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Durability of Epoxy Polymer Concrete Overlays for Bridge Decks

by

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Durability of Epoxy Polymer Concrete Overlays for Bridge Decks

Abstract

Epoxy-based flexible polymer concrete overlays have been used in the past 15 years in North America to protect the bridge deck from deterioration, to extend the service life, and to improve skid resistant of the riding surface. While 15 years of field applications have demonstrated the effectiveness of the protection offered by the technique, cracking and delamination failures have also been observed.

The purpose of the research reported herein is to understand the mechanism of durability failure of the epoxy polymer concrete overlay system. The tests conducted were water permeability, chloride ion penetration, water absorption, strength loss, temperature cycling, and water vapour pressure. Methods of application of polymer concrete overlay play a key role in the success of the overlay. In addition to the two commonly used methods, the multiple layer and the slurry methods, five new application methods were proposed and evaluated.

It was found that the addition of a primer in the overlay system helps reduce water permeability, and that the thin polymer concrete overlay was much less permeable than the thick asphalt overlay. The temperature cycling tests revealed that no significant delamination occurred after 103 cycles from -50°C to 40°C at an accelerated rate. The rapid chloride ion penetration test confirmed that polymer concrete overlays did provide sufficient protection to stop the chloride ion intrusion. Nevertheless, the epoxy polymer concrete overlays were found to absorb 2-3% of water, which caused a significant strength loss. This strength loss could lead to cracking inside the overlay and accelerate delamination thereafter. The water vapour pressure generated from the saturated concrete substrates was not large enough to promote delamination. Overall, the newly proposed overlay applications methods have proven effective in constructing a thin, durable, less expensive and fast overlay for aged bridge deck protection.

La durabilité des revêtements en béton polymère époxyde pour les chaussées de ponts

Résumé

Les revêtements flexibles en béton polymère epoxyde sont utilisés depuis 15 ans en l'Amérique de Nord pour protéger la chaussée des ponts contre la détérioration, pour augmenter leur durée de vie et pour améliorer leurs propriétés de friction. Bien que ces 15 ans d'usage aient prouvé l'efficacité de la protection offerte par ce matériau, on a aussi constaté des fissures et des défauts de liaison polymère e chaussée.

Le but de cette recherche est de comprendre le mécanismes causcent la détérioration des revêtements en béton polymère epoxyde. Les tests réalisés sont la perméabilité à l'eau, la pénétration d'ions chlorines, l'absorption d'eau, la perte de résistance en flexion, le comportement sous variation cyclique de la temperature et sous la pression de la vapeur d'eau. La méthode d'application du revêtement est la clé du succès. En plus de deux méthodes normalement utilisées, soit les couches multiples et le coulis, cinq nouvelles méthodes d'application sont proposées et évaluées.

L'étude a montré que l'ajout d'un apprêt dans le revêtement réduit la perméabilité à l'eau et qu'une couche mince de béton polymère est moins perméable qu'une couche épaisse d'asphalte. Les tests de température ont révélé qu'aucun déliement significatif entre le polymère et le chaussée ne s'est produit après 103 cycles de -50°C à 40°C à un rythme accéléré. Le test de pénétration des ions chlorines confirme que le revêtement de béton polymère procure une protection suffisante. Néanmoins le revêtement de béton polymère époxyde absorbe 2-3% de l'eau causant ainsi une perte de résistance en flexion significative. Cette perte résistance peut conduire à la fissuration à l'interieur de la couche de béton, et ce qui accélère le déliement polymère-pavé. La pression de la vapeur d'eau produite n'est toutefois pas assez forte pour causer le déliement polymère-pavé. D'une manière générale, les nouvelles méthodes proposées se sont avérées efficaces pour produire un revêtement mince, durable, moins coûteux et de pose rapide pour la protection des chaussées des vieux ponts.

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Chapter 1

Introduction

1.1 BRIDGE DETERIORATION

Bridges that were designed to last at least 50 years are showing advanced deterioration and aging. Approximately 230,000 out of 580,695 bridges in the United States alone are in need of some form of repair or complete replacement [Belle 1995]. Of these 580,695 bridges in the United States, 143,000 are 50 years old or more and unsuitable for current or projected traffic demands.

The bridge component that is fundamental in transportation engineering, is the deck. The role of the bridge deck is to carry the dead and live loads between the supports. They must be resistant to abrasion, water intrusion, chloride ion penetration, delamination, spalling, cracking, and freeze-thaw cycling.

There are essentially nine different types of bridge decks. The different decks are: cast-in-place concrete, precast concrete, open steel grid, closed steel grid, steel plate, corrugated plate, aluminum, timber, and decks that do not fit any of the other categories (table 1.1). The Portland cement concrete bridge deck counts for 63% of all bridges and 85% of all bridge deck area (table 1.2). Therefore, most of the bridges that are deteriorating are made from Portland cement concrete. The effective protection of the reinforcing steel from chloride ions and water intrusion becomes increasingly important in concrete bridge decks.

The extent of deterioration varies according to environmental conditions, method of construction, construction details and quality of materials used. Regardless of what stage of deterioration the bridge is in, a solution (or solutions) is required that will slow the process of degradation, enhance public safety, and help extend the service life of the bridge. This vital need has made the art of repairing, rehabilitating and protecting as well as the identification of the source of degradation extremely important.

Table 1.1 Types of Bridge Deck in the United States [Bettigole et al. 1997]

Deck type	No. of Bridges	Percent of total
Cast-in-place concrete	330,063	56.8%
Precast concrete	37,887	6.5%
Open steel grid	3,447	0.6%
Closed steel grid (concrete filled)	1,467	0.3%
Steel plate (orthotropic)	1,412	0.2%
Corrugated (plate)	9,887	1.7%
Aluminum	443	0.1%
Timber	12,974	2.2%
Other	183,111	31.5%
Total	**580,691**	**100%**

Table 1.2 Bridge Deck Area in the United States [Bettigole et al. 1997]

Deck type	Deck area 000's m^2	Area % of total
Cast-in-place concrete	245,550	80.56%
Precast concrete	11,244	3.69%
Open steel grid	2,410	0.79%
Closed steel grid (concrete filled)	1,442	0.47%
Steel plate (orthotropic)	523	0.17%
Corrugated (plate)	1,381	0.45%
Aluminum	81	0.03%
Timber	8,405	2.76%
Other	5,690	1.87%
101,066 culverts	28,080	9.21%
Total	**304,806**	**100%**

There are five common types of failures in the concrete bridge deck. ***Delamination*** occurs when the Portland cement concrete layers separates from the near top or outmost layer of reinforcing steel. The cause of the delamination is the expansion of corrosion products produced from the corrosion of the reinforcing steel. The extent of failure can be detected by using a hammer or chain drag to identify areas with a hollow sound.

Spalling is defined as the depression resulting when a fragment is detached from a larger mass by either a blow, weather, pressure, or expansion of the larger mass. The cause of spalling is the same for delamination, the creation of tensile stresses in the concrete due to corrosion products. The detection of potential spalling is conducted in the same manner as delamination. However, it should be noted that the potential for spalling is the total area where corrosion of steel is occurring and not just the area with a hollow sound.

The third common failure mode is ***scaling*** defined as the local flaking or peeling of the surface portion of concrete or mortar. Scaling can range in severity, from light where the coarse aggregate is undetected, to heavy where loss of aggregate has occurred. The cause of scaling is the increase of internal pressure due to freezing and usage of deicing salts.

The fourth and fifth failure modes consist of ***cracking*** and ***loss of skid resistance***. Of the different types of cracks, many do not require repair and some cannot be repaired. These unrepairable cracks are defined as moving cracks, and are a result of type of loading, bridge design and differential settlement. The current practice is to rout or widen the cracks and then fill them with the desired material. Loss of skid resistance is defined as the compression, shifting, polishing or removal of concrete along the paths of traffic wheels. The result of abrasion is reduction in cover depth, which ultimately means greater chloride ion penetration. Loss of skid resistance can be repaired with the use of an epoxy resin coating. The only way to prevent loss of skid resistance is by using good quality overlay material and ensuring that the traffic loads are within the specifications.

1.2 CAUSES OF DETERIORATION OF CONCRETE BRIDGE DECKS

Numerous studies and field observations have identified two major factors that contribute to the deterioration of bridges. These factors are salts and loads exceeding the original design criteria.

The bridge deck comes into contact with salts from the deicing salt that is routinely applied in the winter on bridge decks to prevent ice formation and from salt spray in a marine environment. It is these salts, sodium chloride (NaCl) and calcium chloride (CaCl), that produce chloride ions which are by far the most destructive element for concrete bridges. These chloride ions are what penetrates through the concrete cracks and pores to cause the corrosion of the reinforcing steel. [Babaei et al., 1990, Brinckerhoff, 1993]

The corrosion of the reinforcing steel begins with the ions breaking down the passive oxide layer on the surface. With the additional presence of water and oxygen, an electrical current is formed (electrolysis) and begins to convert iron (Fe) into iron ions (Fe^{+2} and Fe^{+3}). The formation of these ions (oxide and rust) tends to induce high tensile stresses in the surrounding Portland cement concrete. The tensile stresses cause the initial small cracks to become larger. Large cracks cause delamination and eventually spalling of the concrete. [Babaei et al., 1990, Brinckerhoff, 1993]

Besides tensile stresses from corrosion products, cracks widen due to traffic loads. The reason being that until 1973, most bridges were designed for the weight of H10 trucking loading, with a total weight of 10 tons, while recent studies have shown that circulating HS25 trucks weigh 45 tons. In addition to this higher than anticipated load, trucks travel much faster (inducing greater impact forces), consist of a much larger percentage of traffic mix, and the overall traffic volume has increased over the years. This increase in traffic volume and load has resulted in the wear and polishing of the bridge deck overlays, which in turn means that the deck becomes more susceptible to damage. [Babaei et al., 1990, Brinckerhoff, 1993]

The increase in width, length and number of the Portland cement concrete cracks augments the permeability of the bridge deck. This increase in permeability means that more chloride ions will penetrate and increase the rate of corrosion. An increase in rate of corrosion implies an increase in corrosion products which in turns implies more cracks. This circular cycle ends with the complete failure of the bridge, or with extensive repairs.

1.3 IMPROVEMENTS TO NEW BRIDGE DECK DESIGN

In the last few years, extensive research has been conducted and a better understanding of the structural and material behavior has helped improve bridge design. The additional benefit is that these developed techniques can be used to rehabilitate existing bridges. The improvements consist of amended loading factors, updated design codes, improved load distribution, reduction in allowable shear stress, development of overlays and coatings for Portland cement concrete, use of prestress concrete, and the upgrading of Portland cement concrete quality.

In addition to these crack control improvements, other steps are available to protect the reinforcing steel in the bridge deck against chloride-induced corrosion. They include: [McDonald 1995]

- increased cover
- reduced water-cement ratio
- addition of pozzolans to mix
- high C_3A cements
- coatings
- membranes
- penetrating sealers
- corrosion inhibitors
- epoxy-coated bars
- galvanized bars
- nickel-clad bars
- stainless steel or stainless steel-clad bars
- non-metallic bars
- cathodic protection

The amount of Portland cement concrete cover over the reinforcing steel can significantly influence the rate of corrosion. The minimum required concrete cover set by the American Association of State Highway and Transportation Officials (AASHTO) for bridge structures is 50mm, however, it is quite common to find 75mm covers. Studies have shown that if the Portland cement concrete cover is less than 40mm in a chloride rich environment, the steel has a high potential to corrode. [McDonald 1995]

While it is desirable to have a thick concrete cover over the reinforcing bars, two problems arise with increasing the cover too much. As the concrete covers increases, the potential for shrinkage and thermal stress cracking augments. These cracks will increase the permeability of the concrete and will eventually lead to delamination and spalling. Furthermore, as the concrete covers increase, the member sizes have to increase. This implies that the quantity of reinforcement used will augment, thereby increasing the dead load of the bridge deck. Thus, the practical limit for effective concrete cover is approximately 75mm. [McDonald 1995]

Besides the thickness of the concrete cover, the quality of the concrete mix will help reduce the chloride-induced corrosion. The use of a low water-cement ratio mix means that the density of the cured Portland cement concrete will be higher, therefore less permeable. AASHTO has recommended that the maximum water-cement ratio for bridge deck concrete be 0.45. In addition to low water-cement ratio, the quality of the concrete mix can be modified by the addition of pozzolanic materials. The addition of these materials (silica fume, ground blast furnace slag, and fly ash) will significantly decrease the permeability of the concrete by as much as 10 fold. [McDonald 1995]

To further reduce the penetration of chloride ions, coatings, membranes and penetrating sealers may be used. The different types of coatings that can be applied to the concrete include epoxy resins, polyester resins, acrylics, vinyl, polyurethane, and cementitious materials. These coatings have excellent adhesion properties, however, their performance is dependent on the moisture content of the concrete prior to application of the coating, and proper proportioning and adequate mixing. On the other hand there is the option of using membranes before placing an overlay. The membranes that are typically used between the overlays and deck are 1.25 to 2.4mm thick, and can be bonded to the concrete using adhesive or fastener. While they have been proven to be effective against chloride ion intrusion, the moisture content of the concrete as well as ultraviolet exposure affects their long-term performance. The next option is to use penetrating sealers such as epoxy resins, silanes and siloxanes. Essentially, the sealers are capable of penetrating the concrete, fill the air voids and discontinue the network of connecting voids. [McDonald 1995]

Apart from inhibiting the intrusion of chloride ions, the corrosion of the reinforcing bars can be eliminated by using non-corrosive bars such as epoxy-coated bars, galvanized bars, nickel-clad bars, stainless steel or stainless steel-clad bars, and non-metallic bars. Studies have shown that while these bars perform well in corrosive environments, however, the cost of the bars, availability of properly trained personnel, as well as bond strength with the concrete are factors that must to be considered.

Lastly, instead of making the bridge deck system impermeable or the reinforcing steel non-corrosive, cathodic protection may be used. This method provides extra electrons in the Portland cement concrete, and thus prevents the iron from transforming into Fe^{++}. The problem with the method is that it deteriorates the concrete surrounding the anodes that provide the extra electrons. Basically, the deterioration is caused by the acidic environment created by H^+ ions moving towards the anodes. [McDonald 1995]

1.4 PROTECTION OF EXISTING BRIDGE DECKS – THE OVERLAY APPROACH

The overlay approach has proven to be a cost-effective method in protecting and extending the service life of the bridge deck. For the overlay system to effectively protect the bridge deck, it must meet the following criteria: it must be able to resist abrasion, possess a high skid resistance, have a coefficient of thermal expansion similar to the substrate, develop a strong bond to the substrate, and must be flexible. In addition, the overlay must be resistant to freeze-thaw cycling, resistant to the alkalinity of the Portland cement concrete, resistant to deicing salts and chemicals, impermeable to water and chloride ions, and environmentally durable.

There are several overlay systems being used on concrete bridge decks by the construction industry. They are asphalt overlay, latex-modified Portland cement concrete overlay, low-slump Portland cement concrete overlay, and polymer concrete overlay.

1.4.1 Asphalt Overlay

There are two asphalt overlay systems used on bridge decks: asphalt by itself, and asphalt with a waterproof membrane.

The membrane option is used whenever an impermeable overlay system is required. It is a known fact that asphalt overlays are extremely permeable. The typical coefficient of permeability of asphalt is $1x10^{-4}$ to $1x10^{-6}$ m/s [Illston, 1995] while the typical coefficient of permeability for uncracked Portland cement concrete is approximately $1.6x10^{-11}$ m/s [Ludirdjia et al., 1989]. However, the use of the membrane increases the overlay construction cost substantially.

The waterproof membrane is applied to the bridge deck before the asphalt concrete is placed. To ensure that the membrane remains flat and that the asphalt-membrane system is bonded properly with the substrate Portland cement concrete, a layer of tack coat (typically epoxy resin) is applied between the deck and membrane as seen in figure 1.1.

Once the membrane has been placed and the binder is set, the asphalt concrete is applied using the hot mix asphalt application technique. The typical thickness of applied asphalt concrete is 10 mm (2.5 inches). The equipment used to apply the asphalt is shown in figure 1.2.

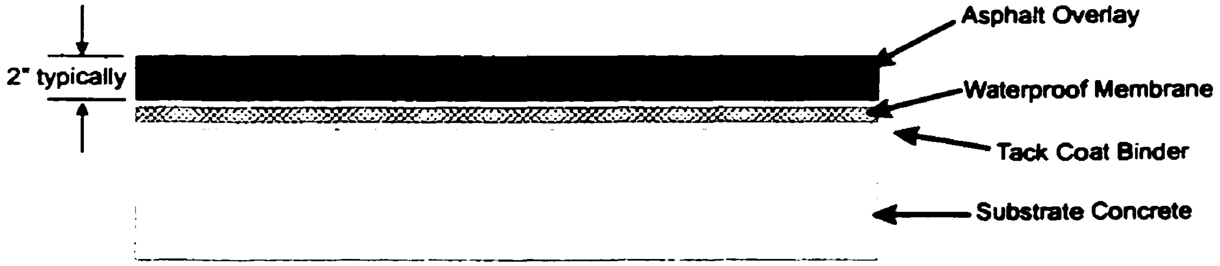


Figure 1.1 Schematic of the asphalt overlay system

Figure 1.2 Hot Mix Technique used for applying Asphalt [Miller Industries Brochure]

The primary reasons why the asphalt overlay system is extensively used are as follows: the system is relatively inexpensive, the materials and skilled contractors are easily available, and the material behavior is well understood. Despite these advantages, there are serious problems with the system. The problems are as follows: the service life of the asphalt overlays is approximately 15 years, extensive repair and patching is required in the first 10 years, the system is thick and adds dead load to the bridge deck, skid and wear resistance is inadequate.

Besides these problems, there are a variety of deterioration associated with the asphalt concrete overlay system leading to cracks, potholes, surface deformation, and surface defects (figures 1.3, 1.4, 1.5).

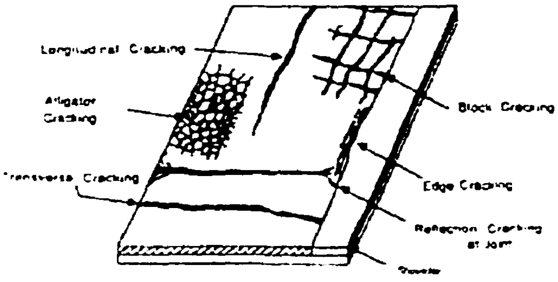


Figure 1.3 Cracking in asphalt

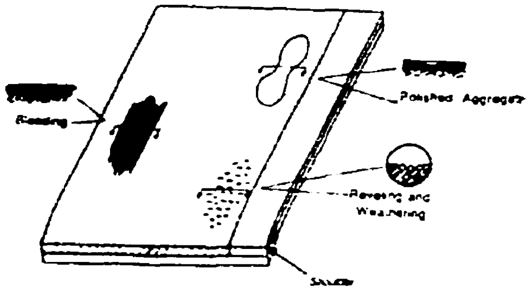


Figure 1.4 Surface Defects in asphalt

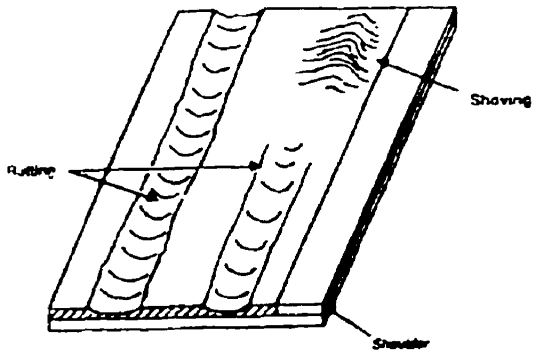


Figure 1.5 Surface deformation in asphalt

1.4.2 Latex-Modified Portland Cement Concrete Overlay

The latex-modified concrete overlay system consists of mixing styrene-butadiene latex with a regular Portland cement concrete mix. The result of adding latex is that the cured modified Portland cement concrete will have a continuous film within the concrete matrix. This film effectively seals pores and bridges micro-cracks, making the overlay highly impermeable to water, chemicals, chlorides and sulfates. [Babaei et al., 1990, Brinckerhoff, 1993]

Before the overlay can be placed, a 6mm (¼ inch) layer of the bridge deck is peeled off to remove all oil, grease and solvents. The surface is then blast cleaned with air and water jets, and thoroughly wet for an hour prior to placement of the overlay. The latex-modified Portland cement concrete is then distributed with shovels, brooms and brushes. A vibrating, screed-type finishing machine is then used to remove excess material and fill in the low spots. The thickness normally specified for a latex-modified concrete overlay is 32mm (1¼ inches), although overlays as thick as 76mm (3 inches) have been used. [Babaei et al., 1990, Brinckerhoff, 1993]

The advantage of using latex-modified concrete is that the latex effectively seals the network of pores in the Portland cement concrete. Thus, the concrete becomes impermeable to water and chloride ion penetration. However, there are at least three identified disadvantages associated with the latex-modified Portland cement concrete overlay. The most important is that the overlay must be wet-cured for 24 hours and then allowed to dry for 72 hours before usage. The other two disadvantages are that it must be placed at temperatures between 7°C and 30°C, and the surface must be textured to produce an adequate skid resistance. [Babaei et al., 1990, Brinckerhoff, 1993]

In addition, a study found that the degree of freeze-thaw scaling of the latex-modified concrete overlay depended on the quality of the Portland cement concrete that was mixed with the latex, as well as the amount of deicing salts applied. While the study did not find that the surface wear was lower than the conventional concrete, it did discover that most latex-modified concrete overlays were cracked due to shrinkage of the concrete in its plastic stage. Furthermore, the study concluded that even though some overlays were uncracked, all of them have a high potential to develop surface cracking. The other conclusion of the study was that while some areas had reasonably good bond strengths, other areas were low or had separated from the substrate. [Babaei et al., 1990]

1.4.3 Low-Slump Portland Cement Concrete Overlay

The low-slump Portland cement concrete system is composed of a rich dry Portland cement concrete mix. The mix typically consists of 488.2kg of cement per cubic meter (823 lbm/yard^3), a water-cement ratio of 0.35, aggregates with a maximum size of 13mm (½ inch), silica fume and an air entrainment additive to produce an 8% air content [Brinckerhoff, 1993]. To ensure that the low-slump concrete has the high density and low permeability, sufficient silica fume is added. The result is a dense concrete that is impermeable and has a slump of less then 25.4mm (1 inch). [Brinckerhoff, 1993]

Similar to the latex-modified concrete, the substrate must be free of oil, grease, and solvents before the low-slump concrete overlay can be placed. This is accomplished by removing 6mm (¼ inch) from the top with a scarifying machine. The surface is then coated with a rich cement mortar or an epoxy compound (to serve as a bonding agent) before the low-slump concrete is applied. The resulting thickness of the overlay is at least 51mm (2 inches). [Brinckerhoff, 1993]

The advantage of the low-slump concrete overlay is that the Portland cement concrete that is produced has a high density and a low permeability. However, in like fashion to the latex-modified concrete, the low-slump concrete possesses some problems. Due to the low water-cement ratio and slump, the workability is limited causing consolidation and finishing problems. The surface of the overlay has to be textured to ensure adequate skid resistance. The low-slump concrete has an extensive cure time, which implies substantial lane down time. There is also the potential for surface cracking due to the brittleness of the material. [Babaei et al., 1990]

1.4.4 Polymer Concrete Overlay

The polymer concrete overlay system consists of a polymer resin, used as the binder, and aggregates having a high abrasion resistance. The polymer concrete is placed on the bridge deck by three methods: slurry method, multiple layer method, and premixed method. The polymer concrete overlay is an extremely thin overlay of about 12mm thick.

The permeability of the overlay is very low or almost negligible. Rapid chloride permeability tests have been conducted on various polymer concrete overlays and have found that the number of passing coulombs is extremely low (figure 1.6). This implies that polymer concrete overlays will prevent intrusion of chloride ions, which could cause corrosion of the steel and deterioration of the bridge.

The polymer concrete overlays have a high skid resistance (figure 1.7). This is key for bridge decks which can become slippery during the winter period. They also cure rapidly at ambient temperatures. Epoxy will cure in 2 hours if the air temperature is 32°C and 6-8 hours if the air temperature is 16°C. Polyester will cure in 2 hours if the temperature is 32°C and 5-6 hours if the air temperature is 16°C, while methacrylate will cure in 2 hours if the temperature is 32°C and 4 hours if the air temperature is 16°C [Sprinkel 1993]. Therefore, a polymer concrete overlay can be constructed during the night when the traffic volume is low and it is possible to close a lane.

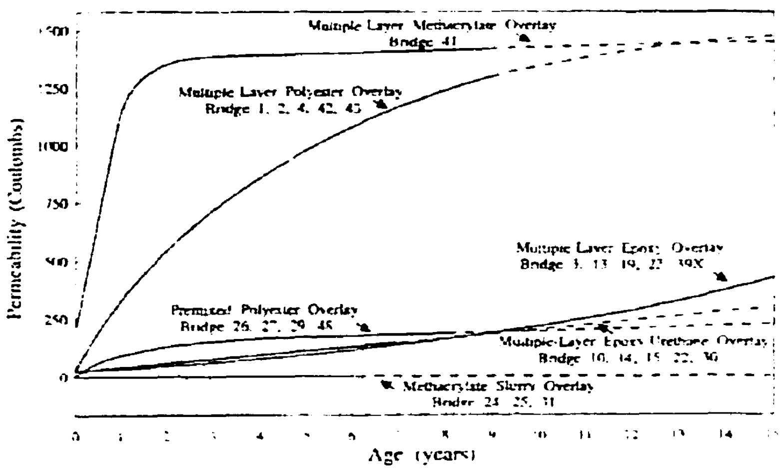


Figure 1.6 Chloride Ion Permeability of Polymer Concrete Overlays [Sprinkel, 1995]

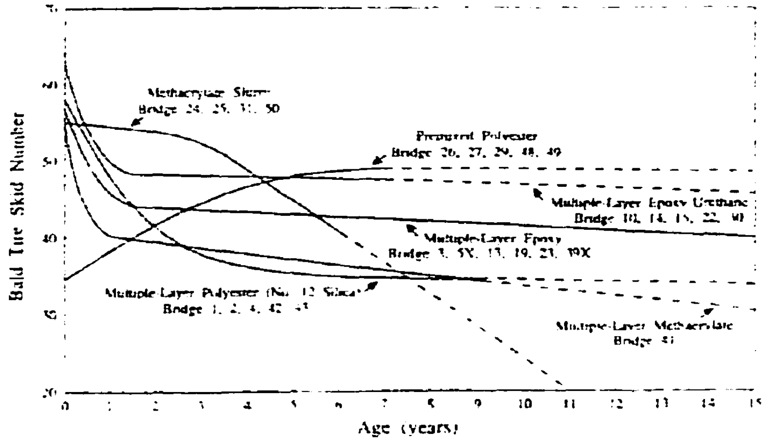


Figure 1.7 Bald Tire Skid Number for Polymer Concrete Overlays [Sprinkel, 1995]

The polymer concrete overlays bond strongly with concrete and steel surfaces. The high tensile and compressive strength of the polymers helps hold the aggregates in place, however they are flexible enough to allow dynamic and thermal movements. They are resistant to deicing salts, acids, bases, petroleum products, and alkalinity of the Portland cement concrete. Lastly, a typical polymer concrete overlay weighs 29-39 kg/m^2, compared to asphalt which weighs 78-98 kg/m^2 [Nabar 1997]. Therefore, bridges that were not designed for current loading conditions can withstand the increase in traffic load with a decrease in dead load.

Despite the numerous advantages, polymer concrete overlays have a coefficient of thermal expansion that is quite different from steel and Portland cement concrete. This difference may lead to the cracking of the polymer concrete, the shearing of the interface, or cracking in the Portland cement concrete ultimately causing delamination of the overlay.

Delamination failure of polymer concrete overlay could be attributed to poor quality control of construction, inadequate substrate surface preparation, and ever-increasing traffic loads, or durability of the material. Since the properties and behavior of polymer concrete overlays are not well studied and documented as the other types of overlays, this research will be focused on the environmental durability of the polymer concrete overlays and the degree of protection that they offer to the Portland cement concrete bridge deck.

Chapter 2

Field Applications of Polymer Concrete

2.1 POLYMER CONCRETE OVERLAYS

Polymer concrete (PC) is a composite material that was developed in the early 1950's. It was first used as a synthetic marble, however, by the end of the decade it was being used to make building cladding. By the early 1970's, it began to achieve recognition as a repair material for Portland cement concrete (PCC), primarily in pavements and bridges. Since then the polymer concrete has been used for structural and decorative panels, linings in carbon-steel pipes for geothermal applications, heavy-duty industrial floors, overlays on spillways of hydraulic structures, sewer pipes and manholes [Vipulanandan et al., 1996].

The first polymer concrete overlay for bridge decks consisted of a single layer of coal tar epoxy broomed over the substrate and seeded with fine aggregate. These overlays were found to be too permeable and unable to withstand the traffic loads. By the mid-1960's, polyester and methyl methacrylate resins were being used. These overlays were brittle, thick and debonded because of high thermal incompatibility. By trial and error, new resins were developed that proved to be more compatible with the Portland cement concrete. [ACI Committee 548, 1993]

2.1.1 Properties of Polymers

The polymer binders used in the polymer concrete overlay system are classified according to their uncured and cured properties. The uncured properties are related to their handling characteristics, while the cured properties are related to their behavior subjected to stimuli. The uncured properties include viscosity, working life, toxicity and flammability. The cured properties include bond strength, coefficient of thermal expansion, tensile strength, tensile elongation, curing shrinkage, and modulus of elasticity.

The viscosity of the polymer refers to the ease of placement. A polymer with a viscosity of 1 centipose ($1x10^6$ Pa/sec) flows like water while a polymer with a viscosity of 100,000 centipose is like molasses. The degree of viscosity is important when deciding the method of application: the low viscosity polymer is suitable for the slurry method, while the higher viscosity polymer is better suited for the "broom-and-seed" method.

The working time is the length of time before the polymer resin turns to gel and essentially becomes unworkable. The working time property is dependent on the amount of resin mixed, the temperature of the mix and the ambient temperature. Usually, as the ambient temperature and/or the amount of mixed material increases, the working time decreases.

Besides the workability of the polymer resin, the toxicity of the binder should be considered. Toxicity potential varies greatly from one product to another. Before being exposed to the fumes of the hardener or resin, the toxicity information, handling precautions and disposal procedures should be understood and observed. Usually proper ventilation and protective clothing are enough to protect the individuals handling the resin.

The other uncured property of interest is the flammability of the binder. All resins will burn under certain conditions due to their organic compounds. It is vital that the flash point of the polymer be known and that the temperatures found at the job site be below that point.

The cured properties of the polymer binder will determine the performance of the overlay. Of the different cured properties, the bond strength is the most important since it ensures that delamination does not occur. The bond strength depends on the cleanliness, soundness, texture and moisture content of the substrate.

The next important property is the coefficient of thermal expansion. It is a known fact that in general the coefficient of thermal expansion for polymers is considerably higher than that of Portland cement concrete. If the difference in coefficients is too large, thermal stresses will eventually cause failure at the interface leading to delamination and spalling. This property will determine the overlay thickness: thinner overlays will induce smaller thermal stresses in severe environments.

The tensile strength and tensile elongation properties are essential for the overlay to carry the dead and live loads. With high traffic load, the polymer binder must be able to withstand the bending moments, elongation, and dynamic response of the bridge deck, hence, the significance of a fairly low modulus of elasticity that guarantees a flexible overlay.

There are essentially four types of polymer resins that are used for polymer concrete overlays: epoxy, polyester, methacrylate, and polyurethane. Each polymer has it's own characteristic set of properties, and each performs differently. [Sprinkel, 1995]

Epoxy Polymer

The epoxy binder system is a two-part system composed of the epoxy resin and a hardener/catalyst agent. The epoxy binder is capable of producing strong bonds with Portland cement concrete and steel as well as many other surfaces. Their chemical composition also allows them to be unaffected by the alkalinity of the Portland cement concrete. [ACI Committee 548 1993, Sprinkel 1995]

Besides these advantages, the versatility of the epoxy system permits the addition of admixtures to enhance the mechanical properties, flexibility, creep resistance, and resistance to chemical attacks (acids, bases, deicing salts, fuels and others). Even the curing properties of epoxy binders can be altered to allow curing under damp situations as well as underwater. The only major disadvantage is that the epoxy system tends to be more expensive then the other polymer binders. The typical properties of epoxy binders are listed in table 2.1. [ACI Committee 548 1993, Sprinkel 1995]

Table 2.1 Typical Properties of Epoxy Binders [ACI Committee 548 1993]

	Property	Value	Test Method
Uncured Properties	Viscosity	200-2000 centipose	ASTM D 2392
	Working Time	10-60 mins	AASHTO T-237
	Toxicity	Yes	
	Flash Point	Over 204C for 100% solid polymers	
Cured Properties	Bond Strength	min. 7 MPa	ASTM C 882
	Coeff. Of Thermal Expansion	5-9 x 10^{-5} mm/mm/deg C	ASTM D 696
	Tensile Strength	min. 14 MPa	ASTM D 638
	Elongation	min. 30%	ASTM D 638
	Modulus of Elasticity	4-8.3 x 10^2 MPa	ASTM D 695
	Curing Shrinkage	0.02-0.08%	DuPont

Polyester Polymer

The polyester binder system is also a two-part system composed of a polyester resin and a hardener/initiator. The initiator is usually organic peroxide and it controls the rate of curing. The resin on the other hand is the principal ingredient that decides the chemical properties of the binder. [ACI Committee 548 1993, Sprinkel 1995]

Similar to the epoxy polymer, the polyester polymer is resistant to chemicals, deicing salts, acids, gasoline and water. The difference is that polyester polymer experiences more shrinkage during curing and requires a primer to enhance its performance and it is highly volatile at a lower temperature (over 32°C). Additives, inert liquids or fillers, have to be incorporated into the system to minimize the potential hazard. The addition of aggregates also helps increase the fire resistance of the binder. Typical properties for the polyester polymer are listed in table 2.2. [ACI Committee 548 1993, Sprinkel 1995]

Table 2.2 Typical Properties of Polyester Binders [ACI Committee 548 1993]

Property		Value	Test Method
Uncured Properties	Viscosity	100-400 centipose	ASTM D 2392
	Working Time	10-60 mins	AASHTO T-237
	Toxicity	Yes	
	Flash Point	Below 38C is flammable	
Cured Properties	Bond Strength	7 MPa	ASTM C 882
	Coeff. Of Thermal Expansion	36-90 x 10^{-5} mm/mm/deg C	ASTM D 696
	Tensile Strength	14 MPa	ASTM D 638
	Elongation	min. 30%	ASTM D 638
	Modulus of Elasticity	2.4-6.2 x 10^{2} MPa	ASTM D 695
	Curing Shrinkage	1-3%	ASTM D 955

Methacrylates Polymer

The methacrylate binders are normally a two-component system consisting of a resin and an organic peroxide initiator. The resin used is normally methyl-methacrylate (MMA) which is available as a low viscous monomer or a highly viscous polymer in monomer. [ACI Committee 548 1993, Sprinkel 1995]

Similar to the epoxy and polyester systems, the methacrylate polymer is unaffected by water, deicing salts, acids, and bases. It is also highly resistant to UV light and can withstand environmental exposure. Contrarily, the methacrylates are affected by some solvents and require fire retardants due to their flammable nature.

The method of mixing of the polymer will affect the application and performance properties. If mixed as a slurry, the resin should be highly viscous and combined with open gap-graded aggregates. The overlay that is produced will be approximately 3.2 to 9.5mm thick and it can endure thermal stresses. If mixed as a multiple layer, a low viscosity resin should be used with precisely graded aggregates. This overlay will have a higher moduli, less voids, and be able to endure higher traffic loads. The average thickness of the mortar overlay is approximately 13 to 25mm. The typical properties of the methacrylate polymer are listed in table 2.3. [ACI Committee 548 1993, Sprinkel 1995]

Table 2.3 Typical Properties of Methacrylates Binders [ACI Committee 548 1993]

Property		Value	Test Method
Uncured Properties	Viscosity	1-50 centipose	ASTM D 2392
	Working Time	20-40 mins	AASHTO T-237
	Toxicity	Yes	
	Flash Point	Below 38C is flammable	
Cured Properties	Bond Strength	7.14 MPa	ASTM C 882
	Coeff. Of Thermal Expansion	22-54 x 10^{-5} mm/mm/deg C	ASTM D 531
	Tensile Strength	3-8 MPa	ASTM D 638
	Elongation	100-200%	ASTM D 638
	Modulus of Elasticity	Max. 7 x 10^{2} GPa	ASTM D 638
	Curing Shrinkage	1-2%	DuPont

Polyurethane Polymer

The polyurethane system differs from the other polymers in that it can be produced as a one or two component system. The type of polyurethane used as an overlay binder is elastomeric which when cured has the same characteristics as hard rubber. [ACI Committee 548 1993]

The polyurethane binder makes use of fewer aggregates then the other binders. It is used as primarily as a waterproofing membrane between the Portland concrete cement or steel decks and the asphalt overlay.

