dome surfaces after abrasion exposure.

Guidance in Use and Interpretation

This test is an exposure test, and with the exception of a measurement of change in dome height, no evaluation is included in the method. The change in dome height is informational in nature only, and not meant to provide a basis for comparing detectable warning systems. Therefore, no guidance on interpretation is provided.

PART 5

VISUAL AND MICROSCOPIC EVALUATION OF DETECTABLE WARNING SYSTEMS

Need for Test/Exposure

Visual evaluation is a primary method for characterizing a sample. With careful visual observation, the effects of exposure can be preliminarily assessed and documented with photographs. Visual observation can indicate if color is changing, if domes are being abraded, if domes are suffering other types of damage, if the system is cracking, becoming debonded, or if the system is changing in other ways. In some cases, such as cracking of the substrate or the raising of the detectable warning system out of the concrete, visual observation is the only method to assess these changes.

Basis for Method

Visual observation is the most basic method of characterization of the durability of materials, but is very difficult to carry out in a repeatable manner. Visual observations include types of degradation and qualitative assessments of performance not readily measured by other tests. Detectable warning system manufacturers often list qualitative assessments of performance, such as colorfastness and resistance to damage, that are likely assessed on the basis of visual observation, although that is not stated directly.

Microscopic evaluation can provide information about long-term durability not apparent by visual examination. For example, surface distress, such as scaling, may begin on a microscopic scale, and progress with time to become a serious durability problem. Likewise, microcracks on the surface may grow to become visible cracks, and eventually cause chipping or breakage of the detectable warning system.

Key Objectives

The key objectives in the development of the visual and microscopic evaluation were to observe conditions that are not readily measured by other techniques, such as cracking and changes in elevation of the detectable warning system in the concrete, and to relate these observations to anticipated performance in a pass/fail manner. Repeatability of the test procedure is desired because this evaluation was developed to support comparisons of detectable warning system performance, although it is recognized that this evaluation is carried out in a somewhat subjective manner.

Proposed Method

Summary Description of Method

Visual examination is carried out on as-fabricated specimens. Visual examination consists of examining the specimens for discoloration, cracking, surface distress and other evidence of degradation. Any unusual features prior to exposure, including discoloration, chips, cracks, and other features are marked on a data sheet. Test specimens are photographed to document conditions.

Microscopic evaluation is performed with a portable, 10X to 30X magnification field microscope on two spots, approximately one square inch each, on the specimen surface. Microcracking or other forms of surface distress are observed with the field microscope. The observations are documented on a data sheet. Observations conducted after exposure are related to observations made prior to the exposure.

This method has been designated Draft Standard T4-33, Part 5, *Recommended Method of Test for Visual and Microscopic Evaluation of Detectable Warning Systems*.

Important Parameters of Method

The important parameters of the method include:

- Method of conducting visual examination - The visual examination needs to be conducted with the observer close to the surface being examined, so that details of the surface are not missed. The same parameters, such as distance of the observer from the surface and angle of lighting, needs to be followed by all observers to minimize variations in observations between observers.
- Detailed notes - Observations are noted on data sheets, so that comparisons can be made with subsequent examination after exposure.
- Size and location of areas for microscopic examination - The areas for microscopic examination need to be large enough to allow the opportunity to observe typical conditions, but small enough so that microscopic observation is feasible. The two locations should be distributed on the surface of the sample so that microscopic observations correspond to any variations observed visually.

Development Process

The development of the visual observation began by visually observing multiple types of detectable warning system specimens prior to exposure. These observations indicated that certain ways of carrying out the evaluation proved more successful than others. For example, observing the specimens at a close distance (6 to 18 inches from the surface) allowed the observer to view features that were not apparent from a greater distance. Viewing the surface from multiple angles was also allowed for observations of more features than might be apparent from a single viewing angle.

The height at which photographs were taken was standardized in order to simplify comparisons of specimens before and after exposure. Photographs taken at different heights (resulting in different apparent magnification of the sample) or at different angles hamper comparison of features of interest between specimens.

The initial microscopic evaluation included attempts to count features, such as microcracks, and make comparisons from initial evaluation to after exposure. However, not all specimens had distinct features that could be counted. Further, identification of microcracks was not straightforward, and different observers had substantially different tallies of microcracks. The purpose of the microscopic evaluation was to determine if significant changes were occurring as a result of exposure. Micrographs taken of the areas aided in determining changes after exposure; however, this was not required because not all laboratories are equipped to record micrographs. Therefore, a summary of observations, with qualitative comments, was provided for the microscopic examination.

Guidance in Use and Interpretation

Visual and microscopic evaluation, even if carried out according to the standard method and consistently performed by the same observer, is a subjective, but still important, evaluation test. For this reason, anticipated performance ratings are not assigned using the same incremental scale as in other evaluation methods. Rather, the evaluation is set up as a pass/fail with the test result assigned either a 2 (likely to produce acceptable performance) or a 0 (not likely to produce acceptable performance).

In some cases, visual observation provides the only means to evaluate severe degradation. These types of degradation include breakage of the detectable warning system, and displacement of the detectable warning system out of the concrete substrate sufficient to cause a tripping hazard. These types of observations would be suitable to provide a performance rating of “fail” to a product, regardless of the results of the other evaluation tests. Other observations that may also provide a suitable “fail” rating may be possible. All other observations, which do not indicate imminent or past failure of the system, while providing subjective information on performance, will be considered to receive a performance rating of “pass.” However, individual jurisdictions may choose to incorporate other results of visual observation into their recommendations of qualified products.

Table A7. Performance Rating Guidelines

Representative Criteria	**Anticipated performance rating**
• Any changes that do not impact system usability	2 (likely to produce acceptable performance)
• Displacement of the detectable warning system relative to the concrete sufficient to create a tripping hazard • Debonding of the detectable warning system from the concrete sufficient to create a tripping hazard or of sufficient area that a substantial amount of the surface no longer has a suitable detectable warning surface • Through-thickness macrocracking of the specimen sufficient to indicate imminent or past debonding of significant areas • Other changes that negatively impact system usability	0 (likely to produce unacceptable performance)

PART 6

COLOR MEASUREMENT OF DETECTABLE WARNING SYSTEMS

Need for Test/Exposure

The ADAAG recommend that detectable warning systems have a light-on-dark or dark-on-light contrast with the surrounding sidewalk. Excessive color fading can reduce the color contrast of a dark-on-light system. Exposure to ultraviolet radiation and chemicals, degradation of the coating, and abrasion of the surface can cause significant color degradation, and may lead to non-compliance with adopted specifications.

Basis for Method

Color can be measured visually or instrumentally. Visual color measurement requires the observer to visually compare the color to a set of standard color cards, and the observer determines what standard color is most similar to the material being observed. Changes in color can be documented by noting if the matching standard color is different than the previous matching standard color. However, the perception of color varies from person to person. For consistency's sake, visual color observation should be carried out by the same person, which is not realistic for nationwide standard.

Instrumental color measurement is not observer-dependent. Colorimeters, instruments designed for this purpose, provide a numerical representation of color in one of many available scales. Changes in color are measured by changes in the numerical representation of the color. The advantages of using instrumental color measurement are that color changes of various samples can be compared by comparing the change in measured values, and that the numbers are less observer-dependent, although some variations in color measurement from instrument to instrument can occur. A commonly used color scale is the CIELAB system, first implemented in 1976, and is intended to approximate colors and color differences as observed visually. Color is measured with three coordinates: L* is the lightness, a* is the degree of redness or greenness, and b* is the degree of yellowness or blueness. Color difference is measured according to ASTM D2244 *Standard Practice for Calculation of Color Tolerances and Color Differences from Instrumentally Measured Color Coordinates.* Changes in color can be measured by overall change in color (ΔE) according to the following equation, or by the change in any of the individual coordinates.

$$\Delta E = \sqrt{[(L^*_2 - L^*_1)^2 + (a^*_2 - a^*_1)^2 + (b^*_2 - b^*_1)^2]} \qquad (1)$$

Most detectable warning system manufacturers offer products in specific colors. Often the colors provided are given in terms of federal standard colors. Federal standard colors are provided to customers as colored cards. The color matching can be performed either visually or instrumentally. Manufacturers do not specify how they determine that their products match the federal standard colors.

Key Objectives

The key objectives in the development of the color test were: 1) to develop a method that provided useful color data for comparison on the detectable warning system surfaces, and 2) to use a standard method capable of providing values, which can be compared before and after exposure.

Proposed Method

Summary Description of Method

The proposed method consists of measuring the color of domes and field areas of a detectable warning system using a colorimeter. The CIELAB system is used to measure color. Measurements are made on ten dome or field areas, and the L*, a*, and b* values are averaged. Because the surfaces of many detectable warning system products are very rough, and, even with an instrument with an integral light source, readings may vary somewhat because of the roughness. Averaging the results of ten readings minimizes the effect of the variability in the readings.

Color difference as a result of exposure is measured as the change in lightness, ΔL^*, the change in redness/greenness, Δa^*, the change in yellowness/blueness, Δb^*, or the overall change in color, ΔE. The overall change in color, ΔE, is suggested as the means for judging color change, although individual agencies may find differences in one of the other coordinates more useful. For example, if only yellow detectable warning systems are allowed under specification, an agency may find Δb^* more useful, or for agencies that specify any color or range of colors, ΔL^* may provide a measure of fade from dark to light.

This method has been designated Draft T4-33, Part 6 *Recommended Method of Test for Color Measurement of Detectable Warning Systems.*

Important Parameters of Method

The important parameters of the method include:

- Aperture size - The aperture of the colorimeter should be small enough to fit over the top of the dome, so stray light does not get into the detector and alter the measurement. Changes in the lighting conditions can have a dramatic effect on the measured color.
- Measurement head size - The measurement head of the colorimeter should be small enough to fit between the domes to allow accurate measurement of the color of the field. If the measurement head does not fit between the domes, stray light will affect the color readings.
- Alignment of the measurement head - The repeatability of the color test depends, in part, on accurately lining up the measuring head with the surface being measured. If the measurement head is aligned at an angle, or not aligned properly on the dome, stray light will affect the color readings.

Development Process

The development process for the color measurement test consisted of two efforts. The first focused on evaluating equipment suitable for taking the desired measurements, while the second effort involved fine tuning the parameters of the test.

Originally, the colorimeter used had a measuring head that was too large to fit between the domes on the detectable warning system. It became apparent after several measurements that the ambient lighting conditions had a significant effect on the measured color of the field areas. In effect, the sample was not being illuminated by the standard illuminant, but by a combination of the standard illuminant and the ambient lighting conditions. The large size of the measuring head also made collecting measurements on the domes difficult because the instrument was hard to balance. A different colorimeter with a smaller measuring head was acquired. This allowed easier measurement of the field areas, and the instrument was easier to balance on the sometimes rough surface of the domes, decreasing the range in measured color from area to area.

Early in the program, it was decided to measure 10 areas each representing the domes and the field, and to average the values to obtain a color reading for a particular detectible warning system specimen. Multiple measurements are required for a variety of reasons. Because of the pronounced surface roughness of many types of detectable warning systems, some of the measurement can be affected by the increased distance of the aperture from the substrate, which allows some ambient light into the measurement head. On some products, small variations in color are visually apparent. Finally, the effects of any exposure are not known in advance. For these reasons, averaging the values of ten readings taken from random areas distributed over the surface of the detectable warning system can more reliably be used to measure actual changes in color as a result of exposure.

As seen in Table A8, there is more variation in the ten readings after a particular amount of exposure to ultraviolet (as evaluated by determining a "ΔE" value of those ten readings) than there is when comparing the averages of ten readings from one exposure level to another. The average "ΔE" of the ten readings in a measurement set is higher for the domes than for the field. This is likely because it is easier to balance the measurement head on the field than on the top of the dome. Therefore, some stray ambient light is likely to have affected some of the readings of the dome. Likewise, the ΔE from one exposure to another tended to be somewhat higher for the domes than the field. Care must be taken to position the measurement head as carefully as possible to minimize the effect of misalignment.

Table A8. Color change (ΔE) of detectable warning systems, as measured after 250 h ultraviolet exposure.

Type	Feature	"ΔE" of 10 measurements at a single exposure level	ΔE from one exposure level to another (calculated from average L*, a*, b* values)
Surface applied flexible polymeric mat	Domes	1.4	0.8
		1.7	
		2.0	
		2.4	2.6
		3.0	
		4.0	
	Field	1.6	0.8
		1.8	
		2.0	
		2.1	0.3
		3.0	
		3.6	
Cast in place polymer concrete	Dome	1.5	2.6
		4.6	
		4.9	
		6.5	0.1
		6.7	
		7.8	
	Field	1.7	0.4
		3.1	
		3.2	
		3.4	0.2
		3.9	
		4.4	
Surface applied rigid polymer composite	Dome	4.2	4.2
		5.2	
		5.7	
		6.1	1.3
		6.8	
		7.6	
	Field	2.0	0.4
		3.6	
		3.8	
		4.2	0.2
		6.0	
		7.4	

Guidance in Use and Interpretation

The color test was developed as a method to repeatedly evaluate overall color change of a detectable warning system as a result of exposure. During this project, three types of detectable warning systems were tested before and after ultraviolet exposure. While it was found that a specific colorimeter could provide real and repeatability measurements of color change, it is important to note that different models of colorimeter, even if using the same color scale, can produce slightly different color values. Therefore, the same instrument should be used for color evaluation prior to exposure and after exposure.

Studies may be required to determine the effect of color fade on detectability; however, such investigations were outside the scope of this effort.

Target result likely to coincide with acceptable performance

Correlating color fading of detectable warning systems to durability and suitability for their intended purpose is difficult because of standards for acceptable color fade have not been widely developed and accepted, even for other types of products, Literature on the CIELAB color system indicated that a ΔE of less than 1 - 3 is generally noticeable for most people (Billmeyer Jr. & Hammond III, 1995) (Schanda, 2007). However, because of the as-manufactured slight variability in color of some detectable warning systems, the difficulties of obtaining repeatable measurements, and the assumption that some degree of color fade is acceptable, a ΔE less than or equal to 9 is considered likely to produce acceptable performance, interpreted to mean that change in color is slight. Based on this guidance and the laboratory testing conducted, the following general guidelines for interpreting the results of the color test are given:

Table A9. Anticipated performance rating for color measurement

ΔE initial to final exposure	Anticipated performance rating
<3	4 (likely to exceed acceptable performance)
3.1 - 6	3 (likely to slightly exceed acceptable performance)
6.1 - 9	2 (likely to produce acceptable performance)
9.1 - 12	1 (likely to produce slightly less than acceptable performance)
>12.1	0 (not likely to produce acceptable performance)

PART 7

DOME SHAPE AND GEOMETRY MEASUREMENT OF DETECTABLE WARNING SYSTEMS

Need for Test/Exposure

The ADA Accessibility Guidelines for detectable warning systems give specific details about the shape of the truncated domes. In practice, dome height and allowable ranges for dome diameter and inter-dome spacing are specified by the governing jurisdiction, many of which choose to adopt the ranges provided in the ADA Accessibility Guidelines. Measurement of the shape and dimensions of the truncated domes is required to evaluate compliance with these requirements. Additionally, shape measurements can be used to quantify damage to domes as a result of exposure or evaluation tests.

The shape test method is referenced by a number of the test methods that make up the Draft T4-33 Test Protocol. Dome shape is likely to be degraded significantly by the abrasion exposure test method. The height of the dome in needed to set up the equipment for the snow removal resistance test and is used to quantify performance in the wear resistance evaluation test.

