Satisfactory performance of non-composite box-beam bridges depends on the effectiveness of the key way, waterproofing membrane and tie rods, and the related construction practices. Development of cracks at the longitudinal joints of such bridges is often a recurring problem that causes water leakage at the joints and corrosion of the embedded prestressing strands. The primary objective of this study was to identify the sources, causes and effects of inadequate waterproofing at the joints and to develop prevention measures. The performance of waterproofing membranes and the structural performance of key way joints with the existing and new grout materials were evaluated and correlated with field measurements recorded under traffic loading. Construction practices for new bridges, and the investigation of a bridge that was in service for 32 years at the time of its demolition were also documented. Mechanical tests on membranes revealed that they are able to accommodate at least one inch of tensile and shear deformations without losing their waterproofing properties. That kind of elongation allows membranes to bridge over any cracks that may develop at the longitudinal joints. Therefore, membrane deficiencies may not the primary cause of water leakage. Key way joints with a combination of the currently specified ODOT geometry and ODOT-approved grouts were found to be incapable of carrying any shear loads in conjunction with out-of-plane moments. From the limited site inspections done in this project, the practices followed at construction sites seem to be seriously flawed and may be largely contributing to water leakage problems in box-beam bridges. Recommendations on new key way geometries and the grouts that were developed and tested in this project are suggested for implementation.
Waterproofing Details of Connections for Adjacent Precast Concrete Box-Beam Bridges

Interim Report on Membrane Performance

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The contents of this report reflect the views of the author(s) who is (are) responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Ohio Department of Transportation, Ohio’s Research Initiative for Locals, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.
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Keyways should be grouted after erection of box beams. Generally, plastic rope or jute is
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CHAPTER I
INTRODUCTION

1.1 Description

Precast concrete adjacent box-beam bridges are commonly deployed by ODOT and many counties in Ohio for short and medium spans (30 to 100 ft.). Such bridges are popular because of the low depth-to-span ratio, which allows better clearance under the bridge than stringer supported bridge decks. The life-cycle cost of such bridges is low because of the superior performance, rapidness of installation, and ease of construction.

Adjacent box beams need to work together in a bridge to function structurally as a single unit (Fig. 1.1). The satisfactory performance of non-composite box-beam bridges depends on the shear key details, waterproofing membrane, and tie rods.

Fig. 1.1 Longitudinal Joints with Shear Keys Formed Between Adjacent Box-Beams

In Ohio, adjacent box beams are connected using partial depth grouted key ways along the longitudinal joints. Development of cracks at the interface of the grout and the box beam key ways is a recurring problem. Water leakage at longitudinal joints is generally believed to be due to the failure of the key ways and waterproofing membranes. Seeping water is one of the primary causes for corrosion of the prestressing strands and non-prestressed steel embedded in box beams (Fig. 1.2).

Fig. 1.2 Severe Deterioration of Underside of ODOT Box Beams at the Longitudinal Joints Due to Corrosion and Spalling (left) and PennDOT Documentation of Leakage (right)

Key way recesses are formed in precast concrete box beams at the time of casting. Box beams are usually installed next to each other and are tied together with mild steel tie rods or post-tensioned strands. The tie rods or prestressing forces from the strands provide a clamping
force normal to the joint. The key ways along the longitudinal joints are then grouted with cement mortar. The hardened grout in the key way is expected to transfer the interacting forces between the adjacent box beams to enable the assembly of box beams to act as one unit. The use of cement-based mortar grouts is a common practice for adjacent box beam bridges. One layer of waterproofing membranes is provided on the deck surface to prevent water from entering and leaking through the longitudinal joints. A wearing course of 2- to 4-inch asphalt concrete is provided on the top of the waterproofing membrane.

The joint performance and strength can be affected by many factors such as the geometry of key ways, properties of grout material, interface characteristics, the amount of transverse force applied to the beams, type of the applied loads, and construction practices.

1.2 Objectives

The broader objective of this study was to develop insight into the performance of longitudinal joints with a particular reference to cracking and differential deflection that is believed to cause the waterproofing membrane to fail. The specific objectives of the study are to:

(i) Identify the sources, causes and effects of inadequate waterproofing at the joints
(ii) Develop measures that would assist in the prevention of water leakage by carefully evaluating alternatives

1.3 Research Methodology

In order to address the problem and to develop potential solutions, a systematic study was conducted in this project to include the following major tasks:

(i) Membrane performance studies
(ii) Structural performance of key way joints
(iii) Study of grout material and the development of a new high-performance grout
(iv) Field measurements of vertical differential deflection and separation of longitudinal joints
(v) Beam assembly tests with symmetric loading
(vi) Analysis for eccentric loading and structural tests
(vii) Observation of construction practices
(viii) Investigation of a bridge that was in service for 32 years at the time of its demolition

However, only the items related to the performance of waterproofing membranes are included in this interim report. A tentative set of conclusions is also presented based on the relevant items on membrane evaluation. A brief chapter on pertinent literature is included, and several relevant publications have been added to the references. Recommendations for implementation are outlined for consideration by ODOT and county engineers.
CHAPTER II
LITERATURE REVIEW

The structural performance of the bridge deck in adjacent box-beam bridges depends on the integrity of the adjacent box beams, which should act as one unit under loads. The shear key is formed between the adjacent beams to connect the bridge deck. Keyway geometry, grout material, the transverse forces, end support connections, and traffic and environmental loads are the main influencing components of the joint. A waterproofing membrane for the bridge deck is recommended to prevent water leakage through the keyway. Typical damages are often recorded throughout the longitudinal joints and especially at the abutment locations of simply supported box beams. A summary of the intensive efforts of other researchers in the past to identify the causes of joint failure and the alternative practices are reported in this chapter.

2.1 Background

Protective systems can be divided into four general methods to prolong the service life of a bridge deck. The first method is to physically or electro-chemically protect the steel reinforcement by using either of these techniques: epoxy-coated reinforcing steel or cathodic protection. The second method is to limit moisture and chlorides from reaching the steel reinforcement by providing a larger concrete cover over the steel reinforcement. The third method is to use less permeable concrete mixes. The fourth method is to use protective systems at the top of the deck to prevent moisture and chlorides from penetrating the concrete. The use of multiple protection methods can be more effective for new bridges than other methods. However, for older bridges, the use of the fourth method of using a protective system can be more suitable (Frosch, Kreger, & Strandquist, 2013).

When studying the durability of a bridge, the concrete deck is commonly the most susceptible element and can be the restrictive factor affecting the service life. In general, a protective system is often provided as an enhancement of the durability for both new and existing bridge decks. In cold states where deicing salts are used, bridge deck deterioration is a serious concern. Deicing salts are passed along with water through permeable concrete to the reinforcement, which would accelerate the corrosion process. Moreover, chlorides and moisture seeping through cracks, which provide a continual path to the reinforcing steel, can be destructive. Spalling can occur in the concrete as a result of the increase in the volume of reinforcement steel due to corrosion. The loading capacity of the bridge and riding quality are negatively affected due to this type of deterioration (Frosch, Kreger, & Strandquist, 2013).

2.2 Introduction

According to Russell (2011), a waterproofing membrane is defined as a thin impermeable membrane that is used in combination with a hot-mix asphalt wearing surface to protect the deck concrete from penetration by water and deicing salts. Waterproofing membrane
systems have been used to protect the concrete on a deck slab from freeze-thaw induced deterioration and essentially to defend the embedded steel reinforcement against corrosion. In several New England states, transportation agencies began using membranes to prevent deterioration of concrete beneath asphalt surfaces. Elsewhere in the United States, waterproofing membrane systems have been used since 1972 as part of the Federal Highway Administration (FHWA) requirements to protect bridge decks against corrosion (Manning, 1995).

Corrosion-related deterioration is one of the most widespread problems that can affect the durability of concrete bridge decks. Concrete itself and steel rebar and/or strands can be damaged in the case of moisture and chloride intrusion. In fact, proper use of waterproofing systems can extend the life of the structure and delay major bridge deck maintenance. The most common deteriorations that concrete can face are spalling, cracking, and scaling. Spalling is considered a dangerous deficiency due to the high potential of corrosion of the reinforcing steel and/or strand underneath it. Maintaining the durability of concrete bridge decks is still a big challenge due to the nature of steel reinforcement corrosion. The primary cause of deterioration is the accumulation of water between the waterproofing materials and the bottom layer of the asphaltic concrete. Other causes of deterioration are the presence of large temperature changes during freezing and thawing, as well as frequent built-up of hydraulic pressure from cyclic vehicular loads. As a result, the waterproofing material becomes weak and the bond between the asphaltic concrete and the waterproofing material weakens. This leads to leakage, and the bridge deck may be exposed to moisture and chloride intrusion that attack the concrete and reinforcement (Russell, 2011).

One of the challenges in terms of protecting bridge decks is the exposure of the horizontal surface of the deck to a massive amount of deicing salt during winter seasons. Table 2.1 shows chemicals that might be used by transportation agencies during winter seasons to maintain the operation of roads and highways. In addition, due to the horizontal profile of bridge decks, drainage from the deck becomes difficult and slow. Moreover, bridge decks face very heavy cyclic loading, which aggressively enlarges the cracks that allow seepage of chlorides into the concrete. Furthermore, thermal loading is another cause of initiation and propagation of cracks in asphalt and concrete layers that have unequal thermal behavior.

Table 2.1: Chemicals Used for Winter Maintenance (Frosch et al., 2013).
2.3 Waterproofing Membrane Systems

Concrete bridge decks can be damaged due to many factors. The corrosion of reinforcing steel is one of the main factors leading to bridge damage. In fact, steel material has low corrosion resistance and needs to be protected from exposure to corrosive solutions, especially those having chloride ions (Cl+). When water seeps through concrete voids to reinforcing steel containing corrosive materials, the corrosion process starts and the volume of steel increases, which will lead to the initiation of cracks that propagates further into the concrete.