Similar to the other polymers, cured polyurethanes will burn under certain conditions. It is possible to mix additives to improve fire resistance, however, special care should be taken because poisonous cyanide fumes may be generated. Besides this, this system is capable of resisting acids, alkalis, fuels, water and deicing salts. Typical properties for this binder are listed in table 2.4. [ACI Committee 548 1993]

Table 2.4 Typical Properties of Polyurethane Binders [ACI Committee 548 1993]

Property		Value	Test Method
Uncured Properties	Viscosity	1000-8000 centipose	ASTM D 2392
	Working Time	15-60 mins	AASHTO T-237
	Toxicity	Yes	
	Flash Point	Over 204C non-flammable	
Cured Properties	Bond Strength	n/a	n/a
	Coeff. Of Thermal Expansion	n/a	n/a
	Tensile Strength	6-10 MPa	ASTM D 412
	Elongation	150-600%	ASTM D 412
	Modulus of Elasticity	0.3-1 MPa	ASTM D 638
	Curing Shrinkage	0.02-0.08%	DuPont

2.1.2 Properties of Aggregates

The type of aggregate used will determine the skid resistance, the percentage of voids, abrasion resistance, and durability of the overlay. The coefficient of thermal expansion of the overlay is also affected by the type and quantity of aggregate used.

There are essentially four types of aggregate that can be used for polymer concrete overlays: quartz, silica, basalt, or aluminum oxide [ACI Committee 548]. Independent of the type used, the aggregates should be hard, dense, durable, dry, clean and resistant to polishing and crushing. These properties will ensure proper bond between the aggregates and the polymer binder as well as ensure a durable system.

The typical aggregate size distribution is listed in table 2.5 for different application methods. It is important that there be enough fines to fill as many voids as possible, and that they are angular to produce the desired skid resistance. Table 2.6 provides typical chemical and physical properties of the aggregates.

Before the polymer concrete overlay can be constructed, the surface of the bridge deck must be evaluated and prepared. This step in the construction of the overlay is vital in that it will determine the bond strength as well as the durability of the overlay.

Table 2.5 Typical Aggregate Size Distribution (Percentage Passing Sieve) [Sprinkel, 1993]

Sieve Size	Multiple Layer Overlay	Slurry Overlay		Premixed Overlay
1.3 cm	-	-	-	100
1.0 cm	-	-	-	83-100
No. 4	100	-	-	65-82
No. 8	30-75	-	-	45-64
No. 16	0-1	100	-	27-48
No. 20	-	90-100	-	-
No. 30	-	60-80	-	12-30
No. 40	-	5-15	-	-
No. 50	-	0-5	-	6-17
No. 100	-	-	-	0-7
No. 140	-	-	100	-
No. 200	-	-	98-100	0-3
No. 270	-	-	96-100	-
No. 325	-	-	93-99	-

Table 2.6 Typical Physical and Chemical Properties of the Basalt Aggregate [Nabar 1997]]

Property	Specification
Hardness	6 to 6.5 mohs
Specific Gravity	2.99
Burbank Abrasion Index	1.412
Fin. Friability Index	78.0
Loss of Ignition	0.24

Ingredient	% Weight
Silicon Dioxide	52-53
Aluminum Oxide	13.9
Iron Oxide	9.6
Calcium Oxide	11.2
Magnesium Oxide	8.1
Sodium Oxide	1.95
Titanium Oxide	0.89

2.1.3 Surface Preparation

The evaluation consists of determining if the Portland cement concrete deck is structurally sound and strong enough to withstand temperature-induced shear stresses due to difference in thermal expansion coefficients. Drawn cores and Schmidt impact hammer can be used to determine the compressive strength of the concrete as well as determine weak areas. Concrete with a tensile rupture strength of less than 1.0 MPa (150 psi) should be removed and replaced with fresh Portland cement concrete. [ACI Committee 548 1993, Sprinkel 1993 and 1995]

Furthermore, chain dragging should be conducted to find hollow sounding areas (where the Portland cement concrete has delaminated from the top reinforcing steel). Particular attention should be paid to the cracks in the deck where salt and water could have penetrated. Copper sulfate electrode tests (ASTM C 876) may be conducted to locate areas were there is corrosion of the reinforcing steel, which will eventually cause delamination. Delaminated concrete should be removed and corroded steel cleaned using sandblasting.

Once the deck has been evaluated, all defects such as honeycombed areas, small and large holes, ruts, sharp protrusions, broken edges and cracks have to be repaired. Before placing the overlay, the deck should be cleaned by shotblasting (figure 2.1). The shotblasting of the deck will remove asphaltic material, oils, dirt, rubber, curing compounds, paint, carbonation, laitance, weak surface mortar, and other materials that will interfere with the bonding or curing of the overlay. [ACI Committee 548 1993, Sprinkel 1993 and 1995]

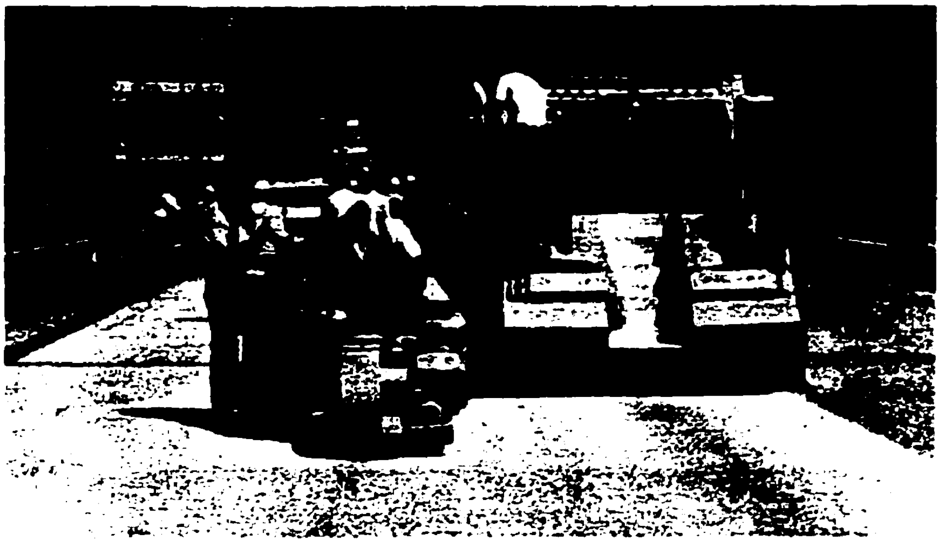


Figure 2.1 Shotblast equipment used to clean a deck [Sprinkel 1993]

Once the deck is clean and repaired, all substrate rough surfaces must be removed. These surfaces will cause premature wear and failure of the overlay due to high impact stresses on the high spots. The deck surface should then be tested for moisture content, wet decks are normally unacceptable. At least, the concrete deck should be saturated surface dry.

2.1.4 Methods of Application

Once the surface has been prepared, the method of constructing the overlay must be considered. Currently there are three methods that polymer concrete can be applied to a bridge deck. These methods of application are known as the slurry overlays, the multiple layer overlays, and the premixed overlays.

The ***slurry overlay*** method comprises of mixing the polymer resin and gap-graded aggregate (table 2.5) in a continuous or batch mixing equipment. The slurry is distributed on the bridge deck by using gage rakes, towels, or beam boxes (figure 2.2). Once placed the excess polymer from the polymer-rich slurry bleeds to the surface. Aggregate is broadcast immediately until all the wet areas are covered to achieve the required skid resistance. Some slurry overlays require that a primer (a thin layer of polymer) be placed on the existing bridge deck before the overlay is installed. The typical overlay thickness is between 8mm (0.31 in) and 19mm (0.75 in). For the slurry overlay the material quantities are: approximately 0.41 kg/m^{2}of polymer for the primer, about 2.7 kg/m^2 of polymer mixed with 3.8kg/m^2 of silica sand and 2.7 kg/m^2 of silica flour for the slurry mixture, and enough gap-graded aggregate to cover the surface. [ACI Committee 548 1993, Sprinkel 1995]

The ***multiple layer overlays***, also called "broom-and-seed" overlays, is constructed by distributing a layer of polymer resin on the existing bridge deck and broadcasting the aggregate over the binder (figure 2.3). The polymer binder is spread over the deck with the use of a roller, squeegee or broom. Hand, shovel or an automated spreading device can broadcast the aggregate as long as the polymer binder is not disturbed. Once the binder has cured, the excess aggregate is removed and a second layer is applied. The typical overlay thickness for two or three layers of resin and aggregate is 10mm (0.4 in). The first layer consists of approximately 5.4 kg/m^2 of aggregate broadcast on approximately 1.1 kg/m^2 of polymer, while the second layer consists of approximately 7.6 kg/m^2 of aggregate broadcast on approximately 2.2 kg/m^2 of polymer. [ACI Committee 548 1993, Sprinkel 1995]

The ***premixed overlays*** are constructed by mixing dense-graded aggregates with about 12 percent binder by weight. Before the mixture is placed on the bridge deck, a primer (0.41 kg/m^2) is applied to enhance the bond strength. A vibratory screed is used to strike off and to compact the premixed material. To obtain the desired skid resistance, aggregate can be broadcast on top or grooves can be placed in the freshly placed polymer concrete. The typical overlay thickness is about 25mm (1 in). [ACI Committee 548 1993, Sprinkel 1995]

Figure 2.2 Construction of a Slurry Overlay [TAMMS]

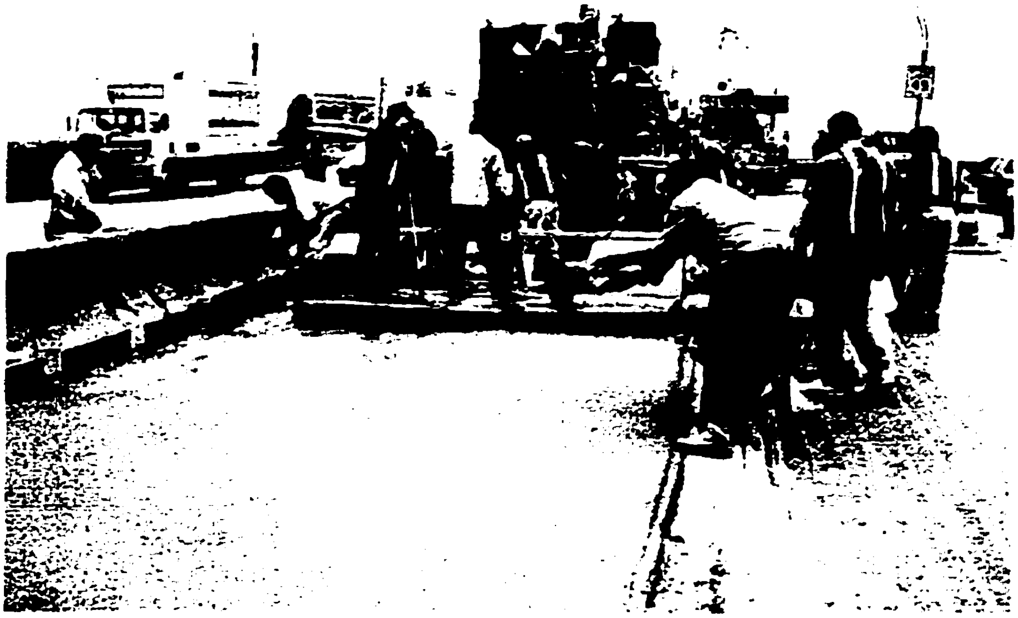


Figure 2.3 Construction of a Multiple Layer Overlay [TAMMS]

2.1.5 Bridge Deck Candidates for Application

Bridge decks that are candidates for polymer concrete overlays are those that are likely to corrode and deteriorate. The polymer concrete overlay is a preventative measure and will not be useful if the deterioration is in an advance stage.

The polymer concrete overlay may be used on a variety of bridge decks. These decks include the conventional Portland cement concrete and steel bridge decks as well as the newly proposed extruded aluminum bridge deck and fiber reinforced plastic composite bridge decks. The polymer concrete overlays can also be used as protection for parking garage decks.

The Portland cement concrete decks that are candidate are those with chloride ion content less than 1.2 kg/m^3 in the top concrete cover so that corrosion will not occur after the overlay has been constructed. Furthermore, decks with permeability of the top concrete cover higher than 2000 coulombs, concrete cover less than 50mm thick, improperly air entrainment, extensively cracked, or been extensively patched are all candidates for application. Other bridge decks that are candidates for polymer concrete overlays are those that require a skid resistance, surface protection, that cannot withstand large dead loads, cannot be closed except during off-peak traffic periods. [ACI Committee 548 1993, Sprinkel 1993 and 1995]

Portland cement concrete decks that have a tensile rupture strength of less than 1.0 MPa (150psi) should not be overlaid with polymer concrete because the overlay will eventually delaminate and spall [ACI Committee 548 1993, Sprinkel 1993 and 1995]

2.1.6 Material Handling and Safety

The use of polymer resins and the materials that are mixed with them can be hazardous. There are a number of resins and even a greater number of curing agents, hardeners, fillers and other chemical additives, which may be mixed in various combinations. This flexibility allows for the creation of polymers with different properties and hazard levels. It is important that the manufacturer provide all safety and handling literature. [ACI Committee 548 1993]

The typical health problems are eye irritation, redness, tearing, blurred vision, skin irritation, dermatitis, burns, rashes, nasal irritation, dizziness, nausea, headache, and gastrointestinal irritation. In some instances, the effect may be immediately, while in other instances it may require continuous exposure. These health problems may arise from the fumes emitted during the handling or accidental burning of the chemicals, as well as skin contact. [ACI Committee 548 1993]

The safety precautions for handling polymer components are: washing hands immediately afterwards, wear protective clothing (gloves, dust masks, apron, safety glasses), proper ventilation, and keep away from heat sources (radiators, sparks, steam pipes) [ACI Committee 548 1993]

2.2 FIELD APPLICATIONS IN THE UNITED STATES

In the United States, various Departments of Transportation (DOT) are experimenting with polymer concrete overlays. California, Virginia, New York, Washington and Ohio are the leading users of the technology, with a combined expenditure of $9.25 million US in overlaying bridge decks in 1991. [Tarricone 1992]

State of Virginia

By the 1980's, the State of Virginia realized the benefits of using polymer concrete, and since then polymer concrete overlays have been installed on eight to ten bridge decks per year. In 1991, the state of Virginia spent $2.83 million US on polymer concrete overlays (30% of the $9.25 million used in the United States). [Tarricone 1992]

In a Strategic Highway Research Program (SHRP) study, 30 polymer concrete overlays, 19 of which are in Virginia, had reached a service life of 15-20 years. The criteria used was skid resistance, chloride ion impermeability, durability and tensile bond strength. The bridge deck overlays in the state of Virginia are expected to maintain a skid resistance of 30-40 (below 20 is unacceptable, and 50-60 is for fresh polymer concrete) after 15 years of service. Furthermore, the overlays are expected to remain impervious to chloride ion penetration and maintain a bond strength over 0.7MPa (100psi) after 15 years of service. [Tarricone 1992]

State of California

The state that invested the most capital in 1991 in the construction of polymer concrete overlays was the state of California with an investment of $3.2 million US (35% of the national value). The first time that the state of California began to use premixed polyester overlays was in 1982 on Interstate 80 in the Sierra Nevada Mountains in Northern California. The reason for overlaying the road was that it was subjected to large amounts of deicing salts, heavy tire-chain wear and a high traffic volume. A report on polymer concrete overlays in 1992 revealed that the overlay is in good condition and that the state expects the overlay to exceed the 20 years service life. [Tarricone 1992]

Another recent project conducted in the state of California was the six lane Marina Viaduct approaches to San Francisco's Golden Gate Bridge. The construction of the overlay was completed in July 1992 and cost the state $1.8 million US. Periodic tests for bond strength, riding surface, and delamination have been conducted and so far the overlay is performing as expected. [Tarricone 1992]

State of New York

The use of polymer concrete overlays in New York City began in 1980 on the Queensboro Bridge followed by a project on the Brooklyn Bridge. Since then the State and City of New York have expanded its' use of polymer concrete with an investment of $290,000 US in 1990, and $2.4 million US in 1991 (26% of the national value). [Tarricone 1992, Mendis 1987]

The Brooklyn Bridge, connecting Manhattan and Brooklyn, was completed in 1883 with the original bridge deck being made of wooden blocks. At that time, the bridge traffic consisted of passenger and trolley cars as well as an elevated rapid transit train. In 1953 the deck was replaced with a steel grid deck filled with Portland cement concrete and only passenger cars were allowed to circulate on the bridge. A few years later, steel studs were welded to the deck to provide skid resistance. [Mendis 1987]

In the 1980's, the city of New York decided to rehabilitate the deck with polymer concrete (figure 2.4). The reasons were that (1) the traffic volume of 100,000 cars per day had polished the steel grid and delaminated the Portland cement concrete, reducing the skid resistance of the deck, (2) water and deicing salts caused corrosion of the steel grid, and (3) the steel studs created an objectionable noise level. The polymer concrete used for the project was FLEXOLITH, produced by the Dural International Corporation. The constructed overlay had a thickness of 13mm and covered an area of 28,787m^2. [Mendis 1987]

The polymer concrete overlay has been in service for over 10 years. The condition of the overlay in July 1997 was adequate (figure 2.5). However, there was some apparent delamination as seen in figure 2.6.

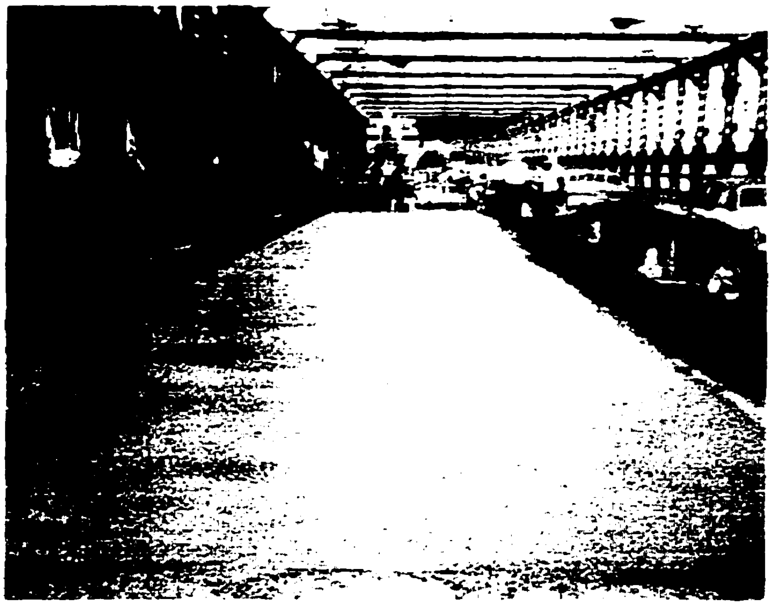


Figure 2.4 Placement of PC Overlay on the Brooklyn Bridge (1980's)

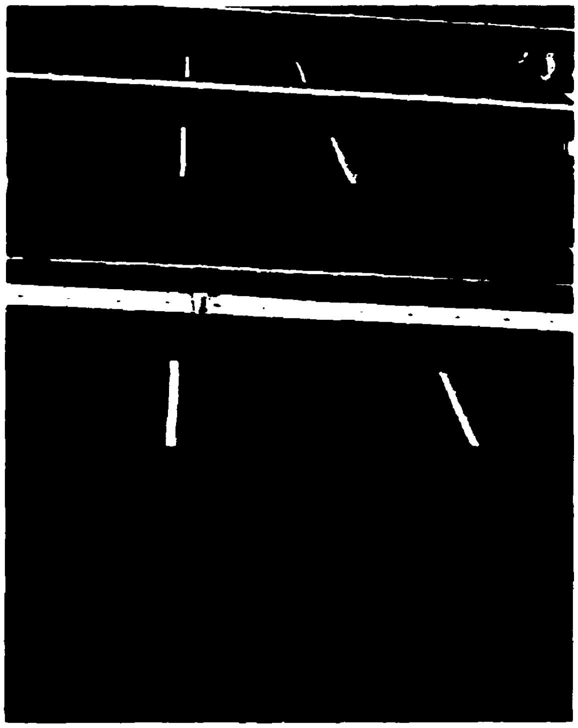


Figure 2.5 Condition of PC Overlay on the Brooklyn Bridge (July 1997)

Figure 2.6 Delamination of PC Overlay on the Brooklyn Bridge (July 1997)

State of Montana

The state of Montana has 4,400 bridges and approximately 112,000 kilometers of paved roads [Krauss 1997]. The environmental conditions in this state are severe, with temperatures ranging from -48 to 49°C along with a heavy snowfall. Corrosion of the reinforcing steel due to permeating chloride ions, delamination, spalling, and low skid resistance has forced the Montana DOT to consider other paving alternatives.

In 1994 the DOT decided to overlay 8000m^2 of bridge deck with methyl methacrylate at a cost of $375,000 US. Previously, the Montana DOT had used epoxy polymer concrete to overlay 8500m^2 of bridge deck at a cost of roughly $1.2 million US. [Krauss 1997]

In August 1995, a number of the methyl methacrylate overlays showed tears and cracks, and one overlay had delaminated over a third of the bridge span. A similar amount of delamination occurred on another methyl methacrylate overlay in 1996. On the other hand the epoxy polymer concrete overlays have survived the harsh winters and are performing adequately.

The thickness of methyl methacrylate overlays was greater than the epoxy polymer concrete overlays, which might cause more thermal incompatibility. Montana DOT decided to continue the use of polymer concrete overlays, however, only with flexible epoxy resin-based material system. [Krauss 1997]

Other Polymer Concrete Overlays in the United States

The Harlem Street Bridge in Chicago, Illinois was overlaid with polymer concrete in 1984. The bridge deck is steel grid filled with Portland cement concrete. Figure 2.7 shows the bridge overlay in June 1997. While the condition of the overlay is good, delamination had occurred in some areas (top-most left corner of figure 2.7). Figure 2.8 shows a close-up of the delamination.

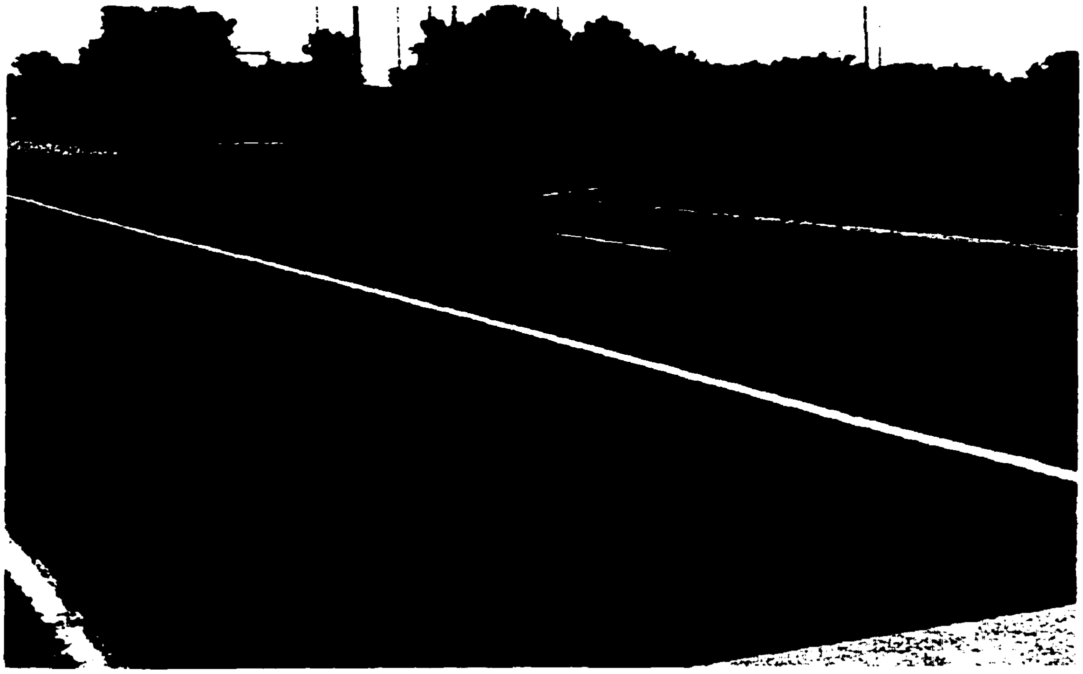


Figure 2.7 Condition of PC overlay on the Harlem Street Bridge (June 1997)

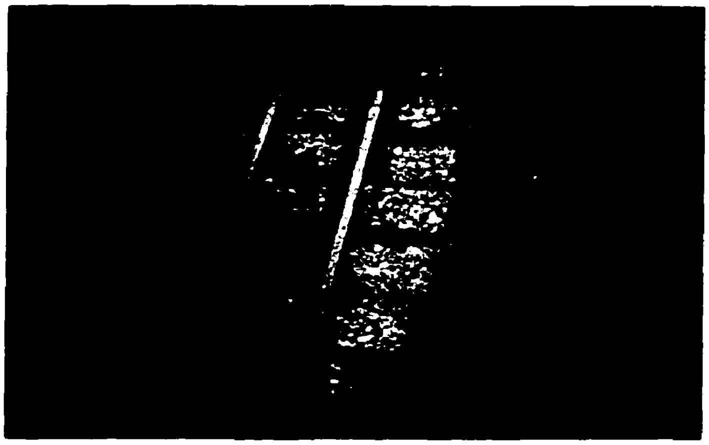


Figure 2.8 Delamination on the Harlem Street Bridge (June 1997)

Table 2.7 gives other bridge decks overlaid with polymer concrete in the United States. These overlays have over 10 years of service.

Table 2.7 Some Other Polymer Concrete Overlays in the United States [Nabar, 1997]

Construction Year	Project	Location	Method of Application
1976	Rt. M-44, over the Grand River	Grand Rapids Michigan	multiple layer
1976	Rt. 106 & 107 Southbound Roadway	Hicksville New York	multiple layer
1979	Rt. LA572 Bayou Macon Bridge	Chase Louisiana	multiple layer
1984	Remington St. Bridge	Baltimore Maryland	slurry
1984	Clakamas River Bridge, Highway 99	Oregon City Oregon	multiple layer
1985	Yakima River Bridge, Route 82	Ellensberg, Washington	slurry
1986	Edgewood Ave. Rt. 17	Milwaukee Winsconsin	multiple layer
1986	Jonesport River Bridge	Jonesport Maine	multiple layer
1986	Lackawanna Luzerne Counties Rt. 52, L.R. 439	Moosie Pennsylvania	multiple layer
1994	Smithfield Bridge	Pittsburg, Pennsylvania	multiple layer

2.3 FIELD APPLICATIONS IN CANADA

Attempts were also made in Canada to use polymer concrete overlays to protect ageing bridge decks. The harsh environment in Canada generates more concern about using this material system. The thermal incompatibility would be more noticeable in form of delamination and spalling.

Notwithstanding these concerns, there have been more than twenty polymer concrete overlays constructed in Canada: mainly in Alberta and Ontario. The first bridge to be overlaid with polymer concrete was the Red Deer River Bridge located in Sundrie, Alberta (1984). The other Alberta overlays were constructed during the following two years, and include the Strawberry Creek Bridge (highway 2) located in Kinuso and the Dawson Bridge located in Edmonton. The bridge overlaid in Ontario is the Seaway International Bridge near the city of Cornwall (1991).

Province of Alberta

The province of Alberta has currently 1688 bridges, 1250 with an asphalt surface and 438 with a concrete surface. Field experience has shown that the Alberta bridge decks are (1) deteriorating due to penetration of moisture, chlorides and other foreign substances into the concrete, (2) have a limited live load capacity that prohibits the addition of dead load, (3) surface cracking, and (4) have a poor skid resistance. To extend the service life of the decks, the Alberta DOT in the 1960's decided to try polymer concrete overlays, and by 1984 had learned how to install a proper PC overlay. [Carter 1989, 1997]

In 1990, the Alberta DOT conducted a survey of the condition of the 21 PC overlays. The survey found a total damage of 120m^2 or 0.6% of the total 22,052m^2 installed on the 21 bridge decks. By 1995, the failed surface area had increased to 454m^2, which is 2.0% of the total area. Table 2.8 gives the age of the polymer concrete overlays, location and degree of damage observed. [Carter 1997]

A study was conducted and reported on the corrosion mitigation performance of thin polymer concrete overlays. The study made use of copper sulfate electrode (CSE) data collected before and after the overlay was applied. The study found that the PC overlays helped decrease the active CSE readings, and therefore help suppress the corrosion of the reinforcing steel.

Table 2.8 Alberta Bridge Decks using Polymer Concrete [Carter 1997]

Bridge	Highway No.	Deck Age (years)	Deck Area (m^2)	Overlay Age (years)	Area Dam 1990 (m^2)	Area Dam 1995 (m^2)
Bow R.	1X	32	556	10	0	0
Oldman R.	22	36	833	10	16	20
Cline R.	11	28	1037	10	30	35
Highwood	2A	31	451	10	2	2
Oldman Ck.	2	28	326	4	18	25
Battle R.	14	40	575	10	10	10
Heart R.	2	40	605	8	10	12
Strawberry	2	32	347	9	1	35
Rourke	2	33	281	9	0	6
Wapiti R.	6	23	2211	9	0	22
Peace R.	2	27	4871	7	5	49
L. Smoky	S669	35	1133	5	23	68
Matzhiwin	36	35	483	5	0	0
Shunda	11	23	692	8	0	7
Lobstick	local	39	600	8	1	120
L. Bow. R.	2	35	949	8	0	0
Sawridge	2	13	523	8	0	0
Bow R.	1W	39	2096	8	4	4
Carvel Corner	16	34	1354	8	0	0
Wetaskiwin	13	15	816	8	0	0
N. Sask R.	11A	30	1313	8	0	39
		Total	22052		120	454

Besides decreasing the copper sulfate electrode readings, the polymer concrete overlays were found to protect the non-durable concrete from wear, effectively seal deck non-moving cracks, and improve the skid resistance of the riding surface of the bridges. Table 2.9 shows the reasons why the 21 bridge decks were overlaid with polymer concrete and the ability of the polymer concrete to eliminate the problem. In general, the polymer concrete overlays helped extend the service life by 15-20 years, and were more economical than having to rebuild the bridge decks. [Carter 1997]

Table 2.9 Success of Alberta's Polymer Concrete Overlays [Carter 1997]

Bridge	Reason for Polymer Concrete Overlay Installation	Success
Bow R.	Porous concrete	Yes
Oldman R.	Wide shrinkage cracks	Yes
Cline R.	70% active copper sulfate electrode	Yes
Highwood	Transverse cracks and high salt area	Yes
Oldman Ck.	Longitudinal cracks	No
	Surface scaling	Yes
	Poor entrained air	No
Battle R.	37% active copper sulfate electrode(CSE)	Yes
Heart R.	Transverse cracks and 54% active CSE	Yes
Strawberry	Surface scaling	Yes
	Cracks, poor concrete	No
Rourke	Cracks	No
	Surface Scaling	Yes
	Poor air void system	Yes
Wapiti R.	Cracks, 63% active CSE, high salt	Yes
Peace R.	Heavy transverse cracks	Partial
	High salt site	Yes
	38% active CSE	No
L. Smoky	Surface scaling	Yes
	Cracks	No
	Poor air void system	Partial
Matzhiwin	Many cracks	Yes
Shunda	Cracks	Partial
	High salt site	Yes
Lobstick	Surface scaling	Yes
	Inferior concrete	Partial
	Poor air void system	Partial
L. Bow. R.	Cracks, high salt, 84% active CSE	Yes
Sawridge	Poor air void system	Yes
Bow R.	Cracks, high salt, 84% active CSE	Yes
	Slippery wearing surface	Yes
Carvel Corner	Many cracks, high salt, 89% active CSE	Yes
Wetaskiwin	Many shrinkage cracks	Yes
N. Sask R.	High sslt	Partial

Province of Ontario

The bridge that the St. Lawrence Seaway Authorities have overlaid with polymer concrete is the Seaway International Bridge located near the city of Cornwall, connecting the United States and Canada. Figures 2.9 and 2.10, taken in 1997, show the overall condition of the overlay as well as the delamination that occurred on the north side of the bridge. The delamination could be attributed to poor quality control during the construction of the overlay..

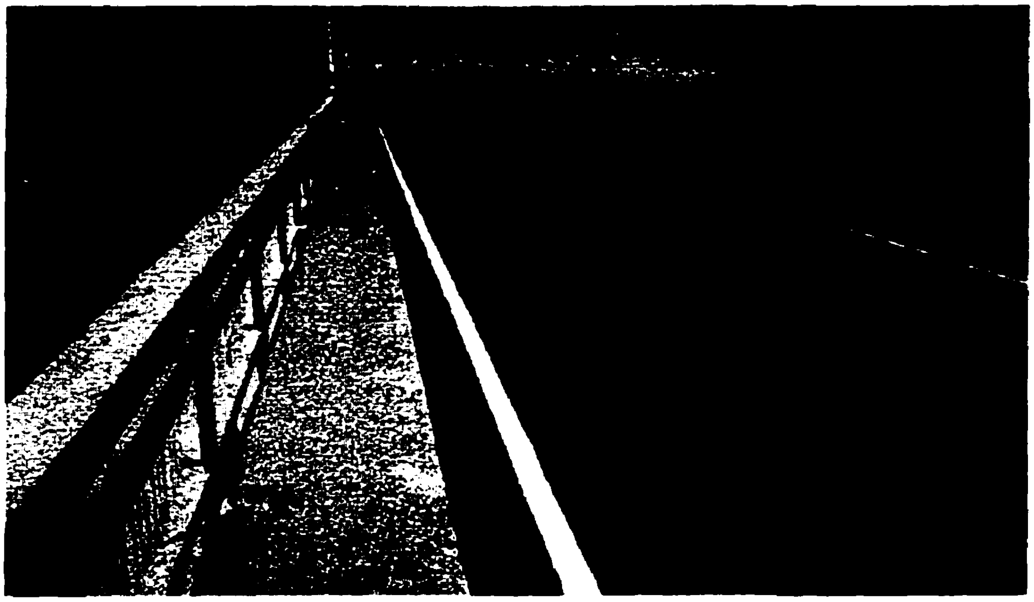


Figure 2.9 Overall Condition of the PC Overlay on the Cornwall Bridge (June 1997)

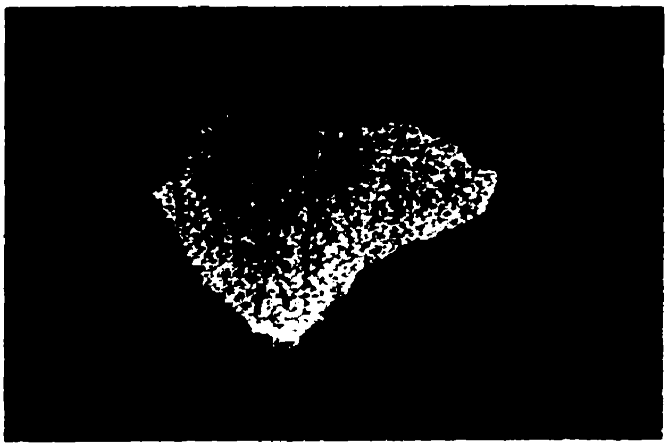


Figure 2.10 Delamination on the Cornwall Bridge (June 1997)

Chapter 3

Objectives of the Research

There are many potential benefits of using polymer concrete overlays on bridge decks: thin overlay, resistant to alkalinity of Portland cement concrete, good skid resistance, strong bond strength, and resistant to chemicals and abrasion. However, despite the success of the overlays in the United States and in Canada in demonstrating the usefulness and durability of polymer concrete, there are still many questions unanswered.

In comparison to other construction materials there is little literature, studies, and understanding of the performance of polymer concrete overlays. This research program is designed answer some of the questions and to understand the mechanisms that govern the effectiveness of the protection of polymer concrete overlays.

3.1 MECHANISMS OF FAILURE IN POLYMER CONCRETE OVERLAYS

The failure of the polymer concrete overlay may be the result of one or more variables. These variables include, but are not limited to, improper surface preparation, improper proportioning of resin components, poor workmanship, poor quality materials, high volume of traffic and weathering durability. The polymer concrete overlay failure is categorized into three main categories:

- Delamination and debonding
- Cracks and increased porosity
- Loss of skid resistance

The delamination or debonding of the overlay can be the result of thermal, mechanical, physical, or environmental conditions or the cumulative effects of other deficiencies in the overlay. Improper or inadequate surface preparation is the single largest reason contributing to this mode of failure. The physical properties of the polymer binder are achieved only when the components of the resin are mixed in the right proportions. Any deviation from the ratio provided by the manufacturer can cause a series of problems later. In addition to this, the difference in coefficient of thermal expansion between the polymer concrete overlay and the Portland cement concrete substrate in an overlay with a thickness greater than 12mm can become significant. This aspect alone accounts for many delamination failures. Another contributing factor to this mode of failure is the inadequate termination of the overlay at joints, drains, dividers and curbs. This can cause water intrusion or edge delamination due to impact stresses. [Nabar, 1997]

The cracking and increasing of porosity of the polymer concrete overlay can be the result of moving cracks, excessive flexing of the substrate, and poor workmanship. The presence of large cracks or moving cracks in the Portland cement concrete deck, if untreated, will cause reflective cracking in the overlay. The cracks in the overlay will cause an increase in the deck porosity, allowing for water intrusion. This water intrusion will cause the corrosion of the reinforcing steel and expansion of corrosion products. The expansion of corrosion products will in turn crack the substrate and overlay. Cracking of the overlay can also be induced from fatigue stress at the bond line from excessive flexing of the bridge deck. [Nabar, 1997]

The increase in porosity of the overlay can cause additional cracking in the overlay. One factor contributing to this mode of failure is the addition of solvents or thinners to the binder causing air voids after their evaporation. Another contributing factor is the use of wet or damp aggregates during the construction of the overlay, which bond improperly with the binder and eventually pop-out. [Nabar, 1997]

The third mode of failure is the loss of skid resistance of the overlay. The major factor contributing to this failure mode is the aggregate type and gradation used to construct the overlay. [Nabar, 1997]

3.2 UP-TO-DATE RESEARCH ON POLYMER CONCRETE OVERLAY

Despite being used since the 1950's, the knowledge on polymer concrete overlays is almost purely based on field applications and field studies. In the recent years, only a hand-full of laboratory research programs on polymer concrete have been published. While the findings of these laboratory researches are significant, they do not address all the concerns on the use of polymer concrete as bridge deck overlays.