While no guidelines exist on how much dome loss is acceptable before the detectable warning system ceases to function effectively, measurement of dome shape and dimensions after testing can be used to evaluate general performance and durability. Systems that maintain dome geometry after exposure and evaluation testing can be considered more durable than those that lose part of or the entire dome.

Basis for Method

Manufacturers of detectable warning systems either list the measurements of the domes in their product literature, or specify that their products are "ADA-compliant." The product literature generally does not discuss how the shape is measured. Discussions with one supplier revealed that they use a coordinate measuring machine to determine dome shape. These machines are specialized and not likely to be found in many testing labs. For this reason, measurement will be conducted with commonly available or easily fabricated hand-held instruments.

Key Objectives

The key objectives in the development of the shape test were to define a standard method of measuring dome dimensions that could be used to 1) evaluate compliance with specifications and 2) evaluate dome loss as a result of exposure.

Proposed Method

Summary Description of Method

The dome diameter at the base, dome diameter at the top, and inter-dome spacing are measured with calipers. The rounded shape of some domes makes it difficult to identify the dome top and dome base for diameter measurements with precision, because edges may not be clearly delineated. Operator judgment will be relied upon to take measurements at the top and the base. Four domes will be measured and the values averaged. The averaging of multiple readings will accommodate slight differences in dome dimensions and operator uncertainty in measurement. Photos showing the use of calipers to measure the dome diameter at the top and the dome diameter at the base are given in Figure A15 and Figure A16, respectively.

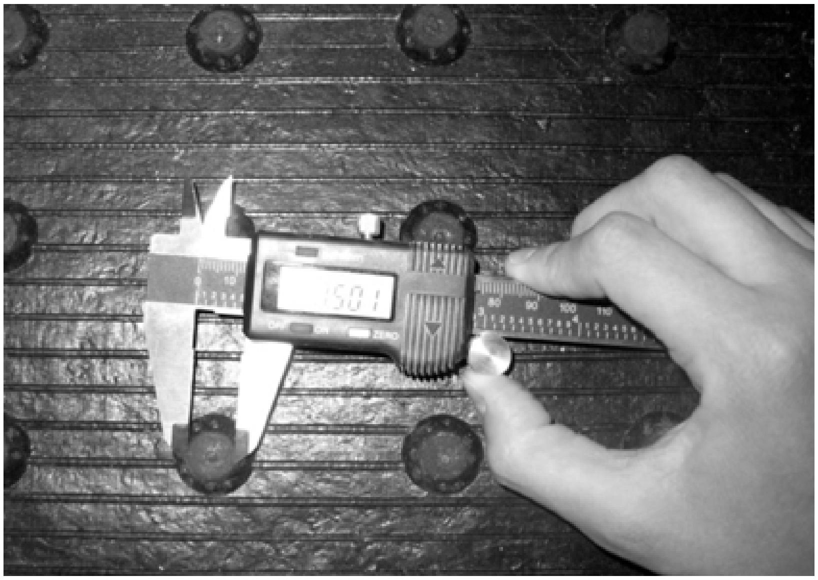


Figure A15. Measuring the dome top diameter of a detectable warning system.

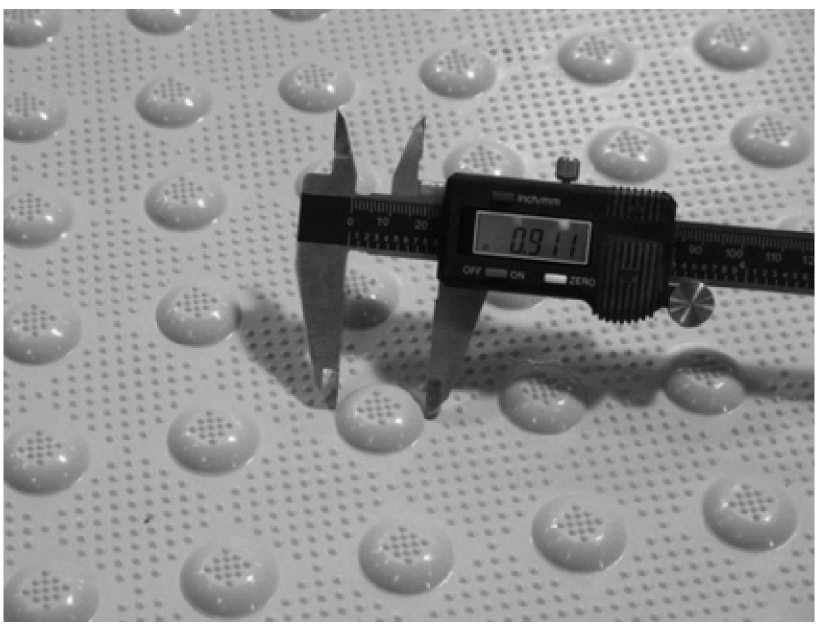


Figure A16. Measuring the dome base diameter of a detectable warning system.

The dome height is measured with a depth gauge mounted to a steel plate that can be placed over the top of four domes. The gage spindle point rests on the bottom of the field, while the plate rests on the highest feature on the top of the domes. A photo of the depth gauge is given in Figure A17.

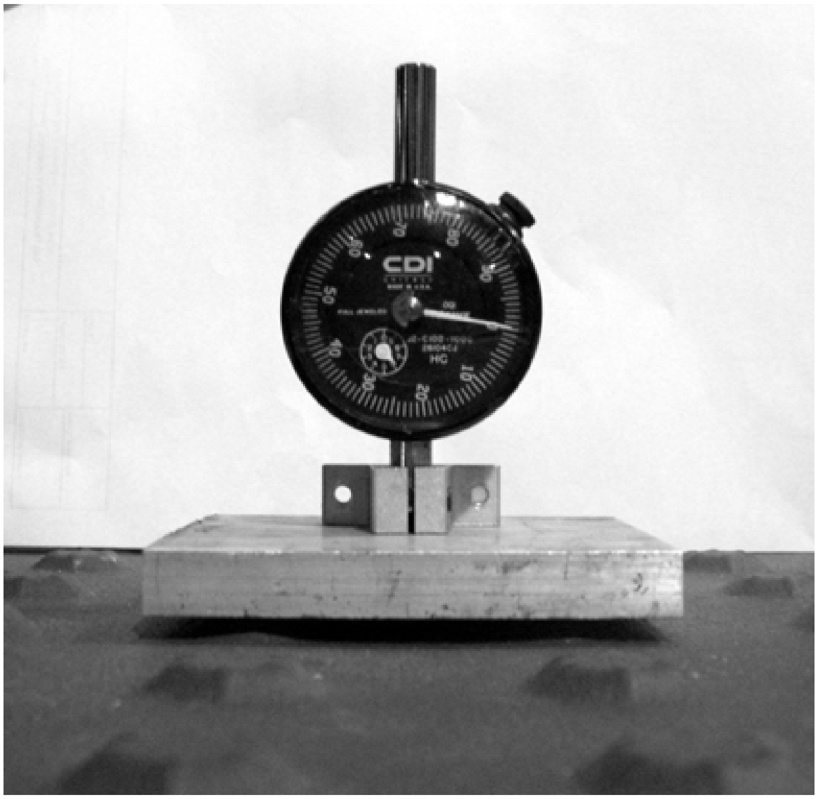


Figure A17. Measuring the dome height of a detectable warning system.

This method has been designated Draft T4-33, Part 7 *Recommended Method of Test for Dome Shape and Geometry Measurement of Detectable Warning Systems.*

Important Parameters of Method

The important parameters of the method include:

- Definition of height -The physical features that make up a dimension must be objectively defined before the dimension can be measured. For that dimension to be useful, this definition must be clear and sufficient so that others can repeat the measurement. Detectable warning systems come in many configurations with varied surface features intended to provide traction, to add to resistance to impact or to improve detectability. For this reason the height of the dome has been defined as the distance from the highest point on the dome regardless of feature to the lowest point in the system field.
- Consistency in measurement of diameters - In some detectable warning systems, the top and base dome diameters are not clearly delineated from the sides. In these cases, consistency in technique used to identify the edge of the top and dome is essential. However, because the wide range of detectable warning system configurations, no overall guidelines could be developed. The designation of dome and base edges is left to the operator's judgment.

Development Process

The dome height gage was developed to allow dome height to be measured based on universally applicable definitions of the top of the domes, where the plate rests, and the lowest point in the field, where the gage spindle point contacts.

The dome top and base diameters are measured with calipers. It became apparent during the development process that domes with a high degree of curvature at the top and base were not measured as easily as products that had a more clear delineation between: 1) the field and the dome, and 2) the top and sides of the dome. No universally-applicable way to define the edges of the domes has been identified, and the operators performing this test must use appropriate judgment in determination of the appropriate dome top and base diameter.

Guidance in Use and Interpretation

Dome shape is considered a pass/fail criterion. Dome shape is dictated by the governing specification. Many jurisdictions choose to adopt the guidelines described in ADAAG, but these guidelines are not necessarily adopted into law in all jurisdictions. When initially supplied, any detectable warning system that has a dome shape within the governing specification is considered acceptable, while a detectable warning system that has a dome shape outside that allowed by the governing specification is considered unacceptable.

Since the primary function of the domes is to provide detectability, judging how much dimensional change is associated with acceptable durability without assessing detectability is not possible. There is currently a lack of information on the effect of changes in dome shape on detectability. Since assessments of detectability were outside the scope of this project, no further interpretation of shape can be provided at this time. If further information on the effect of change in dome dimensions on detectability becomes available, or if an agency develops specifications for dome dimensions after exposure, performance ratings may be applied for post-exposure evaluation.

Therefore, the following general guideline is suitable for the evaluation of unexposed samples only. As described elsewhere, a rating of “0” in this test would mean that a given product would be considered unsuitable for consideration regardless of performance in other tests.

Table A10. Anticipated performance rating for dome shape and geometry measurement

Dome dimensions	Anticipated performance rating
Dome dimensions meet specifications	2 (likely to produce acceptable performance)
Dome dimensions do not meet specifications	0 (not likely to produce acceptable performance)

PART 8

COATING AND SINGLE DOME BOND IN DETECTABLE WARNING SYSTEMS

Need for Test/Exposure

In detectable warning systems that are not integrally colored, a coating may provide one or both of the following two properties: increased slip resistance and greater color contrast with the surrounding sidewalk. If the coating becomes debonded from the substrate, the detectable warning system may no longer be slip resistant in these areas, and if large areas of coating become debonded, the system may not meet the color contrast requirements. In addition to coatings, some systems consist of an array of individually adhered surface applied single domes. The adhesion of these domes can be assessed by the same method as the coating.

Coatings may become degraded and surface applied single domes may lose adhesion through many exposure mechanisms. For instance, ultraviolet exposure can discolor and degrade polymeric coatings. A degraded coating can become less resistant to abrasion, cracking and chipping. Additionally, abrasion from foot or vehicular traffic (including hand carts) can wear away a coating; it can also subject the coating to shear stress, possibly leading to localized debonding (chipping). Moreover, cracking of the substrate from freezing and thawing can lead to local debonding of coating at the crack. Since all of these mechanisms may result in reduction in coating performance or surface applied single dome adhesion, a method to evaluate the bond of coatings and surface applied single domes to the substrate is needed for evaluating detectable warning system durability.

Basis for Method

Manufacturers of detectable warning systems generally do not provide coating bond strength test results. Preferred or specialized procedures for testing coating bond specifically for detectable warning systems have not been identified. While coatings are essentially never subjected to direct tension, standard bond tests often use direct tension methods, although other coating bond methods have been developed. Some ASTM test methods for coating bond are:

- ASTM D4541 *Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Tester*
- ASTM D3359 *Standard Test Method for Measuring Adhesion by Tape Test*
- ASTM C1583 *Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method)*
- ASTM D2197 *Standard Test Method for Adhesion of Organic Coatings by Scrape Adhesion*

Therefore, the research team selected one of these methods, specifically ASTM D4541 *Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers* performed with a Type V tester, to evaluate coating adhesion, since it is a test method commonly used by the coating industry and is adaptable to detectable warning systems. This method is repeatable and standard equipment to produce the direct tension is available.

Key Objective

The key objective in the development of the coating bond test was to use a standard method capable of measuring bond strength of coatings and surface applied single domes, which can be compared from system to system.

Proposed Method

Summary Description of Method

The proposed method consists of adhering dollies to the surface of the detectable warning system that are then pulled off in direct tension. The Type V tension tester provides a reading of the pull-off force required to overcome the bond of the coating to the system. This force is converted to a pull-off strength based on the area of the dollies or the equivalent diameter of the surface area stressed. Testing is carried out in triplicate on the tops of the domes and also in triplicate on the field between domes, because the adhesion may be different in these areas. Tests are carried out at room temperature (approximately 21-27°C [70-80°F]) and also at elevated temperature (60 °C [140°F]).

This test method has been adapted to test the adhesion of surface applied single domes to the concrete surface. If coating is present on the top of the domes, testing on the domes is done in two ways: with the coating in place and with the coating removed with abrasive paper to isolate the dome/substrate interface. Then direct tension is applied to the dolly bonded to a single dome until failure. If the bond strength of the surface applied single dome is less than the bond strength of the coating to the dome, and the dome debonds from the concrete before the coating debonds from the dome, the coating bond to the top of the dome cannot be measured. These tests are also carried out in triplicate at room and elevated temperatures. Any coating present in the field is also tested separately using the method outlined above.

Schematics of the tests for testing coating bond on the tops of the domes, on the field, and testing bond of surface applied single domes are provided in Figure A18**Error! Reference source not found.**.

This method has been designated Draft T4-33, Part 8 *Recommended Method of Test for Coating and Single Dome Bond in Detectable Warning Systems.*

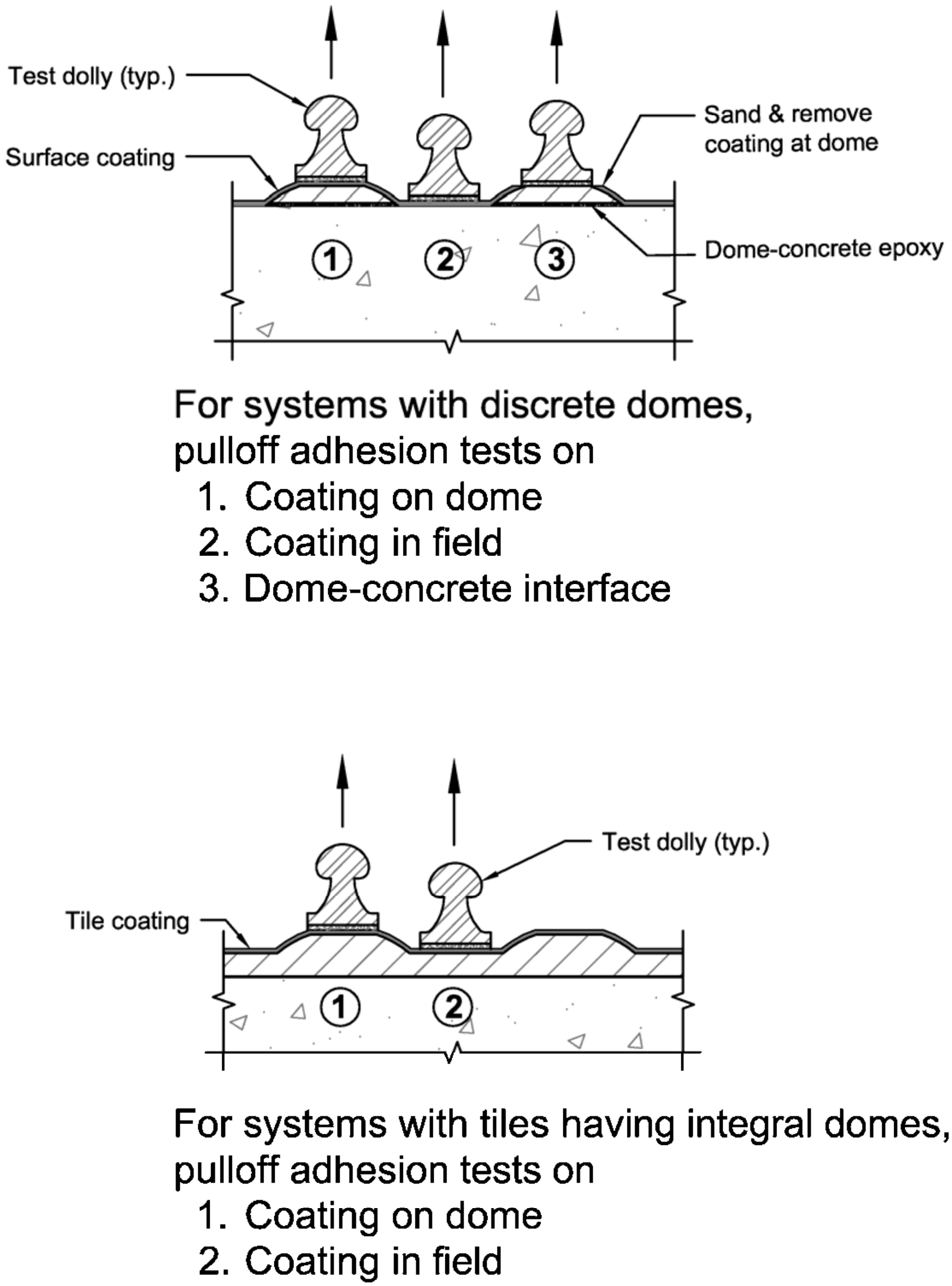


Figure A18. Schematic showing coating bond tests (1 and 2 in the figure) and surface applied single dome bond test (3 in the figure).