The membrane is one component of the waterproofing system and mainly works as a barrier that is typically located on the top of the concrete surface of the bridge deck and is covered by a strong material that functions as the driving surface. Primers and sealants are used as bonding agents to secure the membrane to the bridge deck. Inadequate implementation of any component can result in poor performance of the system as a whole.

Waterproofing membrane systems are divided into two main categories: First is the construct-in-place system, including bituminous and resinous liquid-sprayed systems. Of these, the bituminous is the most frequent material used in practice for this particular system. Second is the preformed membrane system, which is divided into asphalt-impregnated fabric, polymer, elastomer, and asphalt laminated board systems. Asphalt-impregnated fabric has been the most common material used in the industry for preformed membrane systems for the last few decades (Manning, 1995).

2.4 The use of waterproofing membrane in US

The use of the waterproofing membrane systems has changed in many highway agencies. According to a national survey done by Russell (2011), thirty-four out of thirty-five responding agencies stated that they have used waterproofing membranes on concrete bridge decks since 1994. Three departments of transportation have stopped using the waterproofing systems. Four departments of transportation are still using the waterproofing membrane systems, but only on new concrete bridge decks. Eleven departments of transportation use the system only for existing bridges, and sixteen highway agencies have continued using the waterproofing membrane systems for both new and existing bridges. Figure 2.1 shows the current use of waterproofing membrane systems. Figure 2.2 shows the historical use of waterproofing membrane systems from a 1992 survey of agencies in the United States.
The highway agencies that stopped using waterproofing membrane systems responded to the survey with their reasons for discontinuing. Agencies reported that they had experienced insufficient performance of waterproofing membrane systems, or they began to use some alternative protection strategies such as concrete overlays or full-depth low permeability concrete. Some agencies reported that they do not use waterproofing membrane systems in order to make the inspection easier, since using waterproofing may hinder the inspection process. The majority of departments of transportation have continued to use waterproofing
membrane systems and have expanded their use in both new and existing bridges for maintenance purposes.

2.5 Materials

Since 1994, at least 32 different proprietary products from 19 different companies in United States and Canada have been used as waterproofing membrane systems. Based on the nature of the application, the waterproofing membrane system can be classified into two systems: pre-formed sheet systems and liquid systems (Russell, 2011).

The pre-formed sheet systems involve the application of a primer that is applied to clean concrete decks to improve the adhesion of the membrane to the bridge deck. These sheets, which have a self-adhesive face, can be rolled and bonded to the primer-treated deck surface using a simple roller. In other systems, the membrane can be bonded to the deck only by heating the membrane using a machine or a hand torch. Once the membrane is installed, a tack coat can be applied to the top surface to increase the bonding with the overlay asphalt. Manufacturers refer to these systems by various names such as rubberized asphalt, bituminous membrane, polymer-modified asphalt, modified bitumen, polymeric membrane, or bitumen and polymers. Figure 2.3 shows the schematic of possible components of a pre-formed system (Russell, 2011).

![Fig. 2.3 Schematic of Components of Preformed Systems (Russell, 2011)](image)

Liquid systems normally involve the application of a primer to the deck before the membrane is installed. Spray equipment or rollers and squeegees are the main methods to place the membrane. Depending on the manufacturer’s specifications, the membranes can be applied cold or hot. Reinforcing fabric may or may not be included in the liquid system. A tack coat is applied prior to replacement of the asphalt overlay. Manufacturers refer to these systems by various names such as rubberized asphalt, two-component polymer, polyurethane, methyl methacrylate, rubber polymer, polymer-modified asphalt, or rubberized bitumen. Figure 2.4 shows a schematic of the possible components of a liquid system (Russell, 2011)
2.5.1 Primer

Primers are regularly used to maintain a sufficient bond between the concrete and the waterproofing membrane layer. Historically, primers were generally bitumen dissolved in an organic solvent. Due to safety and environmental concerns, these materials were replaced by epoxy. Occasionally, synthetic rubber combined with a resin and dissolved in a solvent is used as a primer. Resinous primers are typically used with resin-based liquid systems (Manning, 1995). Generally, one of the most critical characteristics of a waterproofing membrane system is the bond between the concrete deck and the waterproofing membrane. Primers also provide sealing of small surface cracks in concrete decks. Furthermore, primers need to be flowable to penetrate the textured surface of concrete decks (Strandquist, 2012).

In most cases, a primer can be specified for either liquid application or preformed membrane application. For either type, the primer may be poured and spread by squeegee or sprayed. Figure 38 shows the application of primer by squeegee.
2.5.2 Membrane

The membrane sheet is the main part of a waterproofing pre-formed system. The key function of the membrane is to act as a barrier between the concrete and asphalt layer to prevent moisture and chlorides. Therefore, the membrane must provide a reliable impermeable layer. In many cases, the membrane may be placed in joint areas; therefore, it must have the ability to elongate extensively. Thermal loading, crack movements, and heavy traffic loading can make bridge beams move vertically and/or horizontally, and the membrane must be able to accommodate all these differential movements.

Manufacturers have produced a variety of waterproofing membrane systems. These systems are classified mainly based on five characteristics: preformed versus applied-in-place; thermoplastic versus thermosetting; unmodified versus modified; reinforced versus unreinforced; and wearing course versus no wearing course. Another classification is based on the generic type of material (Manning, 1995).

In terms of preformed (often called sheet/membrane systems) versus applied-in-place (often called liquid systems), the classification is very general; these systems are most commonly used in practice. Preformed membranes are typically produced in sheets, usually come in rolls, and are laid on the concrete surface. The membranes are laid on the concrete surface after application of adhesive materials or the membrane sheets can be self-adhesive (often called “peel and stick” membranes). Figure 2.6 shows the preformed system. Figure 2.7 shows the applied-in-place systems. Both systems have advantages and disadvantages, which are summarized in Table 2.2.

![Preformed System Installation](image_url)

**Fig. 2.6 Preformed System Installation (Strandquist, 2012)**
Table 2.2: Comparison of Preformed System versus Liquid System (Manning, 1995)

<table>
<thead>
<tr>
<th>Preformed Systems</th>
<th>Liquid Systems</th>
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<tr>
<td>• Tend to perform well in laboratory evaluations</td>
<td>• Tend to perform less well in laboratory evaluations</td>
</tr>
<tr>
<td>• Quality of material controlled under factory conditions</td>
<td>• Difficult to ensure consistent quality of materials</td>
</tr>
<tr>
<td>• Thickness and integrity controlled at the factory</td>
<td>• Difficult to control thickness of membrane and detect presence of pinholes</td>
</tr>
<tr>
<td>• Labor-intensive installation, especially if not self adhesive</td>
<td>• Usually applied in one application by spray or squeegee; built-up systems are labor intensive</td>
</tr>
<tr>
<td>• Laps required</td>
<td>• Laps not required</td>
</tr>
<tr>
<td>• Difficult to install on curved or rough decks</td>
<td>• Application independent of deck geometry. Thin membranes require a smooth deck</td>
</tr>
<tr>
<td>• Vulcanized sheets may be difficult to bond to substrate, protection layer and at laps</td>
<td>• Bonding not usually a problem if substrate prepared properly; self adhesive</td>
</tr>
<tr>
<td>• Vulnerable to quality of work at critical locations such as curbs, expansion joints and deck drains</td>
<td>• Less vulnerable at critical locations</td>
</tr>
<tr>
<td>• Blisters must be repaired by puncturing and patching</td>
<td>• Blisters and blowholes easily repaired in self-sealing materials, but not in thermosetting materials</td>
</tr>
<tr>
<td>• Tend to be more expensive</td>
<td>• Tend to be less expensive</td>
</tr>
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The next classification is in terms of thermoplastic versus thermosetting materials. Thermosetting materials are petrochemical materials which, following the initial permanent set through chemical reaction, are not modified noticeably in terms of viscosity with a change of temperature. Thermosetting materials consist of vulcanized rubber sheets and resin-based liquid membranes. The resin-based liquid could be produced from epoxy, polyester,
polyurethane, acrylic, or polysulfide resins. However, the viscosity of thermoplastic materials could change with a change in temperature, and the thermoplastic materials do not set permanently through chemical reaction (Manning, 1995).

Regarding the classification between unmodified versus modified membranes, when additive material is added until the point of changing the material properties, the membrane is considered to be modified. Adding coal tar to resins or using fillers with asphalt membranes are examples of modifications. Conversely, materials added for ease of application or to promote setting (such as emulsifiers or solvents) are not considered to be modifiers; thus, the membranes are considered as unmodified (Manning, 1995).

In terms of reinforced versus un-reinforced membranes, a membrane can be classified as reinforced when continuous sheets or fibers are used. Examples of reinforcements are glass fiber, polypropylene or nylon fabrics, and polyethylene sheets. Membranes with discontinuous reinforcement are considered un-reinforced as those discontinuous additives could be considered as modifiers or fillers (Manning, 1995).

In laboratory and field investigation of 48 waterproofing membranes in the United Kingdom, an alternative classification system was developed. This classification distinguishes between preformed membrane sheet and liquid systems. Also, this classification offers a secondary classification with respect to material composition. Figures 2.8 and 2.9 show the preformed system and liquid systems, respectively, which were included in that investigation (Manning, 1995).

![Fig. 2.8 Preformed Waterproofing Systems (Manning, 1995)](image-url)
Preformed systems were divided into four categories: asphalt-impregnated fabric sheets, polymeric sheets, elastomer sheets, and asphalt-laminated boards. Asphalt-impregnated fabric sheets are impregnated absorbent material coated with asphalt cement. The impregnated absorbent material could be either polyester fleece, glass cloth, or woven polypropylene. Polymeric sheets were based on either bituminized, laminated, or chlorosulfonated polyethylene; ethylene propylene; ethylene vinyl acetate; or polymer plasticized polyvinylchloride. The elastomer sheets were based on vulcanized butyl or polyisoprene rubber. With asphalt-saturated felt on the underside, the butyl type became laminated. In North America, other types of elastomeric sheets, such as those made of polychloroprene, ethylene propylene diene monomer, butyl, and Hypalon rubbers, have been used mainly in experimental work in the 1970s. The forth category is asphalt laminated boards, which are made of finely crushed aggregates filled with asphalt cement between layers of asphalt-saturated felt; this type was used as protection boards for some systems (Manning, 1995).