In a study published in 1996, the performance of polyester polymer concrete and glass fiber reinforced polymer concrete was investigated. The study specifically looked at the static properties: stress-strain relationship, modulus, Poison's ratio, peak strength, and peak strain. The study found that the peak compressive strength of polyester polymer concrete was approximately 55 MPa. It also found that the use of 6% glass fibers to the polymer concrete system improved the compressive strength by 16% and doubled the splitting tensile strength. A fifty-percent improvement in the peak compressive strain was also observed. The use of this particular polymer concrete is for chemical industry floors. [Vipulanandan et al., 1996]

Palmese et al. (1996) examined the effects of water, motor fluids and freeze-thaw cycling on the behavior of polymer concrete systems. For the purposes of the study, three resins were used: a vinyl ester, a high T_g unsaturated polyester and a low T_g unsaturated polyester. T_g is the glass transition temperature of the polymer. From the experimental program, the study concluded that type of resin used and cure history influenced the behavior of the polymer concrete. Furthermore, the study concluded that water partial affected the polymer concrete by degrading the interface between the aggregate and polymer binder.

Moriyoshi et al. (1996) looked at the thermal properties of methacrylate polymer concrete at low temperatures. The glycerol methacrylate polymer concrete system was hardened at low temperature, and then thermal fracture tests and flexural tests were conducted. The study found that the polymer concrete samples that were cured at low temperatures were capable to resisting higher thermal stresses than the polymer concrete samples cured at normal temperatures. In addition, the study found that the flexural strength of the polymer concrete was unaffected by curing at low temperatures.

A study presented at the 1994 Materials Engineering Conference, submitted the findings with regards to the development a procedure for testing the bond strength of the polymer concrete and Portland cement concrete. Four polymer resins were used for the purposes of this research: polyester, epoxy, methacrylate and polyurethane. Deming et al. examined the ACI field test method, ASTM slant shear test method, and a proposed direct testing procedure. The research concluded that the proposed direct testing method was consistent and presented representative values of tensile strength. [Deming et al., 1994]

In 1993, O'Connor and Saiidi carried a research on the compatibility of polyester-styrene polymer concrete overlays with Portland cement concrete. They concluded that the compressive strength of the polymer concrete dropped by 25% with an increase in temperature of 49°C and that the polymer concrete had a modulus of rupture four times that of Portland cement concrete. In addition, using two finite element models, they concluded that the thermal gradient along the depth of the bridge deck should be considered when thermal stresses were a concern. They also found that the compressive strength of polyester polymer concrete increased during the first 15 temperature cycles, but then decreased with more temperature cycles. The temperature cycle consisted of a six hour soak at 66°C followed by 18 hours at room temperature.

In an earlier study, Sprinkel (1983) found that polyester polymer concrete overlays failed when subjected to temperature changes. The temperature fluctuation used for the study were the typical temperature changes experienced in the state of Virginia (-12°C to 39°C). The samples had a thickness between 8mm and 15mm. Sprinkel (1983) also concluded that a longer service life should be possible if the resin was more flexible.

The unanswered questions from these studies include: what is the coefficient of permeability of the polymer concrete? How does polymer concrete compare to asphalt in terms of water permeability and chloride ion diffusion? Will the thin overlay fail when the water vapor pressure accumulated from the Portland cement concrete substrate? What is the relationship between thickness and durability? And how much water does the polymer concrete absorb? Is it possible to use thinner overlays to resist thermal mismatching stresses?

3.3 OBJECTIVES OF THE RESEACH

The objectives of the research reported in this thesis are to examine the effectiveness of protection of the bridge deck by using polymer concrete overlays, to study the environmental durability of the existing polymer concrete system and to propose the modified application methods for a more durable and economic overlay.

Study of Currently used Polymer Concrete Systems

The current polymer concrete application methods include the two-layer overlay method and the slurry overlay method. A comprehensive durability study of these existing overlay methods will be conducted through a series of new tests. The objectives were to understand the level of protection, weather durability and failure mechanisms of the existing polymer concrete overlay systems.

Study of Newly Proposed Polymer Concrete Systems

Five newly proposed polymer concrete application methods will be studied and compared with the current polymer concrete system. These proposed methods are: one layer overlay, ½ layer overlay, ½ layer with a primer overlay, ¾ layer overlay and ¾ layer with a primer overlay. These newly proposed application methods make use of less material and take less time to construct than the current polymer concrete overlay systems. The evaluation of these new application methods includes a durability assessment and whether they provide the same effective protection as the current methods. Specifically, the thickness of the traditional and newly proposed methods of application will be compared to determine how the addition of polymer binder increases the thickness and if this has an effect on the durability and degree of protection of the polymer concrete.

Tests to be Conducted

The experiments that were conducted are: (i) water permeability, (ii) temperature cycling, (iii) rapid chloride ion permeability, (iv) water absorption, (v) strength loss due to absorption, and (vi) water vapor pressure test.

The water permeability test will determine the coefficient of permeability for each of the application methods. This test is not accelerated and will give a realistic value of permeability. While the rapid chloride ion permeability test (RCPT) has provided some information regarding the permeability of polymer concrete in relation to Portland cement concrete and asphalt, the RCPT is an accelerated method in that it forces the ions through the medium and does not consider the natural rate of permeability. Besides determining the coefficient of permeability, the relationship between the method of application and the overlay permeability will be studied. Specifically, does the manner in which the aggregates are placed in the polymer binder affect the porosity of the overlay? The research will also try to determine how the thickness of the polymer concrete affects the permeability of the overlay. A numerical relationship will be drawn between the content used of polymer and the decrease in permeability. Addition of a primer as a possible solution to further reduce the permeability of the overlays will also be examined.

The temperature cycling test will assess the effect of thickness on the weather durability of the polymer concrete overlay. The current and newly proposed methods will be subjected to temperature cycles of -50°C to 40°C. After each cycle, an inspection will be conducted to determine whether delamination or substrate cracking has occurred. Once the application methods have been subjected to numerous cycles, the rapid chloride permeability test will be conducted. This test will allow for a quantitative analysis of the effect of the temperature cycling on permeability and delamination. Furthermore, rapid chloride ion permeability tests will be conducted on control samples to determine the diffusion of the chloride ions and whether the newly proposed application methods are as effective as the current application methods.

The water absorption and flexural strength tests will evaluate the ductility, load capacity and air voids of the application methods. The environmental durability of polymer concrete with regards to being subjected to water submersion for an extended period of time will be analyzed. The tests will determine whether a relationship exists between the thickness of the application methods and the percent absorption and loss of strength due to absorption.

The water vapor pressure test will determine if the pressure generated from the evaporation of water in the substrate during a hot sunny day will crack the thin polymer concrete overlay. Furthermore, there is concern that if the temperature on the surface of the overlay is too high, then the properties of the polymer binder will be affected and this may initiate cracking in the polymer concrete and reduce the durability of the overlay. Therefore, this test will subject the different polymer concrete application methods to the combined effect of water vapor pressure and high surface temperature and determine the durability of the polymer concrete.

Structure of the Thesis

The structure of the thesis is organized as follows:

- Chapter 1 will consist of a general introduction on bridge decks
- Chapter 2 will be a summary of the literature survey.
- Chapter 3 will list the objectives of the research and a preliminary examination of the tests that will be conducted
- Chapter 4 will present the experimental program that was conducted, including the theory, setup, duration and procedure of each experiment.
- Chapter 5 will explain how the samples were prepared for each experiment. In addition, the properties of the epoxy and aggregates used for the experimental program will be presented. The different application methods, current and new, will be discussed in further detail in this chapter.
- Chapter 6 will present the results of each experiment. A preliminary analysis of the results will be conducted in this chapter.

- Chapter 7 will contain a complete analysis of the experimental program. The analysis will combine the experimental results to assess the durability of the different overlay methods. Furthermore, recommendations for future work will be discussed.
- Chapter 8 will contain the conclusions that were drawn form the experimental program and analysis of the results.

Chapter 4

Experimental Program

4.1 WATER PERMEABILITY TEST

The durability of a bridge deck is related to the permeability of the materials used. It is believed that concrete that has been well designed and manufactured is watertight and that the pores are discontinuous. However, with time the increasing traffic loading and the continuous exposure to severe weathering creates a network of micro-cracks. It is through these cracks that water, saturated with aggressive chemical ions, penetrates and ultimately causes the corrosion of reinforcement and deterioration of the concrete.

To help slow down this process of deterioration, different overlay systems have been designed. The extent of protection offered by an overlay system to a concrete or steel bridge deck is understood by way of the coefficient of permeability (k, m/s). The higher the value of the coefficient, the more permeable the material and therefore the greater the possibility that the water and chloride ions will be able to penetrate the overlay towards the bridge deck.

While there is no recognized standard test method, researchers have designed a test based on Darcy's Law [Ludirdja et al., 1989, Wang et al., 1997]. This water permeability test is simple to conduct and allows for the calculation of the coefficient of permeability of polymer concrete. The coefficient of permeability is described by Darcy's law for a falling water head and is calculated according to the following equation [Ludirdja et al., 1989, Wang et al., 1997]

$$\frac{QL}{hA} = kt \qquad (4.1)$$

where

Q = water permeated, m^3
A = area of polymer concrete sample, m^2
t = time, sec
h = head of water, m
L = thickness of specimen, m
k = coefficient of permeability, m/s

The polymer concrete specimens were cast in plexiglass rings with a dimension of 12.7cm diameter, 6.35mm thick and 5.1cm high. Each specimen was placed between two other plexiglass rings and two plates, and then clamped by four threaded bars. The schematic of the test setup can be ascertained from figures 4.1 and 4.2.

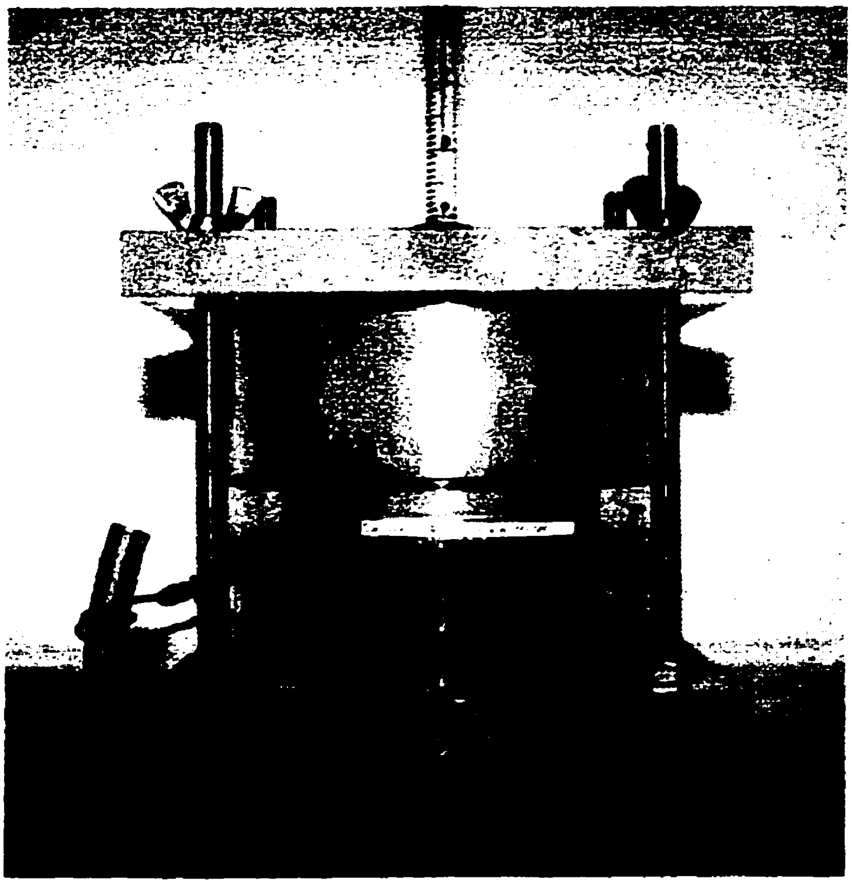


Figure 4.1 Water Permeability Testing Apparatus

Water was then introduced in the upper chamber through the 10ml pipette. Flow of water was monitored to record the drop in water level in the pipette. Measurements were conducted at regular intervals, normally once a day depending on the rate of flow. The pipette was filled after each reading to keep the same water pressure head. The bottom chamber was kept empty. A reference pipette with the same water level was set next to the water permeability testing apparatus to monitor the influence of water evaporation.

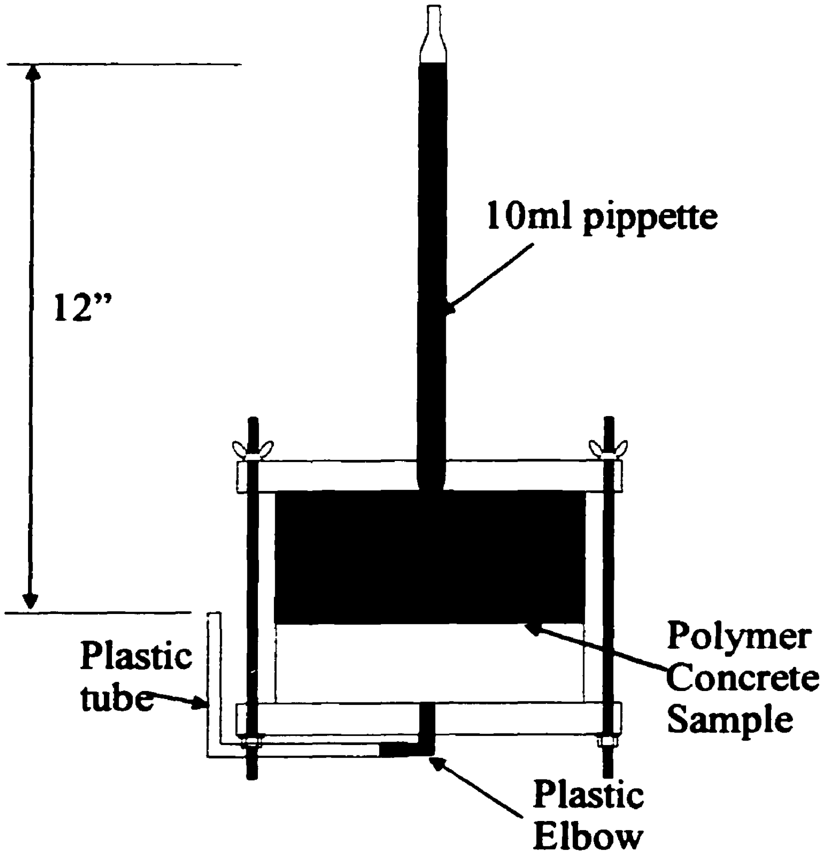


Figure 4.2 Schematic View of Water Permeability Testing Apparatus

4.2 TEMPERATURE CYCLING TEST

The temperature cycling test allows to understand the thermal compatibility of the Portland cement concrete overlaid by polymer concrete in extreme temperature conditions. This test is important since the thermal coefficients for these two materials are different. For normal strength (fc' = 30 to 35 MPa) Portland cement concrete the thermal coefficient (α_c) is approximately $10\times10^{-6}/^{o}C$, while for flexible epoxy polymer concrete the thermal coefficient (α_{pc}) is approximately $90\times10^{-6}/^{o}C$ [ACI Committee 548, 1993]. The difference in the coefficients means that the rate of expansion and contraction are not the same, and therefore the system will experience residual thermal stress in both materials as well as along the interface between the two materials. These stresses could be significantly large and therefore cause debonding or delamination. The principal cause of these high thermal stresses is the thickness of the materials, which augment the effect of difference in thermal coefficient.

This stress can be explained by using basic solid mechanics principles. The first principle states that in any static system, the summation of forces is equal to zero (equilibrium of forces).

$$Fpcc + Fpc = 0 \tag{4.2}$$

where:

F_{pc} = force in the Polymer Concrete
F_{pcc} = force in the Portland Cement Concrete

The second principle (compatibility of deformations) states that the expansion or contraction of two or more materials that are bonded together is the same. This means that if one material expands or contracts *x* mm, then the other bonded material will expand or contract the same amount.

$$(\delta_P)_{pcc} + (\delta_T)_{pcc} = (\delta_P)_{pc} + (\delta_T)_{pc} \tag{4.3}$$

which is equivalent to:

$$\frac{Fpcc * Lpcc}{Apcc * Epcc} + \alpha pcc * Lpcc * \Delta T = \frac{Fpc * Lpc}{Apc * Epc} + \alpha pc * Lpc * \Delta T \qquad (4.4)$$

where:

pcc = Portland cement concrete
pc =polymer concrete
(δ_p) = expansion due to internal forces
(δ_T) = expansion due to thermal change
F = force
A = cross-sectional area
L = length
E = modulus of elasticity
α = thermal coefficient
Δ_T = change in temperature

The temperature cycling tests were conducted at Hydro Quebec's IREQ research center. The freeze-thaw chamber allowed for temperatures of -50°C to 40°C as well as the possibility of adding and removing water. The cycle that was used was based on a study conducted by Dr. Mirza of Hydro Quebec. [Mirza et al., 1994] The temperature curves at different cycle rates are shown in figure 4.3 to 4.6.

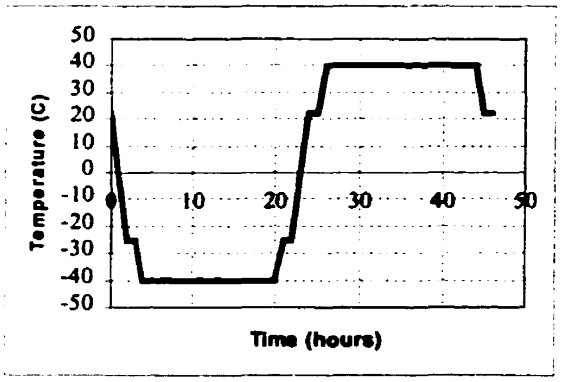


Figure 4.3 Cycle 1 (Temp. vs. Time)

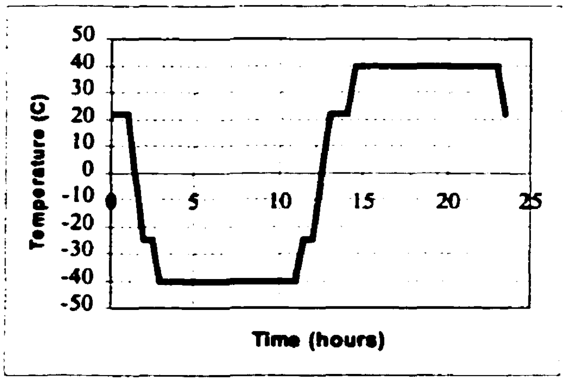


Figure 4.4 Cycle 2 (Temp. vs. Time)

Table 4.1 Description of Cycle 1

Cycle 1		
Steps	description	duration
1	start at 22C	0
2	drop to -25C	2h
3	maintain -25C	1h
4	drop to -40C	1h
5	maintain -40C	16h
6	rise to -25C	1h
7	maintain -25C	1h
8	rise to 4C	1h10
9	fill with water	0
10	rise to 22C	0h50
11	maintain 22C	1h
12	empty tank	0
13	rise to 40C	1h
14	maintain 40C	18h
15	drop to 22C	1h
16	maintain 22C	1h

Table 4.2 Description of Cycle 2

Cycle 2		
Steps	description	duration
1	@ 22C fill water	1h
2	empty tank	0h
3	drop to -22C	1h
4	maintain -22C	0h30
5	drop to -40C	0h30
6	maintain -40C	8h
7	rise to -22C	0h30
8	maintain -22C	0h30
9	rise to 4C	0h35
10	fill with water	0
11	rise to 22C	0h25
12	maintain 22C	1h
13	empty tank	0
14	rise to 40C	0h30
15	maintain 40C	8h30
16	drop to 22C	0h30

The cycle was essentially divided into four steps. The first part was lowering the temperature from room temperature (22°C) to a below freezing temperature (-40°C). The following step was maintaining the temperature at -40°C long enough so that water in the concrete had time to freeze and expand. The next step was a gradual increase in temperature and the introduction of water so that the specimens could thaw in water. Upon reaching 40°C, the water had been removed and the temperature was maintained for some time so that excess water in the concrete dried out. The first applied cycle finished in 48 hours (figure 4.3 and table 4.1). Given that the specimens were responding favorably, the cycle was modified to have a higher cycling rate to simulate more severe conditions.

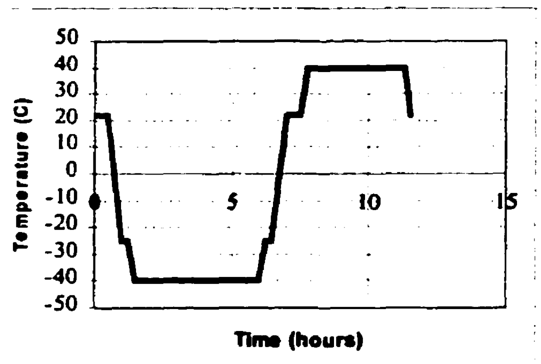


Figure 4.5 Cycle 3 (Temp. vs. Time)

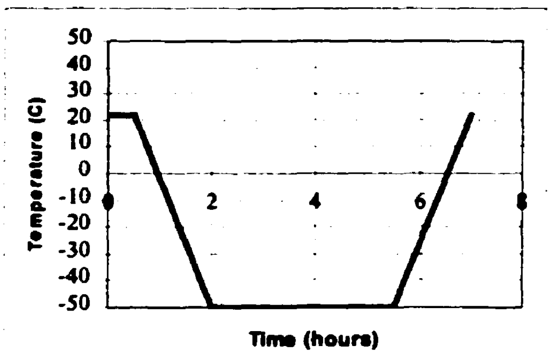


Figure 4.6 Cycle 4 (Temp. vs. Time)

Table 4.3 Description of Cycle 3

Cycle 3		
Steps	description	duration
1	@ 22C fill water	0h30
2	empty tank	0
3	drop to -22C	0h30
4	maintain -22C	0h15
5	drop to -40C	0h15
6	maintain -40C	4h30
7	rise to -22C	0h15
8	maintain -22C	0h15
9	rise to 4C	0h20
10	fill with water	0
11	rise to 22C	0h10
12	maintain 22C	0h30
13	empty tank	0
14	rise to 40C	0h15
15	maintain 40C	3h30
16	drop to 22C	0h15

Table 4.4 Description of Cycle 4

Cycle 4		
Steps	description	duration
1	fill with water	0
2	maintain 22C	0h30
3	empty tank	0
4	drop to -50C	1h30
5	maintain -50C	3h30
6	rise to 22C	1h30

The second set of cycles (figure 4.4 and table 4.2) had a duration that was half of the first set; i.e. one cycle in the second set lasted 24 hours. Besides changing the duration of the cycle, the specimens were submerged in water before they were frozen. That is, the temperature of the chamber was lowered to 22°C and the tank was filled with water. The samples were submerged for one hour before the water was removed. The temperature was then lowered to -40°C in 2 hours. The following step maintained the temperature at -40°C for 8 hours. Afterwards, the temperature was raised to 4°C, the tank was filled with water, followed by a rise in temperature to 22°C. One hour later, the thawed samples were dried by increasing the temperature to 40°C. The last step in the second set of cycles was maintaining the temperature at 40°C for 8½ hours.

After a few cycles of the second set, it was decided to make the conditions more severe by reducing the duration to 12 hours. The third set of cycles (figure 4.5 and table 4.3) was exactly the same as the second set of cycles except all time duration were divided in half. Since the specimens sill showed no signs of distress, the cycle was modified again (figure 4.6 and table 4.4). The fourth and final set of cycles had a cycle duration of 7 hours and the temperatures varied from -50°C and 22°C. In addition to a decreased duration, the specimens were saturated with water before the temperature was lowered, and thawed in air instead of water.

To determine if delamination had occurred between the polymer concrete and the Portland cement concrete after a freeze-thaw cycle, three different inspections were conducted: visual, acoustic, and ultrasonic pulse velocity. The visual inspection consisted of determining if there were any irregularities in the PC surface (i.e. polymer concrete overlay was no longer flat). The acoustic inspection consisted of tapping a hammer on the surface and determining if there were any hollow sounds indicating delamination. The ultrasonic pulse velocity method was used to detect internal structure changes in the samples.

The ultrasonic pulse velocity method is a nondestructive test, which sends sonic waves through a medium and records the time it takes for the pulse to go from one point to another. To avoid incorrect time measurements, a layer of grease is applied between the sensor and the sample to be tested. The grease essentially eliminates air pockets that would increase the pulse travel time. The transmitter disc was placed on top of the polymer concrete overlays while the receiver disc was placed on the opposite side against the Portland cement concrete. [Naik and Malhotra 1991]

4.3 RAPID CHLORIDE PERMEABILITY TEST

To determine if the specimens subjected to temperature cycling had experienced any distress, the Rapid Chloride Permeability Test (ASTM C1209-91) was conducted. Besides determining the distress due to temperature cycling, it will also be possible to understand the level of protection against chloride ion penetration offered by the polymer concrete overlay with different thickness.

This test was conducted on three different sets of cores. One set consisted of plain normal strength Portland cement concrete cores. The second set consisted of cores extracted from the specimens subjected to temperature cycling, and the final set consisted of cores of overlaid specimens that did not undergo temperature cycling.

Table 4.5 Chloride Penetrability based on Charge Passed [ASTM C1209]

Charge Passed (coulombs)	Chloride Ion Penetrability
>4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very Low
<100	Negligible

The Rapid Chloride Permeability Test (ASTM C1202-91) consists of monitoring the amount of electrical current passing through 51mm (2 in.) thick cores with a 102mm (4 in.) nominal diameter during a period of 6 hours. A potential difference of 60 V dc is maintained across the ends of the specimen, one of which is immersed in a sodium chloride (3.0% by mass in distilled water) solution, the other in a sodium hydroxide (0.3N in distilled water) solution. Figure 4.7 shows a schematic view of the rapid chloride ion permeability test cell.

The total charge passed, in coulombs, is related to the resistance of the specimen to chloride ion penetration. The ASTM C1202-91 describes permeability in relation to the number of coulombs passing through the medium (table 4.5). This system allows for the user to sort samples from high permeability to low permeability, however, it does not provide a quantitative approach.

The Rapid Chloride Permeability Test as specified by ASTM C1202-91 is for cores that have a diameter ranging from 14.8 to 15.7mm (3.75 to 4.0 inches). For all other diameters the value of coulombs read must be adjusted according to the following equation:

$$Qs = Qx * \left(\frac{3.75}{x}\right)^2 \tag{4.5}$$

Where

Q_s = charge passed (coulombs) through a 3.75 inch diameter specimen
Q_x = charge passed (coulombs) through x inch diameter specimen
x = diameter (inch) of the nonstandard specimen

The cross-section of the cell can be seen in figure 4.7. The *Proove It* system integrates the area underneath the current (amperes) versus time (seconds) curve in order to obtain the coulombs of charge that passed during the 6 hour period.

The equipment used to conduct the Rapid Chloride Permeability Test is called *Proove It.* It is manufactured by GERMANN Instruments Inc. in accordance with ASTM C1202-91 and AASHTO T277-831. The components of the *Proove It* system (figure 4.8) are:

- Proove It controller/power supply unit for a maximum of 8 cells
- Proove It software in MS-DOS
- Measuring cell with two rubber gaskets (sealing rings)
- Red connecting cord
- Black connecting cord
- Temperature probe

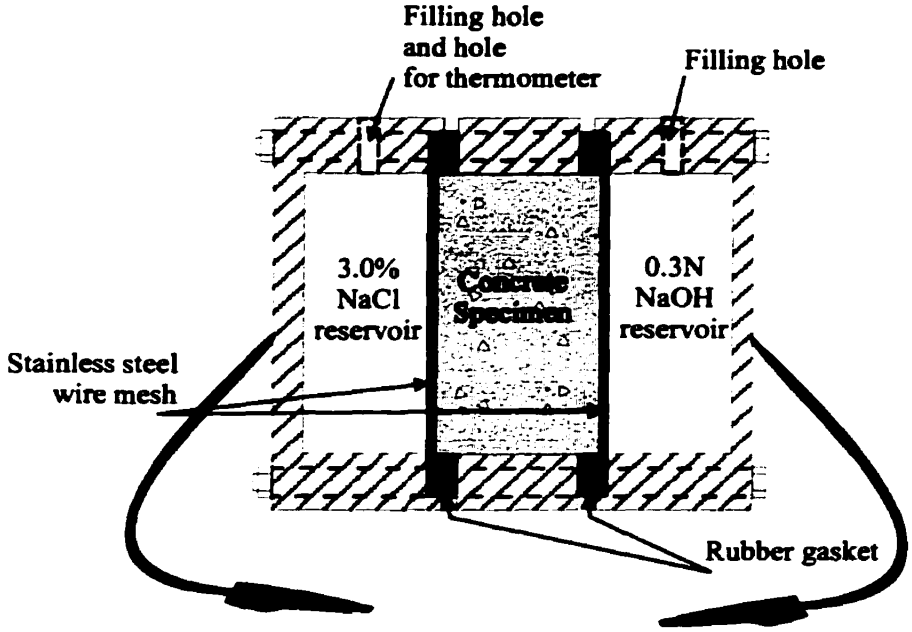


Figure 4.7 Cross-sectional view of Rapid Chloride Permeability Test cell

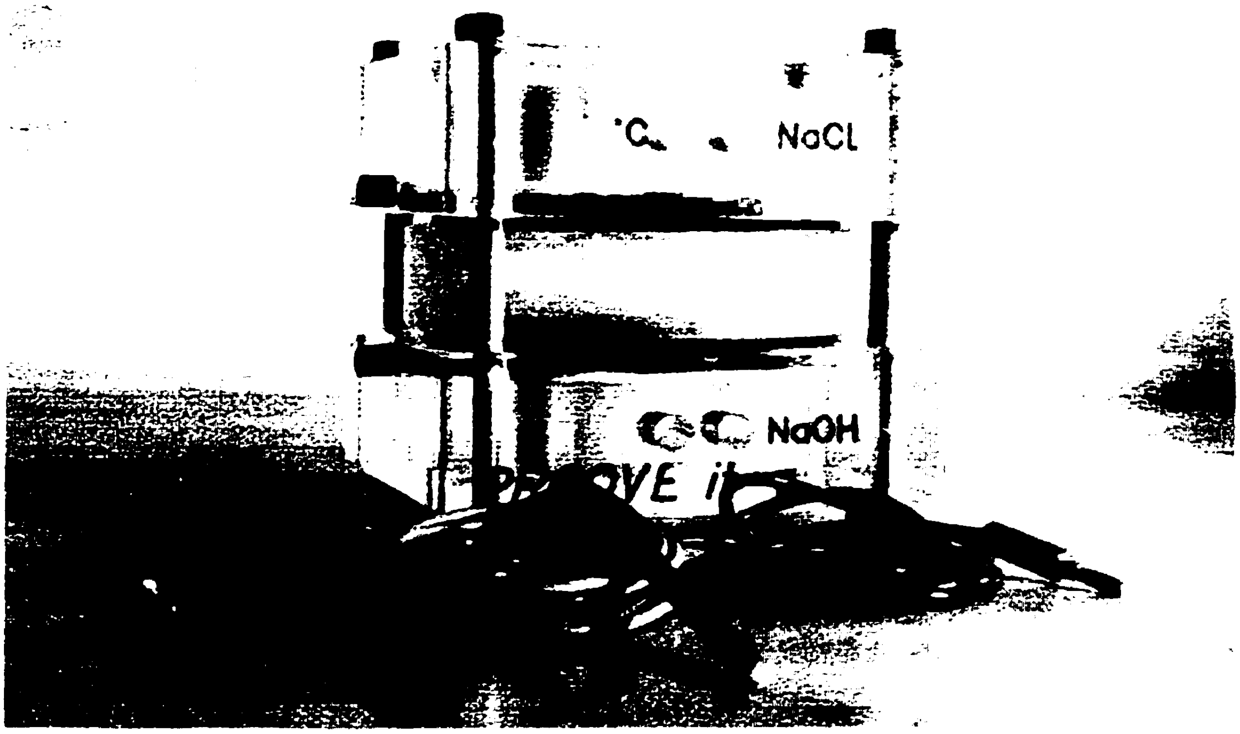


Figure 4.8 *Proove It* Cell for Rapid Chloride Ion Permeability Test

4.4 WATER ABSORPTION TEST

The water absorption test allows to determine how long-term exposure to water undermines the strength of polymer concrete. The amount of water that the polymer concrete absorbs gives an indication of the air pockets between the polymer and the aggregates as well as the porosity of the aggregate.

Similar to the water permeability test, there is no recognized standard test for water absorption. It was therefore decided that the following steps be used to determine the percent absorption of polymer concrete. Each specimen was weighed before being submerged in water to determine the dry initial weight. At regular intervals, each specimen was removed from the water tank, surface dried, weighed and re-submerged in water. Surface drying allowed for measuring the increase in weight only due to water absorption and not water that was on the surface. The test was conducted at ambient temperature and pressure until the percent absorption was constant over time. No acceleration process was adopted.

4.5 FLEXURAL STRENGTH TEST

Polymer concrete overlays are normally 6 to 12 mm thick to minimize the thermal mismatching between concrete or steel bridge deck. These overlays are subjected to high traffic loads, and therefore it is important to know the flexibility of the polymer concrete as well as the maximum flexural stress that polymer concrete can sustain before developing many cracks. Knowing this, the mechanism of cracking in polymer concrete can be further understood.

Polymer concrete specimens were subjected to 3 point flexural strength test. The end conditions were simply supported and a roller at midpoint was used to apply the load. The apparatus used to apply the load is the MTS Sintech 30G apparatus. Figure 4.9 shows the schematic of the flexural strength test. The applied force and central deflection was recorded. Using solid mechanics principles and assuming elastic behavior, maximum stress was calculated using the following equation:

$$\sigma = \frac{M * y}{I} \tag{4.6}$$

where

σ = normal stress

M = max. bending moment

y = distance from neutral axis to outer fiber

I = moment of interia

Polymer concrete specimens that have been submerged in water for 7 days and 28 days were also tested in 3 point bending. The effect of water absorption on the flexibility and the maximum flexural stress of the polymer concrete were examined.

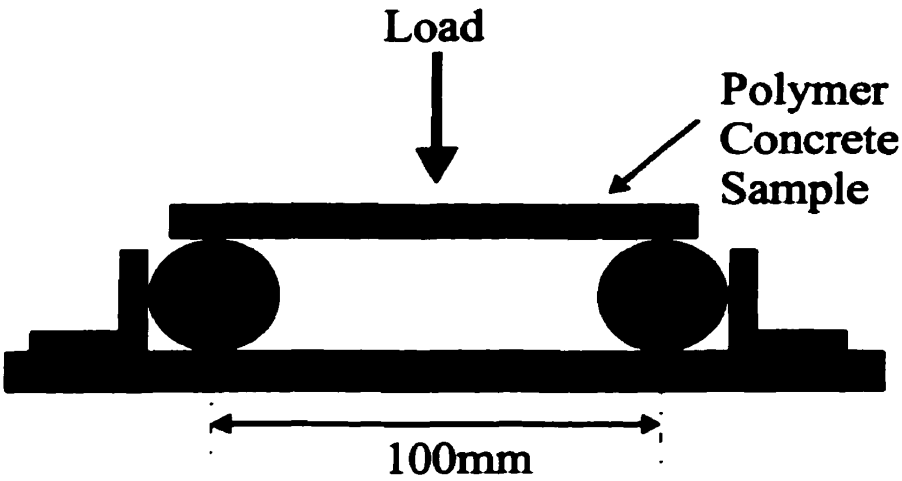


Figure 4.9 Schematic of the Flexural Strength Test

4.6 WATER VAPOR PRESSURE TEST

The water vapor pressure test is designed to determine if the polymer concrete overlay will delaminate from the substrate due to the pressure created from the evaporating water inside the concrete. This water vapor pressure is created by the temperature rise on the surface of the bridge deck. With a thickness of approximately 10mm, it is believed that little pressure is needed to delaminate the overlay. Many think that Leonhardt was correct in stating that "temperature plays a much more important role in causing stress than most engineers are aware of." [Leonhardt, 1977]

The water vapor pressure test consisted of placing Portland cement concrete slabs (0.5m wide, 0.5m long, 0.05m thick) overlaid with polymer concrete under ultraviolet heat lamps (250W, 120V) to simulate the sunlight exposure. The ultraviolet heat lamps were placed such that the temperature inside the Portland cement concrete would rise to approximately 50°C. This temperature for the Portland cement concrete was selected to produce the worst condition - high temperature in the concrete bridge deck and therefore the highest possible water vapor pressure to be generated inside the pore structure as well as along the bond interface between the overlay and the substrate.