Important Parameters of Method

The important parameters of the method include:

- Test of detectable warning/concrete performance - For systems with a coating applied in the field, testing of the detectable warning system/concrete composite system is essential, because the coating is applied as part of the installation process. Testing of shop-applied coating systems is also carried out on the detectable warning system/concrete system, because some deterioration mechanisms that may degrade bond are can only be realistically simulated on the combined system.
- Dolly size - The dollies chosen should be suitable for adhering to the tops of the domes, which may be as small as 0.45 inch (1.1 cm).
- Adhesion tester - The tester selected should be of a geometry suitable for testing both the tops of the domes and the field on a detectable warning system. A tester that has too large a footprint may not fit adequately between the domes. In addition, the tester should comply with the definition given in ASTM D4541 for a Type V self-aligning adhesion tester. The use of different type of tester is expected to give different results.
- Adhesive - The adhesive used to bond the dollies to the surface to be tested needs to be strong enough that the failure occurs primarily at the coating/substrate interface, within the coating, or within the substrate. Additionally, an adhesive suitable for testing at 60ºC (140°F) must be used for elevated temperature testing.

Development Process

The development can be divided into three main parts, which include: 1) selecting proper sample preparation techniques, 2) evaluating which adhesion tester is best suited for this application, and 3) testing and interpretation of the results.

To perform proper adhesion testing, the test surfaces needs to be prepared so that the dollies are well bonded to the surface. This includes a surface roughing step to improve adhesion but not be destructive to the coating or dome. A light scour with 600-grit silicon carbide abrasive paper prior to attaching the dolly was generally found to be adequate. After this step, the area should be cleaned so that it is free of debris.

The epoxy adhesive used to bond to dolly can often be directly applied to the dome top, although in some cases, a temporary dam was applied to keep the epoxy on the dome top instead of allowing it to flow down the sides. The dams were fashioned from a clay-based weather stripping. The epoxy adhesive was mixed according to the manufacturer's instructions and applied to the domes. Sufficient epoxy should be applied to ensure a good bond between the area being tested and the dolly. Due to the varying geometries of the domes from sample to sample, the amount of epoxy that is applied must be adjusted to maintain full contact between the dolly and dome. This is so the test is reproducible, and the results can be compared.

ASTM D 4541 describes several types of adhesion testers potentially available for testing. For the detectable warning panels, the Type V self aligning tester was chosen because of the geometry of the domes. This tester is designed to produce a more nearly uniform force across the dolly, instead pulling the dolly to one side producing a peeling action resulting in a lower measured pull off force. The contact surface of the dolly was thoroughly scarified to enhance the bonding to the surface of the dome. The dolly diameter of 20 mm was chosen based on a standard size that would cover the greatest surface area of the domes. In some cases, the tops of the domes were not flat and the epoxy adhesive was used to compensate for the height difference and maintain full contact with the test dollies. The same size dolly was used to test the field.

Tests were carried out on cast-in-place metal panels, where the coating was shop-applied to the system, and surface applied single domes, where the coating was applied to the domes as part of the system installation process. Data from the tests are provided in Table A11.

Table A11. Results from coating bond testing.

Type	Location	Bond Strength (MPa)
Cast-in-place metal panel	Dome	>5.0*
		5.0
		>5.6*
		7.0
	Field	>2.2*
		1.2
		>1.4*
Surface applied single dome	Field	3.8
		3.8
		>3.0*

* Failure occurred within the adhesive or at the adhesive sample interface; therefore, the bond strength reported represents a minimum bond strength, and not the actual bond strength.

According to Section 8.5 of ASTM 4541, a test should be disregarded when 50% or more of the failure is because of the adhesive used to bond the dolly to the surface, although the value obtained can be considered as a lower limit of bond at that location. This may be useful if the test value surpasses a minimum acceptable criterion. In some cases, the data presented in Table A11 represent failure of the adhesive used to bond the dolly to the substrate. These values are considered a proof load; the actual bond strength of the coating is expected to be higher.

Guidance in Use and Interpretation

The coating and single dome test was developed using an ASTM standard test method as a repeatable, material-independent method for evaluating coating bond. This test is not intended to simulate a particular type of stress that is likely to promote debonding of a coating or dome, but is rather a standard method for obtaining information useful for making comparisons about likely bond performance. This coating bond test provides basic information as to whether a coating may be expected to remain adhered to a system. Further study is required to link performance in this test with actual field performance.

Target result likely to coincide with acceptable performance

Correlating field performance of detectable warning systems with coating bond is somewhat difficult without field data describing the coating bond strength after periods of long-term exposure. Additionally, the data collected during the test development, presented in Table A11 above, is limited, because only two coated systems were included in the overall test program, since most detectable warning systems are integrally colored. Therefore, the following general guidelines for interpreting the results of the coating bond tests given below are based on these two tests, but the experience of the research team with testing of conventional coatings was also strongly considered.

Since the assignment of a performance rating of “0” could lead to the detectable warning system product being considered unacceptable regardless of performance in other evaluation tests, a performance rating of “0” (not likely to produce acceptable performance) is not included. This is because such a strong conclusion is not justified based on the limited understanding of how this test correlates with field performance.

Finally, is emphasized that these values were obtained with an ASTM D4541 Type V adhesion tester, and cannot be directly translated to tests conducted with other types of adhesion testers.

Table A12. Anticipated performing rating for coating and single dome bond

Bond strength (MPa)	Anticipated performance rating
Greater than 7	4 (likely to exceed acceptable performance)
5 - 7	3 (likely to slightly exceed acceptable performance)
3.5 - 5	2 (likely to produce acceptable performance)
Less than 3.5	1 (likely to produce slightly less than acceptable performance)

PART 9

SLIP RESISTANCE OF DETECTABLE WARNING SYSTEMS

Need for Test

Slip resistance is a very important property for any walking surface and is quantified in terms of the coefficient of friction. The higher the coefficient of friction, the higher the slip resistance, and the less likely a pedestrian is to fall on a particular walking surface. Slip resistance is unique among the performance parameters being considered in this program in that some guidance is available, as seen in Table A14 below, recommending acceptable values for walking surfaces. Coefficient of friction, and retention of coefficient of friction after exposure, is anticipated to be a key factor in determining durability if detectable warning systems, because a slippery surface is a well-recognized danger for pedestrians.

Over the lifetime of a detectable warning system, slip resistance is likely to be affected primarily by abrasion exposure. Abrasion may wear away surface texture that provides a high coefficient of friction. However, surface degradation and scaling associated with freeze/thaw, thermal cycling, or ultraviolet exposure may also affect slip resistance by affecting the surface of the detectable warning system.

Basis for Method

Many detectable warning system manufacturers report slip resistance values for their products. Several test methods are in common use for measuring the coefficient of friction of a walking surface. These include:

- ASTM C 1028 *Standard Test Method for Determining Static Coefficient of Friction of Ceramic Tile and Other Like Surfaces by the Horizontal Dynamometer Pull-Meter*
- ASTM D 2047 *Standard Test Method for Static Coefficient of Friction of Polish-Coated Flooring Surfaces as Measured by the James Machine*
- ASTM E 303 *Standard Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester*
- ASTM F 609 *Standard Test Method for Using a Horizontal Pull Slipmeter (HPS)*
- ASTM F 1679 *Standard Test Method for Using a Variable Incidence Tribometer (VIT)* (Withdrawn 2006)

All of these methods have been used by manufacturers or researchers in studying slip resistance of detectable warning systems, but were developed for surfaces without truncated domes. One critical difference between detectable warning systems and other types of walking surface is that pedestrians are anticipated to walk on both the tops of the domes and the field. Correspondingly, high slip resistance is required in both locations.

The texture of some detectable warning systems is different on the tops of the domes and the field, leading to different coefficients of friction. Additionally, abrasion will affect the surface that is exposed to the greatest degree of foot traffic, likely the tops of the domes. Therefore, slip resistance measurements should be made on both surfaces.

Key Objective

The key objective in the development of the slip resistance evaluation test was to measure coefficient of friction on both the field and tops of domes with a test apparatus adjustable to fit detectable warning systems of all allowable geometries. Repeatability of the test procedure is essential because this test protocol was developed to support comparisons of detectable warning system performance.

Proposed Method

Summary Description of Method

Slip resistance is measured in general accordance with ASTM F 609-05 *Standard Test Method for Using a Horizontal Pull Slipmeter (HPS)*. A modified slipmeter, denoted here as a detectable warning system slipmeter (DWS), is used to measure coefficient of friction on both the tops of the domes and the field. The Neolite rubber feet are adjustable such that all three feet can be placed on dome tops or the field of detectable warning systems of all allowable dome sizes and spacings.

Each coefficient of friction measurement is obtained by averaging readings performed in four perpendicular directions. Two sets of measurements are taken on both the domes and the field. These eight measurements are reported separately and are averaged to obtain an overall coefficient of friction for the domes and a separate overall coefficient of friction for the field.

This method has been designated Draft T4-33, Part 9 *Recommended Method of Test for Slip Resistance Measurement of Detectable Warning Systems.*

Important Parameters of Method

The important parameters of the method include:

- **Normal force on DWS -** Friction is classically idealized as force resisting relative motion of two materials, independent of an applied normal force. This simplification implies that the friction between two surfaces is a constant, such that the same value could be obtained by measuring friction forces over a wide range of normal forces. However, these simplifications are not valid for resilient surfaces or surfaces with macroscopic irregularities (Marpet, 2002). Many detectable warning systems tested have a variety of intentional surface irregularities on the domes and field to provide slip resistance. Additionally, the Neolite rubber feet used may deform differently around these areas at varying normal forces. These properties result in friction coefficients that vary non-linearly with normal forces. For this reason, the weight of the DWS is specified to standardize the normal force for comparison testing.
- **DWS feet material -** The type of material contacting the measured surface greatly affects the coefficient of friction. For example, according to the literature, testing the same surface with the same slipmeter with leather and Neolite feet resulted in coefficient of frictions that varied from 0.57 to 0.79 (United States Access Board, August 2003).
- **Adjustable slipmeter geometry -** The detectable warning system requirements allow for a wide variation in spacing and dome size on a rectangular grid. The feet of commercially available horizontal pull slipmeters may not align with either the tops of the domes or the available field space on any given specimen. The slipmeter developed for this method has an adjustable feet spacing to allow alignment to all acceptable dome geometries, while maintaining its center of gravity in the same position between three feet.

- **Test temperature -** Coefficient of friction is affected by slipmeter and test specimen temperature (Chang & Maynard, 2006). To limit variation in results, both the slipmeter and test specimen are conditioned to room temperature prior to measurement.
- **Surface moisture -** ASTM F 609-05, Section 4, states that the horizontal pull slipmeter “most likely will not give useful information for evaluating liquid contaminated surfaces”. Wet conditions are not included in this evaluation, because this slipmeter is similar in design and operation to the horizontal pull slipmeter referenced in the standard.

Development Process

Development of the test method began with the production of a shop-made slipmeter. This prototype was designed to rest on three adjacent domes on a detectable warning system. One fixed foot and two adjustable feet were included to meet the variation in dome spacing from 1.6 to 2.4 inches on center. A movable weight, designed to meet the specified weight of the ASTM F 609-05 HPS, was necessary to keep the center of gravity of the unit between the three feet for all possible geometries. The weight was aligned on the DWS with a set of pegs and corresponding holes. The center of gravity of the unit was adjusted by positioning the weight in one of these settings. A photograph of the first generation slipmeter is provided in Figure A19.