The liquid systems are categorized into bituminous and resinous systems. Bituminous systems are subcategorized into bituminous solutions or compositions that are blended solutions of various bitumens in hydrocarbon solvents or two-part polymer-modified composition, and mastics. Mastic, a blended solution of refined natural or elastomer-modified mastic asphalts, requires application of heat to be converted into a liquid state. Resinous types were subcategorized into urethane, epoxy, and acrylic resin-based systems. Polyurethanes systems are fast curing elastomer or elastomer-modified, and some are further modified with either carborundum or coal tar. All epoxy resin-based systems are modified with coal tar, minerals or reinforcing polyester fleece. The advantage of these systems is that the concrete does not have to be primed. Acrylic systems are based on
polymethylmethacrylate resin (PMMA) and are typically used as a primer; these systems and can be modified with urethane (Manning, 1995).

Based on an intensive series of field and laboratory tests, general relationships between material composition and the performance characteristics of primers, adhesives, and membranes were established, these relationships are summarized in Tables 2.3 and 2.4.

Table 2.3: Performance of Generic Primers and Adhesives (Manning, 1995)

<table>
<thead>
<tr>
<th>Type of Material</th>
<th>Positive Attributes</th>
<th>Negative Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bituminous primers</td>
<td>Workable over ambient temperature range although some unmodified solvated types increased viscosity at low temperatures.</td>
<td>Drying time was temperature and moisture dependent and took from 1 to 48 hours, depending on composition; limited waterproofing ability and poor long term adhesion.</td>
</tr>
<tr>
<td>Resinous primers</td>
<td>Workable over ambient temperature range; moderate waterproofing ability and good resistance to chloride penetration.</td>
<td>Pot life limited at high temperatures.</td>
</tr>
<tr>
<td>Oxidized bitumen adhesives</td>
<td>Effective barrier to water and chloride transmission when fully bonded and free from blow holes; minimal water absorption.</td>
<td>Significant increase in stiffness at low temperatures; prone to embrittlement and debonding; generally poor long term bond.</td>
</tr>
<tr>
<td>Latex adhesives</td>
<td></td>
<td>Very poor adhesion to concrete; ineffective barrier to water or chloride transmission.</td>
</tr>
<tr>
<td>Self-adhesive backing to sheet membranes</td>
<td>Bond generally effective when applied at above 10°C.</td>
<td>Below 10°C, bond progressively weaker and almost non-existent below 5°C; poor bond if laitance or contamination of concrete; prone to debonding in the long term.</td>
</tr>
</tbody>
</table>
2.5.3 Tack Coat

For many waterproofing systems, a tack coat (also called a bond coat) is applied between the waterproofing layer and the layer above (either concrete or asphalt) and is anticipated to improve the bond. In cases where a protective layer is provided, a tack coat can be placed between the membrane and the protective layer; it can also act as the interface between the protective layer and the asphalt or concrete overlay. In the United Kingdom, the thickness of the tack coat is usually specified with regard to the size of the aggregate being used in the asphalt overlay. If large aggregate is used, a thicker tack coat layer is required. For fine aggregate, a thinner tack coat layer is specified to be used as an interface. The aggregate may penetrate the tack coat but may not penetrate the membrane layer, depending on the compaction severity (Strandquist, 2012).

According to Strandquist (2012), the most critical concern regarding a tack coat is its durability against potential damage caused by construction vehicles, which also depends on the thickness of the layers above. The tack coat is at risk of being stripped and damaged during placement and compaction of the asphalt overlay. Some practices may reduce the severity of this problem, such as providing sufficient time for the tack coat to dry until it has...
set completely and is tack free. It is also helpful to carefully clean the rubber wheels of the paving vehicle and cover them with a soapy solution. Prior to paving, it is recommended to repair any damage to the tack coat with patches.

2.5.4 Protective Layer

The main function of the protective layer is to protect the membrane from damage due to compaction of the wearing surface. Also, the protective layer should protect the membrane sheets from depression by angular aggregate or damage from heavy construction equipment. Many departments of transportation agencies in the US and Canada have specifications for this layer. A variety of materials are used for this purpose, such as fiberglass and polystyrene. In the United Kingdom, a layer of sand asphalt (which is simply asphalt concrete that uses fine sand aggregate) is used as an additional layer to the main protective layer. (Jordan et al., 2007; Strandquist, 2012).

2.6 Specifications and Standards

Many specifications and standards in the United States and other countries specify the use of waterproofing on bridge decks. AASHTO addresses waterproofing in section 21 of LRFD Bridge Construction Specifications (AASHTO, 2010). It covers both types of waterproofing systems, constructed-in-place and preformed membrane systems, and it considers them as protective systems. The concrete surface should be very smooth and free of any holes and projections. Also, the surface should be dry and have a minimum temperature of 35°F. AASHTO provides specific detailed instructions for both asphalt membrane systems and preformed waterproofing membrane systems.

Most transportation agencies in the US have waterproofing membrane specifications that are very comparable to AASHTO specifications. Some differences between state DOTs and AASHTO specifications are documented in Table 2.4.

**Table 2.5: Summary of State Specifications/Requirements versus AASHTO Specifications** (Russell, 2011)
Both AASHTO and state specifications refer to ASTM standards for material specifications and test methods. These requirements cover both liquid applied waterproofing and membrane sheets and bonding agents. A list of the related ASTM standard tests is provided in Table 2.5.

**Table 2.6: ASTM Standards Relevant to Waterproofing Membranes (Russell, 2011)**

<table>
<thead>
<tr>
<th>ASTM Designation</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>D5</td>
<td>Standard Test Method for Penetration of Bituminous Materials</td>
</tr>
<tr>
<td>D36/D36M</td>
<td>Standard Test Method for Softening Point of Bitumen (Ring-and-Ball Apparatus)</td>
</tr>
<tr>
<td>D41/D41M</td>
<td>Standard Specification for Asphalt Primer Used in Roofing, Dampproofing, and Waterproofing</td>
</tr>
<tr>
<td>D146</td>
<td>Standard Test Methods for Sampling and Testing Bitumen-Saturated Felts and Woven Fabrics for Roofing and Waterproofing</td>
</tr>
<tr>
<td>D173</td>
<td>Standard Specification for Bitumen-Saturated Cotton Fabrics Used in Roofing and Waterproofing</td>
</tr>
<tr>
<td>D449</td>
<td>Standard Specification for Asphalt Used in Dampproofing and Waterproofing</td>
</tr>
<tr>
<td>D517</td>
<td>Standard Specification for Asphalt Plank</td>
</tr>
<tr>
<td>D882</td>
<td>Standard Test Method for Tensile Properties of Thin Plastic Sheeting</td>
</tr>
<tr>
<td>D1228</td>
<td>Methods of Testing Asphalt Insulating Siding Surfaced with Mineral Granules (Withdrawn 1982)</td>
</tr>
<tr>
<td>D1668</td>
<td>Standard Specification for Glass Fabrics (Woven and Treated) for Roofing and Waterproofing</td>
</tr>
<tr>
<td>D1777</td>
<td>Standard Test Method for Thickness of Textile Materials</td>
</tr>
<tr>
<td>D3236</td>
<td>Standard Test Method for Apparent Viscosity of Hot Melt Adhesives and Coating Materials</td>
</tr>
<tr>
<td>D4071</td>
<td>Standard Practice for Use of Portland Cement Concrete Bridge Deck Water Barrier Membrane System</td>
</tr>
<tr>
<td>D4541</td>
<td>Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers</td>
</tr>
<tr>
<td>D632</td>
<td>Standard Test Method for Grab Breaking Load and Elongation of Geotextiles</td>
</tr>
<tr>
<td>D4787</td>
<td>Standard Practice for Continuity Verification of Liquid or Sheet Linings Applied to Concrete Substrates</td>
</tr>
<tr>
<td>D6153</td>
<td>Standard Specification for Materials for Bridge Deck Waterproofing Membrane Systems</td>
</tr>
<tr>
<td>D6690</td>
<td>Standard Specification for Joint and Crack Sealants, Hot Applied, for Concrete and Asphalt Pavements</td>
</tr>
<tr>
<td>E154</td>
<td>Standard Test Method for Water Vapor Retarders Used in Contact with Earth Under Concrete Slabs, on Walls, or as Ground Cover</td>
</tr>
</tbody>
</table>

**2.7 Design Details**

A survey of all highway agencies in the United States showed that 56% of agencies have no standard design details for waterproofing membrane systems. Figure 2.10 shows information on the availability of standard details for the installation of waterproofing membranes in the United States for agencies that responded to the survey. In contrast, only two Canadian highway agencies have no standard design details. Figure 2.11 shows examples of standard design details provided in standard drawings of Alberta Transportation, a Canadian highway agency (Russell, 2011).
Fig. 2.10 Standard Details Available for the Installation of Waterproofing Membranes (Russell, 2011).
Fig. 2.11 Examples of Provided in Standard Drawings (A) Composite Deck, (B) Non-Composite Deck, (C) Detail of Composite Deck, (D) Legend, (E) Drain Pipe Detail (Russell, 2011).