To ensure continuous water evaporation, the Portland cement concrete slabs were kept water saturated. That is, the slabs were placed in a tank filled with water, however, the polymer concrete overlays were maintained above the water level. To ensure that no water vapor pressure escaped through the sides of the slab and that all generated water vapor pressure went through the overlay, insulation was placed around the slabs. The setup can be seen in figures 4.10 and 4.11.

The temperature of the Portland cement concrete as well as the temperature at the Portland cement concrete-polymer concrete overlay interface was recorded by using Type K thermocouples and a 12 channel scanning thermometer manufactured by Barnant Company. Type K thermocouples can be used to record temperatures between -250 to 1260°C in oxidizing or inert atmospheres. Each sample contained five thermocouples, one thermocouple was placed in each concrete slab and four thermocouples in between the slab and overlay. The exact placement of the thermocouples is discussed in chapter 5, Sample Preparation.

The condition of each polymer concrete overlay was assessed visually, acoustically and by ultrasonic pulse velocity tests to monitor the occurrence of delamination. In addition, pullout tests were performed to evaluate the strength of the bond and determine if the high temperature had affected the properties of the polymer binder.

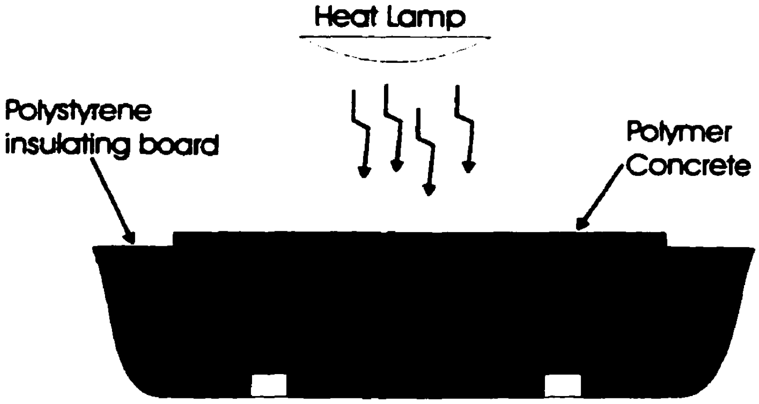


Figure 4.10 Schematic of the Water Vapor Pressure Test

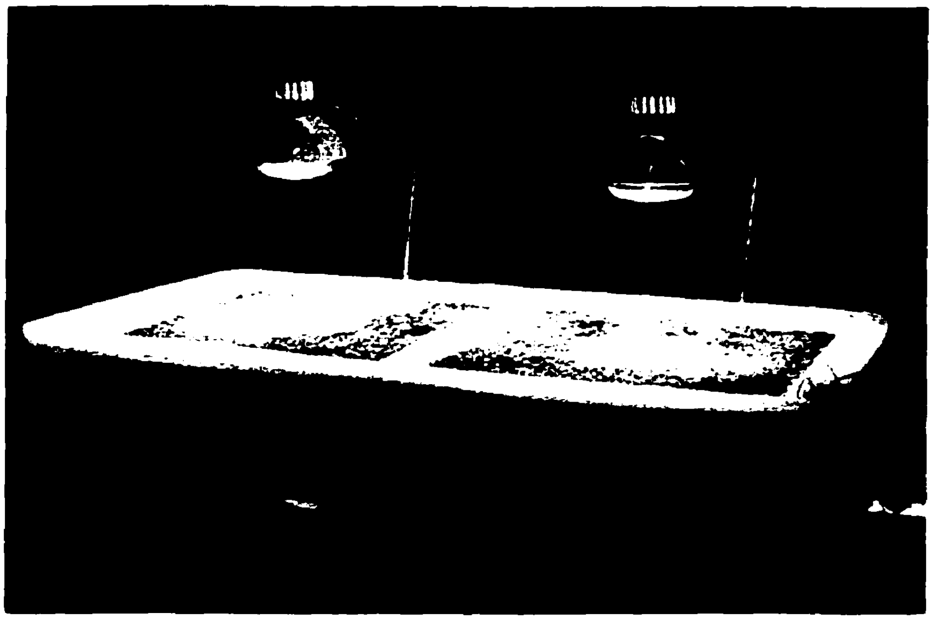


Figure 4.11 Water Vapor Pressure Test Setup

The pullout test consisted of subjecting the samples to tensile loading and determining the failure mode and load. To conduct the test, cylindrical cuts were implemented in each of the samples that underwent water vapor pressure testing. Figure 4.12 shows the schematic view of the partial core and how the steel disc was attached to the samples. Furthermore, cylindrical cuts were implemented in samples that did not experience high temperature and water vapor pressure. The cylindrical cuts were implemented to a depth of at least 20mm so that a uniform state of stress could be established [Cleland et al., 1997]. Once the cores were drawn, a steel disc was attached to the polymer concrete overlay by means of strong bonding epoxy. A steel rod was then screwed into the disc and the samples were placed between two steel plates. One of these steel plates was bolted to the MTS Sintech 30G apparatus. The gripping arm of the MTS Sintech 30G apparatus was attached to the steel rod and a tensile load was then applied. Figure 4.13 shows how the samples were secured down between two steel plates and how the load was applied.

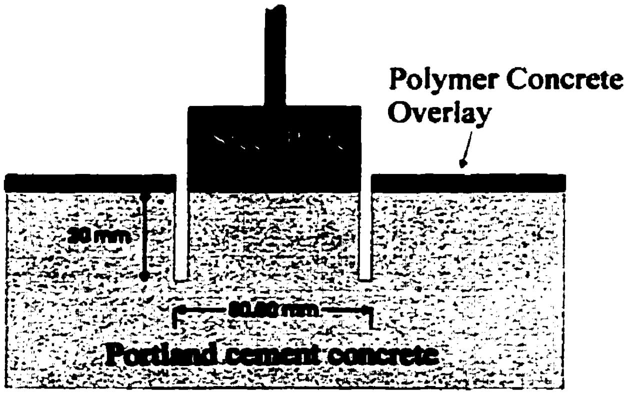


Figure 4.12 Schematic view of the Pullout Test

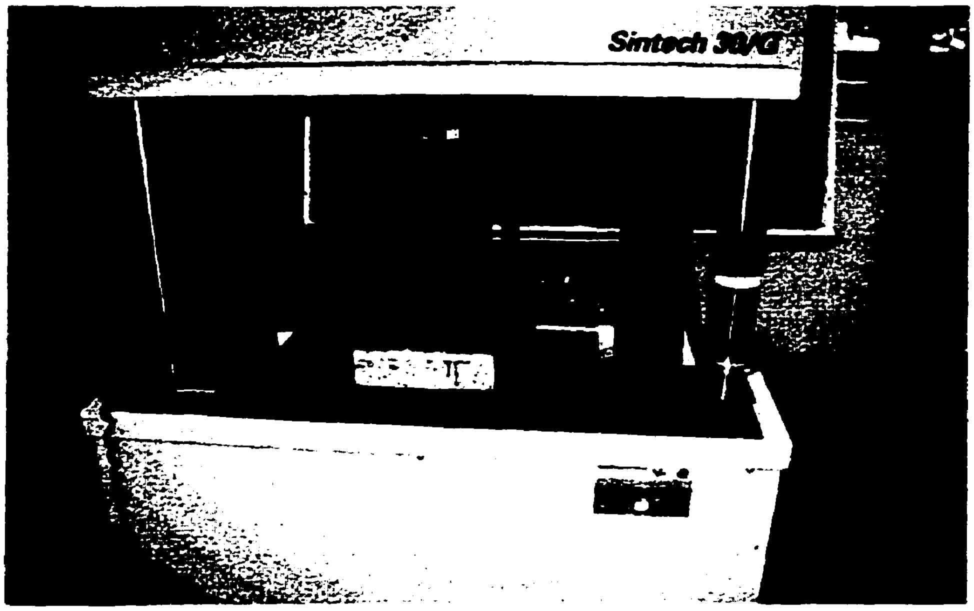


Figure 4.13 MTS Sintech 30G Setup for the Pullout Test

Chapter 5

Material Characteristics and Sample Preparation

5.1 FLEXOLITH POLYMER CONCRETE PROPERTIES

5.1.1 Epoxy Properties

The epoxy used to conduct the experimental program is FLEXOLITH which is manufactured by Tamms Industries (Kirkland, Il., USA). The epoxy resin is a two component, 100% solids, thermosetting, low modulus, flexible, high elongation and moisture-insensitive system.

Tamms Industries established the properties of the hardened epoxy resin by conducting ASTM standard tests. The compressive strength of the epoxy was found to be 9.66 MPa (1400psi) at 4 hours and 48.3 MPa (7000psi) at 7 days, based on ASTM C109, the Standard Test Method for Compressive Strength of Hydraulic Cement Mortars. In terms of tensile strength, it was found that at 7 days the epoxy withstood 17.2 MPa (2500psi) and that the elongation at break was 45% (ASTM D638 the Standard Test Method for Tensile Properties of Plastics). Tamms Industries also conducted ASTM C307, the Standard Test Method for Tensile Strength of Chemical-Resistant Mortar, Grouts, and Monolithic Surfacings, which found that the tensile strength at 7 days was 8.62 MPa (1250psi).

Besides these tests, Tamms Industries investigated the flexural properties of the epoxy resin. Using the Standard Test Method for Flexural Strength and Modulus of Elasticity of Chemical-Resistant Mortars, Grouts, Monolithic Surfacings, and Polymer Concretes (ASTM C580), it was determined that the epoxy had a modulus of rupture of 3600psi (24.8 MPa). These determined properties of FLEXOLITH are shown in table 5.1.

Table 5.1 Properties of FLEXOLITH Epoxy Resin

Properties of FLEXOLITH Epoxy Resin	
Pot Life (AASHTO T-237)	15-20 minutes
Traffic Time (curing time before opening to traffic)	3-5 hours
Mixed Viscosity	10-20 poises
Compressive Strength (4 hours) Compressive Strength (7 days) (ASTM C-109)	1400 psi (9.66MPa) 7000 psi (48.3MPa)
Tensile Strength Elongation at Break (ASTM D-638)	2500 psi (17.2MPa) 45%
Tensile Strength (ASTM C-307)	1250 psi (8.62MPa)
Modulus of Rupture (ASTM C-580)	3600 psi (24.8MPa)
Hardness, Shore D (ASTM D-2240)	65 min
Water Absorption (24hr) (ASTM D-570)	<0.5%
Thermal Compatibility (ASTM C-884)	passes
Effective Shrinkage (ASTM C-883)	passes
Adhesion to Concrete (ACI Method 503R-30)	Concrete Failure

5.1.2 Aggregate Properties

The aggregates used to conduct the experimental program were Basalt #8 Aggregate (supplied by Tamms Industries, Kirkland, Illinois). This particular type and size of aggregate is recommended to be used with epoxy resin system in FLEXOLITH.

In the Tamms Industries specification guide for epoxy-aggregate overlay, the Basalt #8 Aggregate is described as containing at least 10% aluminum oxide with a

Mohrs hardness of 6 to 6.5, a specific gravity of 2.99 and an abrasion index of 1.4. The gradation of the basalt aggregates is specified in table 5.2.

Table 5.2 Tamms Basalt #8 Aggregate Gradation

Mesh Number	Percent Retained
#4	None
#6	0-3
#12	70-97
#20	10-35
<#20	0-3

A sieve analysis was conducted before using the aggregate. The result of the analysis is shown in table 5.3. The aggregate size distribution was found to be as specified by Tamms Industries. This is a typical open-graded aggregate, which can accommodate the overlay system with more resin to ensure the strength and flexibility. The use of open-graded aggregate, instead of dense-graded aggregate is vital to the success of the overlay.

Table 5.3 Results of Sieve Analysis of Tamms Basalt #8 Aggregate

Mesh Number	Aggregate Size (mm)	Percent Retained	Percent Passing
#1	8.35	0.00	100.00
#8	2.36	59.97	40.03
#16	1.18	35.73	4.30
#30	0.6	2.69	1.61
#40	0.425	1.02	0.59
#60	0.25	0.33	0.26
#100	0.15	0.16	0.10
#200	0.075	0.02	0.08
<#200	<0.075	0.08	0.00

5.2 PC OVERLAY APPLICATION METHODS STUDIED

The amount of epoxy and aggregate used and how the materials are applied to the bridge deck are what categorize the PC overlay system. As mentioned in section 2.1.3, there are essentially two overlay methods recommended by industry and practiced in the field. They are the slurry method and the two layer method.

While these overlay methods have been successfully utilized, there is concern about the thermal compatibility with the substrate. Hence, to enhance the fatigue resistance, thermal compatibility and the freeze-thaw resistance, five new application methods are proposed. By conducting the experimental program mentioned in Chapter 4 it will be determined which of these five methods results in the least permeable and the most durable overlay.

Current Slurry Method

The slurry method, as mentioned in section 2.1.3, comprises of mixing the polymer resin with the aggregate in the correct proportions in either continuous or batch mixing equipment. The slurry is then distributed on the bridge deck and once the excess polymer bleeds to the surface additional aggregate is broadcast until all the wet areas are covered. It should be mentioned again that most slurry overlays require a prime coat (a thin layer of polymer) to be placed before the overlay is cast. The primer enhances the bond and reduces the permeability of the PC overlay. [Sprinkel, 1995]

Current Two-Layer Method

The two-layer overlay, as mentioned in section 2.1.3, (also called broom-and-seed-overlay) is constructed by distributing a layer of polymer resin on the existing bridge deck. While the polymer is still wet aggregate is broadcast in such a fashion as not to disturb the polymer layer. Once the matrix has cured, the excess aggregate is removed and the process is repeated to finish the second layer. [Sprinkel, 1995]

Proposed One-Layer Method

The first proposed new method is the one-layer overlay method. This method is similar to the two-layer overlay in that the amount of polymer and aggregate used are the same, except that the polymer and aggregate is placed in one step instead of two in order to reduce the construction time and to achieve similar protection.

Proposed Half-Layer With and Without a Primer Method

The next two new methods are the ½ layer overlay method and the ½ layer plus primer overlay method. Essentially the ½ layer overlay is the first layer of the two layer overlays. That is, by using half the quantity of polymer and slightly less aggregate, a layer of polymer binder is applied to the bridge deck followed by the broadcasting of the aggregates until all wet areas are covered. This method allows for a reduction in construction time as well as an enhanced thermal compatibility. The primer is used as a means to control permeability and not to enhance bond.

Proposed Three-Quarter-Layer With and Without a Primer Method

The next two proposed methods are called the ¾ layer overlay method, and ¾ layer plus primer overlay method. This method is constructed the same way as the ½ layer overlay except it uses slightly more polymer resin, ¾ of the amount used in the two-layer method. Similarly, this method allows for the reduction in construction time and material usage, but it should have a coefficient of permeability lower than the ½ layer plus primer overlay.

5.3 SAMPLE PREPARATION

5.3.1 Samples for Water Permeability Test

The polymer concrete samples for the Water Permeability Test were constructed in plexiglass rings that fitted into the apparatus described in Chapter 4.1. The plexiglass rings that were used at a diameter of 12.7cm, a thickness of 6.35mm, and a height of 5.1cm. They were placed on top of plastic sheets so that the polymer concrete would not bond to table. Silicon rubber was placed along the edges so that water could not permeate through the plexiglass-polymer concrete interface.

Initially there were twenty-six samples, however, an additional five were constructed since there was a high variance for some of the methods. For this test, the overlay methods that were linvestigated were: one layer overlay, two layer overlay, slurry overlay with and without a primer, ½ layer overlay with and without a primer, and ¾ layer overlay with and without a primer. The amount of epoxy and aggregate used as well as the number of samples made are listed in table 5.4. These material quantities were based on ACI recommendations. [ACI committee 548, 1993]

Table 5.4 Samples for Water Permeability Test

Method	No. of Samples Made	Primer (ml)	First Layer Epoxy (ml)	First Layer Aggregate (g)	Second Layer Epoxy (ml)	Second Layer Aggregate (g)
One Layer	4	-	28	131	-	-
Two Layer	4	-	11	61	17	61
1/2 Layer	4	-	14	100	-	-
1/2 Layer + Primer	3	5	14	100	-	-
Slurry	7	-	25	80	-	100
Slurry + Primer	5	5	25	80	-	100
3/4 Layer	1	-	21	131	-	-
3/4 Layer + Primer	3	5	21	131	-	-

5.3.2 Samples for Temperature Cycling Test

For the temperature cycling test, the polymer concrete overlays were constructed on Portland cement concrete substrate. Steps were taken to ensure that the Portland cement concrete was similar to what is used in the construction of bridges. The Portland cement concrete was normal strength concrete (34.5 MPa) and had a width of 150mm (6"), a length of 300mm (12") and a thickness of 51mm (2"). The maximum size aggregate used in the Portland cement concrete was 20mm, and it had 10% air content for frost protection.

The Portland cement concrete blocks were sand-blasted to ensure that the polymer concrete overlay bonded properly. The application methods that were used to construct the testing samples were: one layer overlay, two layer overlay, slurry plus primer overlay, ½ layer with primer overlay, and ¾ layer plus primer overlay. The total number of polymer concrete overlay samples constructed were fifteen, three samples for each method. The quantity of epoxy and aggregate used for each method is listed in table 5.5. The material quantities were based on ACI recommendations. [ACI Committee 548, 1993]

Table 5.5 Samples for Temperature Cycling Test

		First Layer		Second Layer	
Method	Primer (ml)	Epoxy (ml)	Aggregate (g)	Epoxy (ml)	Aggregate (g)
One Layer	-	124.8	590.4	-	-
Two Layer	-	50.4	295.2	76.8	295.2
1/2 Layer + Primer	24	62.4	550	-	-
Slurry + Primer	24	112.8	362.4	-	450
3/4 Layer + Primer	24	93.6	590.4	-	-

5.3.3 Samples for Rapid Chloride Permeability Test

The samples for the Rapid Chloride Permeability Test were produced by coring from the temperature cycled samples as well as coring from control samples that did not experience temperature cycling. The cores drawn were 100mm (4") in diameter, and had a length of 50mm (2").

The total number of cores obtained for the Rapid Chloride Permeability Test was twenty-two. The number of sample for each application method is listed in table 5.6. Each of these cores were conditioned before the Rapid Chloride Permeability Test was conducted. A thin layer of silicon rubber was applied to the walls of the cores to eliminate the possibility of stray current. Once the silicon rubber was dry, the samples were placed in a vacuum desiccator. The vacuum was maintained for three hours before and for one hour after deaerated water was added into the desecrator. The water was added until the samples were covered completely. The cores were maintained in water for another 18 hours to ensure complete saturation.

Table 5.6 Samples for Rapid Chloride Ion Test

Method	Cored Samples	
	control	temp. cycled
Portland cement concrete	2	-
One Layer	2	2
Two Layer	2	2
1/2 Layer + Primer	2	2
Slurry + Primer	2	2
3/4 Layer + Primer	2	2

5.3.4 Samples for Water Absorption Test and Flexural Strength Test

The polymer concrete samples fabricated for the Water Absorption Test were used for the Flexural Strength Test.

For the purposes of these two tests, 152 polymer concrete samples were constructed. Each sample was made in a mold that measured 75mm (3") in width, and 150mm (5") in length. The sides and bottom of the molds were covered with plastic sheets so that the polymer concrete would not adhere to the sides and the bottom.

The amount of epoxy and aggregate used as well as the number of samples made for each method are listed in table 5.7.

Table 5.7 Samples for Water Absorption and Flexural Strength Test

Method	No. of Samples Made	Primer (ml)	First Layer Epoxy (ml)	First Layer Aggregate (g)	Second Layer Epoxy (ml)	Second Layer Aggregate (g)
One Layer	20	-	26	123	-	-
Two Layer	20	-	10.5	61	15	61
1/2 Layer	18	-	12	123	-	-
1/2 Layer + Primer	20	5	13	123	-	-
Slurry	18	-	23.5	75.5	-	94
Slurry + Primer	20	5	23.5	75.5	-	94
3/4 Layer + Primer	18	5	19.5	123	-	-
Epoxy	18	-	50	-	-	-

5.3.5 Samples for Water Vapor Pressure Test

The polymer concrete samples for the Water Vapor Pressure Test were prepared in the similar manner as the temperature cycling test samples. Steps were once again taken to ensure that the Portland cement concrete was similar to what is used in the construction of bridges. The Portland cement concrete slab was made of normal strength concrete (35 MPa), having a width of 0.5m, a length of 0.5m and height of 50mm. The maximum size aggregate used in the Portland cement concrete was once again 20mm, and a type K thermocouple was placed (when the concrete was wet) at the center of the slab. These slabs were sand-blasted to improve the bond with polymer concrete.

Before the polymer concrete overlays were constructed, four type K thermocouples were placed on top of the slab. Each of the thermocouples was placed on a different edge of the slab. The exact location of the thermocouples is shown in figure 5.1. The thermocouples were taped down to the Portland cement concrete substrate.

The five overlay application methods that were studied in this test were: one layer overlay, two layer overlay, slurry plus primer overlay, ½ layer with primer overlay, and ¾ layer plus primer overlay. For this test, only one sample for each method was constructed. The amount of epoxy and aggregate used for each sample is listed in table 5.8.

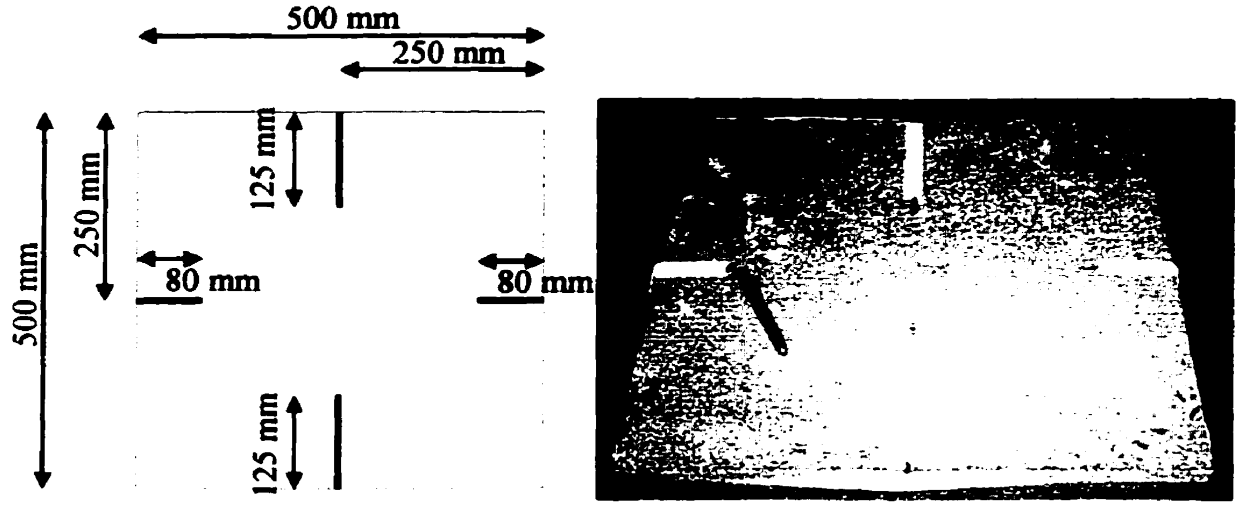


Figure 5.1 Location of Thermocouples for Water Vapor Pressure Test

Table 5.8 Samples for Water Vapor Pressure Test

Method	Primer (ml)	First Layer Epoxy (ml)	First Layer Aggregate (g)	Second Layer Epoxy (ml)	Second Layer Aggregate (g)
One Layer	-	672	3178	-	-
Two Layer	-	271	1589	413	1589
1/2 Layer + Primer	129	336	2960	-	-
Slurry + Primer	129	607	1950	-	2400
3/4 Layer + Primer	129	504	3178	-	-

Chapter 6

Results of Experiments

6.1 WATER PERMEABILITY OF POLYMER CONCRETE

The water permeability tests for the seven different application methods were conducted over a period of three months (May to June 1998). Each specimen was subjected to a water pressure head for approximately 14 days. During this period the flow of water was recorded. The typical permeation curves for the five application methods are shown in figure 6.1. The values of cumulative water flow that were of interest were after 3 days, when it became a steady-state flow. The polymer concrete by methods of ½ layer without primer and slurry without primer do not appear on the graph. This was because their water permeability was too high to record. For these application methods, primer seems essential for success.

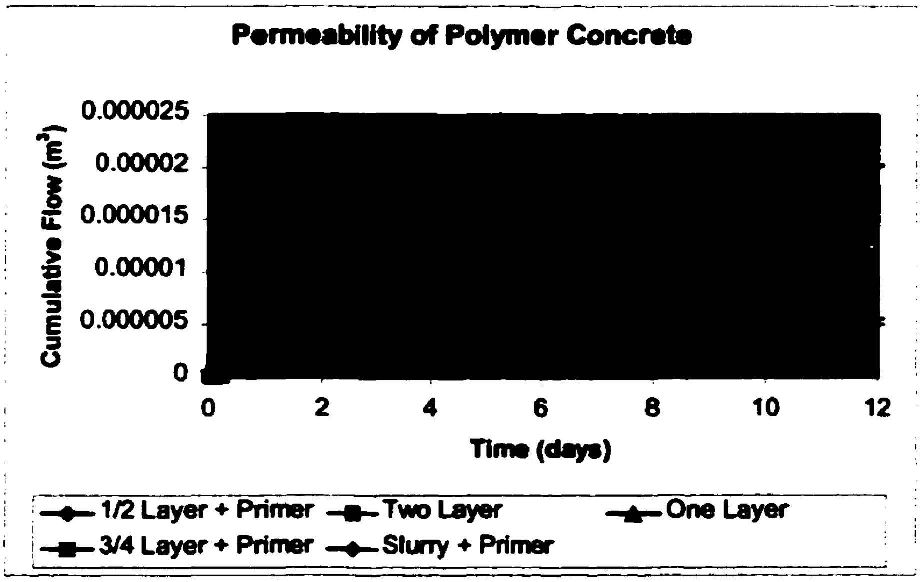


Figure 6.1 Typical Permeation Curves for Polymer Concrete

The coefficient of permeability *k* for each polymer concrete specimen was determined using Equation 4.1. The maximum, minimum and average values of coefficient of permeability for each application method are listed in table 6.1. Their statistic data are shown in table 6.2.

Table 6.1 Coefficients of Permeability for each Method

Method	Max Permeability (10 [illegible] m/s)	Min Permeability (10 [illegible] m/s)	Average Permeability (10 [illegible] m/s)	Rank
One Layer	16.3	6.5	11.4	1
Two Layer	74.3	5.24	24.3	3
1/2 Layer	1800000	1180000.0	1561469	7
1/2 Layer + Primer	24.2	9.78	17.19	2
Slurry	3860000	6.57	1740968	8
Slurry + Primer	730	6.58	254.72	4
3/4 Layer	196700	196700	196700	6
3/4 Layer + Primer	2171	9.07	905	5

The slurry method without primer was the most permeable despite it being the thickest overlay (table 6.2). On the other hand, the ½ layer without primer had the second highest coefficient of permeability, which was expected since it was the thinnest overlay. The addition of a primer helped decrease the coefficient of permeability as was expected. It is interesting to note that despite the primers being approximately the same thickness, the primer had a greater effect on the ½ layer than on the slurry method. The ½ layer plus primer had a decrease by 5 orders of magnitude, while the decrease in *k* for slurry plus primer was by an order of 4.

Besides the benefit of the primer, the test revealed that the one layer overlay (same amount of resin and aggregate as two-layer but constructed in one step) was on average better than the conventional two-layer overlay as far as the impermeability is concerned. This implies that the similar protection is possibly achieved using the one layer overlay, however the construction time can be reduced in half. Furthermore, the test has shown that the ½ layer plus primer overlay has a coefficient of permeability comparable to the one and two-layer overlays. It should be noted that the ½ layer method was basically the one layer method using only half the amount of resin as that used by the one layer method. Therefore, by using the ½ layer plus primer method, construction time can also be reduced and certain amount of epoxy and aggregate can be saved.

Table 6.2 Coefficient of Permeability for all PC Samples

Method	Thickness (mm)	Flow (m^3/s)	Pressure (m)	Permeability (m/s)
One Layer	8.1	3.73E-12	0.2809	1.047E-11
	7.0	6.73E-12	0.2820	1.628E-11
	6.5	2.90E-12	0.2825	6.497E-12
	6.5	5.79E-12	0.3005	1.220E-11
Two Layer	8.1	2.96E-12	0.2809	8.327E-12
	7.0	3.80E-12	0.2820	9.201E-12
	7.0	2.32E-12	0.3020	5.235E-12
	6.5	3.57E-12	0.0305	7.432E-11
1/2 Layer	3.8	1.39E-06	0.2852	1.804E-06
	3.0	1.12E-06	0.2780	1.180E-06
	3.0	1.76E-06	0.2860	1.803E-06
	3.5	1.30E-06	0.3045	1.460E-06
1/2 Layer + Primer	4.0	1.29E-11	0.2850	1.761E-11
	3.5	8.19E-12	0.2855	9.784E-12
	4.0	1.91E-11	0.3075	2.417E-11
Slurry	7.3	7.80E-09	0.2817	1.970E-08
	8.0	1.39E-06	0.2810	3.860E-06
	6.5	2.90E-12	0.2795	6.566E-12
	7.0	1.64E-06	0.3050	3.677E-06
	7.2	1.73E-10	0.3038	3.986E-10
	7.8	9.08E-07	0.3032	2.277E-06
	7.5	9.77E-07	0.3035	2.353E-06
Slurry + Primer	7.0	3.02E-10	0.2820	7.296E-10
	6.0	3.19E-12	0.2830	6.585E-12
	7.0	4.91E-12	0.3020	1.108E-11
	6.8	1.34E-10	0.3042	2.914E-10
	7.3	1.00E-10	0.3037	2.350E-10
3/4 Layer	6.5	8.77E-08	0.2825	1.967E-07
3/4 Layer + Primer	6.5	4.36E-12	0.3045	9.072E-12
	6.3	2.66E-10	0.3047	5.350E-10
	6.2	1.10E-09	0.3048	2.171E-09

The explanation for the performance of the slurry without primer method is that the placement of the slurry mixture is a very random process, which did not make use of a vibrating screed. This randomness results in some samples being highly permeable (10^{-6} m/s) and other samples almost impermeable (10^{-12} m/s). Despite the possibility of having an impermeable system, it is recommended that a primer be used.

A possible explanation for the different coefficients of permeability is that the aggregate attracts epoxy (i.e. when the aggregate is broadcasted on the epoxy, the epoxy migrates up), therefore if enough epoxy is available then there will be more epoxy that remains at the substrate-overlay interface. With more epoxy at the interface, a complete thin film will be produced and therefore a less permeable PC overlay. This explains the difference between the one layer and the ½ layer. As for the case of the two-layer method, the second layer fills up the voids produced in the first layer and thus making the entire overlay impermeable. This also explains why the two-layer method has the best field record [Sprinkel, 1993]

It is interesting to compare the effectiveness of the protection of polymer concrete for bridge deck with that of asphalt overlay and Portland cement concrete overlay. The coefficient of permeability of asphalt is about 10^{-4} - 10^{-6} m/s [Illston 1995] while for uncracked concrete it is approximately 10^{-11} m/s [Ludirdja et al. 1989, and Wang et al. 1997]. It is clear that in terms of water permeability most polymer concrete overlays are much better than asphalt, and better or at least comparable to uncracked concrete. Notice that to achieve such a protection the asphalt overlay and Portland cement concrete overlay need a thickness of at least 50mm while the polymer concrete can serve the purpose with a thickness of only 8mm.

6.2 TEMPERATURE CYCLING RESISTANCE OF POLYMER CONCRETE

The polymer concrete overlays plus the Portland cement concrete substrate underwent 103 temperature cycles. The number of completed cycles for each type of cycle (defined in chapter 4.2) are listed in table 6.3. Recall that with each type of cycle, the duration between high and low temperatures decreases, and the cycle rate increases.

The faster the temperature fluctuates, the more likely the delamination will be induced if the bond is the weak link in the overlay system.

Table 6.3 Number completed for each Type of Cycle

Cycle	Number Completed
1	4
2	5
3	41
4	53

To determine if delamination had occurred between the polymer concrete and the Portland cement concrete after a temperature cycle, three different inspections were conducted: visual, acoustic, and ultrasonic pulse velocity. The acoustic and visual inspections did not reveal any delamination. The only major visual difference that occurred was that the polymer concrete overlays became darker in color after undergoing temperature cycling. Figure 6.2 shows the typical change in overlay color.

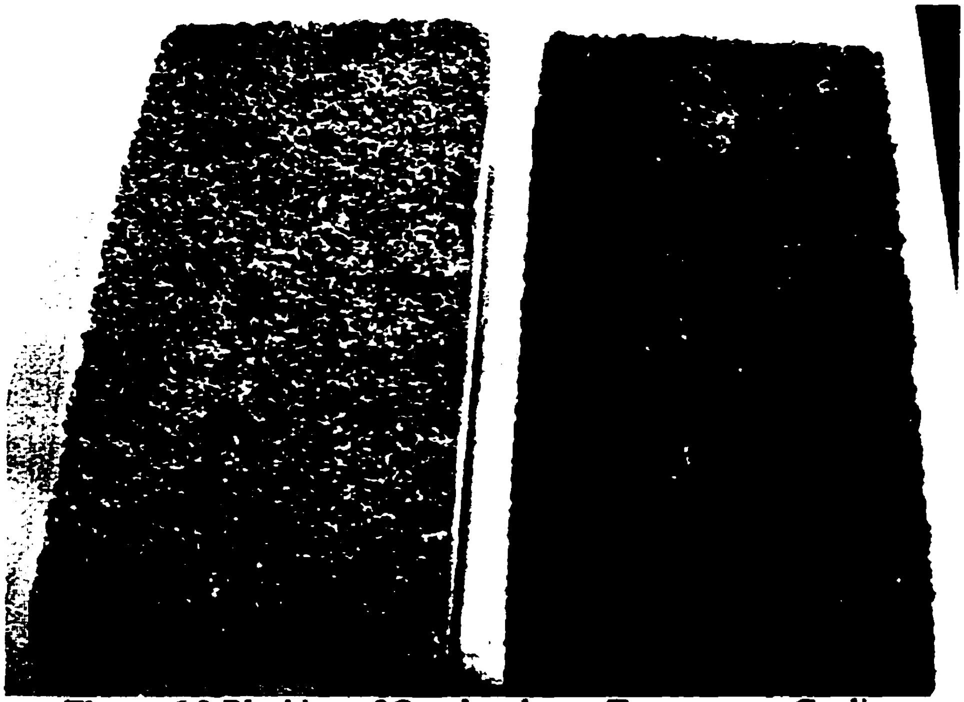
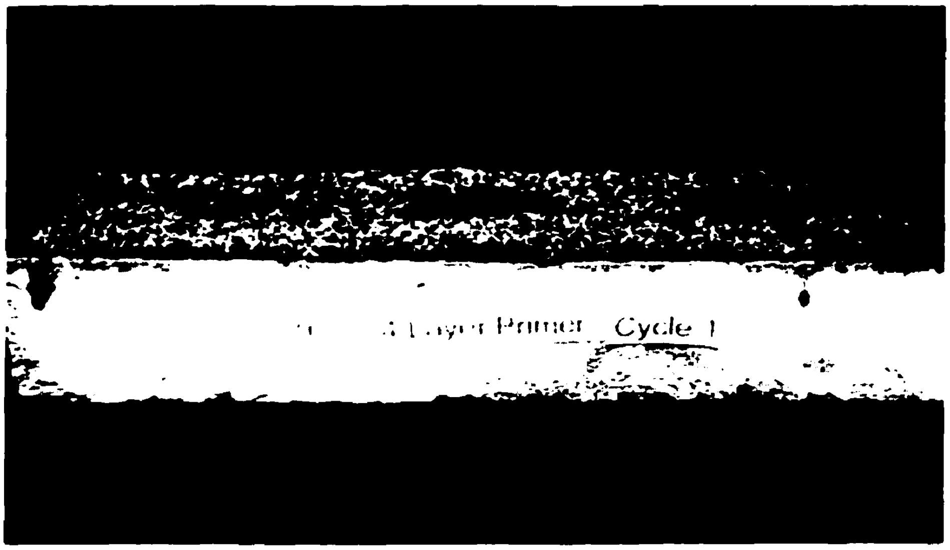
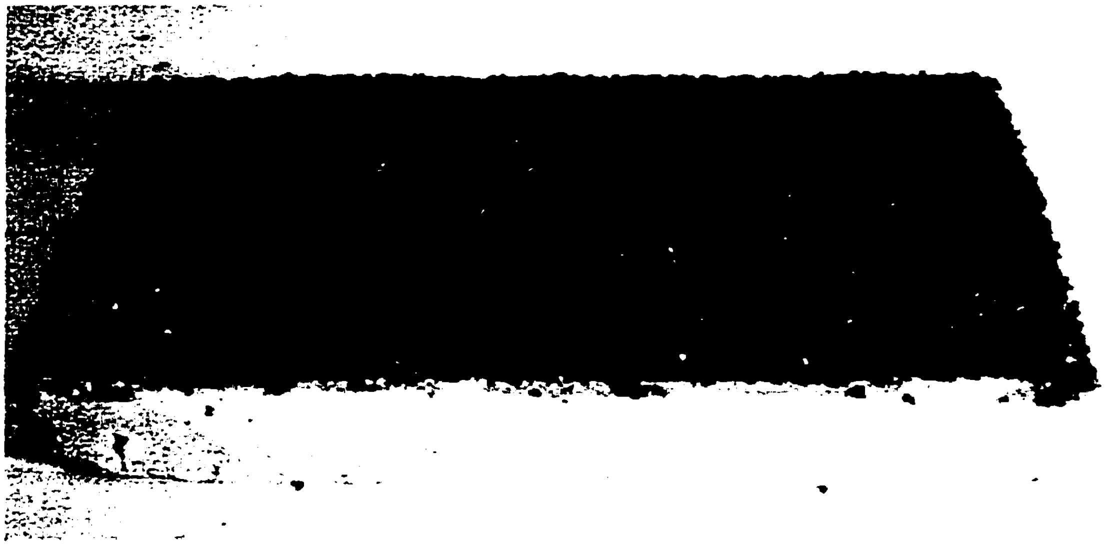


Figure 6.2 Blacking of Overlay due to Temperature Cycling

Cross-sectional views of temperature cycling samples did not show any signs of delamination (figure 6.3). Figure 6.4 shows a typical core taken from a temperature cycling sample for the rapid chloride ion penetration test. The core showed a good bond between the polymer concrete and the Portland cement concrete. Figure 6.5 shows damage experienced by the Portland cement concrete. Note that the aggregates split in half showing the severity of the temperature cycles.