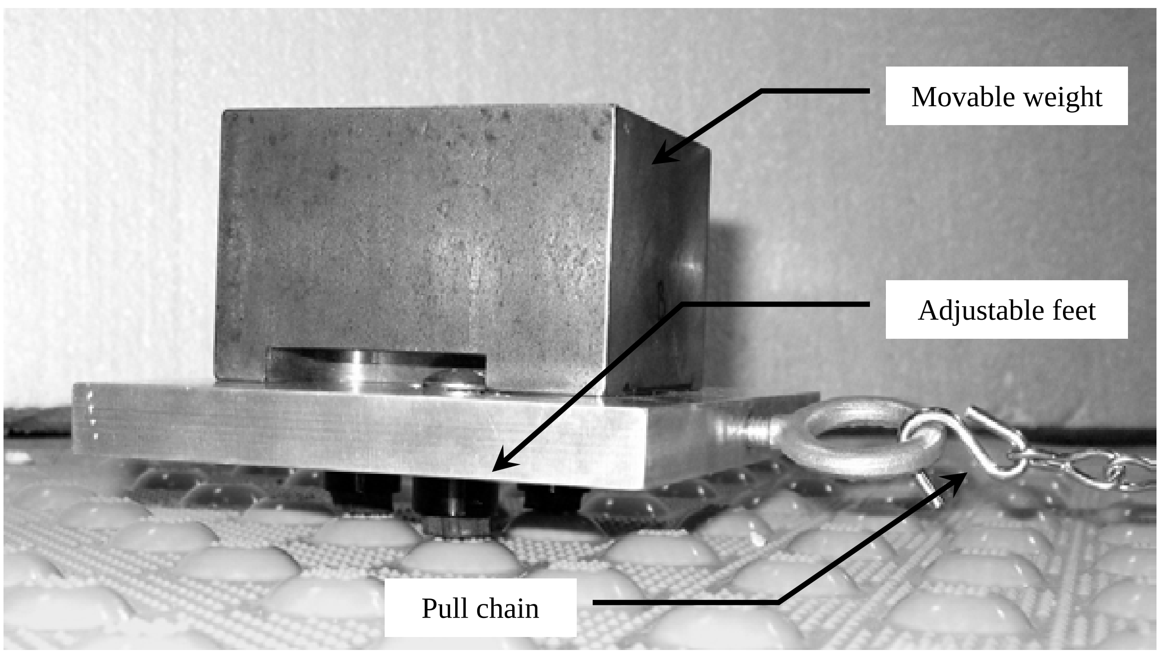
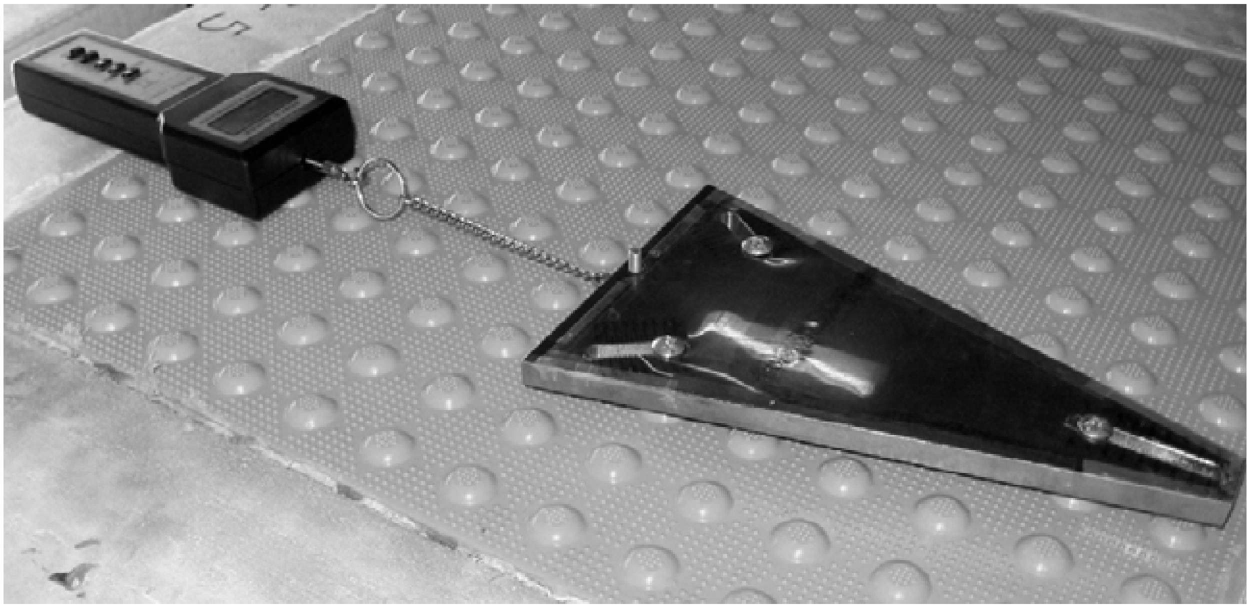


Figure A19. First generation slipmeter, placed on a detectable warning system with the smallest allowed dome-to-dome spacing.

Initial testing of this prototype resulted in multiple usage errors. Variations in the placement of the weight resulted in different coefficient of friction measurements as the center of gravity of the slipmeter changed. Additionally, the narrow spacing of the feet and the shape of the movable weight resulted in stability problems during tests. The force on the pull chain often tipped the slipmeter prior to movement of the feet across the surface.

A second generation prototype was developed to correct these usage difficulties. This prototype was constructed as one, larger, piece which negated the need for a separate movable weight. The wider foot spacing created greater overall stability and eliminated the potential for tipping. Additionally, all three feet were designed to be adjustable. This allowed for the slipmeter's center of gravity to remain constant for all variations in dome spacing without requiring a separate weight. Photographs of the second generation slipmeter are provided in Figure A20.



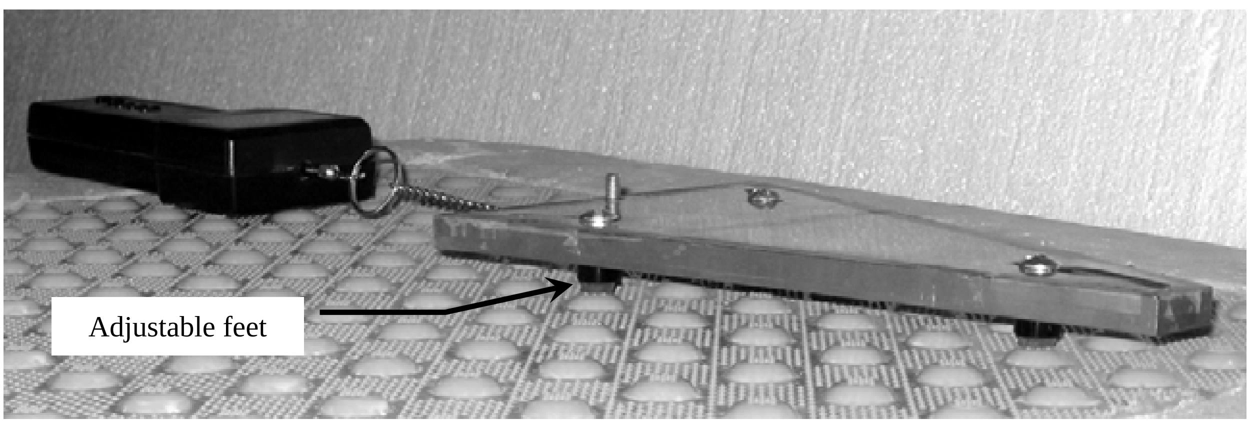


Figure A20 . Photographs of the second-generation slipmeter placed on detectable warning system. Note that the Neolite feet are centered on the tops of the domes.

Multiple types of detectable warning systems were evaluated prior to exposure with the second generation slipmeter. The resulting domes, field, and combined measurements of coefficient of friction are shown below in Table A13.

Table A13. Coefficients of Friction for Detectable Warning Systems

Detectable Warning System Material	Location	Coefficient of Friction (mean ± std. dev.)	Number of measurements
Brick Paver	Domes	0.82 ± 0.04	4
	Field	0.94 ± 0.06	4
Flexible Polymer	Domes	0.71 ± 0.02	4
	Field	0.77 ± 0.07	4
Metal Panel	Domes	0.89 ± 0.11	8
	Field	0.87 ± 0.03	4
Polymer Concrete	Domes	0.80 ± 0.04	8
	Field	0.81 ± 0.05	8
Precast Paver	Domes	0.92 ± 0.09	16
	Field	1.01 ± 0.09	16
Rigid Polymer Cast-in-place	Domes	0.86 ± 0.10	16
	Field	0.86 ± 0.05	16
Rigid Polymer Surface Applied	Domes	0.78 ± 0.12	28
	Field	0.84 ± 0.11	24

Guidance in Use and Interpretation

The slip resistance test was developed as a repeatable and detectable warning system independent method for evaluating coefficient of friction. This test was not intended to directly simulate coefficients of friction obtained by walking or running. However, the test method is based on an established ASTM test method, which has a range of acceptable coefficient of friction measurements.

Target result likely to coincide with acceptable performance

Acceptable performance of surfaces based on a simple coefficient of friction threshold has not been established by a nationally-recognized agency. Multiple standards and regulations have proposed varying numbers, as shown in Table A14. These numbers were either based on specific coefficient of friction test machines or it was unclear which machine or testing conditions should be used to obtain results.

Table A14. Existing Coefficient of Friction Thresholds

Organization	Coefficient of Friction Threshold	Defined Use	Measurement Basis
ASTM D-2047	.5	Polish-coated floors surfaces	Laboratory measured by James Machine
ADAAG 2002 (withdrawn)	.6	Level surfaces	Undefined
	.8	Ramps > 1:20 slope	
ANSI A1264.2	.5	Workplace walking and working surfaces	Undefined

Setting an exact number for acceptable coefficient of friction is impossible without specifying the testing method, tester, and material used to obtain results (United States Access Board, August 2003). Furthermore, a single numeric threshold cannot mean that a surface will be certain to be slip resistant above and slip prone below. Instead of a threshold, slip resistance is a continuous probabilistic function, in which the likelihood of slips increases as the coefficient of friction decreases (Marpet, 2002). For these reasons, the acceptable performance guidelines given below are only intended to rank materials in order of their probability to be slip resistant. The coefficient of friction values used to develop the guidelines are based on the results obtained during initial product testing and consideration of the thresholds provided in Table A14.

Table A15. Anticipated performance rating for slip resistance

Coefficient of Friction (COF)	Anticipated performance rating
COF ≥ 0.8	4 (likely to exceed acceptable performance)
0.7 ≤ COF < 0.8	3 (likely to slightly exceed acceptable performance)
0.6 ≤ COF < 0.7	2 (likely to produce acceptable performance)
0.5 ≤ COF < 0.6	1 (likely to produce slightly less than acceptable performance)
COF < 0.5	0 (likely to produce unacceptable performance)

PART 10

RESISTANCE TO IMPACT FROM SIMULATED SNOW PLOW BLADE OF DETECTABLE WARNING SYSTEMS

Need for Test/Exposure

Snow removal operations, whether conducted with sidewalk plows, snow blowers, a hand-held shovel, or by street plows that cut corners on a curb ramp, are considered to be a significant source of degradation of detectable warning systems in northern states. The responses to the survey conducted of specifying agencies suggested that snow removal operations are a primary concern. Snow removal has been reported to chip and remove domes, to remove colored coatings, and to peel and, in some cases, remove surface applied products. All of these types of degradation can affect the detectability of detectable warning systems and directly limit the durability of such systems.

Basis for Method

There are many types of snow removal equipment, which can exert different degrees of force in different geometries. However, most types of equipment, whether a plow, shovel, or snow blower, have a blade which scrapes the snow off the surface. The impact of this blade moving horizontally is believed to cause the majority of damage to detectable warning systems during snow removal operations.

Despite the consequences of snow removal operations on the durability of a range of pavement-mounted objects, including reflective highway lane markers and detectable warning systems, no standard tests or specifications related to testing snow removal damage were identified. The potential approaches, listed in order of increasing control but decreasing accuracy in representing actual exposure conditions, for such a test method include field evaluations, controlled tests using field equipment, and lab simulations.

Trial installations of detectable warning systems have been conducted by a number of Departments of Transportation (Boisvert, 2003), (Illinois Department of Transportation, 2006). There is precedence for such field tests related to other objects fixed to pavements. For example, ASTM D4383 *Standard Specification for Plowable, Raised Retroreflective Pavement Markers* states specifically that performance of pavement markers is best tested by field application and monitoring. However, such test programs have the disadvantage of taking a long time to perform and providing exposure conditions that cannot be repeated.

Snow plow exposure has been simulated using a truck-mounted plow during studies by various Departments of Transportation, including Chicago and Wisconsin. In this approach, the detectable warning system panels are cast into concrete test slabs or held rigidly and positioned so that a truck-mounted plow can pass over the detectable warning systems at a controlled speed for fixed number times. Observations of the interaction of domes on the surfaces with the steel snow plow blade are made. During one such testing program observed by the research team, the snowplow blade was observed to impact the leading-edge sides of the domes, and bump along the detectable warning surface, repeatedly impacting the surface. Impact damage was not localized to the first rows of domes. There are important parameters of this type testing that can are difficult to control. For example, the conditions of the plow blade used and the ambient temperatures at the time of testing will affect the results.

No currently approved lab-based method, which would be expected to provide the highest level of repeatability, was given in ASTM D4383 or by international standards organizations or the public domain literature. Underwriters Laboratories proposed a snow removal test for the EDWAC program (Evaluation of Detectable Warning Advisory Committee, 2006). In this proposed test, the detectable warning system is mounted 60° from horizontal and a bevel-edged blade is pushed vertically downward against the dome at point 2 mm above the field. The load required to yield the dome is reported. The blade is intended to simulate those found on snow removal equipment. This test provides information on the yield strength of individual truncated domes, but does not simulate the dynamic nature and lateral directionality of snow removal operations.

Key Objectives

The key objectives in the development of the snow removal resistance test were: 1) to produce an accurate representation of the dynamic nature and lateral directionality of the snowplow impact process, and 2) to do this in a manner that was repeatable. Since this test was developed to support comparisons of detectable warning system performance, repeatability of the test procedure is essential.

Proposed Method

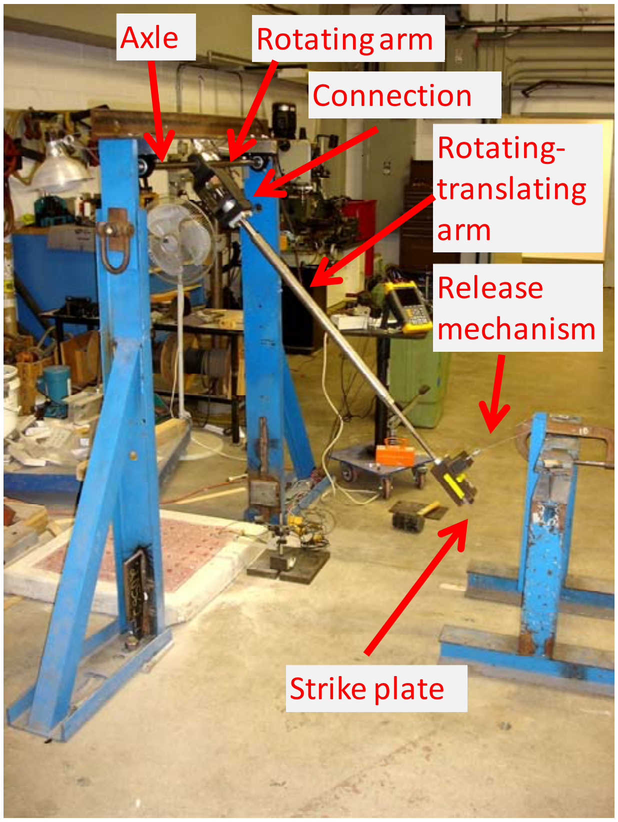
Summary Description of Method

The proposed test method consists of a laboratory-based snow removal resistance test where an impactor, called the strike plate, simulating a snow plow blade and mounted on a pendulum, impacts single domes of detectable warning system/concrete composite systems. The pendulum is designed to simulate the movement of a snow plow blade, so that the strike plate impacts the dome moving in the plane of the detectable warning system. The pendulum shaft allows upward vertical movement of the impactor, so that the impactor can “bounce” upward and lift over the surface of the tested dome at impact. This type of dynamic movement is consistent with that of actual plows, which continue to move over the system after making initial contact. The pendulum consists of two connected rigid arms: 1) a rotating arm and 2) a rotating-translating arm. The rotating arm is mounted to an axle and the rotating-translating arm is attached to the rotating arm by a connection that allows the rotating-translating arm to move along the axis of the pendulum arms. The tests apparatus is shown in Figure A20. (Also see schematic diagram in test method.)

A total of three domes on the edge of the samples are impacted during a single test. The type and extent of damage is ranked from A (least damage) to F (greatest damage) for each of these domes by comparison with standard schematics. The effect of the impact is documented photographically.

The snow removal resistance test is not intended to be conducted to evaluate performance in the Hot Exposure Category.

This method has been designated Draft T4-33, Part 10 *Recommended Method of Test for Resistance to Impact from Simulated Snow Plow Blade of Detectable Warning Systems*.