2.8 Construction

Most specifications provide some construction procedures, which are given in the following steps:

1. Deck surface preparation,
2. Application of a primer to the concrete,
3. Installation of the waterproofing membrane,
4. Installation of protection board (if used),
5. Repair of unacceptable areas resulting from membrane thickness inadequacies, and
Figures 2.12 and 2.13 shows various steps in the construction process for both systems (Russell, 2011).

a) Application of Primer to the Concrete
b) Laying out the Sheet Membrane

c) Heating the Sheet Membrane with a Torch
d) Sealing the Overlap Seams by a Hand Roller

(e) Completed Membrane
(f) Compacting the Hot Mix Asphalt

Fig. 2.12 Steps in the Installation of a Preformed Sheet Membrane (Russell, 2011).
Figure 2.13 Application of Liquid Membrane by Spraying (Russell, 2011).

2.9 Performance

The waterproofing membrane system has many advantages that encourage engineers to adopt it in their design. A waterproofing membrane system can be constructed rapidly and can cover reflective cracks for most moving loads. Moreover, the waterproofing system is flexible; therefore, it can be applied to almost any deck geometry. On the other hand, the waterproofing membrane system has disadvantages that can limit the performance in some cases. The service life of the membrane depends on the wearing surface life. In addition, the waterproofing membrane system cannot be applied on grades of more than 4% because the bonding capacity is very limited for some systems and debonding can occur (Sohanghpurwala, 2006). Due to the advantages of the waterproofing membrane system, its usage is required by most Canadian and European highway agencies. In contrast, the system is not a requirement for many agencies in the United States.
According to Sohangpurwala (2006), the ideal waterproofing system should provide a good impermeable layer, adhesion to both concrete and the riding surface, tolerance to rough surfaces, resistance to traffic of heavy equipment during construction, have the ability to span cracks between adjacent members, and have a life span up to 100 years. Additionally, the waterproofing membrane should tolerate high and low temperatures without a change in its performance.

According to Jin-Zhong (2005), a waterproofing membrane can prolong the lifetime of structure if it satisfies the following requirements:

- Impermeable throughout service life
- Strong bond with surfacing layer and bridge deck
- Resistance to damage induced by concrete cracks when paved on bridge decks
- Good durability
- Resistance to shear stresses imposed by braking, accelerating, and cornering vehicle wheels
- Resistance to aggregate breakdown under heavy traffic
- Resistance to water or solution erosion
- Adaptability to changes in temperature.

Based on a survey conducted by Russell (2011), transportation agencies were asked for their expectations of service lives of the waterproofing membranes they have used. Most transportation agencies expected 16 to 20 years for new bridge decks and 6 to 20 years for existing bridge decks. Based on that survey, there is not enough evidence to determine whether pre-formed systems or liquids systems have longer life spans. Figure 2.14 shows the survey results.

![Figure 2.14](image.png)

**Fig. 2.14** Expected Service Life for Waterproofing Membranes (Russell, 2011).
Many types of deficiencies may occur for waterproofing membrane systems used on concrete bridge decks. In service, existing bridges have more deficiencies than new ones. Lack of adhesion between the waterproofing membrane and the concrete deck is the most reported deficiency, reported by more than 60% of transportation agencies. Based on the survey, moisture penetration through the membrane from an unknown source is the second most commonly reported type of defect, mentioned by 55% of the respondents. Figure 2.15 displays the response regarding defects that may occur in waterproofing membranes.

**Fig. 2.15** Types of Defects in Waterproofing Membranes. (Russell, 2011).

2.10 Summary

Water leakage is a reoccurring problem that negatively impacts the service life of bridges. Many strategies have been deployed in order to control water leakage. One of them is the use
of a waterproofing membrane provided on the top of the deck surfaces as a protective system. Waterproofing membranes are widely used to protect bridge decks from water-induced damage. Common types of damage include steel corrosion and concrete spalling, which can affect the service life of bridges. A protective system is often provided to enhance the durability of both new and existing bridge decks. This chapter included details on the use of the waterproofing for bridges in the United States. The types and classifications of waterproofing were explained. The materials and the primer, membrane and tack coat were also discussed. Furthermore, this chapter summarized the specifications and standards related to the waterproofing membrane as well as the design details. The construction details of waterproofing membrane for both liquid and pre-formed systems were also outlined. It was concluded in this chapter that the waterproofing membrane features and the requirements that lead to waterproofing will provide satisfactory performance if installed with adequate care. However, research on the performance of waterproofing membranes was found to be limited.
CHAPTER III
WATERPROOFING MEMBRANE EVALUATION

3.1 Introduction

Waterproofing membranes are widely used as a protective system for concrete members that are exposed to rainwater and moist conditions. In this chapter, the testing methods and evaluation of the waterproofing systems that are normally used for adjacent box beam bridges are briefly described and the performance of some of the typical membranes evaluated. Most of the earlier research studies on membranes emphasized the evaluation of the membrane sheets alone. Membrane performance by itself is an important part of the system in providing watertightness, but the performance of the waterproofing membrane as a system in conjunction with concrete is equally important. In this project, the evaluation of waterproofing systems was done in two conditions, i.e., (i) membrane performance in isolation and (ii) performance when the membrane was adhered to a concrete substrate. The primary objective in this task was to evaluate sheet membranes based on their ability to accommodate stretching, adhere to concrete, and resist punching while providing an adequate water barrier in a box beam bridge configuration. The following tests were conducted for the evaluation of typical waterproofing membranes:

1. Tensile tests at different temperatures
2. Adhesion tests
3. Differential deflection tests
4. Punching tests
5. Tests to detect initiation of leakage
6. Membrane performance under passenger car wheel load

Laboratory testing of membrane sheets provided good insight into the sheet behavior and was a good starting point to understand the waterproofing membrane system. Mechanical properties such as tensile strength and elongation were evaluated first. More complexities such as the effects of concrete surface condition and adhesion, sharp edges within joints and tearing potential, wheel load condition and the directionality of wheel loads were also studied. Tensile tests were used to determine the elongation characteristics. The bond between a waterproofing membrane and the adjoining concrete surface was studied using adhesion tests. After the adhesion test, the potential for leakage of water during extension of membrane was established using a new type of leakage initiation test. Waterproofing membranes were also tested for punching resistance to address the effects of sharp edges and pointed surfaces caused by debris and loose aggregates present on concrete surfaces.

The ODOT Qualified Product List (QPL) of waterproofing membranes for both Type II and Type III membranes was considered in developing a test plan. Type II membranes are "peel and stick" membranes that are normally used on vertical surfaces. ODOT mostly does not use this type of membrane for waterproofing bridge decks. Type III membranes are commonly used on flat horizontal surfaces with just primer or with primer and sealant. All
waterproofing membranes are standardized based on ASTM tests and need to meet the ODOT requirements before these membranes are approved for use. The required ASTM tests for the prequalification of membranes were reviewed from the existing literature. Table 3.1 shows the requirements for ODOT Type III membranes and Table 3.2 shows the requirements for Type II membranes (Ohio Department of Transportation, 2013). Moreover, the entire list of waterproofing membrane test results was reviewed based on the data sheets provided by manufacturers.

**Table 3.1: Type III Waterproofing Membrane Requirements**

(Ohio Department of Transportation, 2013)

<table>
<thead>
<tr>
<th>Physical Properties</th>
<th>Requirements</th>
<th>ASTM Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>0.135 inches (3.43 mm) min.</td>
<td>-</td>
</tr>
<tr>
<td>Width</td>
<td>36 inches (914 mm) min.</td>
<td>-</td>
</tr>
<tr>
<td>Weight</td>
<td>0.8 lb/ft2 (3.875 kg/mm2) min.</td>
<td>-</td>
</tr>
<tr>
<td>Tensile strength (machine direction)</td>
<td>275 lb/in (48.1 N/mm)</td>
<td>ASTM D 882 Modified [1]</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>150 lb/in (26.2 N/mm)</td>
<td>ASTM D 882 (90° machine direction) Modified [1]</td>
</tr>
<tr>
<td>Elongation at break</td>
<td>100%</td>
<td>ASTM D 882, Modified [1]</td>
</tr>
<tr>
<td>Brittleness</td>
<td>Pass</td>
<td>ASTM D 517</td>
</tr>
<tr>
<td>Softening point (mastic)</td>
<td>200°F (93°C) min.</td>
<td>ASTM D 36</td>
</tr>
<tr>
<td>Peel adhesion</td>
<td>2.0 lb/in (0.35 N/mm)</td>
<td>ASTM D 413 [1]</td>
</tr>
<tr>
<td>Cold flex ASTM D 146 2X5 inch (50x125 mm) specimen-180° bend over 2 inch (50 mm) mandrel</td>
<td>No cracking</td>
<td>-</td>
</tr>
<tr>
<td>Heat stability 2x5 in. (50 x125 mm) specimen vertically suspended in a mechanical convection oven 2 hr @ 190 °F (88 °C)</td>
<td>No dripping or delamination</td>
<td>-</td>
</tr>
</tbody>
</table>

[1] Measured at a test speed of 12 inches (300 mm)/minute with 1 inch (25 mm) initial distance between the grips.
### Table 3.2: Type II Waterproofing Membrane Requirements  
(Ohio Department of Transportation, 2013)

<table>
<thead>
<tr>
<th>Physical Properties</th>
<th>ODOT Requirements</th>
<th>ODOT/ASTM Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>60 mils (1.5 mm) min.</td>
<td>ASTM D 1777</td>
</tr>
<tr>
<td>Width</td>
<td>36 inches (914 mm) min.</td>
<td>-</td>
</tr>
<tr>
<td>Pliability</td>
<td>No Effect</td>
<td>ASTM D 146 [1]</td>
</tr>
<tr>
<td>Elongation</td>
<td>300% min</td>
<td>ASTM D 412 (Die C)</td>
</tr>
<tr>
<td>Puncture Resistance-Membrane</td>
<td>40 lb (18 kg) min.</td>
<td>ASTM E 154</td>
</tr>
<tr>
<td>Permeance (Grains/ft²/hr/in Hg)</td>
<td>0.1 max.</td>
<td>ASTM E 96 (Method B)</td>
</tr>
<tr>
<td>Water Absorption (% by Weight)</td>
<td>0.2 max.</td>
<td>ASTM D 570</td>
</tr>
<tr>
<td>Adhesion to concrete</td>
<td>5.0 min.</td>
<td>ASTM D 903</td>
</tr>
</tbody>
</table>

[1] Tests conducted using a 180° bend over a ¼ inch (6 mm) mandrel @ -25° F (-32° C)

Five different representative waterproofing membranes were selected for the evaluation in this study as listed in Table 3.3. Some of the waterproofing membranes tested were selected from ODOT's Qualified Product List (QPL), and the remaining membranes were not from the approved list. Both self-adhesive (SA) type and traditional, non-adhesive type membranes were tested. These five membranes are considered to be representative of the membrane types commonly used in the industry.