(a) before temperature cycling



(b) after 103 cycles of temperature cycling

Figure 6.3 Cross-sectional view of Temperature Cycling PC samples

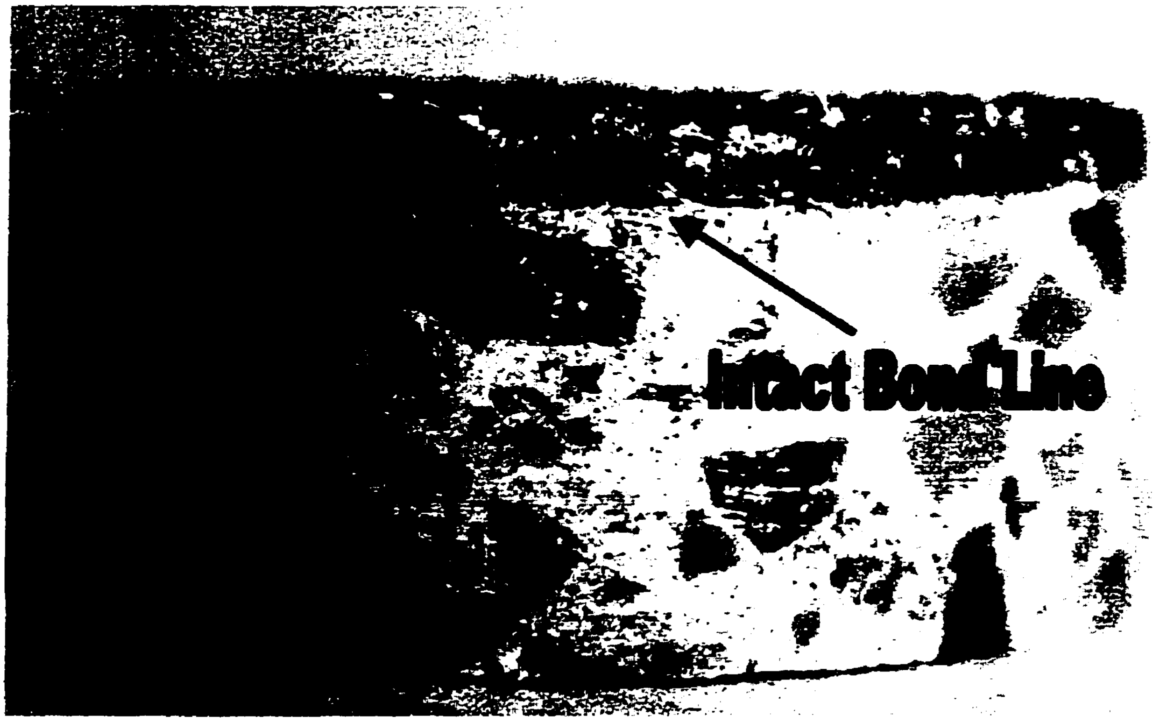


Figure 6.4 Core taken from Temperature Cycling sample

Figure 6.5 Damage to Portland cement concrete after Temperature cycles

Before the ultrasonic pulse velocity readings could be analyzed, a calibration test was conducted to determine the effect of delamination on the pulse velocity. A Portland cement concrete slab (same mix as the samples subjected to temperature cycling) was overlaid with polymer concrete. On one side of the slab the polymer concrete overlay bonded with the Portland cement concrete, while the other side was unbonded (figure 6.6). The unbonded side was possible by placing a plastic sheet on top of the Portland cement concrete. Once the polymer concrete overlay was cured, the plastic sheet was removed so that it would not affect the pulse velocity.

The ultrasonic pulse velocity sensors were placed opposite to each other, one sensor on top of the polymer concrete overlay and the other sensor on top of the Portland cement concrete. The time required for the ultrasonic pulse to travel through the sample was recorded for both the bonded and unbonded sides. This procedure was conducted three times.

The recorded time for the bonded side was approximately 12.3 milliseconds, while the recorded time on the unbonded side was approximately 16.3 milliseconds. Thus, the effect of delamination decreases the pulse velocity, and increases the time by approximately 4 milliseconds.

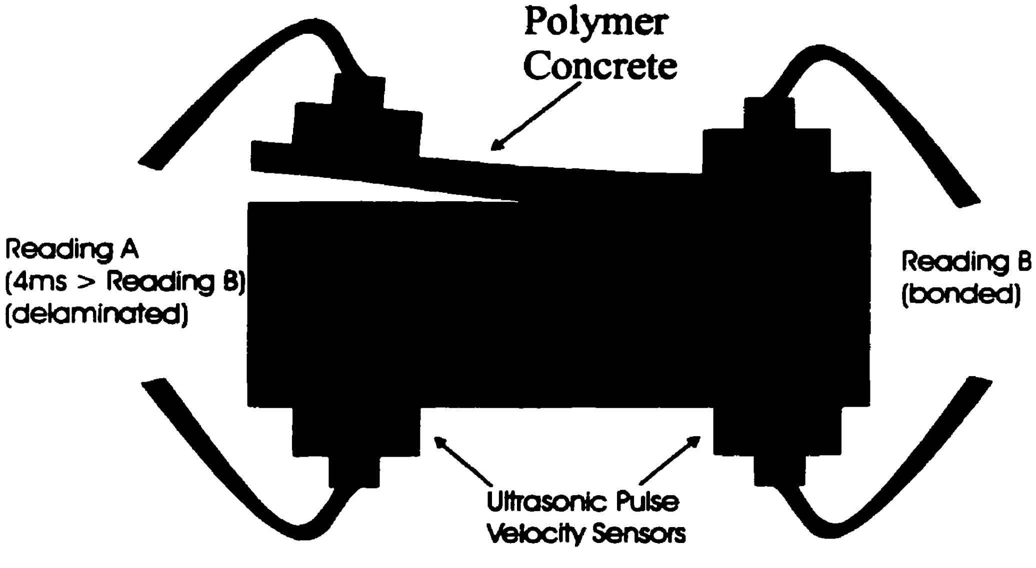


Figure 6.6 Calibration Test for Ultrasonic Pulse Velocity Test

The ultrasonic pulse velocity readings, in milliseconds, for the temperature cycled samples are listed in table 6.4. These readings were taken from the center of the samples. Cycle 0 represents readings taken before the samples underwent temperature cycles. Readings were also taken at the ends of the samples (denoted N and S) and these ultrasonic pulse velocity readings are shown in figure 6.7. A table of all ultrasonic pulse velocity readings can be found in appendix A.

Table 6.4 Ultrasonic Readings (milliseconds) taken at center of PC Samples

Overlay Method	Sample No.	Cycle Number											
One Layer	1	15.0	12.6	12.8	13.1	13.2	13.3	13.4	13.5	13.0	13.2	13.3	15.5
	2	16.9	13.7	14.5	13.6	13.0	12.9	12.9	13.2	13.2	13.2	13.2	15.2
	3	14.1	13.5	13.1	13.6	13.0	12.8	13.0	13.1	13.5	13.4	13.5	15.8
Two Layer	4	15.0	13.2	13.8	13.2	14.5	13.7	13.5	13.4	13.2	13.5	13.4	15.4
	5	13.8	13.4	13.4	13.7	13.5	13.5	13.4	13.5	13.4	13.4	13.5	15.3
	6	16.6	14.3	13.3	13.2	13.6	13.7	13.5	13.6	13.5	13.2	13.3	16.8
3/4 layer plus primer	7	13.6	13.4	13.0	13.5	13.0	13.2	13.4	13.2	13.5	13.5	13.5	15.3
	8	15.5	13.5	13.7	13.8	14.0	13.9	13.9	13.8	13.7	13.5	13.7	14.1
	9	14.7	12.8	13.0	13.6	13.0	13.0	12.9	12.6	13.2	13.3	13.3	13.8
1/2 layer plus primer	10	16.5	15.5	14.0	13.8	14.0	13.8	13.8	13.9	13.7	13.8	13.9	14.0
	11	14.9	15.0	14.5	14.5	13.0	13.2	13.3	13.3	13.7	13.7	13.4	13.7
	12	14.2	13.1	13.5	12.9	12.7	12.8	12.9	13.0	13.2	13.0	13.5	14.3
slurry plus primer	13	17.0	17.3	14.0	14.8	13.5	13.5	13.5	13.6	13.7	13.7	13.7	15.5
	14	17.0	15.2	14.8	14.8	14.2	14.2	14.1	14.2	13.8	13.6	13.4	15.8
	15	14.2	14.6	14.6	13.2	13.2	13.5	13.5	13.5	13.7	13.7	13.7	15.8

The initial decreases in ultrasonic pulse velocity readings, the difference between the zero cycle and the first cycle readings, are most likely attributed to the change of the type of grease used between the sensors and the sample. The recorded readings as shown in table 6.4 and figure 6.7 were constant from cycle 2 until cycle 15. This would indicate that no significant damage in the Portland cement concrete substrate or delamination of the overlay occurred. A small change of approximately 0.3 milliseconds is the result of either a lose of a surface aggregate or a slight misalignment of the sensors. At the end of the temperature cycling test, 103rd cycle, the ultrasonic pulse velocity readings increased for all the samples. The increase was approximately 2½ milliseconds and this would seem to indicate that some damage has occurred in either the substrate or the bond of the overlay.

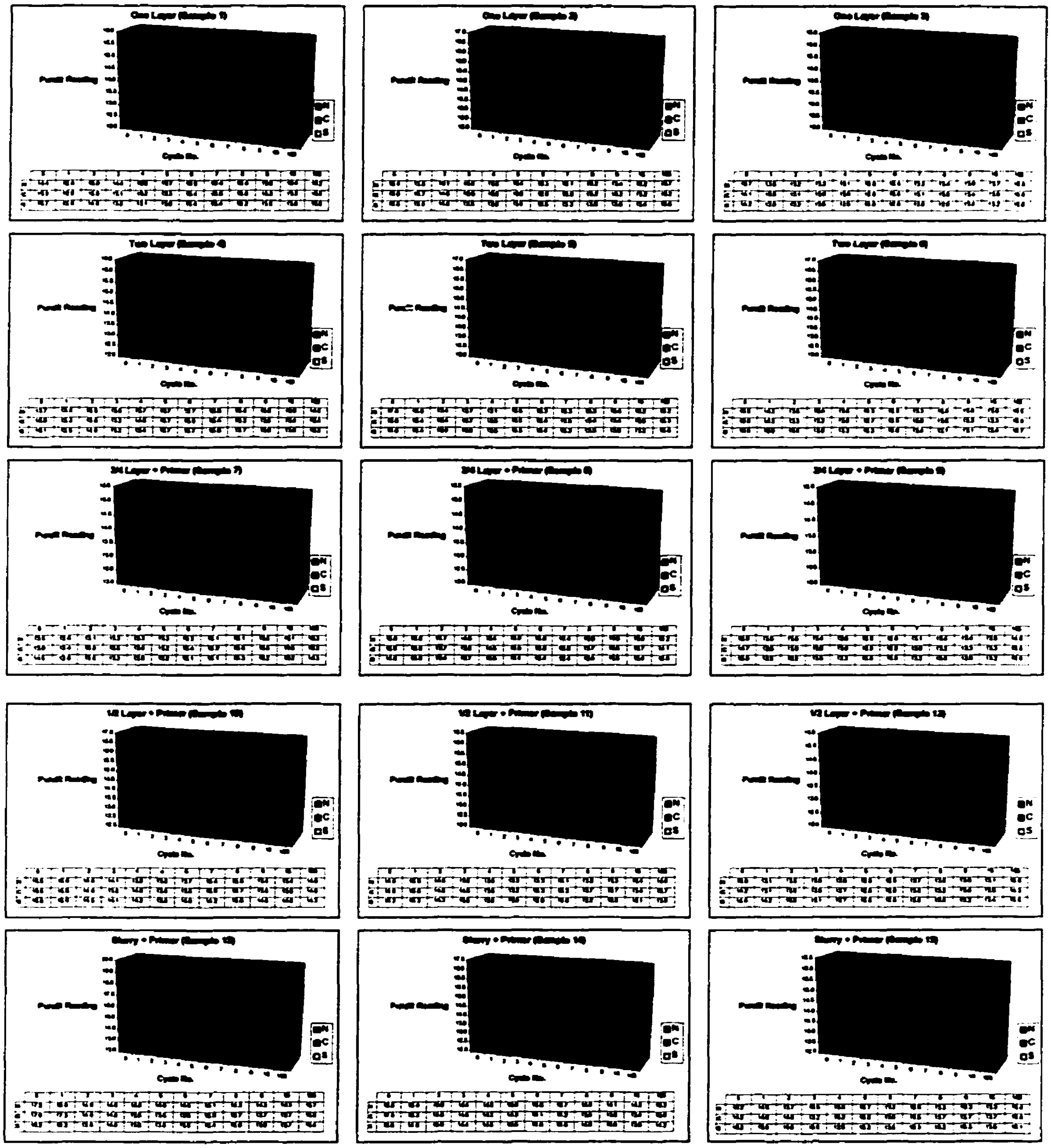


Figure 6.7 Pundit Readings for Temperature Cycling PC Samples

While the ultrasonic pulse velocity readings at the 103rd cycle had indicated either partial delamination or cracking in the Portland cement concrete, the visual evidence does not support the fact that delamination has occurred. Therefore, it is probable that the increase in pulse time was due to micro-cracks in the Portland cement concrete. The rapid chloride ion penetration test conducted on cores from the temperature cycling samples could give more quantitative suggestion of what has happened during the temperature cycles.

6.3 RAPID CHLORIDE PERMEABILITY OF POLYMER CONCRETE

The samples used for the rapid chloride permeability test were cored from the temperature cycled samples, as well as from control samples that did not experience any temperature cycling. The results of the rapid chloride permeability test are listed in table 6.5. The final thickness of all the samples were close to 50mm. If overlaid, the sample had a thinner concrete substrate.

The Portland cement concrete had the highest value of passing coulombs. The results for the Portland cement concrete were in accordance with theory that states that concrete with water-cement ratio of 0.45 should allow pass approximately 2000 to 4000 coulombs [ASTM C1209]. The rapid chloride permeability test showed that the addition of polymer concrete overlays helped reduce the passing coulombs by approximately 7.5 times. That is, the Portland cement concrete on average had 4802 coulombs passing through it, while the polymer concrete (worst case) had 634 coulombs passing through (table 6.5). Besides this, the test proved that the addition of primers to the polymer concrete overlays helped reduce the passing coulombs. The uncycled one layer allowed 100 coulombs to pass while the slurry with primer allowed approximately 39 coulombs to pass, which is 2.6 times less (table 6.5)

The non-cycled polymer concrete overlaid samples had negligible coulombs passing. The samples that experienced temperature cycles had a higher value of coulombs passing, approximately 4 times as much. The increase in chloride ions penetration implies that the temperature cycling caused some damage. The possible damages are micro-cracks in the Portland cement concrete, micro-cracks in the polymer concrete, or delamination along the bond line. To be able to clearly state what the cause was, Portland cement concrete samples should be tested at the same temperature cycling and then undergo rapid chloride permeability testing. If the coulombs passing were higher than the values recorded for the plain Portland cement concrete, then it would mean that the concrete had micro-cracks. If no change were detected, then it would mean that the polymer concrete had suffered some damage. This test was not done through the course of the study.

Regardless of not knowing if the damage was in the overlay or substrate, it seems that the most severe temperature cycling has no noticeable effect on the permeability of polymer concrete overlays. The polymer concrete overlays, cycled or non-cycled, are highly beneficial in terms of decreasing chloride ion permeability.

Table 6.5 Polymer Concrete Resistance to Chloride Ions

Method	Sample No.	Temp. Cycled	Thickness (mm)	Coulombs Passing
Portland cement concrete	1	No	50	3716
	2	No	50	5888
Two Layer	3	Yes	6.9 PC + 43.1 PCC	216
	4	Yes	7 PC + 43 PCC	634
	5	No	6.2 PC + 43.8 PCC	100
	6	No	6.8 PC + 43.2 PCC	100
One Layer	7	Yes	6.4 PC + 43.6 PCC	176
	8	Yes	7.1 PC + 42.9 PCC	59
	9	No	6.5 PC + 43.5 PCC	164
	10	No	6.2 PC + 43.8 PCC	133
1/2 Layer +Primer	11	Yes	3.3 PC + 46.7 PCC	532
	12	Yes	3.6 PC + 46.4 PCC	47
	13	No	3.8 PC + 46.2 PCC	126
	14	No	3.8 PC + 46.2 PCC	36
Slurry + Primer	15	Yes	6.6 PC + 43.4 PCC	220
	16	Yes	6.2 PC + 43.8 PCC	159
	17	No	6.4 PC + 43.6 PCC	28
	18	No	6.5 PC + 43.5 PCC	39
3/4 Layer + Primer	19	Yes	5.3 PC + 44.7 PCC	179
	20	Yes	5.4 PC + 44.6 PCC	207
	21	No	5.1 PC + 44.9 PCC	25
	22	No	5.3 PC + 44.7 PCC	27

PC = Polymer concrete PCC=Portland cement concrete

6.4 WATER ABSORPTION OF POLYMER CONCRETE

The results for the water absorption test for PC overlay by the different application methods are summarized in figure 6.8. From the figure, it is observed that the ½ layer plus primer overlay has the highest percent absorption, approximately 4.25-4.75%. As the thinnest overlay, the ½ layer without the primer has the lowest percent absorption, approximately 2.25-2.75%. It seems that the primed overlays are likely to attract more water relative to their self-weight. This phenomenon is also seen with the slurry and the slurry plus primer overlays, with respective absorption of approximately 2.7% and 3.2%.

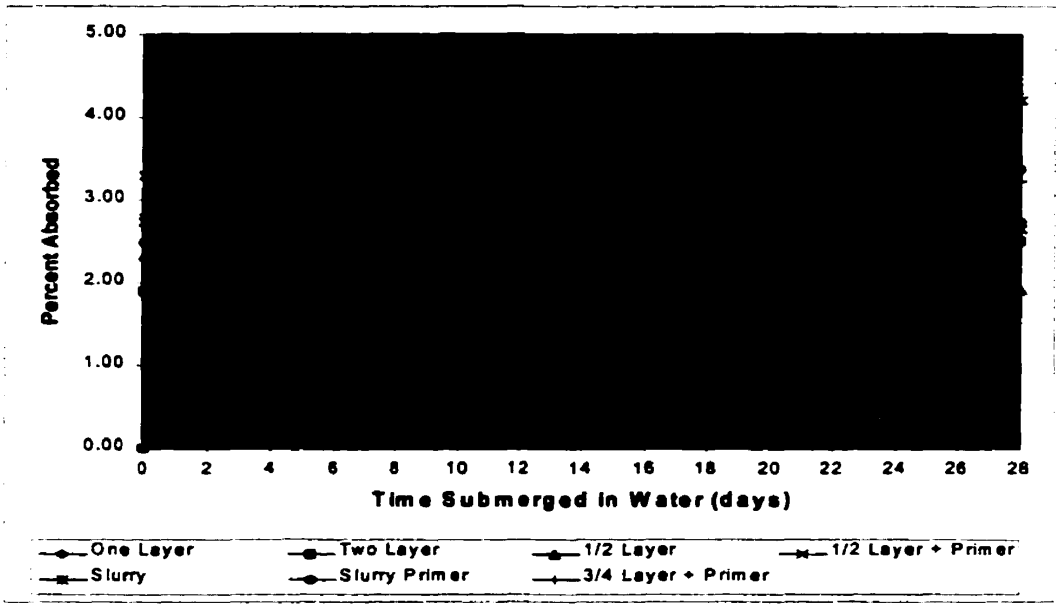


Figure 6.8 Water Absorption of Polymer Concrete

It is interesting to note that the majority of the absorption occurs at the beginning of the test during a period of 1½ hours. The slight increase seen afterwards is due to smaller cavities that eventually fill up. The fluctuations in the percentage of absorption for any given method can be explained as the loss of aggregate particles, as well as the water loss during the surface drying process. Again, the two-layer overlay performed the best with a percent absorption close to ½ layer with no primer overlay. However, the thickness of the former was more than doubled than that of the latter. The next overlay that performed well in terms of water absorption was the one layer overlay followed by the slurry without primer overlay, slurry plus primer overlay, ¾ layer with primer overlay, and ½ layer with primer overlay.

6.5 STRENGTH LOSS OF POLYMER CONCRETE DUE TO ABSORPTION

As mentioned in section 5.3.4, the polymer concrete samples used in the water absorption test were also used in the 3-point flexural strength test. The resulting 3-point flexural strengths for samples that were water submerged for 7 and 28 days, as well as samples that were kept dry as control, are shown in figure 6.9 and listed in table 6.6. These values are the average of 152 samples. Appendix B contains all the stress versus deflection graphs of all the samples tested. The width and length of the samples was 75mm and 150mm respectively. The span between the supports (rollers) was 100mm.

The test results have clearly shown that flexural resistance of polymer concrete decreases with the increase of the time submerged in water. Of the seven different methods of application tested, the ½ layer without primer showed the greatest decrease in flexural capacity (56% decrease) after seven days of submersion. The least affected after seven days was the slurry with primer overlay (18% decrease).

The situation changed after 28 days of water submersion. The flexural resistance of the ½ layer without primer was unchanged (0% decrease) while the slurry with primer had the largest decrease (an additional 23% decrease). An explanation for this phenomena is that the ½ layer overlay is considerably thinner than the slurry primer, therefore taking less time for the water to affect the polymer concrete and giving a higher initial decrease for the ½ layer. The percentage decreases for the other application methods are listed in table 6.6.

Table 6.6 Flexural strength of polymer concrete with days submerged in water

Overlay Method	Ave. Stress (MPa)			% Reduction after	
	Dry	7 Days	28 Days	7 Days	28 Days
One Layer	14.2	9	8.6	37%	39%
Two Layer	15.6	9.8	8.5	37%	46%
1/2 Layer	14.3	6.3	6.5	56%	55%
1/2 Layer + Primer	15.7	10	8.6	36%	45%
Slurry	13.5	8.1	6.3	40%	53%
Slurry + Primer	15.8	12.9	9.4	18%	41%
3/4 Layer + Primer	21.4	15.4	13.4	28%	37%

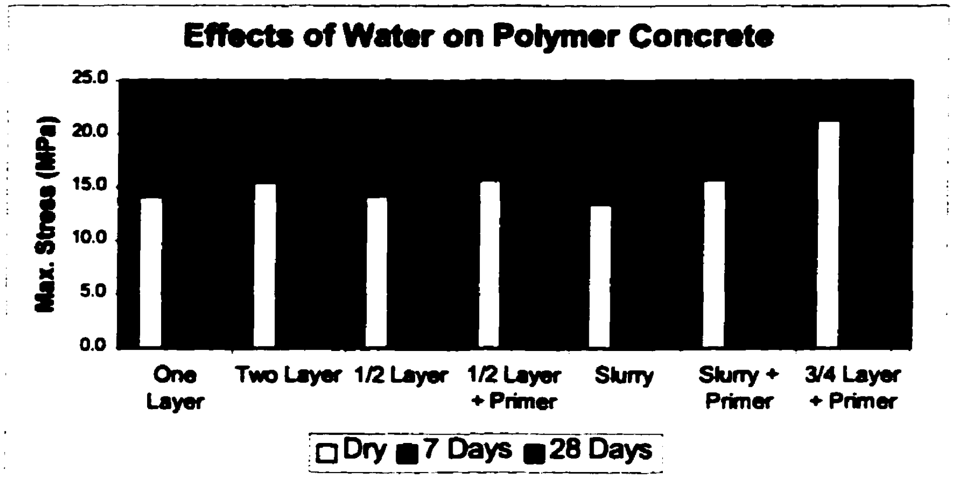


Figure 6.9 Decrease in flexural strength with time

The test also revealed that the addition of a primer increased the flexural strength of the polymer concrete overlay. Furthermore, the primer helped decrease the change in flexural resistance as seen after 7 and 28 days of water submersion. That is, the ½ layer with primer overlay has shown less reduction than the ½ layer without primer overlay. At 28 days, the former had a strength decrease of 45% while the latter displayed a strength decrease of 55%. The same phenomenon was also observed in overlays of slurry with primer and of slurry without primer. The overall decrease at 28 days was 41% and 53% respectively.

Besides affecting the load-carrying capacity, water submersion also altered the deflection behavior of the polymer concrete (figure 6.10 and table 6.7). The recorded deflection at maximum flexural strength in general increased with the number of days of submersion. The slurry overlay had the greatest increase (5.8mm) while the ½ layer with primer overlay had the smallest (3.8mm).

Table 6.7 Deflection at maximum flexural stress

Overlay Method	Ave. Deflection (mm) at max. Stress		
	Dry	7 days	28 days
One Layer	5.2	6.0	9.6
Two Layer	4.3	5.6	10.0
1/2 Layer	5.7	8.8	11.2
1/2 Layer + Primer	7.8	10.0	11.6
Slurry	2.6	5.8	8.4
Slurry + Primer	5.0	6.8	9.8
3/4 Layer + Primer	8.2	8.9	13.8

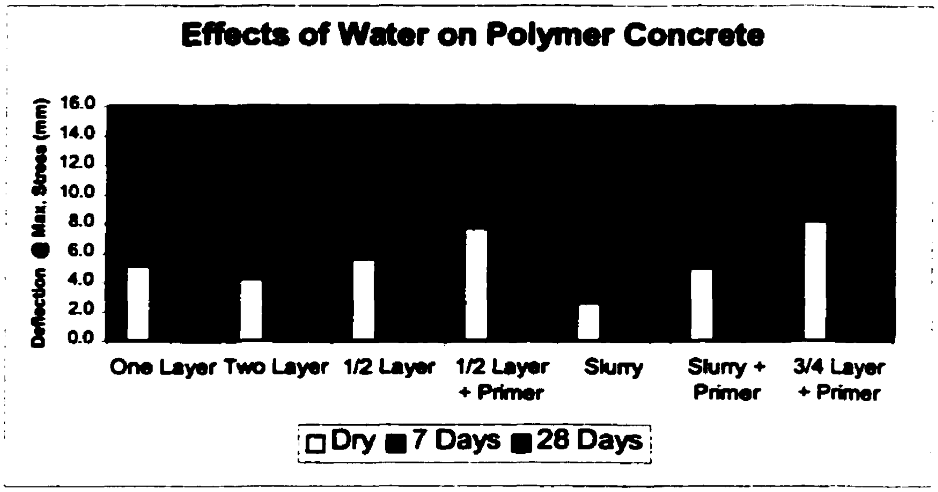


Figure 6.10 Increase of deflection at maximum flexural strength

The addition of the primer to the ½ layer and slurry overlays resulted in less deflection after 28 days of water submersion. That is, the ½ layer and ½ layer with primer overlays had an increase in deflection of 5.5mm and 3.8mm respectively, and the slurry and slurry with primer overlays had an increase in deflection of 5.8mm and 4.8mm respectively. The primer maintained the stiffness of the overlays. It is apparent that as maximum flexural capacity decreases the maximum deflection increases (figure 6.11). In other words, the continuous submersion in water will make polymer concrete less strong, but more ductile.

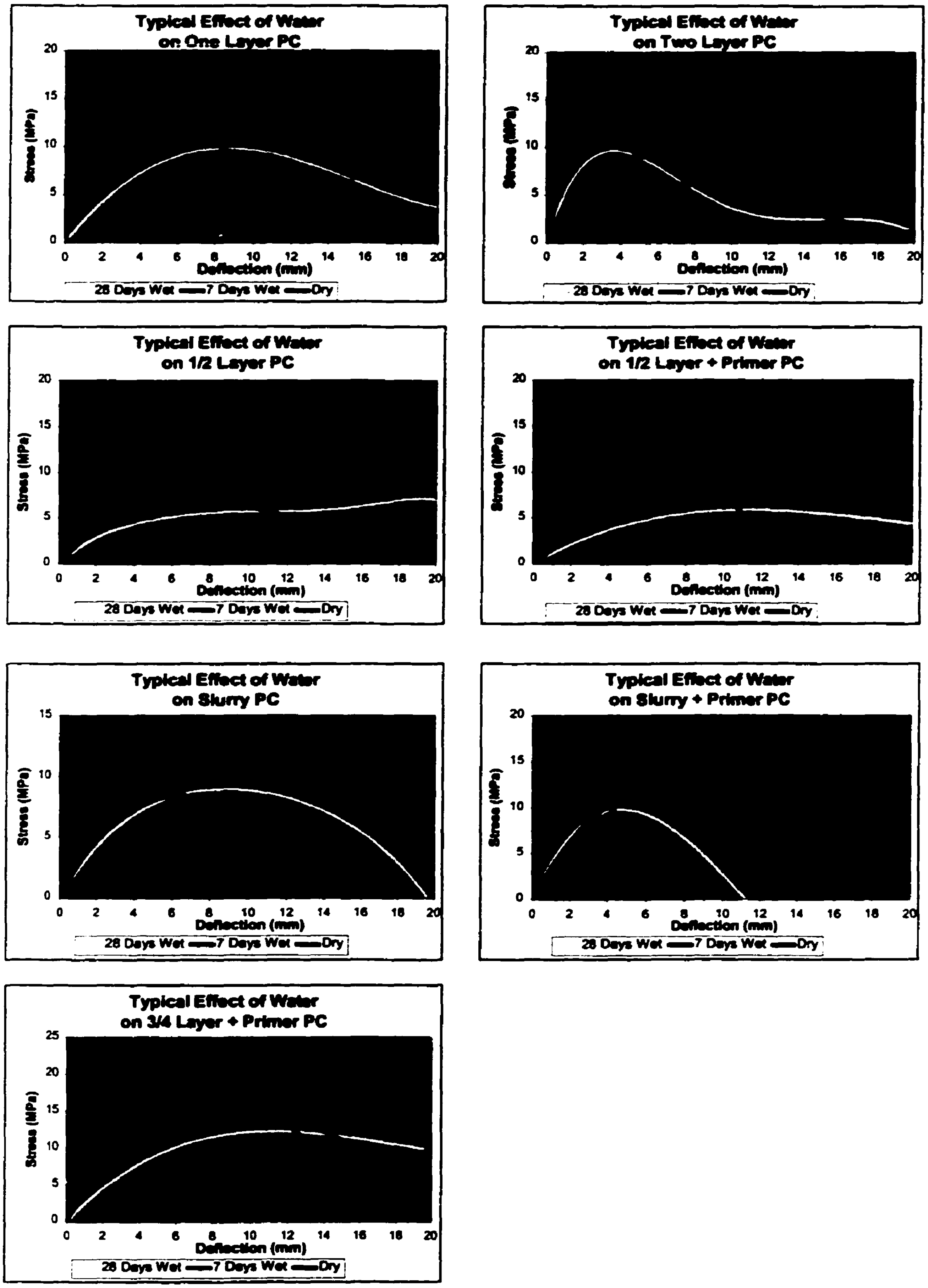


Figure 6.11 Typical Flexural Strength Curves

6.6 EFFECTS OF WATER VAPOR PRESSURE

The five polymer concrete overlay samples were placed continuously under the heat lamps for a duration of two weeks. During the time the temperatures of the Portland cement concrete substrate and the interface were recorded. The initial temperature readings were equal to room temperature, however, the temperatures changed quickly once placed under the lamps. After two weeks the surface temperature of the samples were approximately 90°C, the temperature of the water in the containers was approximately 48°C, and the Portland cement concrete slabs was approximately 53.0 ± 3.1°C. Furthermore, after two weeks the temperature at the interface was approximately 48-73°C (table 6.8). The interface temperature was the highest for the thermocouple closer to the center of the slab (where the lamp was focused).

The significance of these temperatures is that water vapor pressure was possibly generated from the water-saturated Portland cement concrete. From thermodynamics, for a system that is fully saturated at a temperature of 50°C the water vapor pressure generated is 11.7kPa (1.6927psi) [Haberam et al. 1989]. The system was closed, therefore, the water vapor pressure was forced to go through the polymer concrete overlay. The vapor pressure seems small enough that no debonding should occur. To ensure that the bond was not affected, ultrasonic pulse velocity tests were taken at the beginning and at the end of the experiment. The ultrasonic test does not indicate delamination or any generation of cracks (table 6.9). In addition, the sonic testing (tapping with a hammer) and visual inspection did not reveal any failure in the samples either.

To further ensure that the high temperature had not affected the bond and/or polymer binder, pullout tests were conducted on the center part of the samples. The results were compared to pull out tests conducted on polymer concrete samples that were not under the heat lamps. When subjected to a purely tensile force, the Portland cement concrete failed in all cases. The tensile failure stresses are listed in table 6.10. Since, the bond strength is higher than 3.8 MPa, the 11.7kPa water vapor pressure will not cause delamination.

The typical pullout response can be seen in figures 6.12 and 6.13. It seemed that the bond and polymer binder were unaffected by the water vapor pressure as well as the high temperature. A closer look at the cores revealed that the bond between the polymer concrete and substrate to be in good condition.