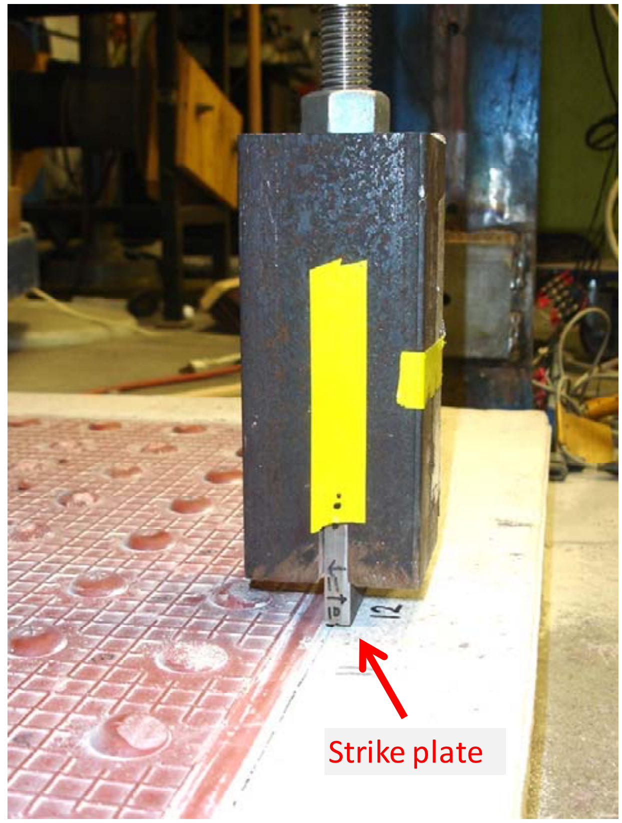


Figure A21. The snow removal resistance test setup.

Important Parameters of Method

The important parameters of the method include:

- Test of detectable warning/concrete performance - Since the mechanical response of the detectable warning system sample is directly influenced by the manner in which it is supported, it is essential that the system be held in place in a manner representative of actual installations.
- Energy - Measuring the response to a force acting on the detectable warning systems does not provide a uniformly equivalent test of performance across material types, since the stiffness of the systems may vary greatly and so the response to an applied force will be not be consistent. The best method for inducing damage representative of actual snowplow activities in consistent manner is to do so at a constant energy. The energy applied to the sample is controlled by the weight of the pendulum and the height from which it is released. The weight of the pendulum was selected to provide a similar resistance to upward movement as would exist for a pickup truck-mounted plow. This resistance to lifting is provided by gravity acting on the rotating-translating arm, which weights 13 ± 0.5 kg [28.6 ± 1.1 lbs.]. This is comparable to the weight acting over a single dome applied by a 300-lb. plow distributed over 10 domes, which is the minimum number of domes possible over a 24-in. long edge of a detectable warning system. With this pendulum, the height from which the pendulum is released has been adjusted to provide damage consistent with that observed during a controlled field test, as discussed below.

- Strike height - The height at which a truck-mounted blade strikes a detectable warning dome will influence the nature of the resulting damage. The height at which a truck-mounted blade will strike is largely controlled by the detectable warning system relative to the height of surrounding features such as the concrete or other domes. Depending on this height, damage can range from complete removal of the dome to simple abrasion across the top of the dome. The height of the strike on the domes is defined to be 3.0 ± 0.25 mm [0.12 ± 0.01 in.] above the field. This was selected to be consistent across the various types of products and produce damage similar to the controlled field test.
- Blade material/shape - The impactor blade consists of AISI 1065 Steel with controlled microstructure and hardness, which is representative of commonly available truck-mounted plow replacement blades. The blade edge is ground to 90º angle. This allows the edge to be easily reconditioned after the strike plate shows wear.
- Temperature of sample - The impact resistance of some detectable warning system materials, particularly polymers, may be influenced by the material temperatures. Therefore, this test will be conducted with the samples at -7 to -1ºC [20 to 30ºF], a range selected to be representative of actual temperatures during snow events and easy to replicate.

Development Process

The development process for the snow removal resistance test consisted of two efforts. The first focused on developing robust equipment capable of producing the desired motion, while the second effort involved fine tuning the parameters of the test.

After the pendulum system was constructed, stop-motion photography using a strobe light flashing at 150 Hz as the source illumination was performed to verify that the rotating-translating arm was allowing the strike plate to move vertically over the dome as desired. Figure A22 shows the path of the impactor passing over and striking a dome. The desired upward movement was observed.

To evaluate the consistency of the pendulum motion and to provide a secondary means for evaluating the energy of the pendulum prior to impact, a set of timing gates were used to determine the velocity of the head of the pendulum at the bottom of its swing. This was highly repeatable, and the measurement was not judged to be essential for the final recommended test method.

Initial trials using a strike plate fabricated from tool steel demonstrated that detectable warning materials are resilient enough to cause significant wear on the steel plate. This wear resulted in a marked difference in impact-related damage at fixed energies and was judged to be unacceptable in a laboratory test setting. As a basis for selecting a more appropriate material, an actual replacement snow blade was obtained from a snow plow manufacturer and was used to prepare strike plates. This has resulted in more consistent performance, and this steel was characterized metallurgically. The material properties provided in the recommended method are based on the metallurgical analysis.

Figure A22. Stop motion photographs of snow plow head passing over dome without impact (top) and with impact (bottom). Note path of black dots on impact head and change in overlap of strip of tape. Photo taken with strobe flashing at 150 Hz.

Once the test setup was finalized, the energy and strike height were adjusted to levels that would produce damage consistent with that observed during a controlled field test, previously conducted by the research team. In this field test, a 2.4m (8-ft) steel-edged snow plow blade mounted to a pickup truck was scraped across the surface of the tile multiple times at a nominal plowing speed, which averaged 11 kph (7 mph). The self-weight of the plow blade was 144 kg (317 lbs.) Each test series was conducted on a line of three ganged samples and the test repeated in three sets. The types of detectable warning systems tested were cast-in-place rigid polymer composite, cast-in-place metal panel, and cast-in-place polymer concrete. The truck passed over the panels 50 times for each set, and testing was conducted during the winter in the Chicago area.

Photos of the damage produced by testing of detectable warning systems using the pendulum developed above were compared to photos of damage produced during the field tests. The types of detectable warning systems tested during development of the snow removal resistance test were cast-in-place rigid polymer composite, cast-in-place metal panel, and cast-in-place polymer concrete, and surface applied single domes. Various strike heights (ranging from 0.25 to 0.38 mm [0.010 to 0.015 in.]) and energies were tested (ranging from 12 to 61 J [9 to 45 lb-ft]), before the recommended strike and energy was selected.

Guidance in Use and Interpretation

The snow removal resistance test was developed as a repeatable and detectable warning system material-independent method for simulating snow removal operations, characterized by impact from a horizontally moving steel surface. However, the snow removal processes to which the detectable warning systems could be exposed in the field are widely varied in nature and intensity, and the recommended method represents only one set of conditions. Nevertheless, the recommended method provides a means for objectively comparing the responses of differing detectable warning systems.

During this project, four types of detectable warning systems were tested: cast-in-place metal, cast-in-place rigid polymer composite, surface applied single dome, cast-in-place polymer concrete. Further evaluation is needed using this method on a wide range of detectable warning system types to demonstrate the universal applicability of this method. In addition, further study is needed to link performance in this test with actual field performance.

Target result likely to coincide with acceptable performance

Correlating field performance of detectable warning systems exposed to snow removal operations is difficult due to the potential variability in the forces to which the detectable warning systems will be exposed. However, based on the observed performance of the limited number of sample types included in the controlled field test, the following general guidelines for interpreting the results of the snow removal resistance test are given:

Table A16. Anticipated performance rating for impact from simulated snow plow blade

Assigned Damage Classification	Anticipated performance rating
A	4 (likely to significantly exceed acceptable performance)
B	3 (likely to slightly exceed acceptable performance)
C	3 (likely to slightly exceed acceptable performance)
D	2 (likely to produce acceptable performance)
E	1 (likely to produce slightly less than acceptable performance)
F	0 (not likely to produce acceptable performance)

PART 11

RESISTANCE TO IMPACT FROM FALLING TUP OF DETECTABLE WARNING SYSTEMS

Need for Test/Exposure

In use, detectable warning systems are subject to impact from a wide variety of sources. Pedestrians carrying objects may drop them, and if a heavy object lands with a concentrated force on a dome, damage can result. Another potential source of impact damage is from wheeled carts and hand trucks pushed over the surface of detectable warning system. An example of this phenomenon is a delivery person bearing a hand truck or cart loaded with packages or products. If the cart is wheeled over the truncated domes, the cart will repeatedly impact the detectable warning system. The force of this type of impact has the potential to cause more severe damage than could be caused by a pedestrian, because the mass of the material on the cart can be quite high. Other sources of impact can also be envisioned, such as a person riding a bicycle over the detectable warning system.

All exposure regimes are anticipated to affect the impact resistance of detectable warning systems. Surface degradation from ultraviolet exposure can lead to decreased impact resistance, especially of the surface regions. Freeze/thaw and high temperature thermal cycling exposure can lead to cracking of the systems, which can decrease impact resistance. Abrasion may affect impact resistance by reducing the dimensions of the domes, so that a single impact event results in an even greater deviation from the original dome dimensions.

Basis for Method

This test reported here is most directly analogous to damage that may occur due to vertical impacts from a dropped object, from hard-wheeled carts, or from high heeled shoes. A pedestrian could reasonably carry a 3.5 kg (8-lb) object and drop it from approximately waist height (0.75 to 1 m [30 to 40 inches]). Impact damage may also occur from wheeled vehicles (such as hand carts used to deliver packages traversing such surfaces. The magnitude of this impact is more difficult to simulate, as the force depends greatly on the loads carried, the size and type of wheel, and the relative magnitude of the horizontal and vertical forces applied to the cart. However, comparisons of the level of damage from this impact test can be used to assess impact resistance in general. The two types of impacts are expected to occur with different frequencies. Pedestrians will occasionally drop objects, although this is a fairly rare occurrence. This type of impact is anticipated to result in damage to isolated domes. In some locations, such as near retail outlets or places of business, wheeled carts laden with material may traverse a detectable warning system multiple times per day. This type of impact may result to damage to multiple domes, often in the rows where the carts traverse most frequently.

Two test methods for impact resistance have been used by detectable warning systems manufacturers:

- ASTM D5420 *Standard Test Method for Impact Resistance of a Flat, Rigid Plastic Specimen by Means of a Striker Impacted by a Falling Weight (Garnder Impact)*
- ASTM D2444 *Standard Test Method for Determination of the Impact Resistance of Thermoplastic Pipe and Fittings by Means of a Tup (Falling Weight)*

A similar method is available in the literature:

- ASTM D5628 *Standard Test Method for Impact Resistance of Flat, Rigid Plastic Specimens by Means of a Falling Dart (Tup or Falling Mass)*

All of these methods are component tests and measure the mean failure energy of an unsupported plastic specimen. However, the impact resistance of a detectable warning system/concrete composite will be significantly affected by the underlying concrete support, so a component test of an unsupported detectable warning system is not a suitable test to evaluate potential field performance.

Key Objectives

The key objectives in the development of the impact resistance test were: 1) to adapt a standard test method to conduct impact testing on detectable warning system/concrete composites, and 2) to create a repeatable laboratory test. Since this test protocol was developed to support comparisons of detectable warning system performance, repeatability of the test procedure is essential.

Proposed Method

Summary Description of Method

The proposed test method consists of an impactor that is dropped onto domes of the detectable warning system/concrete system. The energy of impact is controlled by a combination of impactor mass and drop height. The tup is a standardized, 25 mm (1 inch) diameter hardened steel hemisphere, as defined in ASTM D5628. Each set of tests consist of impacting three separate domes at each of three impact energies.

For the testing according to the Cold Exposure Category, tests are carried out at both room and freezing temperatures. The freezing impact resistance test is not intended to be conducted to evaluate performance in the Hot Exposure Category, although tests at room temperature are still carried out.

This method has been designated Draft T4-33, Part 11 *Recommended Method of Test for Resistance to Impact from Falling Tup of Detectable Warning Systems.*

Important Parameters of Method

The important parameters of the method include:

- Test of detectable warning/concrete performance - Since the response of the system is critical to measuring impact durability, this test is performed on the detectable warning system/concrete system only, not on individual components.
- Tup - A standardized tup is used, so that the impactor will always have the same geometry and hardness.
- Impact energy - The tests are performed at up to two impact energies: 27, and, if desired, 54 J (20 and 40 ft-lb). The impact energy is determined by the combination of impactor weight and height of drop. The same energy can be imparted by dropping a 10-kg impactor 40 cm as dropping an 8-kg impactor 50 cm. This allows some flexibility for the testing agencies to devise an impact tester suitable for their facilities.

- Consolidation of concrete under tested domes - The degree of consolidation of the concrete underneath the domes can have an effect on the impact resistance of a detectable warning system. If the concrete is poorly consolidated, the system may be more likely to suffer damage as a result of an impact event. The degree of consolidation underneath the detectable warning system should be as uniform as possible, and should be considered when selecting domes for testing. As stated in the method, any imperfections in the consolidation, determined on the basis of sounding, should be noted.
- Temperature - The impact resistance of the detectable warning systems may be affected by temperature since some materials, particularly polymers, tend to behave in a more brittle manner when cold than at room temperature.

Development Process

The development process of the impact resistance test consisted of two efforts. The first focused on developing equipment suitable for positioning and executing the impacts. The second focused on implementing and refining the test procedure.

An impactor was constructed that allowed a wide variety of impact energies to be imparted to the system, as well as easy positioning of the impactor above the desired dome. The impactor consists of a tup, which screws into a steel weight. The tup and weight were placed into a steel guide tube. The tube is approximately 2 m (7 feet) high, to allow for a variety of impact energies. The tup is raised and lowered via a rope attached to a pulley at the top of the guide tube. The impactor is attached to a rolling frame. The frame has casters that allow movement in multiple directions. This frame can be positioned so that the impactor can be placed directly over any desired dome. A photograph of the impactor is provided in Figure A23. Photographs of impact tests on a detectable warning system sample are provided in Figure A24 and Figure A25.

Prior to the implementation of the rolling impactor, for a similar project, a stationary impactor was used. In that case, the detectable warning system/concrete composite system had to be moved and positioned accurately so that the tup would line up with the center of the dome. This was obviously difficult due to the weight of the concrete slab. The concrete slab was placed directly on a concrete slab floor and could not be placed on rollers because any flexibility or “give” in the support of the slab would affect the impact resistance results. Therefore, the addition of casters to the impact tester was important to allowing single-user operation of the test.