### Table 3.3: Waterproofing Membranes Evaluated in This Study

<table>
<thead>
<tr>
<th>#</th>
<th>Brand Name</th>
<th>Type</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Polyguard 1100</td>
<td>Type III</td>
<td>Polyguard Products, Inc</td>
</tr>
<tr>
<td>2</td>
<td>665 Membrane</td>
<td>SA, Not in ODOT QPL (Type II)</td>
<td>Polyguard Products, Inc</td>
</tr>
<tr>
<td>3</td>
<td>Coldflex 2000 SA</td>
<td>SA, Not in ODOT QPL (Type II)</td>
<td>Polyguard Products, Inc</td>
</tr>
<tr>
<td>4</td>
<td>PavePrep</td>
<td>Type III</td>
<td>Crafco, Inc.</td>
</tr>
<tr>
<td>5</td>
<td>PavePrep SA</td>
<td>Type II</td>
<td>Crafco, Inc.</td>
</tr>
</tbody>
</table>

SA = Self-adhesive

### 3.2 Evaluation Tests for Waterproofing Membrane

#### 3.2.1 Tensile Strength at Different Temperatures

#### 3.2.1.1 Test Setup

Ideally, waterproofing membranes must be able to bridge the cracks at the longitudinal joints between adjacent box beams mostly by stretching without losing its waterproofing property. The cracks at such longitudinal joints widen the most at low temperatures. Waterproofing membranes are generally not strong enough to resist the forces caused by vertical and horizontal movements at a crack. However, membranes need to stretch adequately to accommodate crack widening without losing the watertightness property. Also, membranes need to stretch in such a way that the differential deflections between
adjacent box beams can be accommodated without losing watertightness. Tensile and elongation tests are useful to measure the capacity of the waterproofing membranes to elongate under tensile forces. Furthermore, the effects of temperature changes were also included in this test. Each type of membrane was tested at five different temperatures: 70°, 40°, 23°, 14° and -4° F. Each sample was conditioned in an environmental chamber at the desired temperature for at least one hour before testing. Tensile tests were based on the test procedures specified in ASTM standards D412, D638, D882, D2523, and D4885. The specimens were dog-bone shaped with a total length of 10 inches. Figure 3.1 shows the shape and dimensions of typical tensile test specimens. Steel plates were glued to the membrane specimens at the ends using an epoxy having 3,300 psi bond strength.

![Fig. 3.1 Typical Tensile and Elongation Test Specimen Dimensions (inches)](image)

In this test, two important parameters were determined: the maximum load the specimen can carry and the corresponding maximum elongation. The typical load versus elongation curves for the five types of membranes at room temperature are shown in Figure 3.2. As seen in this figure, specimens elongated even after the maximum load was reached, after which point, the specimens started to lose their ability to resist load. The failure mode (Fig. 3.3) for the test specimens was mostly identical.

![Fig. 3.2 Typical Load-Elongation Curves for Five Membranes at 70° F](image)
3.2.1.2 Test Results and Discussion

The tensile strengths of the waterproofing membranes were found to be very low and therefore membranes cannot be expected to resist much load at the longitudinal joints of box-beam bridges. Therefore, these membranes may be considered as nonstructural. Low tensile strengths of the membrane become less important than their ability to elongate. Nevertheless, all five membranes showed relatively constant tensile strengths at all temperatures (Fig. 3.4). The reduction in the capacity to elongate was however more prominent with up to 40% loss in elongation compared the elongation at room temperature when specimen temperature was reduced to -4° F (Fig. 3.5). This translates to 5% reduction in actual elongation. Tensile tests showed that Paveprep and Paveprep SA were superior in both elongation and tensile strength compared to other membranes. For all membranes, the elongation of over one inch is much larger than what can be expected at the longitudinal joints of adjacent box beams.

![Fig. 3.3 Specimen Failure Mode](image)

![Fig. 3.4 Tensile Strength Curves for Five Membranes at Five Temperatures](image)

3.2.2 Adhesion Test

3.2.2.1 Test Setup

Adhesion failure between a waterproofing membrane and the concrete bridge deck is one of the most common problems in the waterproofing industry. This failure causes water to seep from underneath the membrane sheets; and debonding between a waterproofing membrane
and the adjacent concrete surface can occur due to blistering. This was reported by Frosch, et al. (2013). Both Type II “peel-and stick” and Type III membranes suffer from membrane blistering. For Type III membranes, it is a common practice to use a bonding agent between the membrane and the primed concrete surface. In Type II membranes, the bonding agent is part of the membrane sheet and in some cases an extra bonding agent may also be needed. According to ODOT CMS 2013, the requirements of using a primer coat seem to be general for all cases (Types II and III). However, for Type II the requirement is to use primer if substrate temperature is below 50°F. Some manufactures require primer to be used for Type II membranes when the pavement surface temperature is low. For example, if the deck temperature is below 70°F (21°C), primer is required prior to the installation of Paveprep SA (Type II).

![Percentage Elongation Curves for Five Membranes at Five Temperatures](image)

**Fig. 3.5** Percentage Elongation Curves for Five Membranes at Five Temperatures

Adhesive strength between waterproofing membranes and concrete surfaces was measured by peeling membrane sheet strips from hardened cement mortar blocks at an angle of 180°. Tensile load was applied at a constant rate of 0.4 inch per minute until each strip was peeled off from the specimen’s mortar block completely. The mortar blocks were prepared in sizes of 4”×4”×14” and cut into 4”×4”×2” blocks. Only saw-cut faces were used to attach waterproofing membranes so as to reduce any variation due to different surface roughness of as-cast surfaces and to ensure repeatability of the tests. The manufacturers’ instructions were followed to apply the primer and the sealant. Fig. 2.6 shows the test setup for adhesion tests and the failure mode of the test specimens. A wooden frame was used to stabilize the test specimens during testing.

Direct heat application with a gas torch is used in some countries to increase the bond strength between the membrane and the substrate (Frosch et al. 2013). There is no mention of heat application in the manufacturers’ data sheets for the waterproofing membranes that were used in this study. The sealant used in this study was “Hot-Applied Modified Asphalt Sealant” made by Crafco. The primer was 33140 Crafco Asphalt Primer. In order to comply with the relevant ODOT and membrane supplier requirements, primer was used on all the specimens in this test (i.e., for both Type II and Type III membranes). Three samples (strips) were tested to measure the potential improvement of adhesion strength due to the
application of heat to Type II membranes. A sealant is normally applied to Type III membranes at 380°F as a common practice. The following three combinations were tested:

1. Samples were subjected to direct heat with the use of primer and sealant as bonding agent.
2. Samples with no heat application and with the use of primer and sealant as bonding agent.
3. Samples with the use of direct heat and the use of only primer as the bonding agent, but no sealant.

Fig. 3.6 Adhesion Test Details

3.2.2.2 Test Results and Discussion

Remarkably, all waterproofing membranes that were tested (both Type II and Type III) showed very little peel-off or adhesive strength. For the first set of test specimens that were subjected to direct heat with the use of primer and sealant as the bonding agent, the average peel forces were between 15 to 18 lb per one-inch width. For the second set of specimens, which were prepared similar to the first set but without any application of direct heat, the peel-off strengths were between 13 to 20 lb per inch width. For the third set, when only primer was used as the bonding agent without any sealant, the peel-off strengths were less than 15 lb per one-inch width.

Fig. 3.7 shows typical trend lines for three load-extension curves corresponding to the three conditions. The adhesive strength between the membrane and concrete seems to be negligible and may need to be enhanced for improved waterproofing performance. The improvement in adhesive strength due to the use of direct heat is very limited. Also, tests suggest that the primer and sealant together perform better than when primer alone is used as the bonding agent.
3.2.3 Ultimate Differential Deflection Test

The ultimate differential deflection test is a new type of test intended to simulate the most realistic and extreme condition that a membrane may face during its service life. This test was designed to determine the maximum differential deflection that a membrane can accommodate under shear loading. The loading direction in a tensile test is parallel to the specimen in the plane of the membrane. Differential deflection of adjacent box beams in a bridge would cause a shear type of deformation of the membrane which is out-of-plane of the membrane when adjacent box beams deflect unequally. The objective of this test was to determine the ultimate elongation capacity of waterproofing membranes under shear loading in the presence of differential movement under the asphalt concrete overlay next to the sharp edges of the box beams in a bridge.