Table 6.8 Internal Temperatures Recorded during Water Vapor Pressure Test

			Temperature (°C)		
Overlay Method	Channel	Location	Initial	After 1 week	After 2 weeks
One Layer	1	inner	21.7	54.3	62.8
	2	outer	21.5	48.7	48.6
	3	inner	21.6	71.4	64.9
	4	outer	21.6	46.7	49.4
	5	concrete	21.4	45.4	48.4
Two Layer	6	inner	21.5	65.1	66.8
	7	outer	21.7	48.6	49.1
	8	inner	21.6	63.7	65.1
	9	outer	21.6	48.6	50.9
	10	concrete	21.4	54.9	56.4
Slurry Primer	11	inner	21.7	60.8	67.7
	12	outer	21.7	45.8	48.5
	13	inner	21.5	66.8	67.1
	14	outer	21.3	53.3	52.3
	15	concrete	21.6	51.6	52.3
1/2 Layer Primer	16	inner	21.3	54.9	59.0
	17	outer	21.4	49.7	50.9
	18	inner	21.2	85.0	82.6
	19	outer	21.7	48.3	49.4
	20	concrete	21.4	53.8	55.4
3/4 Layer Primer	21	inner	21.3	54.0	56.4
	22	outer	21.4	45.2	46.8
	23	inner	21.7	70.9	73.1
	24	concrete	21.5	48.1	52.3

Table 6.9 Ultrasonic Readings taken for Water Vapor Pressure Samples

Overlay Method	Location	Ultrasonic Reading Initial	Final
One Layer	1	21.2	21.3
	2	21.7	21.7
	3	21.8	21.8
	4	21.2	21.3
	5	20.6	20.7
	6	21.1	21.1
	7	20.9	20.8
	8	20.8	20.7
	9	21.0	21.1
Two Layer	1	21.3	21.3
	2	21.5	21.6
	3	21.8	21.6
	4	21	21.3
	5	21.5	21.5
	6	21.3	21.5
	7	21	21.1
	8	21.2	21.7
	9	20.9	20.6
Slurry Primer	1	22	22.3
	2	21.8	21.8
	3	21.9	21.7
	4	21.9	21.7
	5	21.8	21.9
	6	22.1	22
	7	22	22.2
	8	22	22.1
	9	21.9	21.9
1/2 Layer Primer	1	19.5	19.5
	2	19.6	19.5
	3	19.9	19.8
	4	19.7	19.9
	5	20.1	19.8
	6	19.8	19.9
	7	19.7	19.6
	8	19.8	19.9
	9	20	20.1
3/4 Layer Primer	1	20.2	20.2
	2	20.1	20.4
	3	20.4	20.3
	4	20.1	20
	5	19.9	19.6
	6	20	20.4
	7	20.3	20.1
	8	20.5	20.5
	9	20.3	20.3

Table 6.10 Results of Pullout Tests

Overlay Method	Type of Sample	Failure in (PC/PCC)	Average Max. Tensile Stress (MPa)
One Layer	control	PCC	3.53
	WVP	PCC	3.60
Two Layer	control	PCC	3.40
	WVP	PCC	3.69
1/2 Layer + Primer	control	PCC	3.54
	WVP	PCC	3.60
Slurry + Primer	control	PCC	3.73
	WVP	PCC	3.54
3/4 Layer + Primer	control	PCC	3.72
	WVP	PCC	3.82

WVP = water vapor pressure PC = polymer concrete
PCC= Portland cement concrete

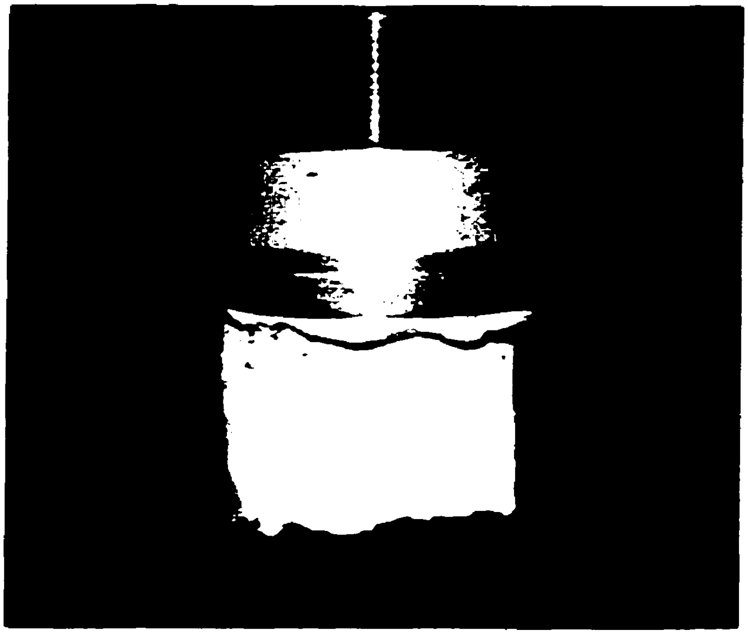


Figure 6.12 Failure of the Portland cement concrete under tensile loading

Figure 6.13 Complete Removal of Core under tensile loading

Chapter 7

Analysis and Discussion

7.1 EFFECT OF A PRIMER

The current construction practice for polymer concrete overlays is to use the primer to augment the bond strength between the overlay and the substrate. However, the experimental program conducted has shown that the addition of a primer to an overlay system provides additional benefits.

From the water permeability tests, the addition of a thin layer of primer to the ½ layer, ¾ layer, and slurry overlays decreased the coefficient of permeability by approximately 4-5 orders of magnitude. With the lower coefficient of permeability, the percent water retention of the overlay increased as shown by the water absorption tests. High water absorption is undesirable in areas where the temperature may quickly drop to zero, causing the water to freeze, expand and increase the internal pressure. However, without the primer the newly proposed ½ layer and ¾ layer application methods would be as permeable as the asphalt overlay system, and therefore their use would only be justified when lightweight overlay was the concern.

Besides improving impermeability, the addition of the thin layer of primer increases the flexural strength of the polymer concrete overlay. Before being submerged in water, the flexural strength of the ½ layer, ¾ layer, and slurry overlays increased by 10% with the addition of the primer. After being submerged in water, the flexural strength of the ½ layer, ¾ layer, and slurry overlays were 35% higher with the addition of a primer versus without a primer. This would seem to indicate that the epoxy primer was unaffected, and that the loss in flexural capacity was in the polymer concrete.

In addition to the flexural capacity, the thin epoxy primer affected the flexibility of the polymer concrete overlay. Comparing the deflection of the ½ layer, slurry, and ¾ layer overlays with and without a primer showed that the primer made the overlay less ductile. Even comparing the overlays with and without a primer after being submerged in water showed that the overlays with primers were stiffer than the overlays without a primer.

Apart from altering bending properties, the use of a primer did not affect the performance of the overlays subjected to temperature cycling and water vapor pressure. On the contrary, after 103 temperature cycles the overlays with a primer allowed less coulombs to pass then the overlays without a primer. This means that the overlays with a primer are less permeable to chloride ions than the overlays without a primer.

Thus, from the experimental program the addition of a thin layer of epoxy primer would seem to generally enhance the performance of the polymer concrete overlays. Without the primer, some of the newly proposed application methods would be ineffective.

7.2 EFFECT OF TEMPERATURE

The difference in coefficients of thermal expansion between polymer concrete and Portland cement concrete is well documented. With overlay temperatures fluctuating between -50°C and 90^{0}C, and substrate temperatures fluctuating between -50°C and 50^{0}C, the potential for delamination becomes quite high. This is reflected in several overlay failures, which are being categorized as thermal induced failures.

To define and understand the internal thermal stresses produced from temperature changes, basic solid mechanics principles are used. Two scenarios are possible: (1) uniform temperature change in both the overlay and substrate, and (2) a higher temperature change in one of the two materials. Using Equations 4.2 and 4.4, the information in table 7.1, tables 7.2 and 7.3 were generated to show the thermal stresses induced in the overlay and substrate. The change in temperature is relative to room temperature (27°C). The coefficient of thermal expansion and modulus of elasticity for epoxy polymer concrete were taken from the ACI Committee 548 report. [ACI Committee 548, 1993]

Table 7.1 Properties used for Thermal Calculations

	Modulus Of Elasticity (GPa)	Thermal Coeff. (1/°C)	Thickness (mm)
Cement Concrete	26.4	1.00E-05	50
Polymer Concrete	0.8	9.00E-05	variable

Table 7.2 Stresses due to Uniform Temperature Change

PC Thickness (mm)	Stress pcc (MPa)	Stress pc (MPa)
4	-0.37	4.60
5	-0.46	4.59
6	-0.55	4.59
7	-0.64	4.59
8	-0.73	4.59
9	-0.82	4.58
10	-0.92	4.58
11	-1.01	4.58
12	-1.10	4.57
13	-1.19	4.57
14	-1.28	4.57
15	-1.37	4.57
20	-1.82	4.55
25	-2.27	4.54
30	-2.72	4.53
35	-3.16	4.51
40	-3.60	4.50

$\Delta T_{pcc} = \Delta T_{pc} = -72°C$

PC Thickness (mm)	Stress pcc (MPa)	Stress pc (MPa)
4	0.09	-1.15
5	0.11	-1.15
6	0.14	-1.15
7	0.16	-1.15
8	0.18	-1.15
9	0.21	-1.15
10	0.23	-1.15
11	0.25	-1.14
12	0.27	-1.14
13	0.30	-1.14
14	0.32	-1.14
15	0.34	-1.14
20	0.46	-1.14
25	0.57	-1.13
30	0.68	-1.13
35	0.79	-1.13
40	0.90	-1.12

$\Delta T_{pcc} = \Delta T_{pc} = 18°C$

Table 7.3 Stresses due to Uneven Temperature Change

PC Thickness (mm)	Stress pcc (MPa)	Stress pc (MPa)
4	0.29	-3.62
5	0.36	-3.62
6	0.43	-3.62
7	0.51	-3.62
8	0.58	-3.61
9	0.65	-3.61
10	0.72	-3.61
11	0.79	-3.61
12	0.87	-3.61
13	0.94	-3.60
14	1.01	-3.60
15	1.08	-3.60
20	1.44	-3.59
25	1.79	-3.58
30	2.14	-3.57
35	2.49	-3.56
40	2.84	-3.55

$\Delta T_{pcc} = 23°C$ $\Delta T_{pc} = 53°C$

PC Thickness (mm)	Stress pcc (MPa)	Stress pc (MPa)
4	-0.33	4.12
5	-0.33	3.29
6	-0.33	2.74
7	-0.33	2.35
8	-0.33	2.05
9	-0.33	1.82
10	-0.33	1.64
11	-0.33	1.49
12	-0.33	1.37
13	-0.33	1.26
14	-0.33	1.17
15	-0.33	1.09
20	-0.33	0.82
25	-0.33	0.65
30	-0.32	0.54
35	-0.32	0.46
40	-0.32	0.40

$\Delta T_{pcc} = 0°C$ $\Delta T_{pc} = 63°C$

The stress values in tables 7.2 and 7.3 would indicate that a temperature decrease results in the development of a tensile stress in the Portland cement concrete and a compressive stress in the polymer concrete. The reverse is true for a temperature increase. Furthermore, it would seem that the thickness of the polymer concrete overlay affects the development of thermal stress, i.e. thicker polymer concrete overlays produce higher thermal induced stresses in the substrate.

For failure to occur, either the stresses in the substrate or overlay must be higher than the stress limits. The Portland cement concrete has a compressive stresses of 30 MPa and a tensile stresses about 3 MPa, and the epoxy polymer concrete is capable of withstanding a tensile stresses of 8.6 MPa and a compressive stresses of 48 MPa (table 5.1). Thus, from the theoretical values epoxy polymer concrete overlays thicker than 30mm would cause cracking in the substrate. Since the overlays constructed are normally 8-12mm thick, the development of thermal stresses should not affect the performance of the overlays. However, special attention must be given to the properties of the particular epoxy resin.

7.3 EFFECT OF THICKNESS

The thickness of the polymer concrete overlay seems to affect numerous properties: resistance to temperature cycling, water permeability, chloride ion permeability, water absorption, maximum flexural strength and ductility. The thickness of the polymer concrete overlay is a function of the amount of polymer resin and aggregate used. The average thickness for the experimental program for each application method is listed in table 7.4.

Table 7.4 Average Thickness of Polymer Concrete Overlays

Method	Total Polymer (including primer) (L/m^2)	Total Aggregate (kg/m^2)	Thickness (mm)
One Layer	2.7	12.7	6.6
Two Layer	2.7	12.7	6.7
1/2 Layer + Primer	1.9	11.8	3.6
3/4 Layer + Primer	2.5	12.7	5.3
Slurry + Primer	2.9	17.4	6.4

The effect of the overlay thickness was seen in the ultrasonic pulse velocity readings taken during the temperature cycling test. The average increase in ultrasonic pulse velocity readings after 103 temperature cycles for the one layer, two-layer, ½ layer plus primer, ¾ layer plus primer and slurry plus primer overlays are 2.2, 2.4, 0.4, 0.9 and 2.1 milliseconds respectively. Therefore, the thickest application method had the greatest reading increase while the thinnest application method had the smallest reading increase. The increase in ultrasonic pulse velocity readings results concurs with theory: thicker overlays produce higher stresses and most like more damage in the substrate. Even though the thermal stresses are lower than the material limits, fatigue stresses will ultimately caused internal damage.

Aside from thermal stresses, the thickness of the overlay should normally affect the water permeability of a material. In the case of polymer concrete, the minimum achievable coefficient of permeability is directly related to the thickness as shown in table 7.5. However, this relationship does not hold true when the average coefficient of permeability is considered. The logical reason is that the thickness is affected by the quantities of materials used, while the water permeability is affected by the way the overlay is constructed. The randomness of how the aggregates interlock with one another dictates whether an application method is more or less permeable. The primer simply reduces the permeability of a given overlay, but does not make an overlay more resistant to permeation than the two-layer and one-layer overlays.

Table 7.5 Overlay Thickness and Coefficient of Permeability

Method	Thickness (mm)	Min. Permability (10^{-12} m/s)	Average Permability (10^{-12} m/s)
Two Layer	6.7	5.24	24.3
One Layer	6.6	6.5	11.4
Slurry + Primer	6.4	6.58	254.7
3/4 Layer + Primer	5.3	9.07	905
1/2 Layer + Primer	3.6	9.78	17.19

With regards to chloride ion permeability, the same trend as the water permeability should be seen. That is, it should be the application method and not the thickness of the overlay that affects the chloride ion permeability. In case of rapid chloride ion permeability testing, the non-cycled overlays with a primer were more impermeable than the non-cycled two-layer and one-layer overlays as seen in table 7.6. This may be because the test is accelerated and forces the ions through even micro-cracks through which water could not ingress.

Comparing just the overlays with primers, slurry with primer (thickest of the three primed overlays) in general had the lowest coulombs passing while ½ layer with primer (thinnest of the primed overlays) in general had the highest passing coulombs (table 7.6). This would suggest that thickness dictate chloride ion permeability.

Table 7.6 Overlay Thickness and Chloride Permeability

Method	Thickness (mm)	Ave. Coulombs Passing	
		uncycled	cycled
Two Layer	6.7	100	425
One Layer	6.6	149	118
Slurry + Primer	6.4	33.5	190
3/4 Layer + Primer	5.3	26	193
1/2 Layer + Primer	3.6	81	290

In terms of water absorption, the thickness of the polymer concrete should be inversely related to the percentage of absorbed. The overlays absorb water through the surfaces (top and sides) and the rate of absorption is proportional to the surface area (i.e. more surface area, more water absorption). Since the percent absorption is relative to the weight of the overlay, and since increasing the thickness will not increase the volume and surface area equally, the thicker overlay weights more but has almost the same absorption rate.

For example: a cube that is 1mm long, 1mm thick, and 1mm wide has a volume of 1mm^3 and a surface area of 6mm^2. If the thickness is increased to 2mm, the new volume is 2mm^3 and the new surface area is 10mm^2. Thus, given that the density is the same the weight of the cube has doubled while the surface area has increased 1.67 times.

In the case of the water absorption test, the length and width of the samples were 150mm and 75mm respectively. From table 7.7, the two-layer overlay is thicker and heavier than the ½ layer plus primer overlay, however, the surface area is almost the same. Therefore, these two overlays will absorb the same quantity (ml) of water but the percent absorption (weight of water divided by weight of overlay) will be less for the two-layer method.

Table 7.8 shows the experimental results obtained from the water absorption tests. These results prove that the percentage absorption and thickness are inversely proportional, and that the material is does not become 100% saturated with water.

Table 7.7 Thickness and Volume, Surface Area Increase

Method	Thickness (mm)	Volume (mm^3)	Relative Volume Increase	Surface Area (mm^2)	Relative Surf. Area Increase
Two Layer	6.7	75375	1.86	25515	1.06
One Layer	6.6	74250	1.83	25470	1.06
Slurry + Primer	6.4	72000	1.78	25380	1.05
3/4 Layer + Primer	5.3	59625	1.47	24885	1.03
1/2 Layer + Primer	3.6	40500	1	24120	1

Table 7.8 Overlay Thickness and Water Absorption

Method	Thickness (mm)	Water Absorption (%)
Two Layer	6.7	2.5
One Layer	6.6	2.75
Slurry + Primer	6.4	3.1
3/4 Layer + Primer	5.3	3.1
1/2 Layer + Primer	3.6	4.1

In terms of flexural capacity and ductility, from the results obtained it would seem that the relationship between the thickness of the overlay (ignoring overlays with primer) and flexural capacity to be directly proportional, while it is inversely proportional to ductility. That is, as the thickness increases the flexural strength increases and the ductility decreases.

7.4 OVERALL RANKING OF APPLICATION METHODS

The ranking of the application methods was based on the performance in terms of highest flexural strength, most ductile, smallest coefficient of water permeability, smallest thermal stresses, and smallest passing coulombs. Since all the polymer concrete overlays that were subjected to water vapor pressure test performed well, this test was not considered in the ranking of the application methods. The results of application method ranking (1=best performing, 8=leastest performing) are listed in table 7.9.

Table 7.9 Overall Ranking of Application Methods

Method	Flexural Strength			Ductility		
	Dry	7 Days	28 Days	Dry	7 Days	28 Days
One Layer	6	5	4	4	5	6
Two Layer	4	4	5	6	7	4
1/2 Layer	5	7	7	3	3	3
1/2 Layer + Primer	3	3	3	2	1	2
Slurry	7	6	6	7	6	7
Slurry + Primer	2	2	2	5	4	5
3/4 Layer	-	-	-	-	-	-
3/4 Layer + Primer	1	1	1	1	2	1

Method	Water Perm.	Temp. Cycling	Chloride Ion		Water Absorp.
			Uncycled	Cycled	
One Layer	1	4	5	1	2
Two Layer	3	5	4	5	1
1/2 Layer	7	-	-	-	-
1/2 Layer + Primer	2	1	3	4	5
Slurry	8	-	-	-	-
Slurry + Primer	4	3	2	2	3
3/4 Layer	6	-	-	-	-
3/4 Layer + Primer	5	2	1	3	4

Of different criteria tested, a greater importance should be given to the coefficient of permeability, the thermal stresses developed and the rapid chloride ion permeability value. The reason is that these parameters determine the effectiveness of the overlay system in protecting the substrate from corrosive ions. However, this does not imply that the other parameters can be ignored, on the contrary, they are important in terms of durability of the overlay.

Since a high ranking is desirable for each parameter to ensure a durable and protective overlay, and since the exact importance (weight factor) of each parameter is highly subjective, it is difficult to calculate an overall ranking of the overlays. Despite this, in general terms the newly proposed methods (one layer, ½ layer plus primer, and ¾ layer with primer) performed as well as the current methods (two layer and slurry primer). This seems to indicate that it is possible to construct a polymer concrete overlay in a shorter time and that uses fewer materials.

7.5 RECOMMENDATIONS FOR FUTURE WORK

Based on the results obtained form the experimental program, the following recommendations for future work are proposed:

- To perform the same temperature cycling on plain Portland cement concrete,
- To perform rapid chloride ion permeability tests on temperature cycled Portland cement concrete,
- To perform water permeability tests on samples made of polymer concrete overlay and Portland cement concrete substrate,
- To perform field test of the one-layer, two-layer, ½ layer with primer, ¾ layer with primer, and slurry with primer overlays,
- To perform abrasion and skid resistance tests on the different application methods,

The temperature cycling test, complemented by the rapid chloride ion permeability test, on plain Portland cement concrete will determine if the increase in ultrasonic pulse velocity readings was due to damage in the Portland cement concrete or in the bond. Furthermore, the tests will determine whether the damage was induced or not by the polymer concrete. If the plain concrete shows similar signs of damage, then the polymer concrete did not cause the damage. If the plain concrete does not show signs of damage, then the damage recorded in earlier was induced by the addition of the polymer concrete.

The water permeability test on samples comprising of both materials will give a more realistic idea of the potential of corrosion. The randomness of how the aggregates interlock, as well as the randomness of how the holes in the polymer concrete line up with the holes in the substrate, will affect the permeability of water saturated with chloride ions. Knowing the combined coefficient of permeability will give the true protection of the overlay system.

Field testing of the overlay application methods will combine all factors together: traffic load cycling, temperature cycling, generation of water vapor pressure, carbonation, deicing salts, abrasion, and impact loading.

Chapter 8

Conclusions

The following conclusions were drawn from the results of the experimental program on the epoxy polymer concrete overlay:

1) That all the overlay types tested have a coefficient of permeability smaller than asphalt, and equivalent or better than uncracked concrete. Of the different application methods, the two and one layer methods had the smallest coefficient values. It was found that a primer makes polymer concrete overlays less permeable, and that thin layers are more permeable than thick layers.

2) Primer plays a critical role in slurry overlay, ½ layer overlay, and ¾ layer overlay. Without the primer, the corresponding overlays can have a permeability 4-5 orders of magnitude higher. Primer provides an excellent seal that is not easily disturbed or damaged by the broadcasting of aggregate. However, to apply the primer additional time is required which might prolong the entire construction project. The first layer epoxy used in the two layer method and the one layer (same amount of material as two layer but placed in one step) method actually functions similarly as the primer which leads to a low permeability with a low percent absorption.

3) In terms of water absorption, all the overlays seemed to absorb the most in the initial 1½ hours and quickly reach their saturation states. Over the next 28 days the percent absorbed hardly changed except for some occasional disruptions (due to loss of aggregates). The polymer concrete overlays absorbed about 2 to 3% with the slurry plus primer overlay showing the highest absorption. Furthermore, the overlays with primer absorbed more water than unprimed overlays. It is related to the quality of the

construction of the overlay. The two-layer overlay had the lowest absorption, indicating that two-layer overlay had the least open structure.

4) As for the effects of water absorption on the flexural strength of polymer overlays, results show that the longer that polymer concrete overlays are exposed to water, the lower the flexural strength and the more ductile the overlays become. Drying up the specimens resulted in the stiffening of the ductile overlays.

5) The results showed that the primer helps increase the flexural capacity of the overlay as well as stiffness the overlay. The overlays with a primer were effected less by the long-term exposure to water, that is, their flexural strength did not decrease as much as the overlays without primer.

6) The conventional two-layer overlay performs better than the conventional slurry plus primer overlay in terms of permeability, percent absorption, flexural strength and flexibility.

7) The thickness of the polymer concrete overlay is important with regards to the thermal compatibility with the substrate. The results showed that if the epoxy polymer concrete is based on an epoxy with similar properties to FLEXOLITH and that the thickness of the overlays is less than 8mm, then there should be no major problems. However, proper surface preparation, good workmanship and proper curing are necessary as well.

8) In general, the new one layer overlay application method performs as well as the traditional two-layer overlay method. This method would decrease the construction time of the overlay, therefore reduce cost as well as traffic disturbance. However, abrasion and field tests should be conducted before being used on a large project.

9) The other proposed overlays (½ layer and ¾ layer overlays) preformed adequately if a primer was used. These applications methods would reduce construction time and

would use less polymer resin. However, care must be taken during the construction of the overlay to achieve low water permeability. Abrasion and field tests should also be conducted on these methods before being used on a large project.

10) The generation of water vapor pressure (due to high temperatures) from the saturated Portland cement concrete does not seem to be large enough to cause delamination failure.

General Conclusion

Flexible epoxy-based polymer concrete overlays, constructed on Portland cement concrete substrate in the laboratory condition, have shown excellent freeze-thaw cycling resistance, high temperature resistance and saturated water vapor pressure resistance. No delamination was observed. To reduce the strength loss of the overlay due to the absorption of the system, particular attention should be paid to the construction details to avoid any possible accumulation of water on the overlay surface. This can be accomplished by installing proper draining system.

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Appendix A

Ultrasonic Pulse Velocity Readings for Temperature Cycling Samples

Pulse velocity times for the samples that underwent temperature cycling. N represents one end of the sample, C represents the center of the sample and S represents the other end of the sample. Readings are in milliseconds.

Overlay Method	Sample No.	Cycle 0			Cycle 1			Cycle 2		
		N	C	S	N	C	S	N	C	S
One Layer	1	14.4	15.0	15.7	12.8	12.6	13.6	13.0	12.8	14.0
	2	15.4	16.9	16.8	13.5	13.7	13.0	14.1	14.5	14.8
	3	13.7	14.1	14.2	13.5	13.5	12.8	13.2	13.1	13.2
Two Layer	4	13.7	15.0	16.1	13.0	13.2	13.5	13.5	13.8	14.0
	5	17.0	13.8	14.0	15.8	13.4	13.4	13.4	13.4	13.0
	6	15.5	16.6	16.5	14.2	14.3	15.9	13.5	13.3	13.0
3/4 layer plus primer	7	13.5	13.6	14.5	13.6	13.4	12.8	13.1	13.0	13.0
	8	15.0	15.5	14.8	13.6	13.5	13.6	13.7	13.7	13.4
	9	15.0	14.7	15.0	13.5	12.8	12.5	13.5	13.0	12.2
1/2 layer plus primer	10	15.5	16.5	16.8	15.5	15.5	15.6	14.0	14.0	14.5
	11	14.6	14.9	16.3	16.5	15.0	15.2	14.5	14.5	14.3
	12	13.8	14.2	14.0	13.1	13.1	14.2	13.5	13.5	15.5
slurry plus primer	13	17.2	17.0	16.2	19.9	17.3	19.2	14.6	14.0	13.8
	14	16.8	17.0	16.5	15.4	15.2	14.5	15.0	14.8	13.6
	15	16.2	14.2	16.2	14.5	14.6	13.5	13.7	14.6	13.5

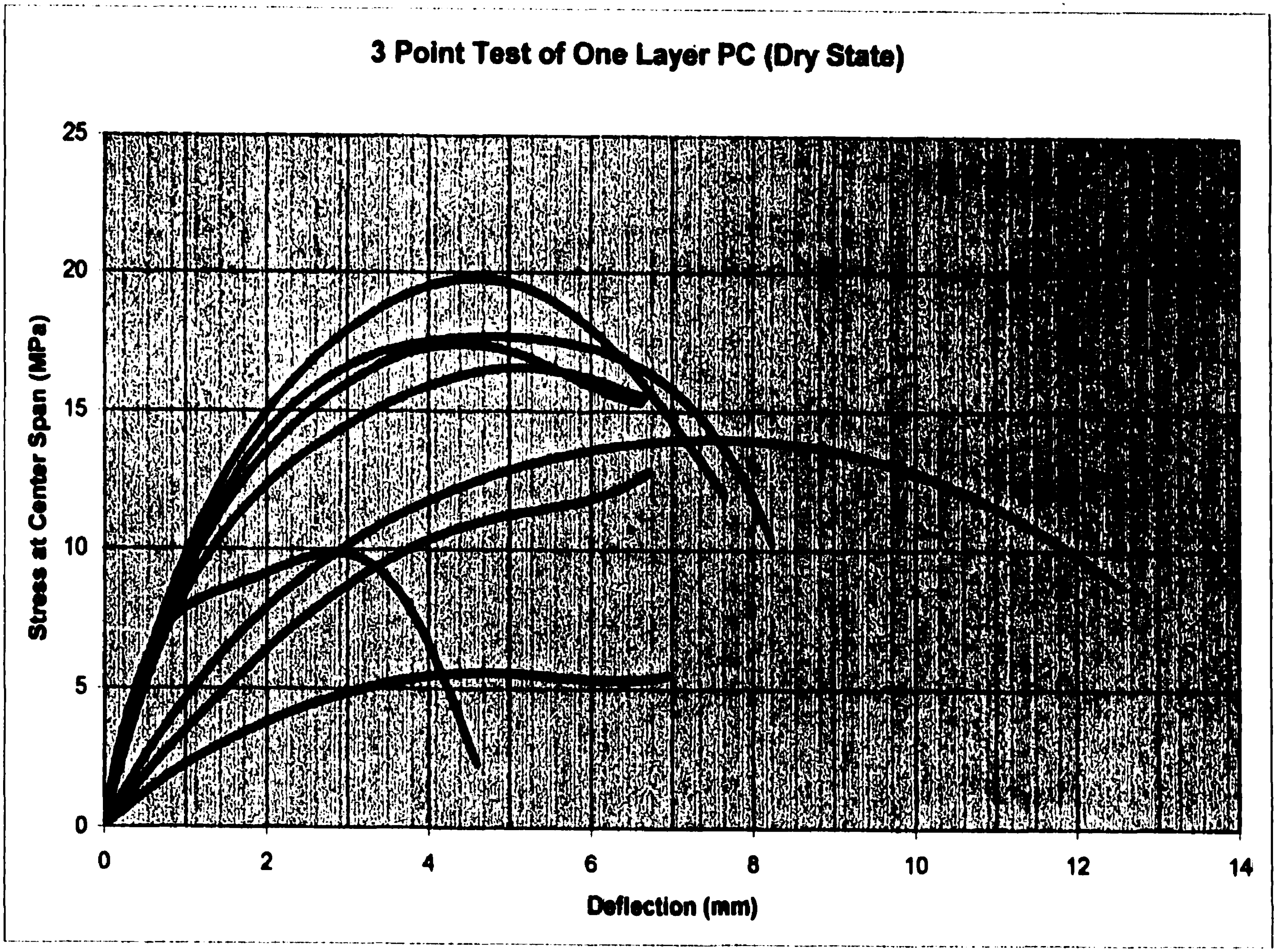
Overlay Method	Sample No.	Cycle 3			Cycle 4			Cycle 5		
		N	C	S	N	C	S	N	C	S
One Layer	1	14.4	13.1	13.0	12.6	13.2	13.1	13.7	13.3	13.9
	2	14.0	13.6	13.5	13.5	13.0	13.6	13.4	12.9	13.5
	3	13.2	13.6	13.5	13.1	13.0	12.5	13.8	12.8	13.0
Two Layer	4	13.6	13.2	13.2	13.7	14.5	13.4	13.7	13.7	13.7
	5	13.7	13.7	13.8	13.1	13.5	13.8	13.5	13.5	13.3
	6	12.4	13.2	13.0	13.0	13.6	13.3	13.3	13.7	13.3
3/4 layer plus primer	7	13.2	13.5	13.2	13.3	13.0	12.9	13.3	13.2	13.2
	8	14.0	13.8	13.7	13.4	14.0	13.0	13.6	13.9	13.4
	9	13.4	13.6	13.5	12.8	13.0	12.3	13.0	13.0	13.0
1/2 layer plus primer	10	14.1	13.8	14.1	13.8	14.0	14.2	13.8	13.8	13.9
	11	13.5	14.5	13.5	12.8	13.0	12.8	13.2	13.2	12.9
	12	12.8	12.9	13.1	12.8	12.7	12.7	12.9	12.8	12.8
slurry plus primer	13	14.6	14.8	14.0	14.0	13.5	13.5	14.0	13.5	13.5
	14	14.4	14.8	14.4	14.0	14.2	14.5	13.8	14.2	13.8
	15	13.5	13.2	13.0	13.5	13.2	12.5	13.7	13.5	13.2

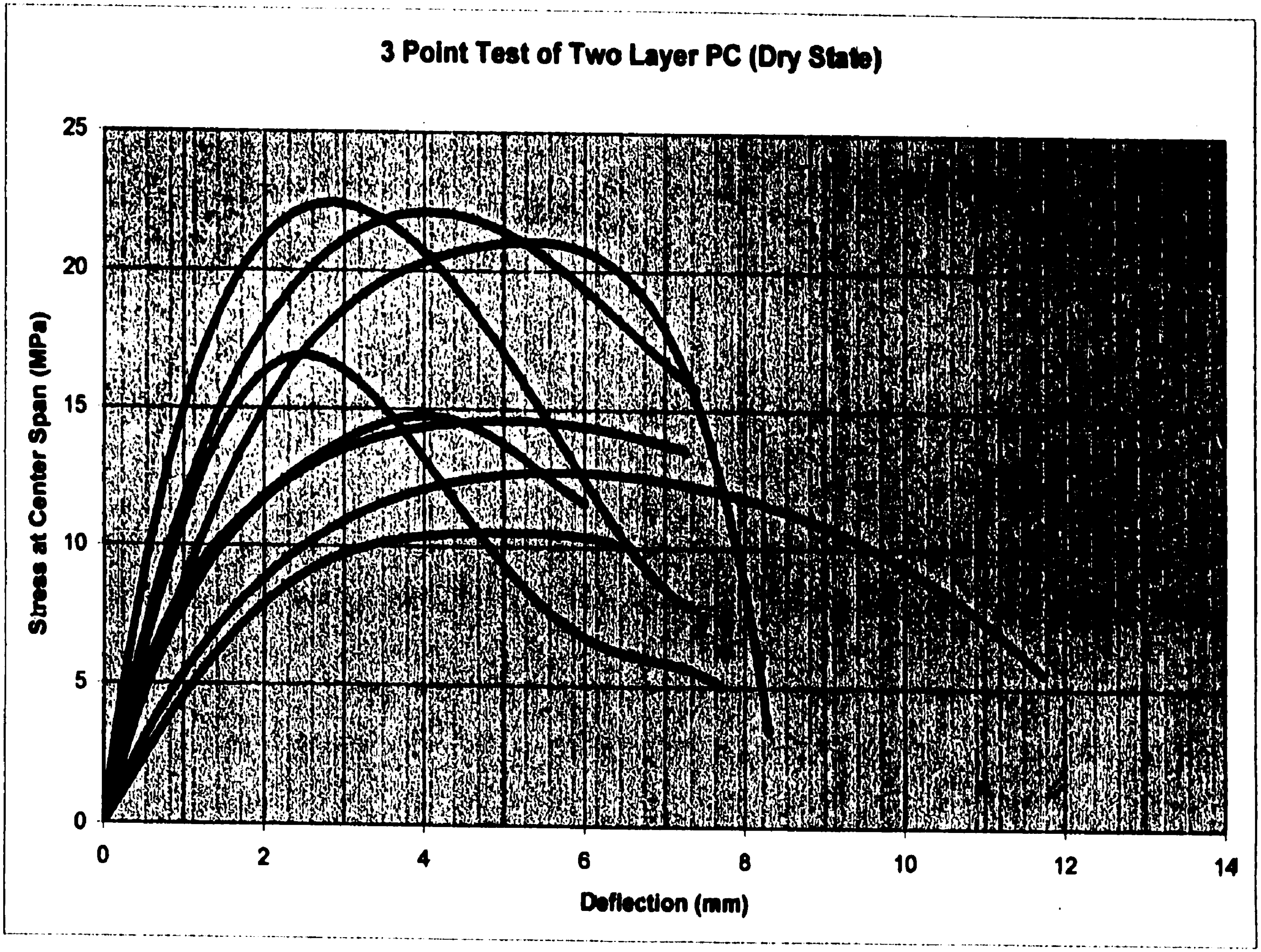
Overlay Method	Sample No.	Cycle 6			Cycle 7			Cycle 8		
		N	C	S	N	C	S	N	C	S
One Layer	1	13.5	13.4	13.4	13.4	13.5	13.4	13.4	13.0	13.2
	2	13.3	12.9	13.5	13.1	13.2	13.2	13.2	13.2	13.5
	3	13.4	13.0	12.9	13.2	13.1	12.8	13.4	13.5	12.9
Two Layer	4	13.7	13.5	13.7	13.5	13.4	13.8	13.4	13.2	13.7
	5	13.3	13.4	13.4	13.3	13.5	13.3	13.2	13.4	13.5
	6	13.3	13.5	13.6	13.3	13.6	13.4	12.8	13.5	13.1
3/4 layer plus primer	7	13.2	13.4	13.1	13.1	13.2	13.1	13.1	13.5	13.3
	8	13.5	13.9	13.4	13.4	13.8	13.4	13.9	13.7	13.4
	9	13.0	12.9	13.0	13.1	12.6	13.2	13.4	13.2	13.0
1/2 layer plus primer	10	13.7	13.8	14.0	13.4	13.9	14.2	13.5	13.7	13.8
	11	13.3	13.3	12.9	13.1	13.3	13.0	13.2	13.7	13.2
	12	12.9	12.9	12.8	12.7	13.0	12.8	13.0	13.2	13.0
slurry plus primer	13	14.0	13.5	13.5	14.1	13.6	13.4	14.2	13.7	13.9
	14	13.8	14.1	14.0	13.7	14.2	14.0	14.0	13.8	14.0
	15	13.2	13.5	13.0	13.5	13.5	13.3	13.3	13.7	13.2