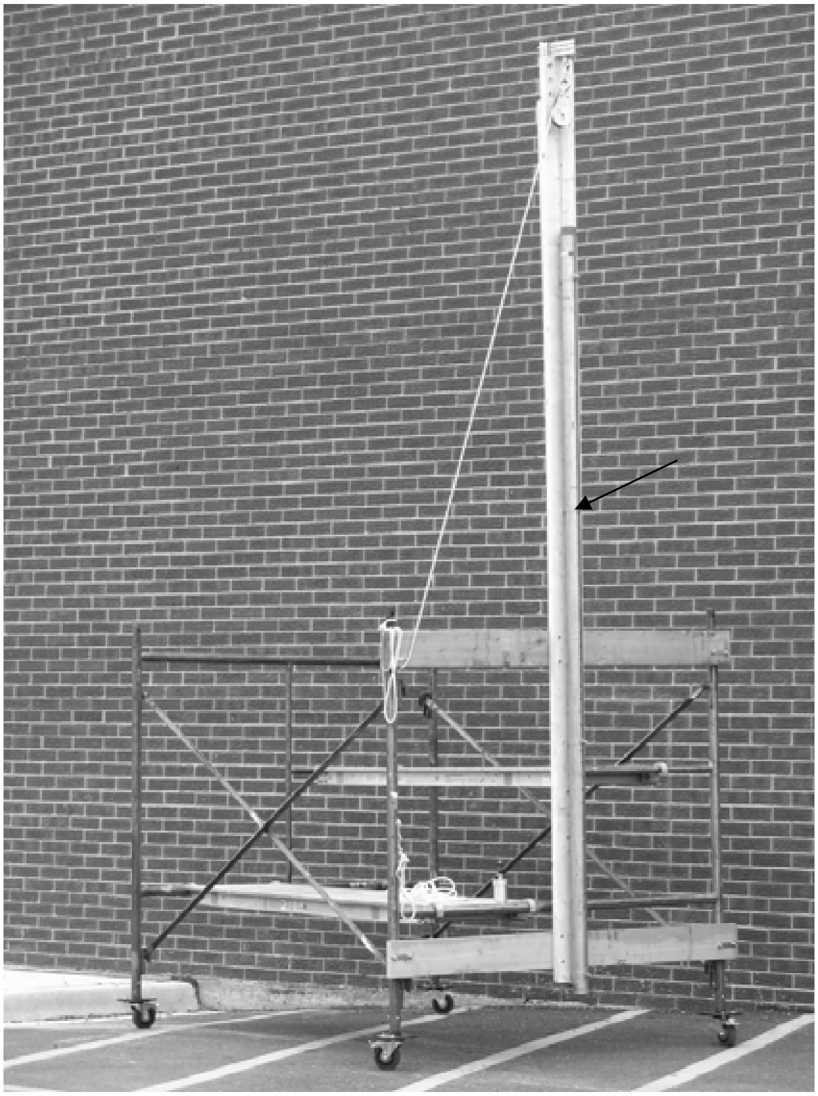


Figure A23. The impact tester. The metal guide tube is indicated with an arrow. The blue casters allow easy positioning of the impactor over the detectable warning system. In this photo, the mass and tup have been retracted through the guide tube.

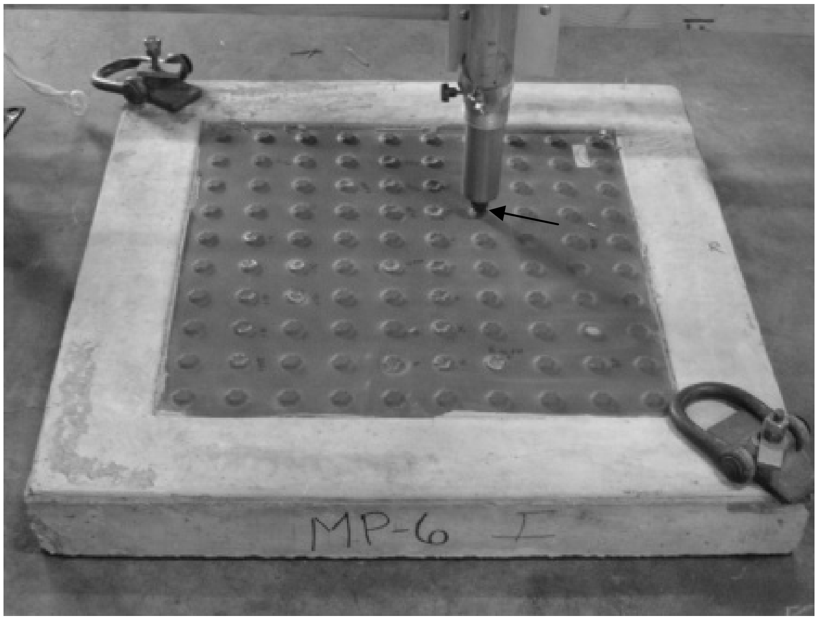


Figure A24. The tup (indicated with an arrow) impacting a dome. The cylinder is the steel weight attached to the tup.

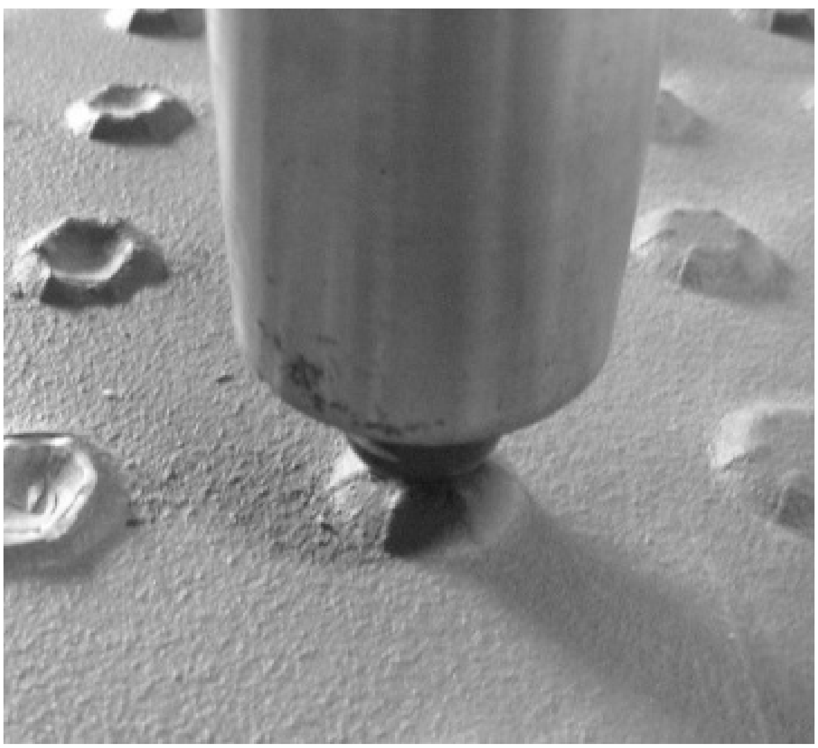


Figure A25. The tup centered on a dome.

Once the equipment was fabricated, development of the testing process began. Different impact energies were imparted to the surface by dropping the impactor from various heights. Three types of detectable warning system were tested: cast-in-place polymer concrete, cast-in-place metal panel, and surface applied flexible mat. Results from the testing at room temperature and freezing are presented in Table A17.

Table A17. Results from Impact testing.

Material	Temperature	Impact Energy (J)	Rating (Impact Method)
Metal Panel	Room Temperature	14	B
		27	B
		40	B or C
		54	C
		81	C
		108	D
	-7 to -1 °C	14	B
		27	B
		40	B or C
		54	C
		81	D
		108	D
Polymer Concrete	Room Temperature	7	B
		14	C
		27	D
		40	E
		54	E
		81	F
	-7 to -1 °C	7	B
		14	B or C
		27	E
		40	E
		54	F
		81	F
Flexible Polymeric Mat	Room Temperature	40	A
		54	A
		108	B
	-7 to -1 °C	40	A
		54	B
		108	B

The response to an impact of a particular energy varied greatly from one system type to another. Also, within a particular sample, the effect of an impact of a particular energy varied if the degree of consolidation of concrete underneath the tested dome varied. The degree of consolidation was tested by sounding the surface. A hollow sound indicated poor consolidation, where there may be a gap or void in the concrete underneath the detectable warning panel. Areas of poor consolidation generally suffered more damage from a given impact energy than areas of greater consolidation. Poor consolidation is not anticipated to be a problem with surface applied systems, where the concrete is finished prior to application of the detectable warning system, but can be a problem with cast-in-place systems. Therefore, prior to testing, the sample should be sounded for consolidation. If possible, testing should be conducted on well-consolidated domes.

Guidance in Use and Interpretation

The impact resistance test was developed as a repeatable and detectable warning system material-independent method for evaluating impact resistance. This test is not intended to simulate a particular impact event, but rather to be a repeatable method for making comparisons between detectable warning systems before and after exposure and between detectable warning systems. However, the impact energy was chosen to have characteristics of events that may occur in use. Further study is required to link performance in this test with actual field performance.

Target result likely to coincide with acceptable performance

Correlating field performance of detectable warning systems exposed to impact is difficult because of the lack of field data on the types of impacts that detectable warning systems receive in use. Based on the observed performance of the limited number of samples tested, the following general guidelines for interpreting the results of the impact resistance test are given, based on impacts at an energy of 27 J (20 ft-lb).

Although no guidelines for retention of detectability are available, these ratings assume that some minor loss of dome dimension is not an indication of unacceptable durability. However, a loss of more than 50% of a dome for a 27 J (20 ft-lb) impact is considered a sign of poor durability.

Table A18. Anticipated performance rating for impact at 27J (20 ft. lb)

Assigned Damage Classification	**Anticipated performance rating**
27 J (20 ft-lb)	
A	4 (likely to exceed acceptable performance)
B	3 (likely to slightly exceed acceptable performance)
C	2 (likely to produce acceptable performance)
D	1 (likely to produce slightly less than acceptable performance)
E	0 (not likely to produce acceptable performance)
F	0 (not likely to produce acceptable performance)

In some locations, agencies may wish to specify a detectable warning system with a higher impact resistance. In this case, testing at a higher impact energy is advisable. For this reason, testing at 54 J (40 ft-lb) may be optionally carried out. Guidelines for interpreting the results of the impact resistance test, based on impacts at an energy of 54 J (40 ft-lbs), are given below. Obviously, the use of this scale will produce a rating that cannot be directly compared to the rating obtained from a 27-J (20 ft-lb) impact.

Table A19. Anticipated performance rating for impact at 54J (40 ft. lb)

Assigned Damage Classification	**Anticipated performance rating**
54 J (40 ft-lb)	
A	4 (likely to exceed acceptable performance)
B	3 (likely to slightly exceed acceptable performance)
C	2 (likely to produce acceptable performance)
D	1 (likely to produce slightly less than acceptable performance)
E	0 (not likely to produce acceptable performance)
F	0 (not likely to produce acceptable performance)

PART 12

WEAR RESISTANCE OF DETECTABLE WARNING SYSTEMS

Need for Test/Exposure

As noted in the previous section discussing abrasion exposure (Part 4), abrasion is a significant source of degradation of detectable warning systems. Abrasion, from foot traffic or wheeled traffic, may make detectable systems more susceptible to other types of deterioration. Similarly, alteration of dome height and texture can critically affect the function of detectable warning systems.

Because both the ability of a system to resist wear and the effect that abrasion can have on overall durability are significant to the performance of detectable warning systems, the abrasion/wear mechanisms are considered in this detectable warning system testing protocol as both an exposure regime and as an evaluation test. The evaluation test, which is discussed in this section, quantifies the resistance of a detectable warning to abrasion. To differentiate the two, the evaluation test considering abrasion is referred to as the "wear resistance" test.

Basis for Method

The standard test methods available for evaluating abrasion performance were previously reviewed in the section discussing the abrasion exposure (Part 4). In that section, the need for a procedure for simulating the abrasive effects of foot traffic was discussed. However, there is also a need to assess the ability of detectable warning systems to resist wear in a controlled, rapid manner. The wear resistance test, which will be conducted as an evaluation test after the exposure regimes, fulfills the latter need. This test will measure resistance to degradation rather than simulate the abrasive forces that might be encountered in use. The severity of the wearing action is significantly greater than that of the abrasion exposure. The test method was developed based on a modification to ASTM C 241-09 *Standard Test Method for Abrasion Resistance of Stone Subjected to Foot Traffic*.

Key Objectives

The key objectives in the development of the wear resistance evaluation test were to quantify the dome loss caused by abrading the dome surface in a rapid, controlled, and consistent manner. Since this test protocol was developed to support comparisons of detectable warning system performance, repeatability of the test procedure is essential.

Proposed Method

Summary Description of Method

The proposed test method evaluates the surface of a 150 mm (6-in.) diameter specimen cored or otherwise cut from a detectable warning system/slab sample. This surface specimen is held with a fixed weight against an aluminum oxide abrasive sand paper affixed to a lapping wheel, which is rotated at a fixed speed for a specific number of revolutions. The specimen is rotated intermittently during the test to ensure even abrasion. The wear resistance of the detectable warning system is assessed by measuring the dome height before and after the test. A photo of the wear resistance test apparatus is shown in Figure A26 and a schematic drawing of the fixture used to hold the specimen is given in Figure A27.

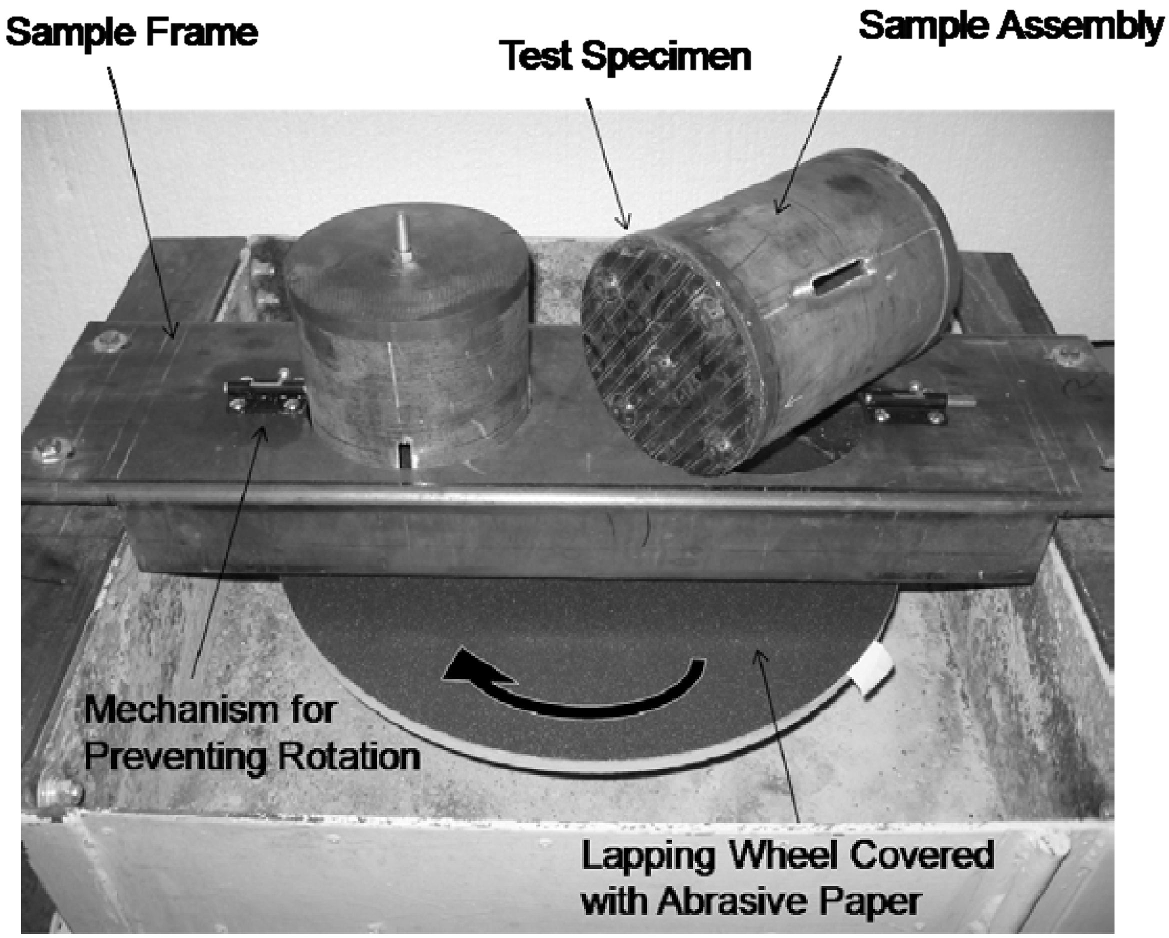


Figure A26. Photo of wear resistance sample frame assembly.