3.2.3.1 Test Setup

In order to simulate the longitudinal joints in a precast box-beam bridge, four mortar blocks of 2”×4”×4” were carefully cut. The lower two blocks were placed close to each other with very little gap between the blocks at the joint. The waterproofing membrane was applied to these two adjacent mortar blocks. Manufacturer's instructions were followed for installation of the different membranes. For both Type II and Type III membranes, sealant was applied to enhance bonding. The membrane was wrapped around the lower two mortar blocks to be well anchored under the clamps. The upper two mortar blocks were placed on the top of the lower blocks without bonding agent to simulate placement of an asphalt/concrete overlay over the membrane without a binder between these two layers. Fig. 3.8 shows a typical setup for these tests.
3.2.3.2 Test Results and Discussion

Fig. 3.9 shows typical load-elongation curves for the five membranes that were tested. The specimens were four inches in width. However, for a comparison of loads and elongations, these curves were normalized to a one-inch width. Large differential elongations of at least 1.0 inch were recorded for each of the five test membranes. Most samples of Polyguard, ColdFlex, and 665 membranes failed partially; others failed by full rupture. Almost all the samples of Paveprep and Paveprep SA failed by full rupture. Fig. 3.10 shows the typical failure modes of the test specimens.
3.2.4 Leakage Initiation Detection

From previous tests (tensile tests and differential deflection tests), the capacity of a membrane to stretch was found to be large. The question to be answered in this test was if the waterproofing membrane can prevent leakage while it stretches by as much as one inch. After many unsuccessful trials were conducted, the test plan was repeatedly revised and improved to develop a suitable water leakage test.

Since the waterproofing membrane is a stretchable material and previous tests in this study showed large elongations, the primary intent of the leakage tests was mainly to investigate if there is any leakage before the membrane reaches its deformation limits. It was important to determine if the membrane can retain its waterproofing property over the entire time of its deformation.

For this test, a one-inch differential deflection limit was assumed to be satisfactory. Furthermore, one inch of elongation is fairly large and was considered adequate to accommodate typical differential deflections in box-beam bridges. These tests were done under extension control of 0.2 inch per minute, which is slow enough to detect with the naked eye any leakage over the blotting paper attached to the membrane.

3.2.4.1 Test Setup

The first test setup tried in this study used a square-shaped specimen and a square-shaped frame loaded with a square-shaped loading plate. The sharp corners of the loading plate damaged the membrane specimen during the trial tests. Therefore, the test results with square specimens were disregarded. The revised test setup comprised a circular transparent plexiglass hollow tube and a circular loading plate. Dyed water was used to fill around the loading plate in the deflected region of the membrane while the loading plate was being plunged into the membrane, which was firmly attached to the top of the tube. Blotting paper was attached to the plexiglass tube on the inside of the tube to detect any dripping of dyed water. The frame for the leakage initiation detection test is shown in Figs. 3.11 and 3.12. A four-inch-diameter loading plate was used to plunge into the membrane. An Instron HDX loading machine was used in this test.
3.2.4.2 Test Results and Discussion

All five types of waterproofing membranes were subject to the detection of leakage initiation test. In this test, loading was continued until a one-inch depression of the membrane was achieved relative to the rim of the hollow tube. All five membranes passed the one-inch deflection criterion used in this test without any indications of water leakage. Fig. 3.13 shows top and bottom views of a typical specimen after the test. These tests demonstrated that there can be no leakage through the membrane for at least about 1.0 inch of differential deformation. Fig. 3.14 shows a typical load-elongation curve. This test confirmed that waterproofing membranes were able to maintain watertightness even after deforming one inch, which is significant.

![Fig. 3.11 Hollow Tube Used in the Test](image1)

![Fig. 3.12 Detection of Leakage Initiation Test Setup](image2)
Fig. 3.13 Typical Top (left) and Bottom (right) Views of a Typical Test Specimen after the Test, Showing no Leakage at the Bottom

Fig. 3.14 Load vs. Elongation for a Typical Detection of Leakage Initiation Test

3.2.5 Punching Test

A waterproofing membrane can tear or be punched through during construction. For example, loose aggregate or debris with sharp corners that exist on the top surface of bridge decks when the waterproofing membrane is laid may punch through the membrane if any wheel load is applied to the bare membrane before the asphalt concrete overlay is placed. Furthermore, asphalt concrete generally contains (over 85% by volume) crushed aggregate with a variety of angularity and sharpness characteristics, and those sharp corners may be a source for punching failures. This test was designed and conducted to determine the punching resistance of waterproofing membranes.

The main objective of this test is to purely determine the punching resistance of membranes. Punching resistance is one of the key factors for membrane classification in terms of watertightness. There is currently no standardized method to perform this test and therefore a new test was designed and used in this study.
3.2.5.1 Test Setup

An Acme laboratory penetrometer was used for the punching tests. This penetrometer is equipped with an arm to apply loads manually and has a load cell to measure the applied load during the test. As a modification to this equipment, an ohmmeter was attached to detect when punching occurred. The ohmmeter terminal wires were connected to the plunging tip on one side and to a steel plate under the membrane test specimen on the other end. The ohmmeter provides an indication of punching by making a beeping sound and changing the digital reading when the circuit becomes closed, i.e., the tip of the plunger penetrates the membrane and touches the steel plate below the membrane. The load was recorded for each punching occurrence. Figs. 3.15 and 3.16 show the punching test setup used in this study.

![Fig. 3.15 Schematic of the Punching Test](image)

![Fig. 3.16 Punching Test Setup](image)
The tip shown in Fig. 3.15 was made from a low carbon steel bar, which provides good electrical conductivity. The tip was designed to simulate the effect of sharp corners of grit, aggregate, or beam corners. A 37.5° angle was used. The schematic details of the setup are shown in Fig. 3.15. Membrane test specimens were cut into 4” wide strips before testing.

Type II membranes, which are self-adhering, are supplied with a non-conductive protective sheet on the surface with the adhesive coating. Type III membranes do not come with such protective sheets. For test specimens made from Type II membranes, the protective sheets were removed before placing the specimen on the bottom steel plate. Aluminum foil was attached to the sticky surface of the membrane so that the membrane would not stick to the steel plate below the specimen. The aluminum foil attached underneath the membrane specimens allowed the current to pass through to the steel plate upon penetration of the plunger. All punching tests were conducted at room temperature.

3.2.5.2 Test Results and Discussion

In this test, five different waterproofing membranes selected in the study were subjected to punching loads. More than forty specimens were tested for each membrane type, and the test results were statistically analyzed after excluding outliers. This test showed superior punching resistance of both PavePrep and PavePrep SA with an average resistance of over 144 lb. Polyguard 665 had the lowest punching resistance with an average of 91 lb.

The punching test results show that waterproofing membranes will be punched through at about 120 lb. For all types of membrane tested in this study, the punching resistance was very low. These membranes have a high risk of getting punched through during construction if they are not properly protected. The movement of heavy construction equipment directly above the membrane will cause such punching type of damage to waterproofing membranes.

3.2.6 Membrane Performance under Passenger Car Wheel Load

A simple test was devised to evaluate the waterproofing membrane performance under a passenger car wheel load of about 1,200 lb. A metal plate assembly was used to test the membrane as shown in Fig. 3.17. A car was driven many times on the top of the membrane installed over a plate assembly in directions parallel and transverse to the sharp edge as shown in Fig. 3.18. After the wheel load application in each test, the test membrane was separated from the plate assembly and visually inspected. It was observed that there was no shearing or tearing of the membrane after the application of the wheel loading several times. Each membrane was then tested for watertightness. No water leakage was detected, suggesting that the membrane retained its waterproofing property even after wheel loading.
3.3 Summary

The test results presented in this chapter demonstrate that the tensile strength of membranes is low and remains mostly constant over a temperature range of -4° F to 70° F. The elongation of membranes at failure can be over one inch, but the ability to elongate is reduced substantially when temperature reduces from 70° F to -4° F. The adhesion (peel-off) strength of membranes is very low for Type II (self-adhesive) and Type III membranes. Direct heat application on binders does not improve adhesion strength, but use of sealant in addition to primer improves adhesion strength. Membranes are capable of accommodating at least one inch of differential (shear) deformation without rupture. Membranes can provide watertightness even after shear deformation of over one inch. Membranes subjected to wheel loads over sharp edges did not fail by rupture. However, punching tests revealed that membranes are susceptible to punching failure when loads are transferred through sharp points similar to corners of grit, aggregate or beam edges. Based on the results developed from the tests described in this chapter, there is clear evidence that membranes will be able to accommodate large elongations and differential deflections between adjacent box beams without losing watertightness property. This suggests that membrane failures by rupture due to tensile or shear deformations may not be the primary cause of water leakage through the longitudinal joints in adjacent box beam bridges as long as membrane is installed properly and punching of the membranes do not occur during construction. At the onset of this project, there was a general feeling that failure of waterproofing membranes may be the sole cause of the problem. However, that school of thought was disproved from the membrane tests conducted in this study.
CHAPTER IV
FIELD MEASUREMENTS OF VERTICAL DIFFERENTIAL DEFLECTIONS
AND SEPARATION OF LONGITUDINAL JOINTS
UNDER TRUCK LOADING

4.1 Objective

The objective of measuring differential vertical deflections and horizontal separation at the longitudinal joints of typical box beam bridges was to determine the movements that can be expected in an actual bridge when subjected to traffic loading. The magnitude and nature of these movements were needed to determine if the waterproofing membrane has adequate capacity to bridge between the cracks at longitudinal joints, as the membrane needs to accommodate these vertical and horizontal movements while maintaining the waterproofing property. Such measurements were also needed to help evaluate key ways and to understand the load paths and the stress condition. The measured differential deflections and separations provide a basis to define failure for these joints in actual bridges. The differential deflections and the horizontal movements of the laboratory test specimens were correlated with the actual site measurements in order to define “failure” in the laboratory test specimens and develop strategies to minimize failures.

4.2 Methodology

4.2.1 Bridge Selection

The database provided by ODOT for the entire state was reviewed and several bridges in various parts of the state were physically inspected to select a suitable bridge for detailed measurements of differential vertical deflections and horizontal movements. Some of the inspected bridges were found to be unsuitable for obtaining detailed measurements.

Based on the bridges inspected in various ODOT districts and based on the discussions with ODOT and county engineers, it is noted that the water leakage problem does not appear to have a geographical or statistical trend. Lack of watertightness, cracking at longitudinal joints, and joint failures seem to be common problems in the bridges on highways throughout the state and on many county roads.