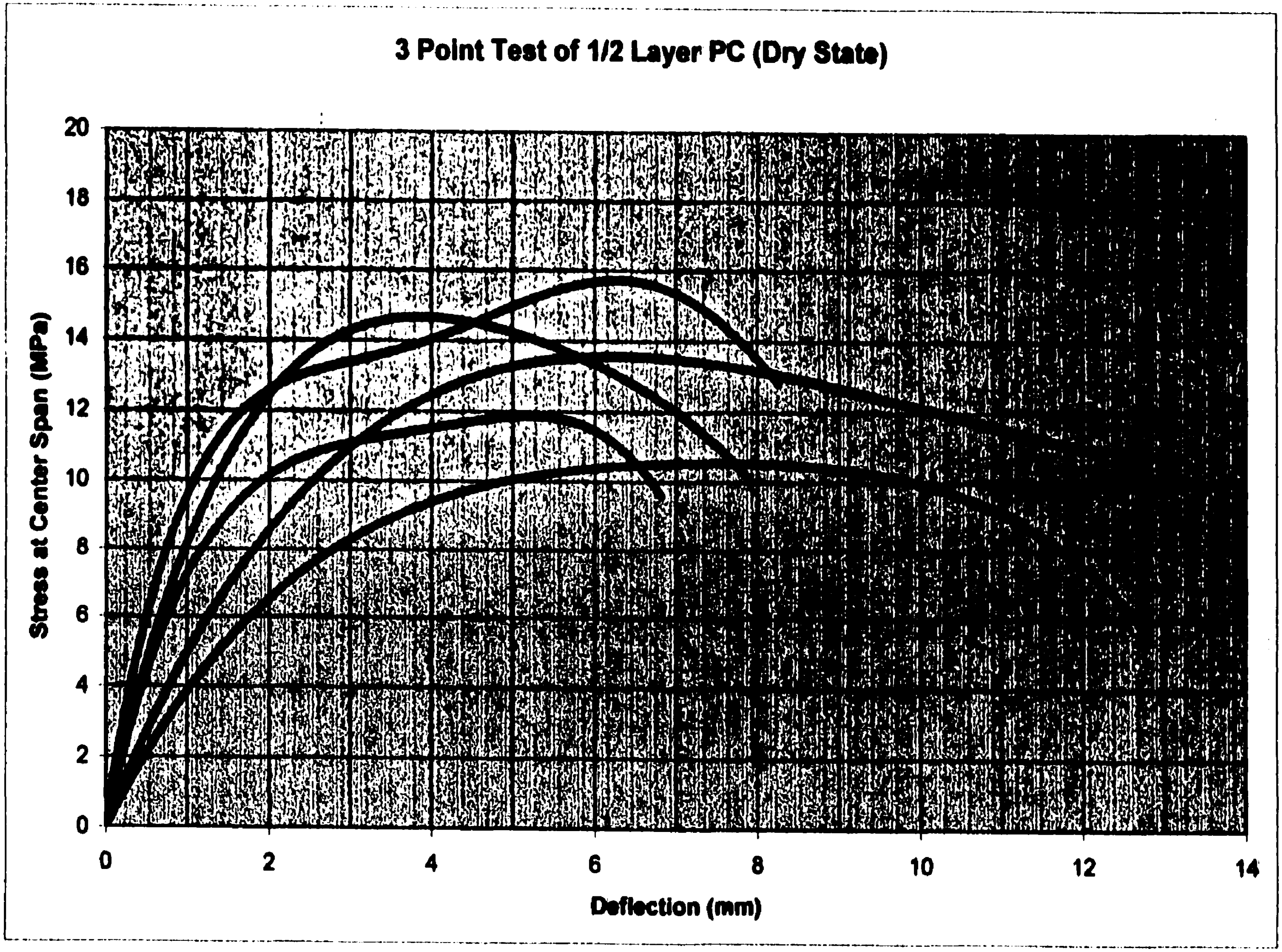
Overlay Method	Sample No.	Cycle 9			Cycle 15			Cycle 103		
		N	C	S	N	C	S	N	C	S
One Layer	1	13.5	13.2	13.5	13.4	13.3	13.8	15.2	15.5	15.6
	2	13.4	13.2	13.6	13.2	13.2	13.4	15.7	15.2	15.8
	3	13.6	13.4	13.0	13.7	13.5	13.2	16.0	15.8	15.8
Two Layer	4	13.5	13.5	13.6	13.6	13.4	13.6	14.6	15.4	15.2
	5	13.4	13.4	13.5	13.2	13.5	13.2	15.2	15.3	15.0
	6	13.0	13.2	13.1	13.0	13.3	13.4	16.5	16.8	16.7
3/4 layer plus primer	7	13.0	13.5	13.2	13.1	13.5	13.2	15.3	15.3	14.3
	8	13.9	13.5	13.5	13.9	13.7	13.4	14.2	14.1	13.8
	9	13.4	13.3	12.9	13.5	13.3	13.2	14.0	13.8	13.6
1/2 layer plus primer	10	13.4	13.8	14.0	13.4	13.9	14.0	14.0	14.0	14.3
	11	13.3	13.7	13.2	13.4	13.4	13.1	14.0	13.7	13.9
	12	13.0	13.0	13.2	13.1	13.5	13.4	15.0	14.3	13.5
slurry plus primer	13	14.3	13.7	13.9	14.3	13.7	13.7	15.7	15.5	15.4
	14	14.1	13.6	13.9	14.2	13.4	13.9	15.2	15.8	14.2
	15	13.3	13.7	13.3	13.3	13.7	13.5	16.0	15.8	16.1

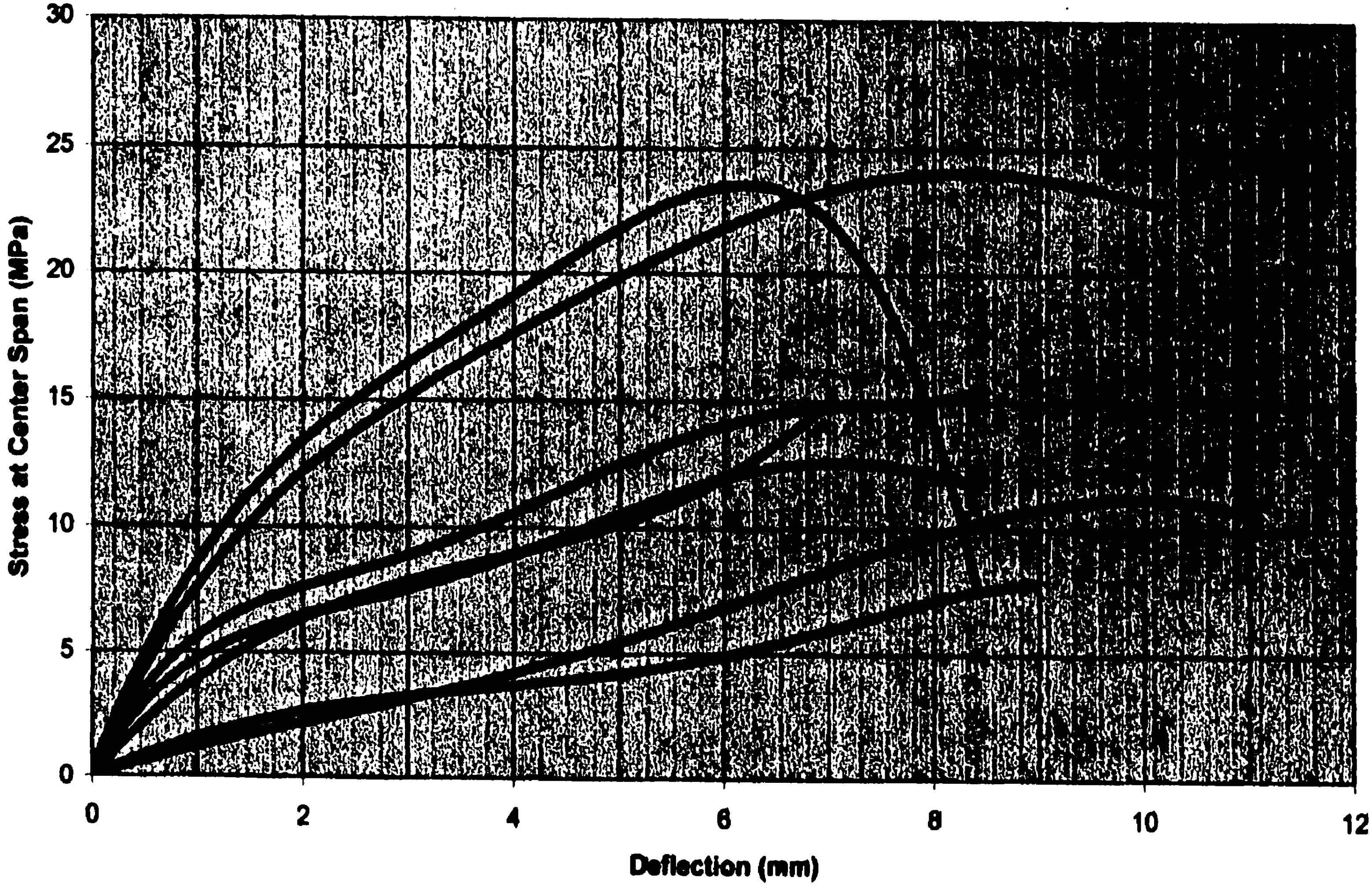
Appendix B

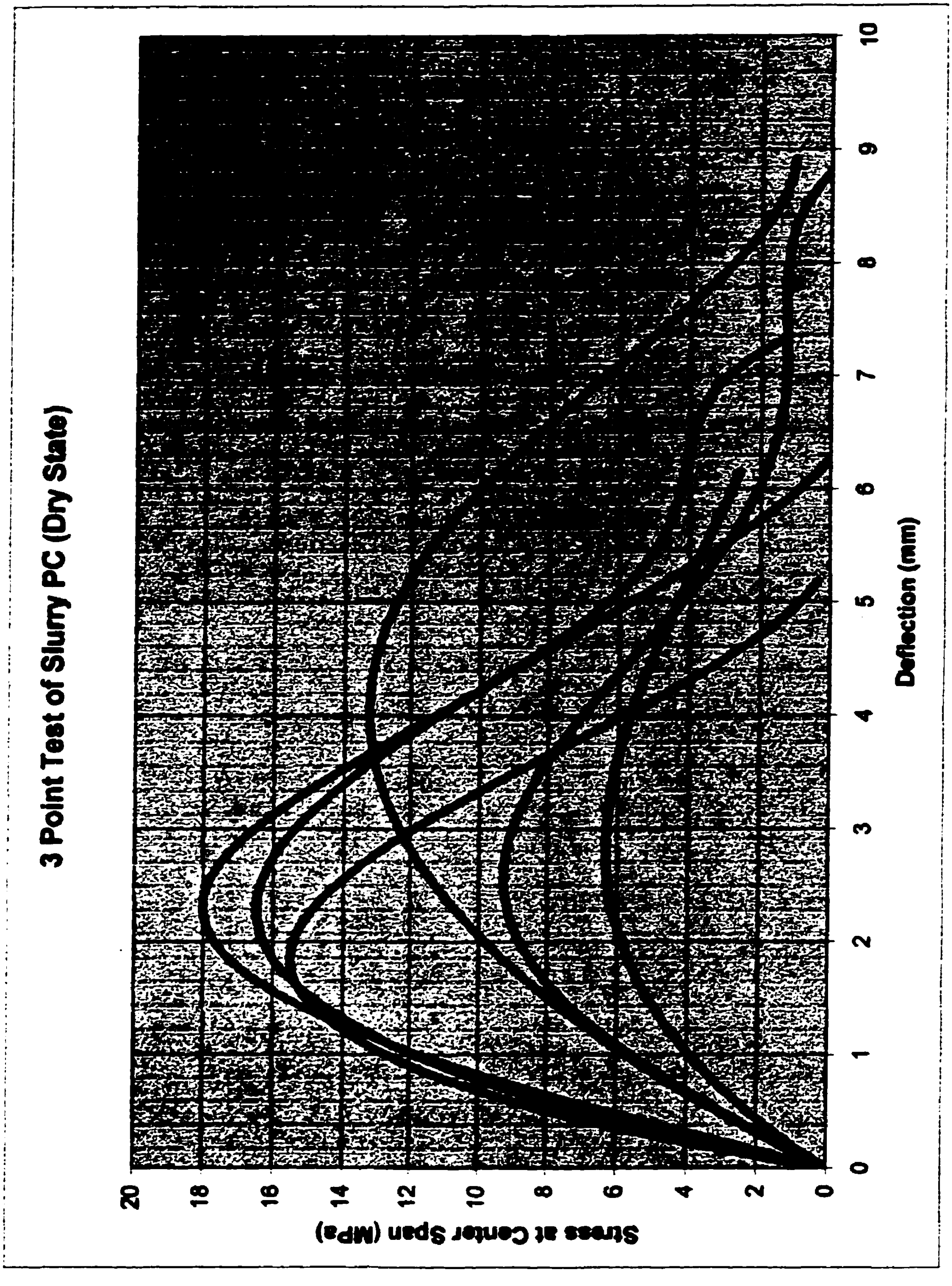
Flexural Strength Curves for each Application Method

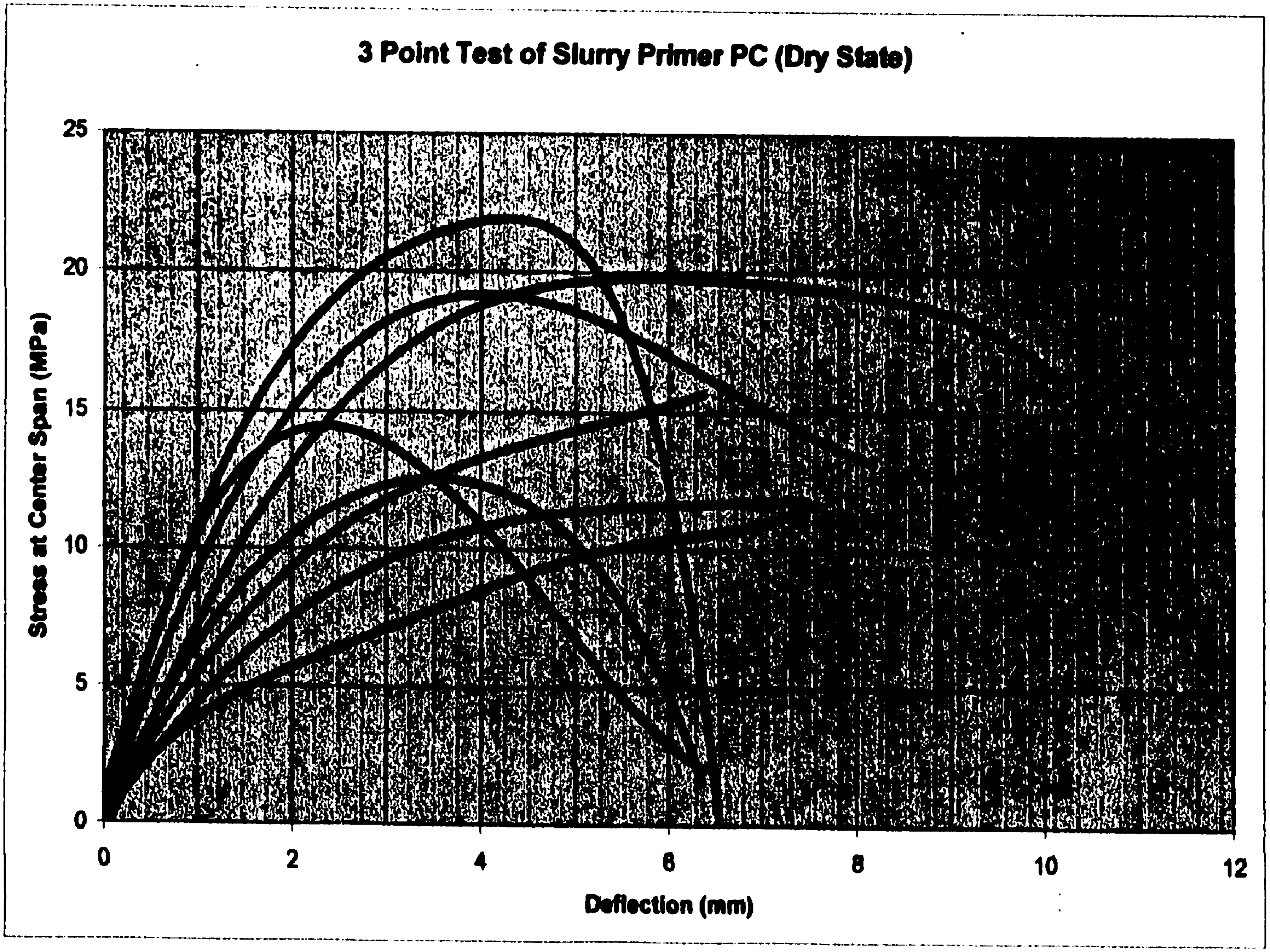

3 Point Test of One Layer PC (Dry State)
Stress at Center Span (MPa)
0
5
10
15
20
25
Deflection (mm)
0
2
4
6
8
10
12
14


3 Point Test of Two Layer PC (Dry State)
Stress at Center Span (MPa)
0
5
10
15
20
25
Deflection (mm)
0
2
4
6
8
10
12
14

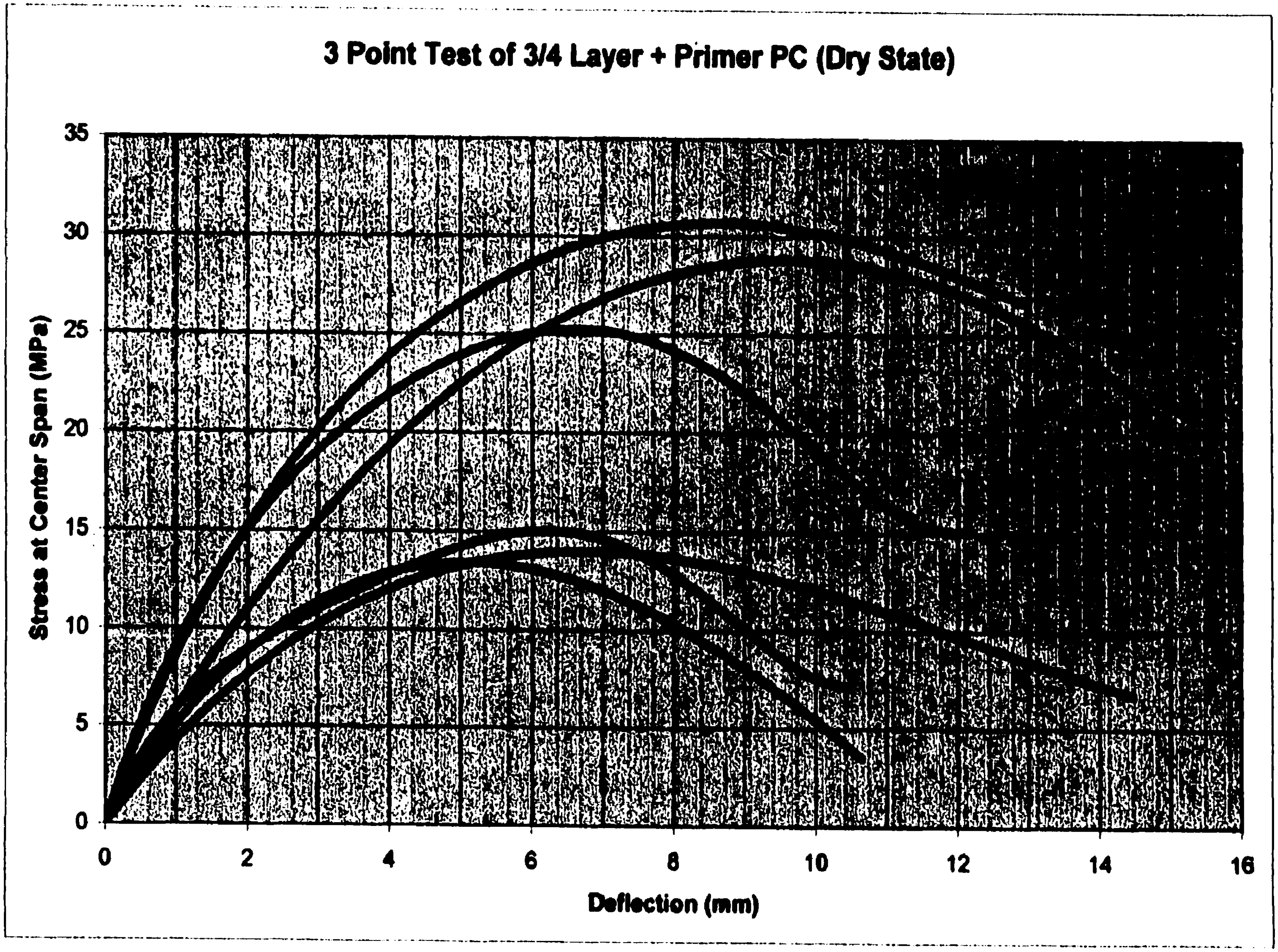

3 Point Test of 1/2 Layer PC (Dry State)
Stress at Center Span (MPa)
0
2
4
6
8
10
12
14
16
18
20
Deflection (mm)
0
2
4
6
8
10
12
14

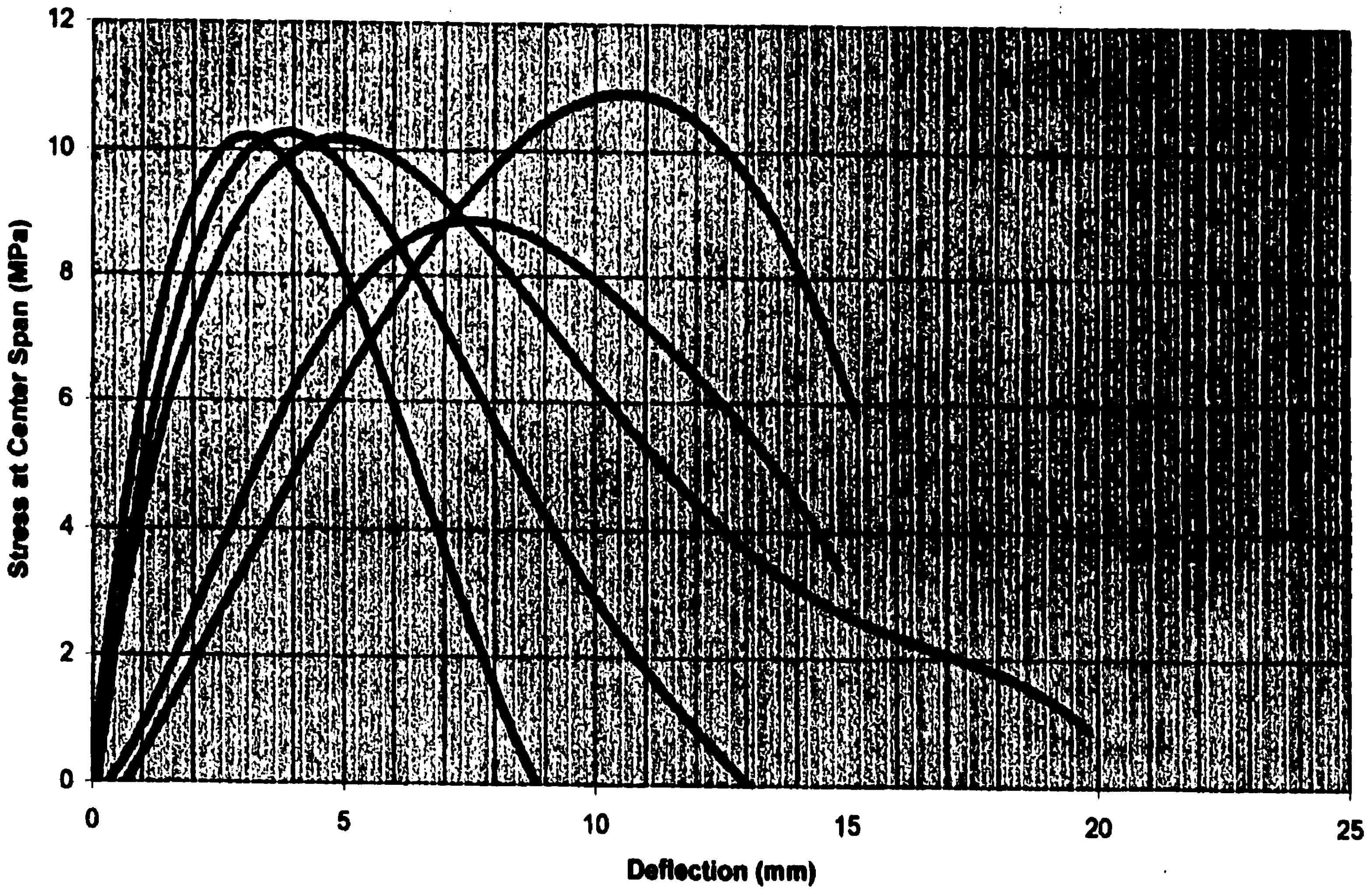

3 Point Test of 1/2 Layer+Primer PC (Dry State)


3 Point Test of Slurry PC (Dry State)
Stress at Center Span (MPa)
0
2
4
6
8
10
12
14
16
18
20
Deflection (mm)
0
1
2
3
4
5
6
7
8
9
10

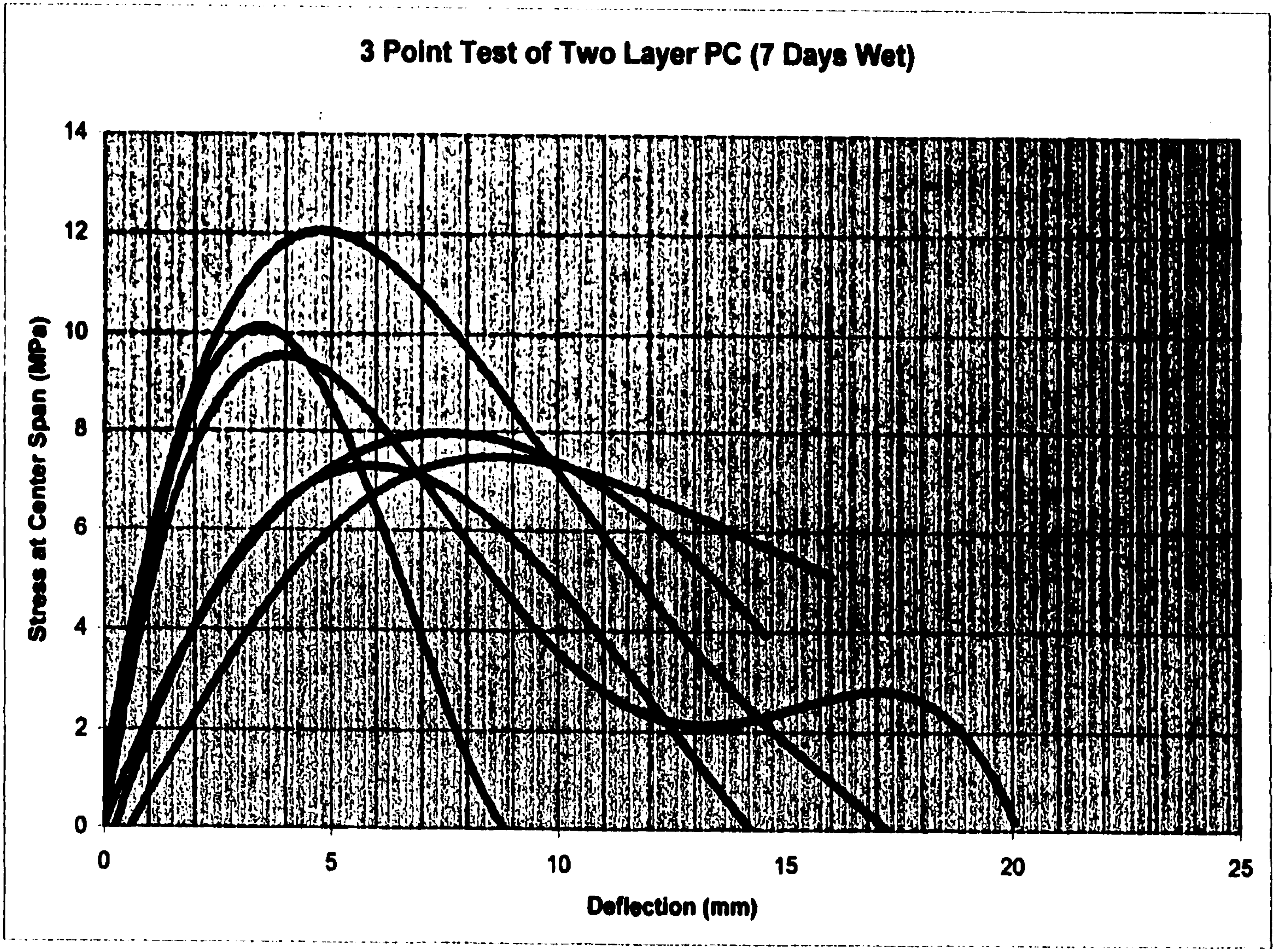


3 Point Test of Slurry Primer PC (Dry State)


3 Point Test of 3/4 Layer + Primer PC (Dry State)
Stress at Center Span (MPa)
35
30
25
20
15
10
5
0
0
2
4
6
8
10
12
14
16
Deflection (mm)

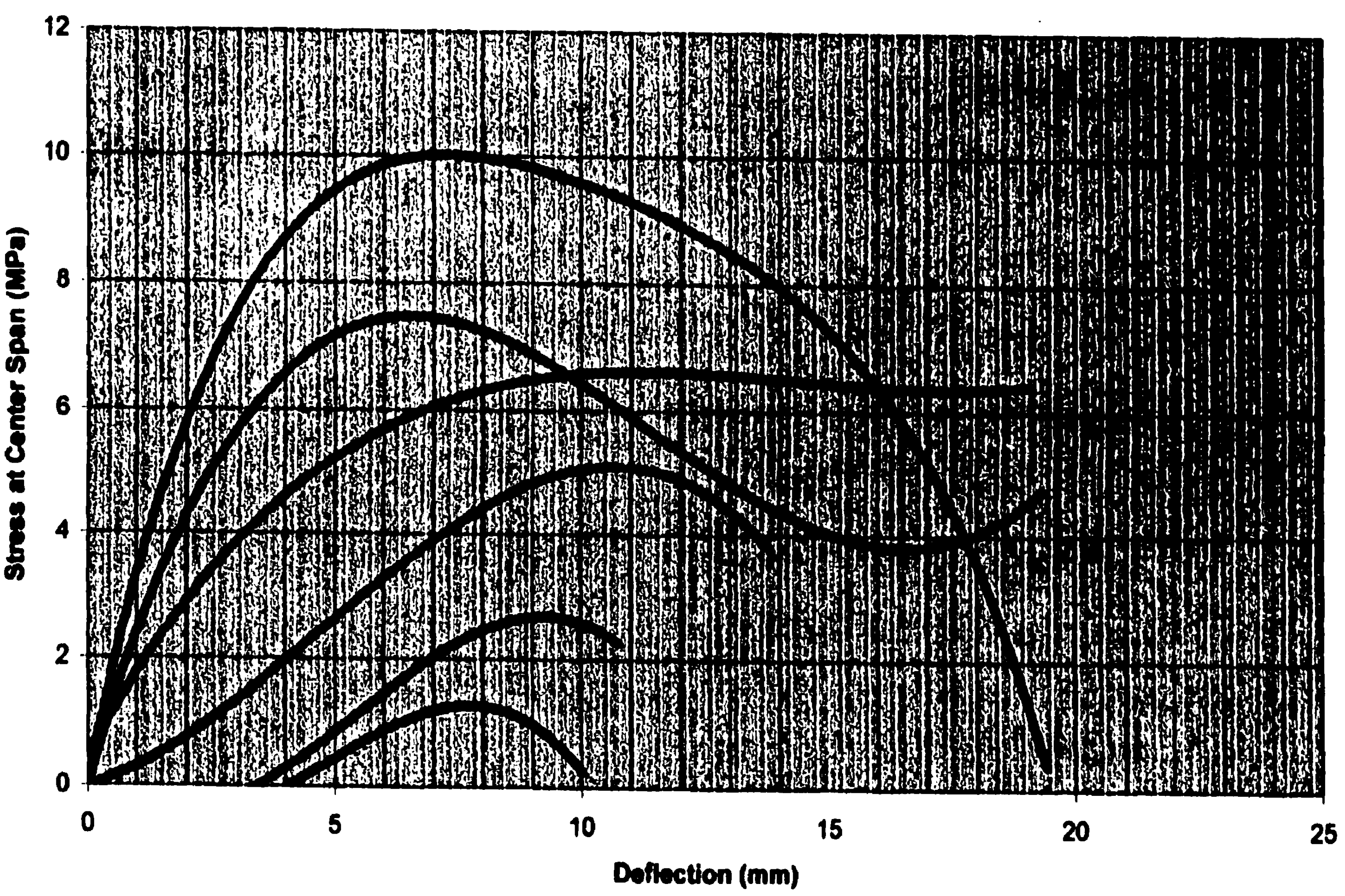


3 Point Test of One Layer PC (7 Days Wet)

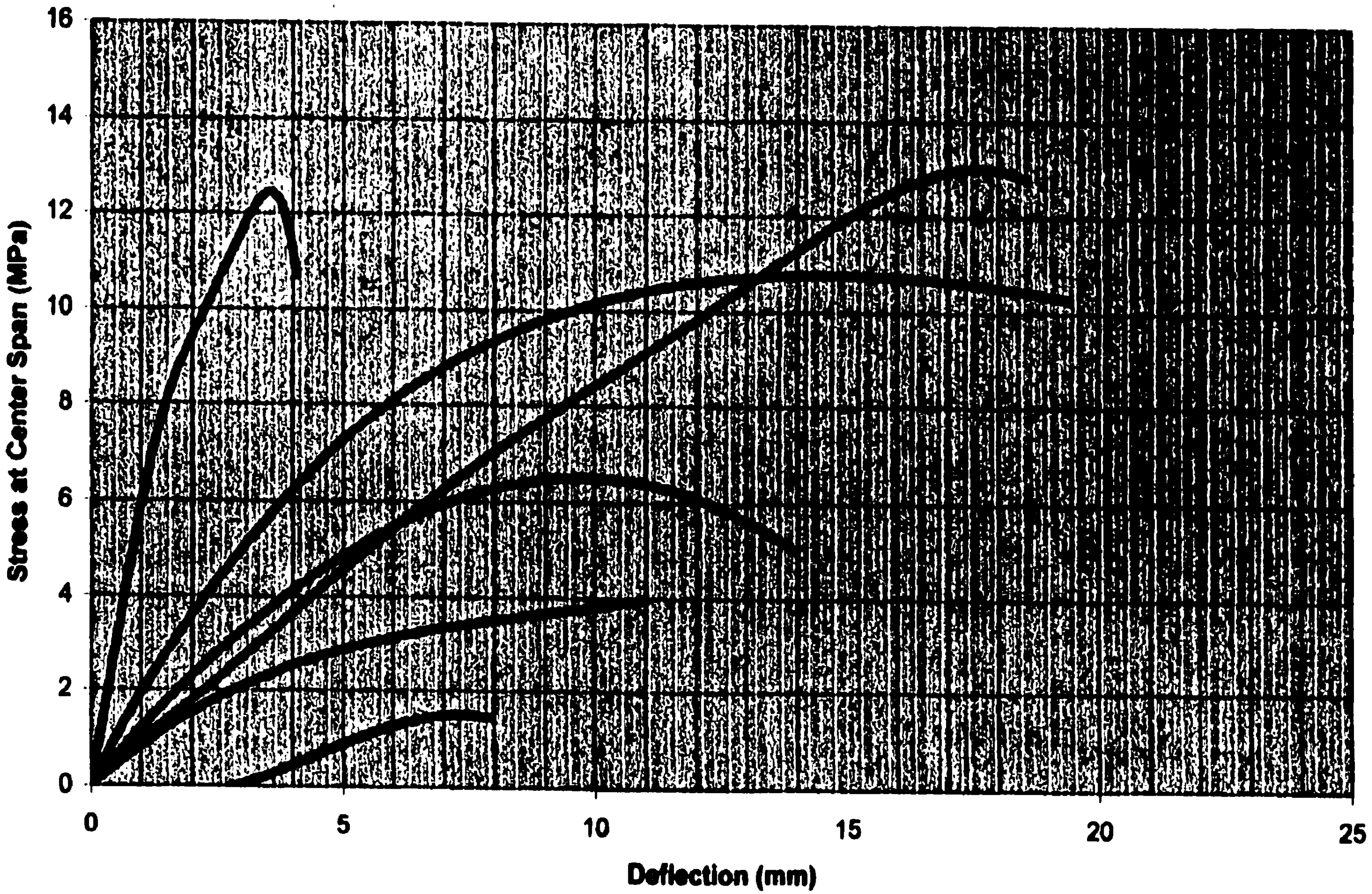


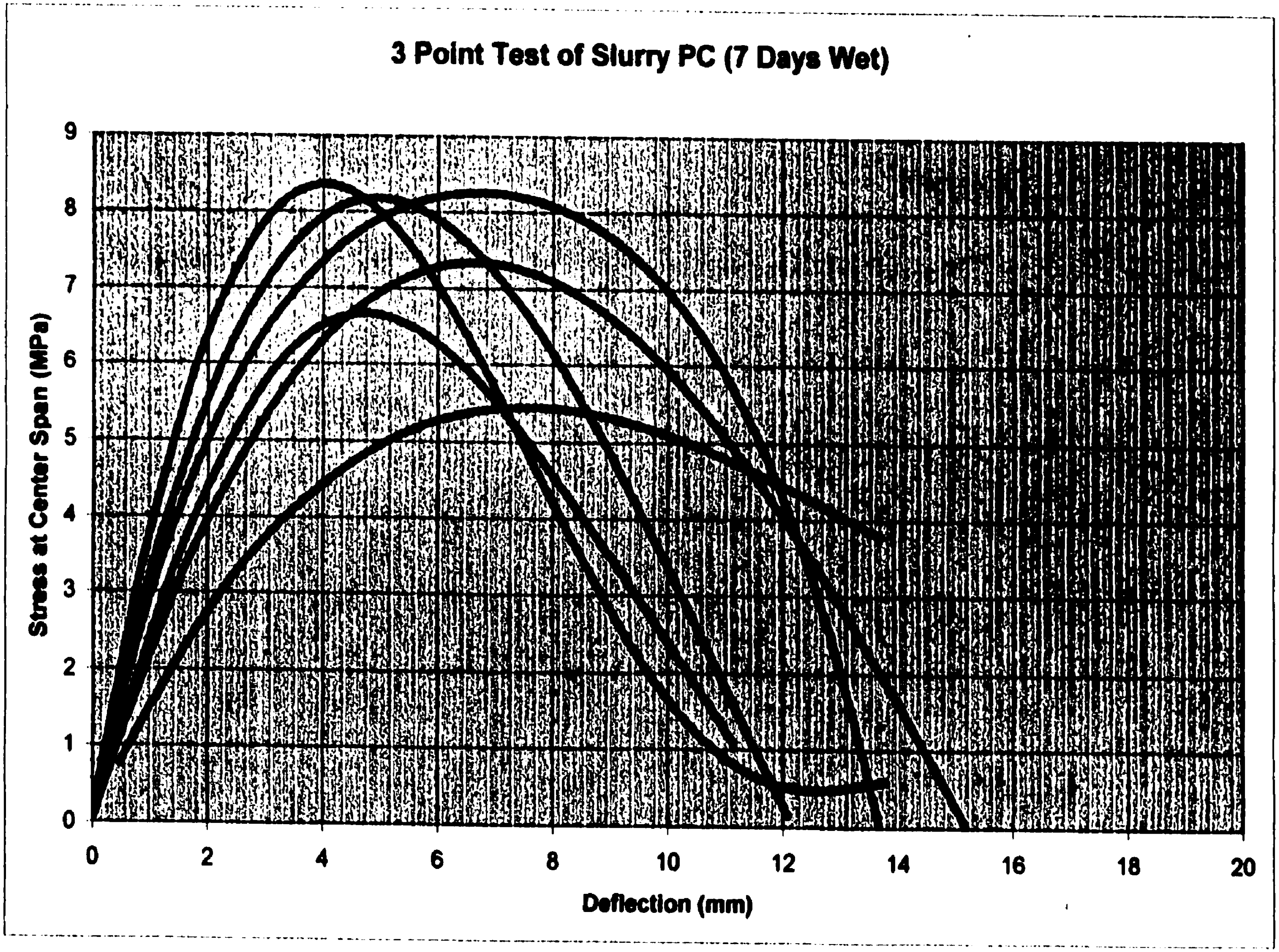
3 Point Test of Two Layer PC (7 Days Wet)