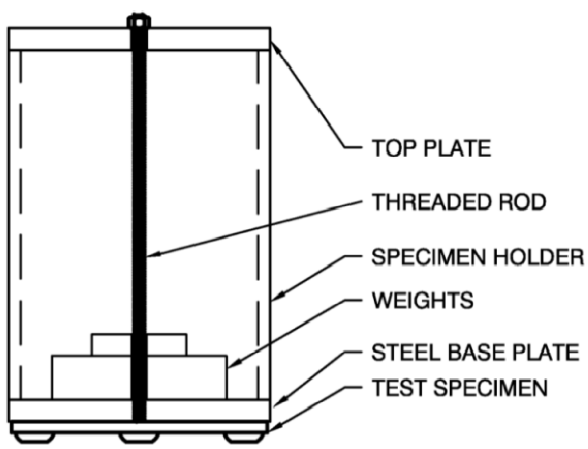


Figure A27. Schematic of cross section of sample assembly used to hold test specimen vertically in sample frame. The amount of weight was adjusted to produce the specified normal force.

This method has been designated Draft T4-33, Part 12 *Recommended Method of Test for Wear Resistance of Detectable Warning Systems*.

Important Parameters of Method

The important parameters of the method include:

- Normal force on sample - The amount of wear experienced by the tops of the domes in the detectable warning system specimen during this exposure is directly influenced by the pressure applied to the abrasive paper. This pressure is determined by the weight of the sample assembly and the amount of dome surface in contact with the abrasive. It is essential that the weight of the combined sample assembly and specimen is adjusted to the specified value before testing.
- Sample position - On a lapping wheel, a specimen positioned closer to the edge of the wheel will be worn by a longer travel path of abrasive during each revolution than a sample placed nearer to the center. To limit variation in results, the specimen position relative to the center of rotation of the lapping wheel is specified by the test method. In addition, the specimen is rotated multiple times during the test so each dome is tested at a similar distance from the center of rotation for an equal amount of revolutions.
- Abrasive paper - The nature of the abrasive will determine the severity of the wearing action, and the binding adhesive and paper used to hold this abrasive against the systems will determine the consistency of exposure during the test cycles. Specifying and achieving uniformity in the wearing action is important for the repeatability of this method.
- Number of cycles - More cycles will result in more abrasive action. Test time and rotation speed of the lapping wheel is specified to control the severity of the abrasion.
- Number of domes included in specimen - For similarly sized domes, increasing the number of domes per unit area of the specimen reduces the effective pressure on the top of each dome, reducing the wearing action on each dome. The same effect will occur on detectable warning systems in use. The test method requires that the maximum number of complete domes that can fit within a 150 mm (6-in.) diameter circle be taken as part of the core, and incomplete domes removed prior to testing. These two steps ensure that the number of domes per unit area on the cored sample is approximately equal to the number of domes per unit area across the entire specimen.

Development Process

Development of the wear resistance method focused on finding a repeatable procedure that produced uniform abrasion over the dome surfaces. Circular samples were cut from the detectable warning systems with a concrete coring machine. The difficulty in removing detectable warning systems from the substrate varied. For systems that were easily removed from the concrete substrate after coring, the detectable warning system specimen was removed and directly adhered to a metal puck, which could be mounted in the sample assembly for testing. For systems that were well-bonded to the concrete substrate, the back end of the concrete core was cut to leave a thin slice of concrete fixed to the detectable warning system, and then both the concrete slice and specimen was adhered to the metal puck in the sample assembly.

Two options for producing the abrasive action were explored. First, loose abrasives applied to a lapping wheel in a dry condition were investigated. However, difficulties were encountered in providing a consistent amount of abrasive to the specimen over the course of the test. Loose abrasive tended to build up on the leading edges of the domes, and the exposure to this abrasive was not uniform from the interior to exterior of the wheel.

Next, adhesive-backed abrasive discs were investigated. These discs had uniform grit distribution and eliminated build up of material on the leading edge of the domes. Multiple types of abrasive, including silicon carbide, zirconia alumina, and aluminum oxide, and multiple grits were explored. Trials were conducted on various detectable warning systems, including polymer concrete, rigid polymer, and flexible polymer materials. With the various abrasive types, the observed wear varied from the removal of very little of the dome height to complete dome removal and abrasion of the detectable warning field. Repeatability was achieved by using a new abrasive disc for each test. The most suitable abrasive was determined to be 60 grit aluminum oxide abrasive cloth. This abrasive tended to produce a wide distribution of dome height reduction between the various materials, without resulting in complete dome loss. Complete dome loss was undesirable for the wear resistance test, because it was difficult to quantify performance when the field of the sample began to abrade.

Due to the difference in tangential velocity between interior and exterior portions of the lapping wheel, it was necessary to rotate the specimen relative to the test frame. It was determined that, after the initial abrasion, three rotations of the specimen through 90º were sufficient to achieve consistency across all of the domes on each specimen. Figure A*28* shows uneven abrasion resulting from insufficient sample rotation during the test.

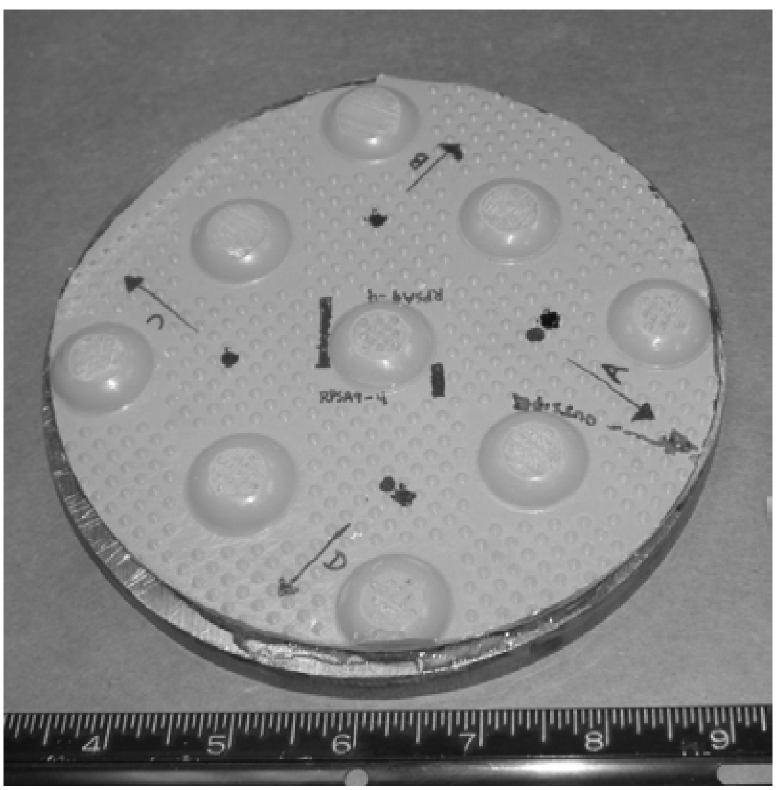


*Figure A*28*. Example of uneven wear resulting from lack of specimen rotation during abrasion exposure: domes at top and left of photo are worn more than domes at bottom and right.*

Table A20 shows some representative results and for the flexible polymer and polymer concrete samples. Table A20 and Table A21 show representative photos of these samples before and after wear resistance testing.

Table A20. Sample Results from Wear Resistance Testing

Sample ID	Average Dome Height Loss (mm [in])
Flexible Polymeric Mat	3.2 [0.13]
	4.2 [0.17]
	4.9 [0.19]
	4.8 [0.19]
	4.2 [0.16]
	5.2 [0.20]
Polymer Concrete	0.9 [0.03]
	1.0 [0.04]
	0.8 [0.03]
	1.0 [0.04]

Guidance in Use and Interpretation

The wear resistance test was developed as a repeatable and detectable warning system material-independent method for evaluating abrasion resistance. This test was not intended to simulate a particular abrasion source, but rather to be a repeatable method for making comparisons between detectable warning systems before and after exposure and between detectable warning systems. Further study is required to link performance in this test with actual field performance.

Target result likely to coincide with acceptable performance

Defining acceptable performance of detectable warning systems tested using this wear resistance method is difficult because data is not available to correlate field performance and these test results. However, based on the performance of the limited number of samples tested, the following general guidelines for interpreting the results of the wear resistance are provided. Dome loss in these tests does not directly correlate to expected dome loss in in-service applications. Furthermore, since the assignment of a performance rating of “0” could lead to the detectable warning system product being considered unacceptable regardless of performance in other evaluation tests, a performance rating of “0” (not likely to produce acceptable performance) is not included. This is because such a strong conclusion is not justified based on the limited understanding of how this test correlates with field performance.

Table A21. Acceptable performance guidelines

Average Dome Height Loss, x (mm [in])	Anticipated performance rating
$x < 1.3$ [0.05]	4 (likely to exceed acceptable performance)
1.3 [0.05] $\leq x <$ 2.5 [0.10]	3 (likely to slightly exceed acceptable performance)
2.5 [0.10] $\leq x <$ 3.8 [0.15]	2 (likely to produce acceptable performance)
$x \geq 3.8$ [0.15]	1 (likely to produce slightly less than acceptable performance)

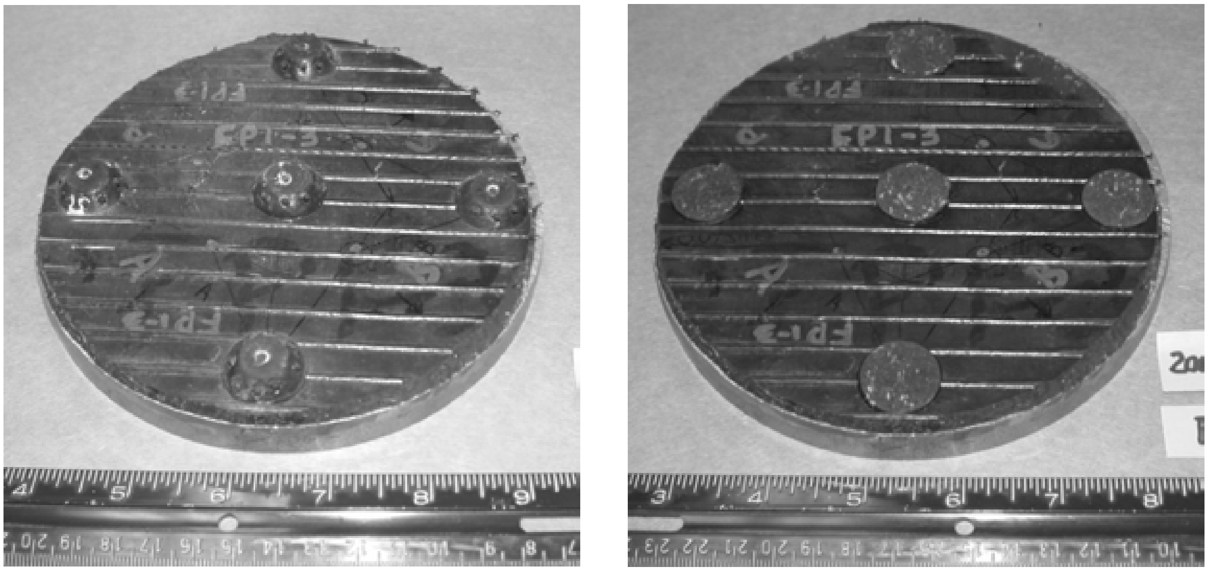


Figure A29. Representative photo of flexible polymer specimen before (left) and after (right) wear resistance test.

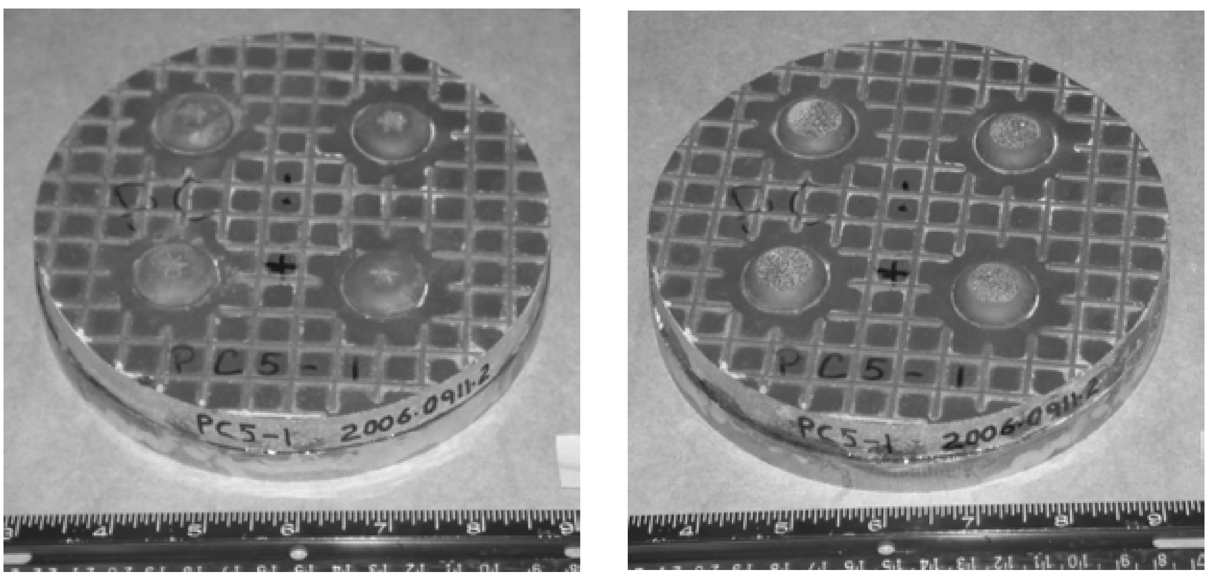


Figure A30. Representative photo of polymer concrete specimen before (left) and after (right) wear resistance test.

PART 13

SYSTEM BOND OF DETECTABLE WARNING SYSTEMS

Need for Test/Exposure

System bond describes the adhesion or anchorage of the detectable warning system to the sidewalk. There are a wide range of methods by which the currently-available systems are fixed in place. Detectable warning systems that are cast-in-place are anchored by several methods, including fins that are an integral part of the detectable warning system and are placed into the concrete, anchors that are attached to the detectable warning system surface by bolts, or pins that are pressed into the fresh concrete. Surface applied systems generally use adhesive to fix the system to the concrete surface, and this adhesive may be supplemented by the use of bolts or pins placed into the cured concrete. Pavers are held in place with mortar or other setting materials.

While a detectable warning system is unlikely to ever experience an upwardly directed vertical load in its service life, an evaluation of the relative system bond performance is important for evaluating detectable warning system durability, because it gives an indication of the overall structural integrity of the system. If the detectable warning system becomes debonded from the sidewalk, at best, the system no longer serves its purpose of detectability, and at worst, becomes a tripping hazard for pedestrians.

Basis for Method

Most manufacturers do not specifically test the adhesion or anchorage of their detectable warning system. This performance is fundamentally a system test, i.e. a test of the detectable warning product and the concrete into or onto which it is installed.

Underwriters Laboratories proposed using two tests for the EDWAC program (Evaluation of Detectable Warning Advisory Committee, 2006) to address adhesion:

- ASTM C1583 *Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension* (Pull-off Method)
- A specifically designed edge peel adhesion test for use with flexible polymer mat systems that use an adhesive for attachment.

A primary drawback of localized testing of only a portion of the surface is the difficulties in selecting a representative area of the system to test. In addition, since many different system configurations exist, a method is needed for normalizing the pull-off force measured in the tested area to the whole system, so that the performance of different systems can be compared. Because of the difficulties in developing a suitable normalization method, a large scale pull-off test of entire detectable warning units embedded in concrete slabs was previously conducted in a study performed by the research team. The smallest commonly available detectable warning unit is 0.6 x 0.6 m (2 x 2 ft), so this was the size of the sample tested. The test was conducted by applying an upwardly directed vertical load to a rigid (25-mm [1-in.] thick) steel plate bonded to the detectable warning surface using a linkage with a universal joint and a frame that rested on the edge of concrete surrounding the system. The plate was fixed to the system surface with high-modulus, high-strength epoxy adhesive.