Bridge ASD-42-12.49 in Ashland County (ODOT District 3) was selected for measuring vertical differential deflections and horizontal differential movements under truck loading. This bridge is a non-composite bridge having a 60-ft. span, thirteen precast-prestressed box beams tied with one set of three overlapping tie rods in the transverse direction, and an asphalt concrete wearing course. A single set of tie rods was provided at an intermediate location as shown in Fig. 4.1. The current ODOT standard PSBD-2-07 requires two diaphragms (and two sets of tie rods) to be provided for spans greater than 50’-0” but less than 75’-0”. Therefore, a single set of tie rods provided in this bridge does not satisfy these requirements. The bridge otherwise met the following selection criteria:
• It had around 12 ft of clear height under the bridge, which was suitable height for installing dial gages at the bottom of the girders.
• The bridge was located on a straight highway to allow the loaded test truck to pick up speed (up to 70 mph) before reaching the bridge and to slow down after driving over the bridge without the need for traffic control.
• There was easy access to the area below the bridge to allow working under the bridge, i.e., no dense vegetation, deep water in the stream, or steep side slopes.

Bridge ASD-42-12.49 was recognized by ODOT bridge engineers to be defective, and the key way joints between adjacent box beams were documented to have longitudinal cracks and known water leakage problem. Longitudinal cracks appeared on the surface of the asphalt concrete layer as seen in Fig. 4.2. Cover spalling and corrosion for the reinforcement was observed at the underside of the box beams of the bridge.

![Fig. 4.1 Plan Dimensions and View of the Underside of Bridge ASD-42-12.49](image)

4.2.3 Measurements

The locations of interest for recording deflections were carefully selected based on the visual inspection of the bottom of the bridge to identify the locations where the water leakage damage had occurred and where cracks were clearly visible on the surface of the asphalt concrete overlay. Four longitudinal joints were selected out of the twelve joints between the box beams. Dial gages were installed on the underside of the beams to measure the relative movements at 11 locations as shown in Figure 4.1.

The locations of the joints between the box beams were located and measured at the bottom of the bridge and marked on the top on the asphalt concrete surface by carefully transferring
the corresponding points from the bottom of the bridge. A truck was loaded to a total load of 67.4 kips (including the self-weight of the truck) and was driven over the bridge at speeds of 50 or 70 mph following specifically marked paths. The loaded truck was guided to drive on the beam next to the longitudinal joint where the gage readings were taken. The differential deflections and the lateral spread were videotaped and later analyzed to obtain measurements of the maximum movements.

![Surface Cracks and Path of Truck Wheels](left) and Typical Cover Spalling on Bottom Surface (right)

An intermediate tie rod was located at 40 ft from the south pier and 18ft-8in from the north pier. No tie rods were present at the supports. Measurements were obtained from gages at Points 2, 5, and 8 at the tie rod location. Points 1, 4, and 7 were located at half the distance between the tie rod and the north pier. Points 3, 6, and 9 were located at half the distance between the tie rod and the south pier to monitor the effects of the clamping forces provided by the tie rod and the effects of the spacing between tie rods and the end supports. Points 10 and 11 were located where severe cracks were visible.

### 4.3 Test Results and Discussion

The measured vertical differential deflection and lateral relative spread between the adjacent girders were the least at the middle tie rod location, with values equal to 0, 0 for Point 2, 0.0020, 0.0018 for Point 5, and 0.0010, 0.0010 for Point 8 (Table 4.1). The maximum vertical differential deflection was recorded at the center of the length between the middle tie rod and the south pier with 40 ft spacing between the tie rods. Fig. 4.3 shows typical vertical differential deflections at three locations. The maximum recorded vertical differential deflection was 0.0045 inch. The maximum horizontal separation at the underside of the box beams was measured to be 0.0150 inch. Fig. 4.3 shows the vertical differential deflection at Points 7, 8, and 9. For all locations, the movements were the largest at the time when the truck was directly above the measured point.
4.4 Summary of Findings

The following findings were noted, based on the field measurements obtained for bridge ASD-42-12.49:

- These measurements provide a basis for defining the extent of stretching and the extent of shear deformation that a waterproofing membrane needs to accommodate without losing its ability to provide watertightness. The membrane tests presented in earlier sections demonstrate that these membranes are capable of extending axially (in-plane) over one inch (10 to 20% of original length) and deform in shear mode (differential deflection out-of-plane) by over one inch. These field measurements and laboratory tests lead to the conclusion that membranes can accommodate the vertical and horizontal differential deflections that can normally be expected in typical box beam bridges known to have cracks at the longitudinal joints and water leakage problems.

- Tie rod clamping-force reduces the relative movements between the adjacent box beams at the location of the tie rods.

- The greater the distance between the tie rod locations, the larger the relative movements between the adjacent box beams in a bridge.

### Table 4.1: Significance of Test Points and Measured Values

<table>
<thead>
<tr>
<th>Test point</th>
<th>Point significance</th>
<th>Vertical differential deflection (in)</th>
<th>Horizontal differential deflection (in)</th>
<th>Truck speed (mph)</th>
<th>Truck load (kips)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>At middle distance between the north pier and the middle tie rod</td>
<td>0.0010</td>
<td>---</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>At middle distance between the north pier and the tie middle rod</td>
<td>0.0020</td>
<td>---</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>At the middle tie rod location</td>
<td>0.0000</td>
<td>0.0000</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>At middle distance between the south pier and the tie middle rod</td>
<td>0.0010</td>
<td>0.0000</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>At middle distance between the north pier and the middle tie rod</td>
<td>0.0015</td>
<td>---</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>At middle distance between the north pier and the middle tie rod</td>
<td>0.0025</td>
<td>---</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>At the middle tie rod location</td>
<td>0.0020</td>
<td>0.0018</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>At middle distance between the south pier and the middle tie rod</td>
<td>0.0030</td>
<td>0.0150</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>At middle distance between the north pier and the middle tie rod</td>
<td>0.0040</td>
<td>0.0000</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>At the middle tie rod location</td>
<td>0.0010</td>
<td>0.0010</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>At middle distance between the south pier and the middle tie rod</td>
<td>0.0045</td>
<td>0.0095</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Cracks on the surface aligned with the joint location</td>
<td>0.0010</td>
<td>0.0015</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Cracks on the surface aligned with the joint location</td>
<td>0.0015</td>
<td>0.0010</td>
<td>70</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 4.3 Differential Vertical Deflections at Points 7, 8, and 9
CHAPTER V

OBSERVATION OF CONSTRUCTION PRACTICES
AT A BRIDGE CONSTRUCTION SITE

To understand the construction processes, the sequence of the activity, and the time frame for each activity, multiple site visits were made to a construction site where a new bridge was under construction in Shreve, Ohio. The construction process was discretely observed so as not to interfere with the normal course of construction. On the first working day, seven box beams were delivered to the site. Within 3 hours of the delivery, the beams were installed in position and tied together with tie rods tensioned to the specified torque to provide the transverse clamping force of 15 kips at each tie rod location. During the second working day, the six longitudinal joints were grouted by noon. The bridge was ready for the waterproofing membrane to be laid within two days.

The box beams for this bridge were B17"-48" with 17 inches of height and 48 inches of width having a 7-inch key way which was sandblasted according to ODOT specifications. The girders were a little out of sweep but within the allowable tolerance of one inch. Oakum (ropes) of one inch diameter was used to fill the gaps between the box beams with the intent of preventing grout from leaking from the bottom of the beams into the stream below.

The grouting process proceeded rapidly. After blowing the dust from the bridge deck and the joints, the grout was mixed in a grout mixer that was placed on the top of the bridge deck. Immediately after mixing, it was transported to the joints in trolleys. An approved grout material from ODOT's QPL was used. The mixing water was around 5 quarts per 50 lb bag to obtain a flowable consistency and to accomplish the filling of the key way with wet grout in a reasonably short period of time. However, the amount of water added seemed excessive, and much more than what would be required to allow the development of the compressive strength to the specified level.

During the installation of the waterproofing membrane, the deck surface preparation was very poor. Many concrete protrusions, grit, debris, and nails (used for nailing the drip strips at the edges of the bridge) remained on the deck surface. A heavy asphalt pavement roller was driven on the deck surface several times, likely perforating the membrane even before the asphalt concrete overlay was placed. Fig. 5.1 shows concrete protrusions and nails on the deck surface after the concrete surface was prepared and just before the membrane was installed. Fig. 5.2 shows the use of a compaction roller and a paver over the unprotected waterproofing membrane after its installation.
The site observations reported in this chapter demonstrate a set of unacceptable construction practices followed by contractors. ODOT specifications provide basic guidance and clear protocols on waterproofing membrane installation and grouting of key ways. These specifications and recommendations need to be expanded to include more details to provide a better understanding of the procedures by both contractors and inspectors. Excessive addition of water to grout material needs to be regulated and controlled so as to prevent the diminishing structural strength of key way joints. Successful implementation for a waterproofing membrane needs careful concrete surface preparation, proper installation of the bonding agent, and laying of membrane sheets. The waterproofing membrane must be inspected before the paving process is started. Driving of heavy equipment needs to be prohibited before the asphalt concrete overlay is placed so as to prevent damage to the membrane.
CHAPTER VI

INVESTIGATION OF A BRIDGE THAT WAS IN SERVICE FOR 32 YEARS AT THE TIME OF ITS DEMOLITION

Bridge RIC-42-12.34, located in Mansfield, Ohio, in ODOT District 3, was constructed in 1983 and scheduled for demolition in August 2015. The width of the bridge was 60 ft. and the span was 34 ft. The primary objective of this task was to evaluate the condition of the waterproofing membrane after the bridge was in service for 32 years. On the day of the demolition, the asphalt concrete overlay was carefully cut to extract waterproofing membrane samples for inspection and watertightness testing. The underside of the bridge was found to have several locations of severe corrosion of strands, spalling and deterioration as shown in Fig. 6.1. Suitable locations to remove the asphalt concrete overlay were selected to expose the membrane on the deck surface based on the amount of corrosion, spalling and cracking on the underside of the box beams.