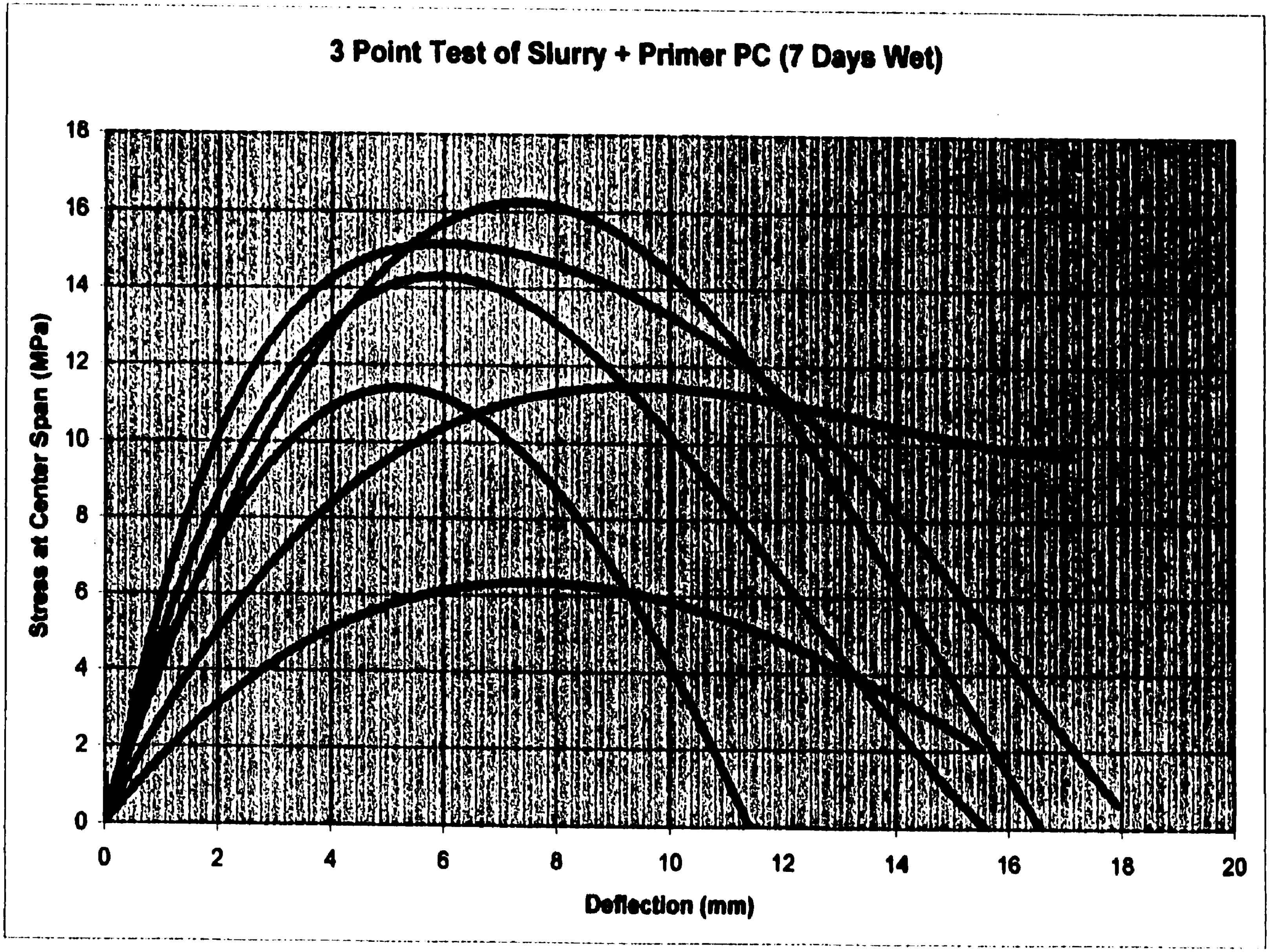
3 Point Test of 1/2 Layer PC (7 Days Wet)

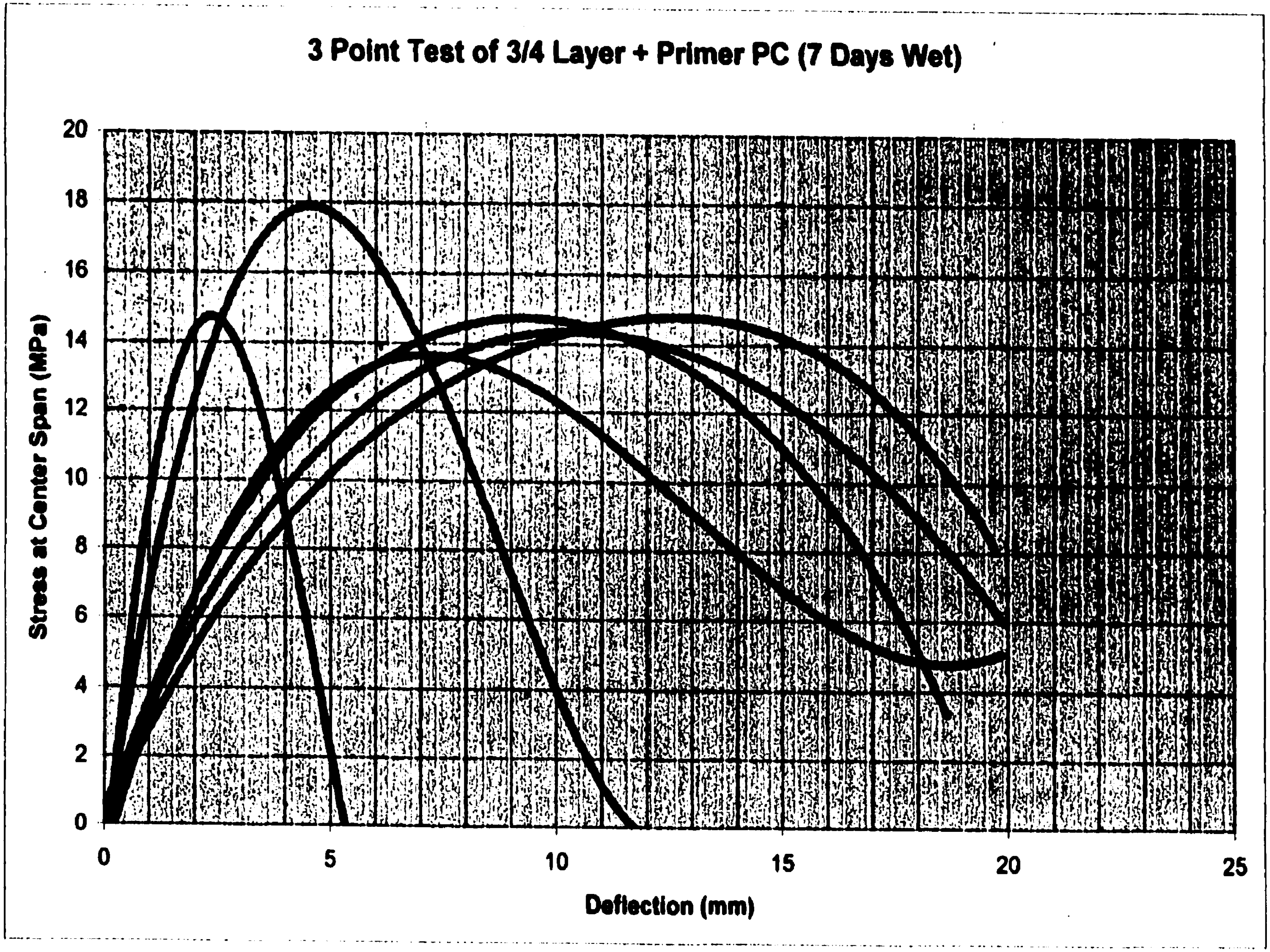


3 Point Test of 1/2 Layer + Primer PC (7 Days Wet)

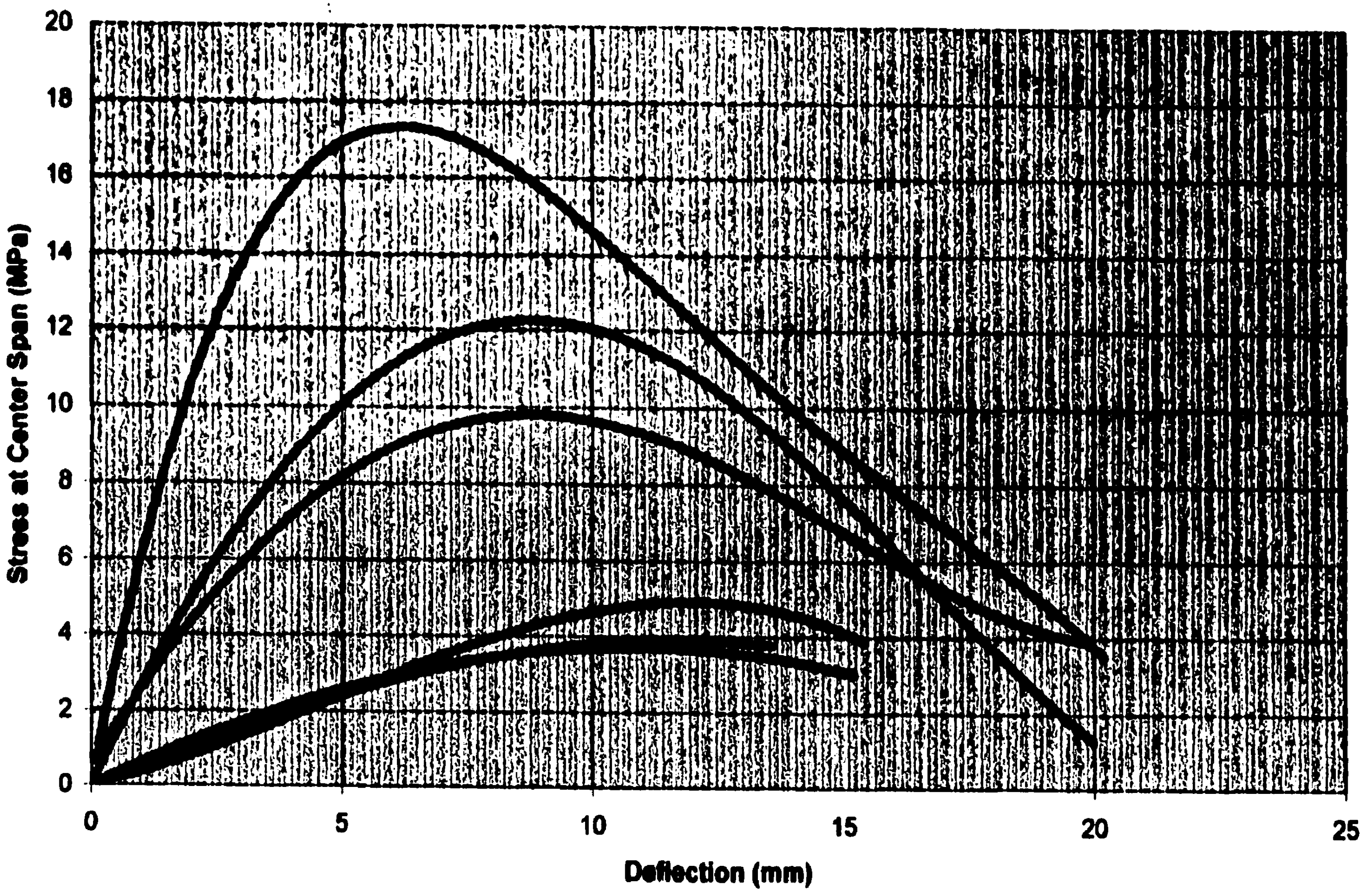


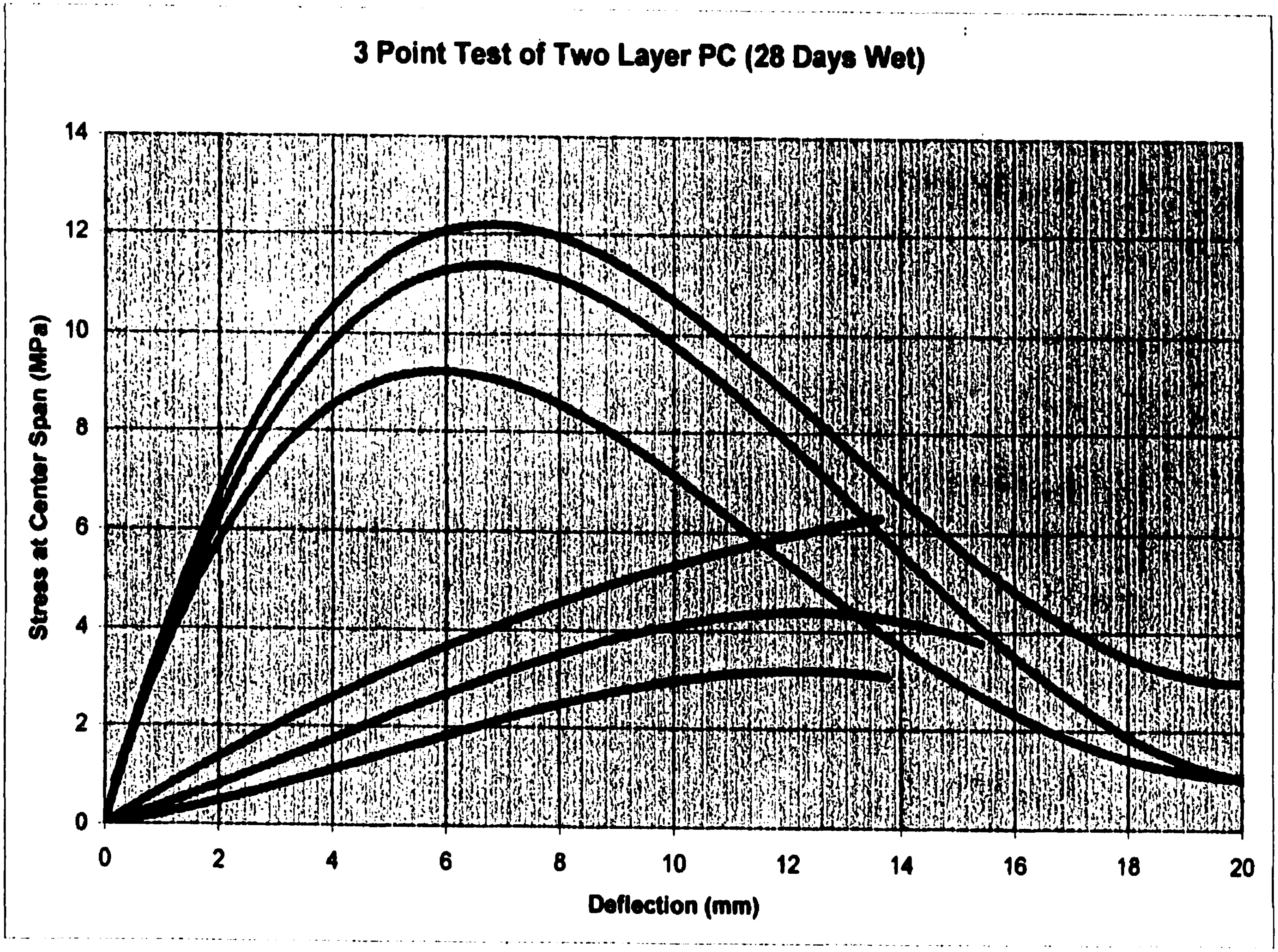

3 Point Test of Slurry PC (7 Days Wet)
Stress at Center Span (MPa)
0
1
2
3
4
5
6
7
8
9
Deflection (mm)
0
2
4
6
8
10
12
14
16
18
20

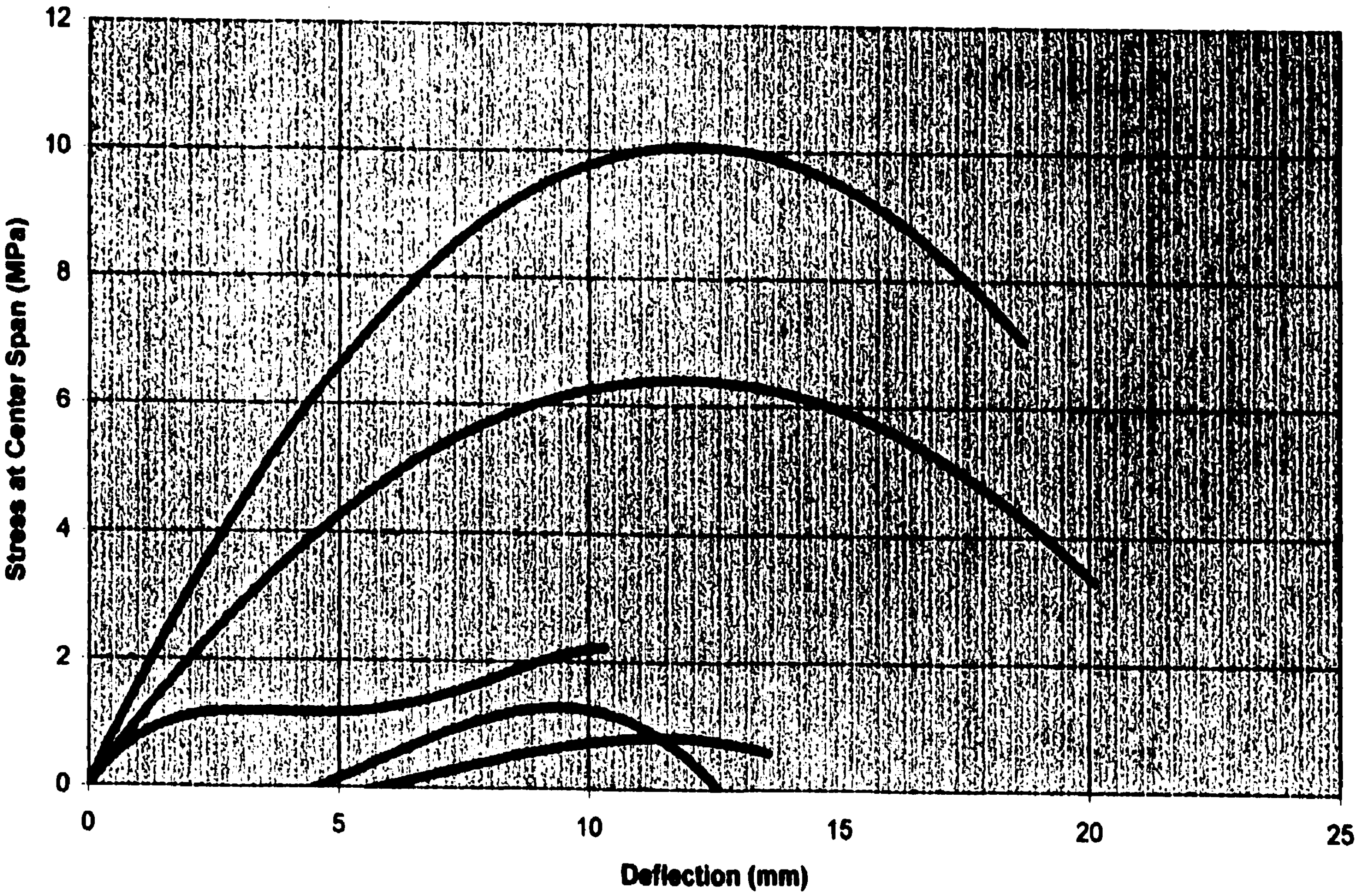

3 Point Test of Slurry + Primer PC (7 Days Wet)
Stress at Center Span (MPa)
0
2
4
6
8
10
12
14
16
18
Deflection (mm)
0
2
4
6
8
10
12
14
16
18
20


3 Point Test of 3/4 Layer + Primer PC (7 Days Wet)
Stress at Center Span (MPa)
20
18
16
14
12
10
8
6
4
2
0
0
5
10
15
20
25
Deflection (mm)

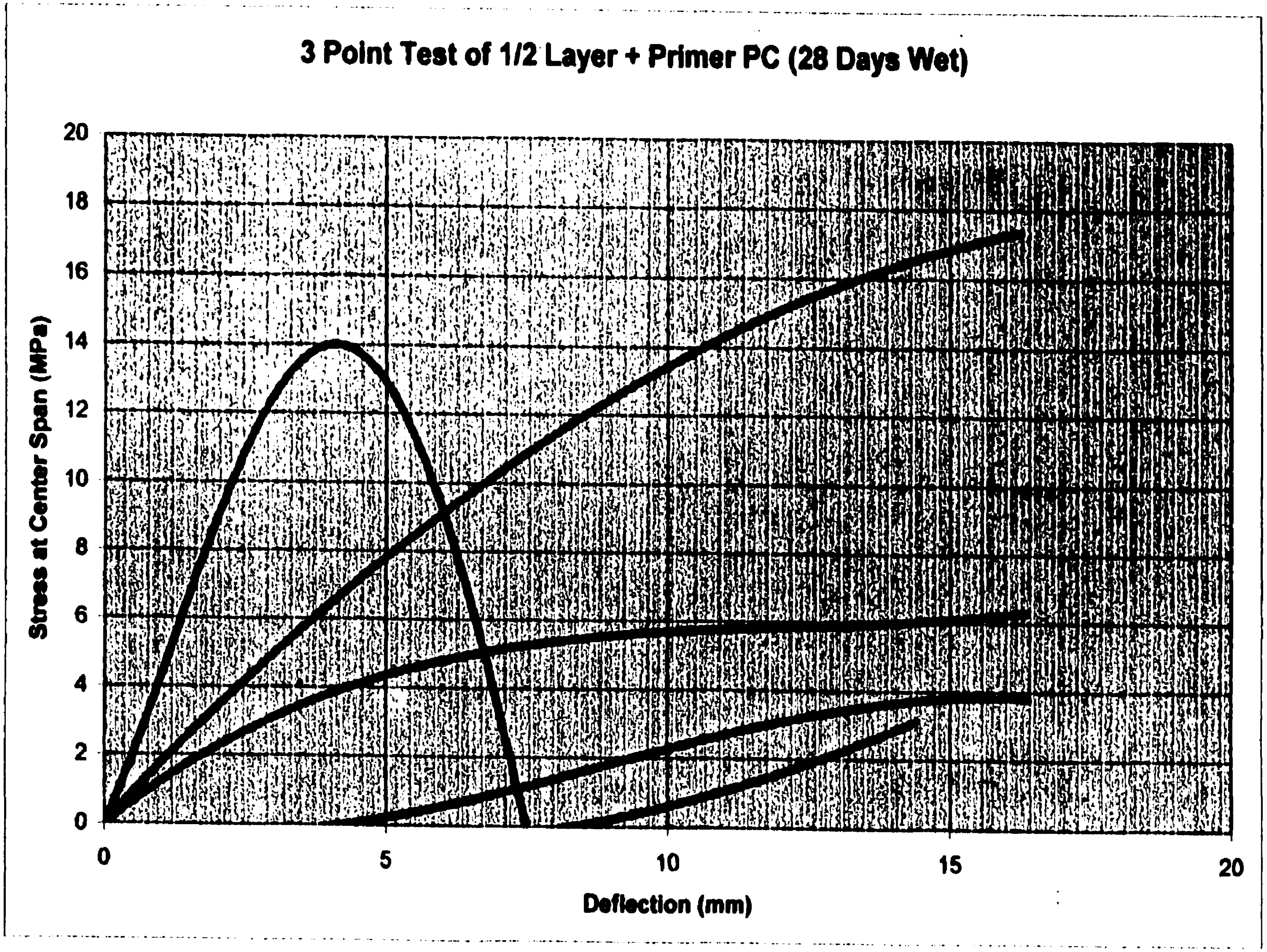
3 Point Test of One Layer PC (28 Days Wet)




3 Point Test of Two Layer PC (28 Days Wet)
Stress at Center Span (MPa)
0
2
4
6
8
10
12
14
Deflection (mm)
0
2
4
6
8
10
12
14
16
18
20

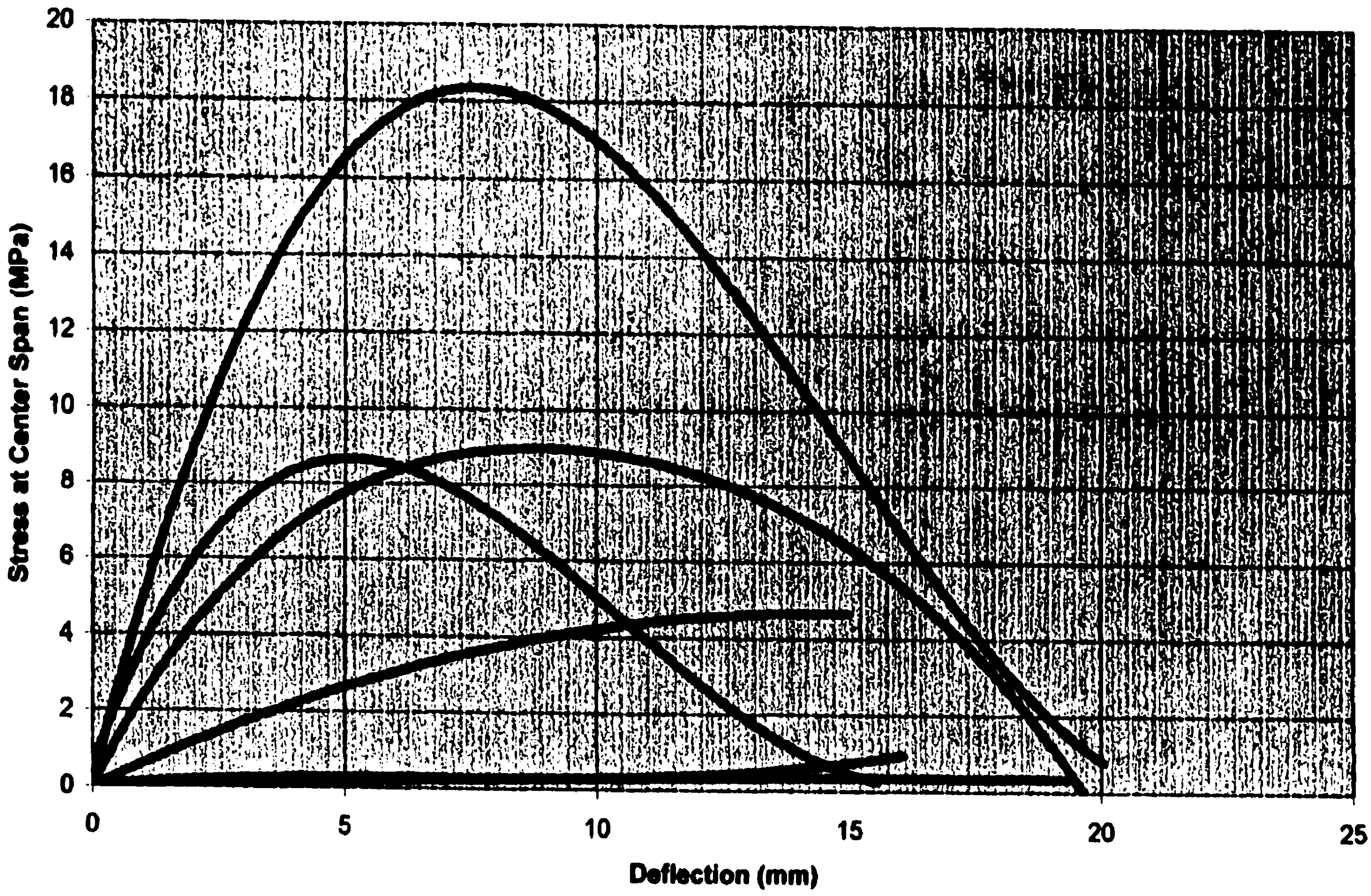


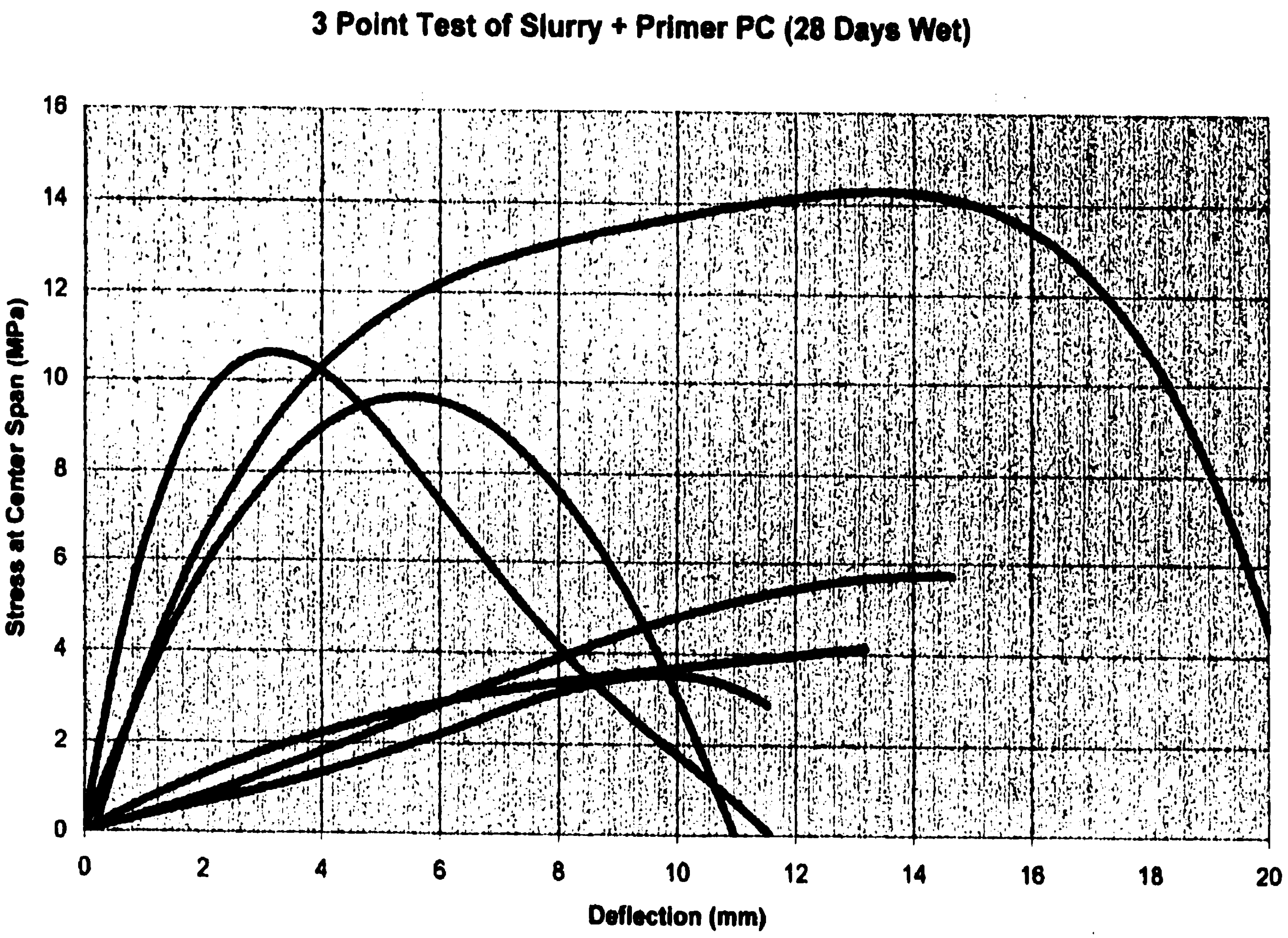
3 Point Test of 1/2 Layer PC (28 Days Wet)



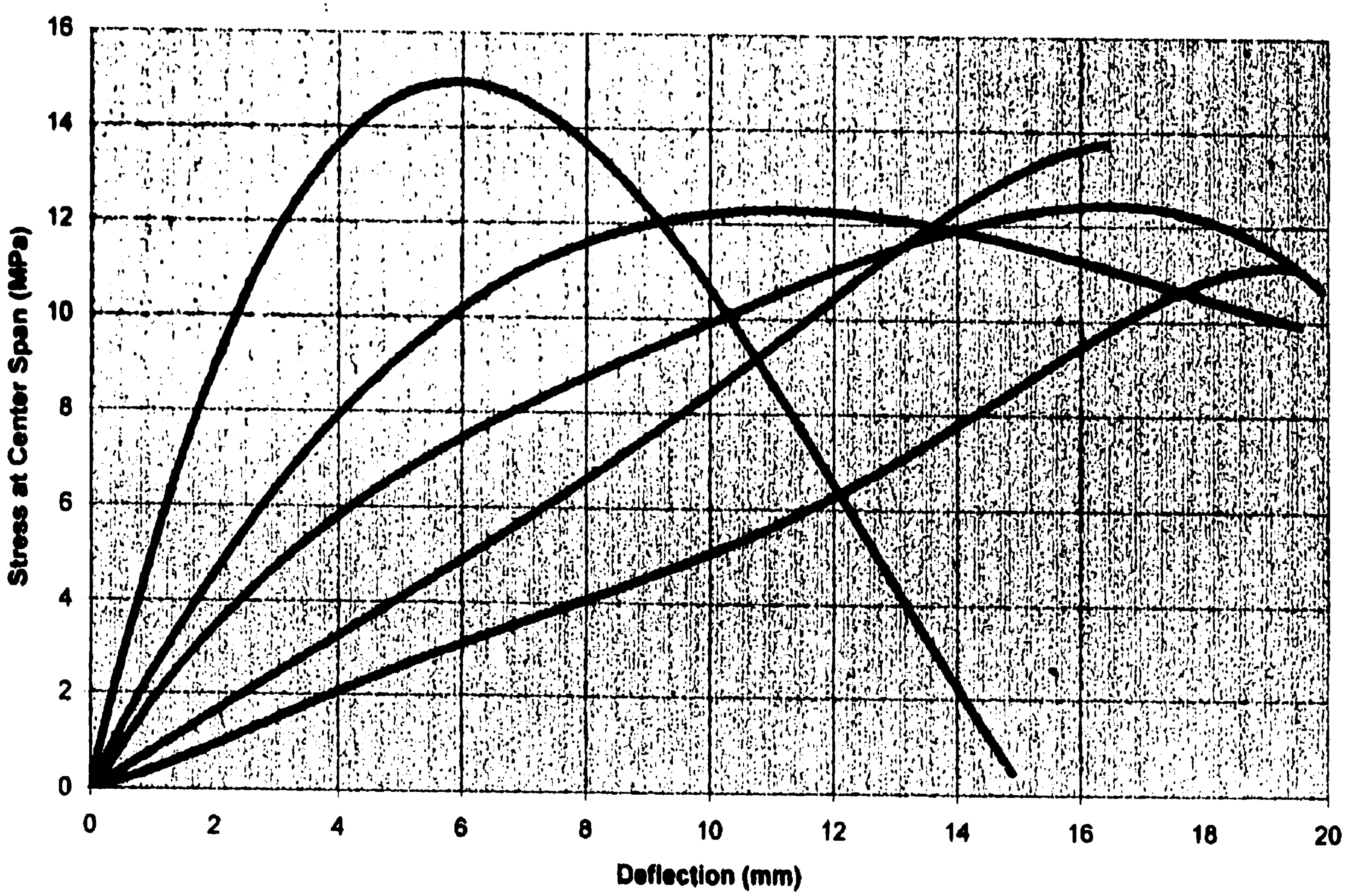
3 Point Test of 1/2 Layer + Primer PC (28 Days Wet)

3 Point Test of Slurry PC (28 Days Wet)





3 Point Test of Slurry + Primer PC (28 Days Wet)



3 Point Test of 3/4 Layer + Primer PC (28 Days Wet)