This full-scale test was generally successful at identifying poorly anchored systems. However, for systems with strong anchorage systems, this testing was hampered by a number of difficulties. First, the large test area made application of a uniform, vertical load difficult. The large test area required loads of high magnitude, so testing was limited by the capacity of the testing frame. In addition, for flexible systems, deflection in the system at locations away from rigidly fixed anchorage points allowed the tile to peel away from the bonded plate. Despite experimentation with various adhesives and surface preparation techniques, bond across the full sample was not achieved for all products tested. Also, even if the deflections did not result in debonding from the plate, their presence meant that the anchorages were not mobilized simultaneously, which introduced variability in the test results. Another disadvantage of testing in this manner was that an entire detectable warning system/slab sample was consumed for each test.

Because of the shortcomings in a full-scale test, this research effort focused on developing a workable test on a localized area that would produce results that could be normalized to represent the entire system area.

Key Objectives

The key objective for the system bond test was to measure the effectiveness of the detectable warning anchorage system, while allowing comparisons between detectable warning system designs and supporting characterization of the effects of exposure on system bond. Since this test was developed to permit comparisons of detectable warning system performance, repeatability of the test procedure is essential.

Proposed Method

Summary Description of Method

As described in the discussion below regarding the development of this test, difficulties in obtaining repeatable results, representative of the full system response, prevented finalization of a method. Therefore, no method has been proposed.

Important Parameters of Method

The important parameters of the method include:

- Test location and preparation for test - Since the response of the detectable warning system sample is directly influenced by the manner in which the anchorage is achieved, it is essential that the anchorage features, e.g. ribs with holes in them or discrete anchors, be included in the tested area. Most pull-off tests are conducted on a piece of the bonded material after it has been isolated from its surroundings, usually by cutting through the bonded material down to below the interface with the substrate. Isolating a portion of the detectable warning system anchorage system must be done with care, since cutting the system may circumvent the anchorage design. For example, cutting through the full depth of anchorage ribs in a detectable warning system may prevent adjacent anchorage features from contributing to the response, as would normally occur. Consideration must also be given the symmetry of the test region, since a non-symmetric response will cause pull out forces to develop components acting in other directions than vertically, introducing another variable in the test.
- Normalization of results - If a localized test is used, a method for normalizing the results, that is, converting the results to an equivalent form, such as force per unit area of system, for all types of detectable warning systems is needed. Simplified methods, such as counting the number of

discrete anchors per unit area of system, are one approach to this problem. However, this method is not easily adapted for some detectable warning systems, such as those with hybrid anchorage systems. An example of a hybrid system is a surface applied system that uses both adhesive and additional discrete anchors for anchorage.

- Size of test area - Larger test areas allow inclusion of more features of the tiles that may influence anchorage. However, large samples require larger forces and introduce challenges in applying the loads to the samples. In addition, more test samples must go through the exposure protocol to provide sufficient samples so that an accurate estimate of response can be determined.

Development Process

Efforts at developing a system bond test focused on a pull-off test based on ASTM C1583. For this testing, a 75 mm (3-in.) diameter core barrel was used to cut down through the detectable warning system to isolate the test area. If the anchorage was provided by a discrete anchor bolted to the system, the bolt was removed and replaced with a longer bolt that could be connected directly to the test frame described below. If the domes were solid (not hollow), the surface domes were ground off to a level approximately even with the field. This helped reduce the thickness of the adhesive line and roughened the surface providing physical features to improve adhesive bond. Then, a steel puck, 75 mm (3 in.) in diameter and 25 mm (1in.) thick, was adhered to the surface with an epoxy adhesive. The puck was then fixed to a pull-off frame, consisting of a hydraulic jack, load cell and coupling device designed to transmit the tensile force parallel to and in line with the axis of the cylindrical test specimen without imparting torsion or bending. A steel plate was placed beneath the frame to provide a rigid surface for the frame to react against. This setup is pictured in Figure A31.

The system bond test was attempted where anchors were present. Tests were conducted on cast-in-place rigid polymer, surface applied rigid polymer, surface applied flexible polymer, cast-in-place polymer concrete, and precast paver systems. The results are reproduced in Table A22. Some photos of samples after testing are given in Figure A32 through Figure A34. A simplified normalization process, based on the quantity and dimension type of the primary anchorage mechanism, as identified in this table, has been applied to these results to produce a “Normalized Anchorage Strength per 2x2-ft System”.

Figure A31. Proposed (and abandoned) system bond test setup.

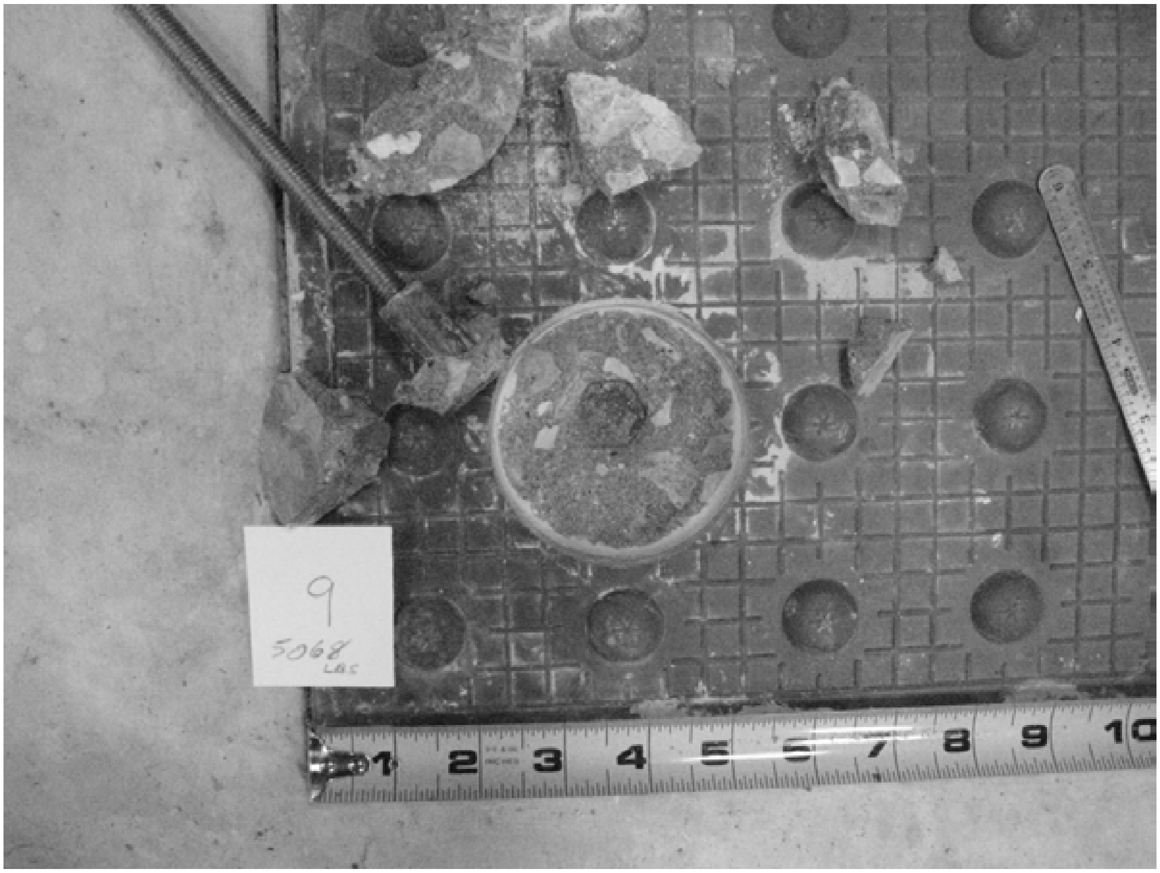


Figure A32. System bond test of cast-in-place polymer concrete system with discrete anchor.

Figure A33. System bond test of surface applied flexible polymer.

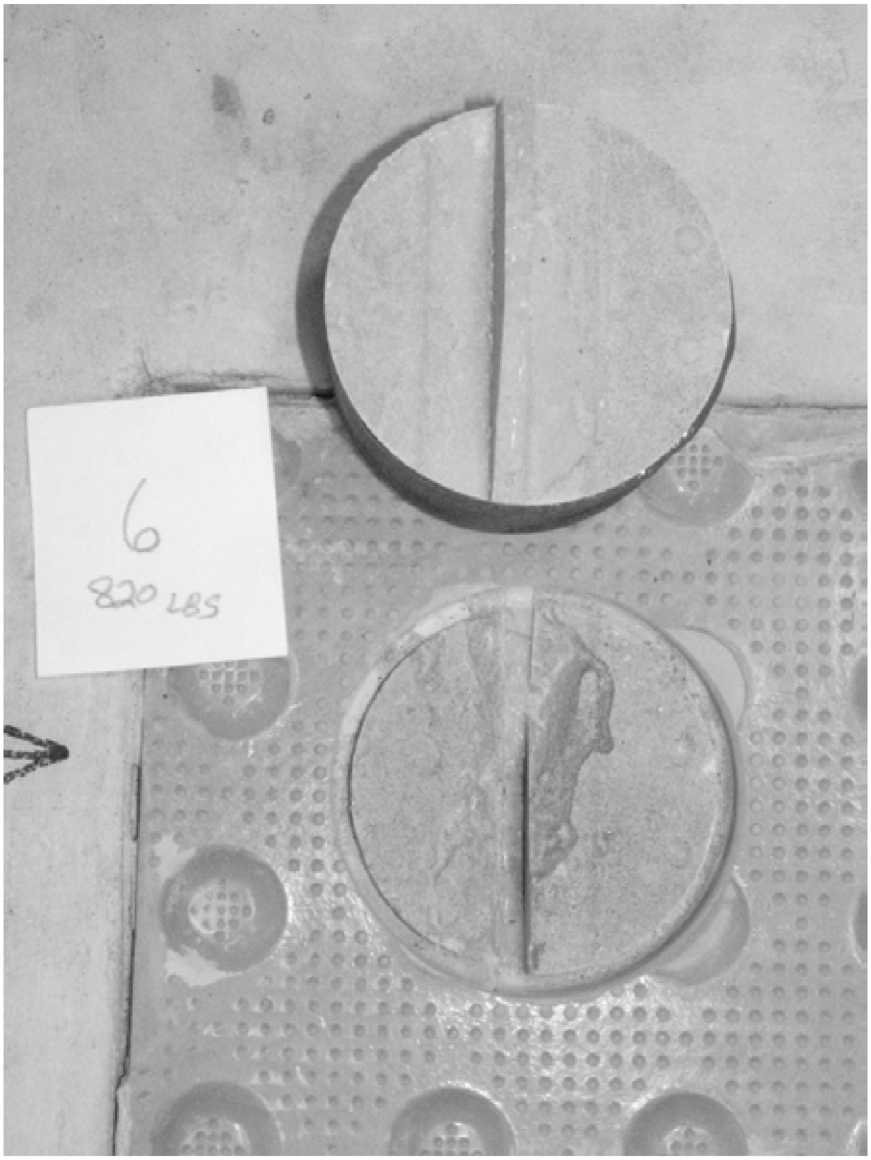


Figure A34. System bond test of cast-in-place rigid polymer.

Table A22. Results of System Bond Testing

Test Tile	Maximum Load (lbs)	Failure Type	Anchorage Included in Test	Units of Anchorage per 2 x 2-ft System	Normalized Anchorage Strength per 2x2-ft System (lbs.)
Cast-in-place rigid polymer	820	Rib torn; some bond to concrete	3 in. linear	264 in. linear	72160
	276	Rib torn; some bond to concrete	3 in. linear	264 in. linear	24288
Surface applied rigid polymer	162	Glue line, puck area only partially bonded	5 in.^{2} area	182 in.^{2} area	5897
Surface applied flexible polymer	8	Glue line	7 in.^{2} area	576 in.^{2} area	658
	144	Pin pulled through rubber	1 pin	6 pins	864
	260	Pin pulled through rubber	1 pin	6 pins	1560
Cast-in-place polymer concrete systems	2711	Discrete anchor pull out	1 anchor	5 anchors	13555
	5068	Discrete anchor pull out	1 anchor	5 anchors	25340
Precast paver	9	At mortar bond line	7 in.^{2} area	529 in.^{2} area	680
	9	At mortar bond line	7 in.^{2} area	529 in.^{2} area	680

As can be seen from the data presented above, the response of the different styles of detectable warning system varied widely and apparently real variations in performance have been quantified. However, the response between repeat tests of the same system varies significantly. For example, the one of a cast-in-place rigid polymer system produced a result less than 1/3 of that of the other test. Based on this variability and the extensive simplification assumptions made to permit the calculation of a normalized anchorage strength, it was determined that this test was not capable of meeting the key objectives of allowing comparison between detectable warning system designs and characterizing the effects of exposure. Therefore, this conception of the system bond test has not been pursued further. However, as stated previously, an evaluation of the system bond performance is important for assessing system durability, and gives an indication of the structural integrity of the system. Therefore, it is recommended that the development of system bond test be a primary objective of future work in detectable warning evaluation methods.

Guidance in Use and Interpretation

Since no method was finalized, no guidance is provided.

REFERENCES

Billmeyer Jr., F. W., & Hammond III, H. K. (1995). Color and Light. In J. V. Koeleske, *Paint and Coating Testing Manual Fourteenth Edition of the Gardner-Sward Handbook* (pp. 447-468). Philadelphia: ASTM International.

Boisvert, D. M. (2003). *Durabilty of Truncated Dome Systems, FHWA-NH-RD-MPS2002-2.* Concord, NH: New Hampshire Department of Transportation.

Celestian, S. B., & Martin, A. C. (2004). Rhizosphere, Surface, and Air Temperature Patterns at Parking Lots in Phoenix, Arizona, US. *Journal of Arboriculture , 30* (4).

Chang, W.-R., & Maynard, W. S. (2006). Factors influencing the slip index measurements with the Horizontal Pull Slipmeter. *Work: A Journal of Prevention, Assessment and Rehabilitation* (2), 99-105.

Derringer, G., & Suich, R. (1980). Simultaneous Optimization of Serveral Response Variables. *Journal of Quality Technology , 12*, 214-219.

Evaluation of Detectable Warning Advisory Committee. (2006). *Forth Draft of the Proposed Standard Test Methods for the Evaluation of Detectable Warnings and Directional Surfaces.*

Fedor, G. R., & Brennan, P. J. (1996). *Comparison Between Natural Weathering and Fluorescent UV Exposures: UVA-340 Lamp Test Results.* ASTM STP 1294.

Grossman, D. (1993). *Errors Caused by Using Joules to Time Laboratory and Outdoor Exposure Tests.* ASTM STP 1202.

Illinois Department of Transportation. (2006). *Experimental Features Program, Pre-Fabricated Cast-in-Place Truncated Domes Summary Reprot.* Hoffman Estates, IL.

Marpet, M. I. (2002). Issues in the Development of Modern Walkway-Safety Tribometry Standards: Required Friction, Contextualization of Test Results, and Non-Proprietary Standards. In *Metrology of Pedestrian Locomotion and Slip Resistance, ASTM STP 1424.* West Conshohocken, PA: ASTM International.

Schanda, J. E. (2007). *Colorimetry Understanding the CIE System.* Wiley Interscience.
United States Access Board. (August 2003). *Technical Bulletin: Ground and Floor Surfaces.*