![Fig. 6.1 Corrosion Damage on the Underside of Box Beams](image)

On the removal of asphalt concrete on the deck top surface, a large area (about 250 to 300 ft²) on the bridge deck was found to have no waterproofing membrane at all. Three membrane specimens were extracted from other locations on the bridge deck. Two of these specimens were full of visible holes. A watertightness test was performed for the remaining membrane specimen, which seemed to be in good condition by visual inspection but miserably failed to prevent leakage.

The most severe corrosion and spalling were found at locations where no waterproofing membrane was present. The waterproofing membrane specimens collected from the locations corresponding to severe corrosion were fully damaged and were not watertight. The bond between the waterproofing membrane and box beams was lacking, even though there was some bonding of the membrane with the asphalt overlay. The box beam surface at
the key way interface was not sandblasted. Longitudinal cracks between the grout and the box beams were wide and were visible throughout the bridge deck (Fig. 6.2). Where provided, the membrane was in very poor condition.

![Fig. 6.2 Condition of a Typical Joint and Deck Surface](image)

Small pieces of the membrane that were retrieved from the locations where the membrane was exposed with a jack hammer (Fig. 6.2) were too fragile to perform any laboratory mechanical tests. Therefore, no tensile tests or other tests were performed on these retrieved membranes.

In summary, the lack of watertightness and the corrosion damage at the bottom surface of the box beams along the longitudinal joints correlated well vertically with the locations where the membrane was missing or severely damaged at the top surface of the bridge. The membrane, where present, was in very poor condition and full of holes that would make it impossible for the membrane to provide any watertightness.
CHAPTER VII

IMPLEMENTATION RECOMMENDATIONS FOR BOX-BEAM BRIDGES
WITH A SIMPLE SPAN

The recommendations outlined in this chapter were developed for potential implementation for box-beam bridges with a simple span of up to about 40 feet. These modified specifications were provided to ODOT for bidding purposes for a box beam bridge in ODOT District 3 (bridge number: RIC T0037 0021 and structure file number: 7032048).

It is evident from Chapter V that the construction practices followed by contractors are far from perfect and are not complaint with ODOT specifications. It is imperative to enforce the compliance of the specifications in order to ensure the desired watertightness expected from waterproofing membranes. While specific to the selected bridge, the following suggested recommendations can be applied to any box beam bridges located on county roads or highways. The effectiveness of waterproofing systems does not seem to depend on the type of box beam employed (i.e., prestressed beams and non-prestressed reinforced concrete beams). Therefore, the following suggested recommendations are applicable to prestressed and non-prestressed concrete box beam bridges.

7.1 Recommended Modified Design and Construction Specifications

All the relevant ODOT specifications from (i) Construction Administration Manual of Procedures (2013), (ii) Construction and Material Specifications (2013), and (iii) standard drawings PSBD-2-07 must be strictly followed in order to minimize the tendency of water leakage through the longitudinal joints in adjacent box-beam bridges. The following additional recommendations are suggested for implementation. ODOT construction and materials specification section 515 may be modified as follows:

515 Prestressed Concrete Bridge Members

Box Beam Grout Installation

Keyways should be grouted after erection of box beams. Generally, plastic rope or jute is installed into the bottom of the keyway to block the grout from flowing out. Utmost care shall be taken to seal the bottom edge of the keyway to prevent leaking of wet grout during and after the grouting process.

1. Ensure that the installation is done properly. Box beam keys have failed because of improper jute installation. However, suitable foam sealant may be used to seal the keyway and make it watertight before the grouting operation begins.

2. The fabricator shall sandblast the keyway surface within four days of shipment to the project site as specified in ODOT standard drawing PSBD-2-07. The sandblasting shall yield a visual appearance and texture equal or rougher than 100 grit sandpaper over the entire keyway surface. When stains are visible before sandblasting the concrete, use a degreaser to ensure removal of grease, oils and other similar contaminates. The
degreaser shall be water soluble so it can be removed before the blasting begins. Before mortaring, remove all dirt, dust, grease, oil and other foreign materials from surfaces using a high pressure wash of at least 1,000 psi at a delivery rate of 4 gal/min.

3. Grout should meet the material requirements of the Office of Structural Engineering’s standard box beam drawings. Additional requirements are to be satisfied for the high performance high strength concrete grout that is recommended to be used in this project. A grout with #8 maximum size aggregate needs to be used in this project with the following specifications:

- Minimum compressive strength of 10,000 psi needs to be achieved before allowing any construction equipment on the deck.
- The grout shall be designed to include well graded #8 coarse aggregate suitable for high strength concrete applications.
- The top surface of the grouted joints shall be cured with an ODOT-approved curing compound that is to be applied on the surface after one hour of grouting.
- The grout shall have workability that is adequate to fill the keyway.
- Suitable needle vibrator shall be used to adequately consolidate the grout.

4. The manufacturer’s mixing instructions are required and should ensure that the grout is properly mixed, vibrated into the joints, cured, and sampled for testing.

5. Grouting should not be allowed if there is construction traffic or erection is still in progress. The grout can be cracked by the vibration and deflection movements and make the keyways worthless. The design of the structure counts on the grout in the shear keys.

6. Do not allow traffic on the deck before the grout has obtained the required strength of 10,000 psi. This includes construction traffic. This specification must be strictly followed.

The mix proportions given in Table 7.1 were found to be satisfactory for the high strength grouts in a laboratory environment. However, other mixes with better optimized aggregate gradation and supplementary cementitous materials may also be used to improve the mix proportions and reduce cement content while maintaining similar minimum strength and performance to achieve very low shrinkage.

**Table 7.1  Possible Mix Proportions for High Performance High Strength Concrete Grout for the Keyways**

<table>
<thead>
<tr>
<th>Mix Proportions</th>
<th>Materials</th>
<th>Description</th>
<th>lbs/yd³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>Type I</td>
<td>1100</td>
<td></td>
</tr>
<tr>
<td>Coarse aggregate</td>
<td>#8 limestone</td>
<td>1596</td>
<td></td>
</tr>
<tr>
<td>Sand</td>
<td>River sand</td>
<td>1450</td>
<td></td>
</tr>
<tr>
<td>W/C</td>
<td>0.35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>Potable water</td>
<td>385</td>
<td></td>
</tr>
<tr>
<td>High range water reducing agent 100ml/100 lb of cement (SIKA 2100)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Installation of Waterproofing Membrane

The specifications on the preparation of the top surface of box beams that are given in Section 512.08 should be carefully followed before and after the installation of the membrane. Remove all protrusions more than 0.1 inch in height from the concrete surface at the top of the box beams. Sweep off dirt and dust, and blow the concrete clean. Fill joints or cracks greater than 3/8 inch (10 mm) wide with Portland cement mortar. In addition to the above, remove oil and grease from surfaces for Type 3 membranes using water and a detergent designed to remove oil and grease from concrete. Flush residual detergent from the surface. Do not allow traffic or construction equipment on the cleaned surface or on the membrane after installation of the membrane and before the asphalt concrete is placed. If any visual damage to the membrane is found after installation of the membrane, suitable repairs must be made to prevent water leakage before placing the asphalt concrete. The repair method and acceptance will be determined by qualified inspectors.
CHAPTER VIII

CONCLUSIONS

The following broad conclusions are drawn from the work completed in this project:

1. The waterproofing membranes tested in this study possess the capacity to stretch adequately both in terms of in-plane elongations and out-of-plane shear deformation by over one inch while retaining their watertightness. Therefore, failure of membranes by elongation or shear at the longitudinal joints of adjacent box beam bridges may not be the sole source of water leakage problems in such bridges.

2. It is expected that the differential vertical deflections at the longitudinal joints of a typical box beam bridge with spans of about 60 ft. and known water leakage problems can be about 0.005 inch under approximate design truck loading. The corresponding horizontal separation between adjacent box beams at the underside of the beams can be about 0.015 inch. Waterproofing membranes can bridge over cracks and stretch adequately to accommodate differential deflections in this range without losing their waterproofing properties.

3. The construction practices followed at the bridge construction site studied in this project were found to be seriously flawed and will not prevent water leakage through the longitudinal joints of the box beams installed at that site. If such poor practices are widespread and are occurring at other sites, those practices need to be reviewed carefully, and suitable modifications to the relevant specifications and inspection protocols need to be developed in order to achieve reliable and consistent outcome of prevention of water leakage at the longitudinal joints in box beam bridges.

4. Many of the problems that lead to the loss of waterproofing of box beam bridges may be preventable if proper quality control protocols are put in place and stringent inspections are carried out constantly by qualified inspectors during the construction period.
REFERENCES


7. Concrete Sealants Inc. (2013). *ConSeal CS-212*. Tipp City: Concrete Sealants Inc.


14. Frosch, R. J., Kreger, M. E., & Strandquist, B. V. (2013). *Implementation of Performance-Based Bridge Deck Protective Systems*. Indiana Department of Transportation and Purdue University. West Lafayette: Joint Transportation Research Program, Indiana Department of Transportation and Purdue University.


34. ODOT. *Study of Non-Shrink Keyway Grout for Strength*. Ohio Department of Transportation ODOT, 26 Pages, Retrieved from Google: https://www.dot.state.oh.us/Divisions/ConstructionMgt/Materials/In%20House%20Research/Non-Shrink-%20grout-evaluation.pdf


36. PCI Committee on Bridges. (2009). *The State of the Art of Precast/Prestressed Adjacent Box Beam Bridges*. Chicago: Precast/Prestressed Concrete Institute.


45. Steinberg, E., & Miller, R. A. (2011). *Assessment of Deteriorated Prestressed Concrete Bridge Box Beams*. Ohio University, University of Cincinnati, Department of Civil Engineering. Columbus: The Ohio Department of Transportation.


