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EVALUATION OF TWO LOW-SLUMP DENSE NON-METALLIC FIBER REINFORCED CONCRETE DECK OVERLAYS AT EXIT 32 ON I-90 IN SOUTH DAKOTA

Study SD97-11- F
Final Report

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DISCLAIMER

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16. Abstract

This report presents the construction and performance evaluation of a bridge deck overlay constructed with a 3M's polyolefin fibers, non-metallic fiber reinforced concrete (NMFRC).

The mixture proportions used, the quality control tests conducted for the evaluation of the fresh and hardened concrete properties, the procedure used for mixing, transporting, placing, consolidating, finishing, tining and curing of the concrete are described. Periodic inspection of the bridge deck overlay was done and this report includes the results of these inspections.

The feasibility of using this NMFRC in the construction of highway structures has been established. The new NMFRC with enhanced fatigue, impact resistance, modulus of rupture, ductility and toughness properties is suitable for the construction of bridge deck overlays and may prolong the life of the deck.

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Executive Summary

Due to a decaying infrastructure and tightening budget constraints, transportation engineers are challenged to rehabilitate existing facilities economically with an increase in performance. However, simultaneous improvements in cost and performance are unlikely unless new material technology can be exploited. The recently developed polyolefin fiber-reinforced concrete(FRC) is one material that promises to provide many advantages, providing a practical approach to enhanced durability and cost-effectiveness in concrete compositions. Polyolefin fibers, as compared to steel fibers, eliminate problems such as staining, inherent corrosion and potentially harmful protrusions. It has been shown in earlier research and publications that FRC, with its enhanced properties beneficial to structural applications, is a highly suitable material for construction and/or rebuilding bridges and other transportation structures. The project involved evaluation of two low slump dense non-metallic FRC bridge deck overlays at Exit 32 on Interstate 90 near Sturgis, South Dakota.

The objective was to extend the life of these badly deteriorated structures through the enhancement of SDDOT's present low-slump dense (LSD) concrete overlay system by incorporating 3M's polyolefin fibers. SDDOT wanted to enhance their present LSD concrete overlay system because, the condition of these bridges was so poor that there was a question whether the normal LSD concrete would last. Also, a LSD NMFRC would be more likely to hold together and minimize large cracks, spalling, and loss of material from the top of the deck. Therefore, the potential for hazards to the public would be reduced.

The ACI Committee 224 report on cracking has recommended that the maximum crack width that can be tolerated under the environmental conditions at the bridge (exposed surface subjected to deicing chemicals) is 0.18 mm (0.007 inches). Therefore the performance of the bridge will be determined by comparing visible cracks and their respective widths to ACI Committee 224's recommended maximum tolerable crack width for preventing the intrusion of deicing chemicals.

The research activities involved were the development of mixture proportions, quality control testing, and advice on the construction, monitoring and evaluation of the

structure by periodic condition survey. The test program on fresh concrete included: slump, concrete temperature, fiber content, air content, vebe time, and unit weight. The hardened concrete properties determined were: compressive strength, static modulus, modulus of rupture, load-deflection curves, first crack toughness, strength and post crack behavior, ASTM toughness indices, Japanese toughness index, equivalent flexural strength, and impact strength. The mixture proportions used, the procedure used for mixing, transporting, placing, consolidating, finishing, tining and curing are described.

The polyolefin fibers were incorporated in the concrete at a rate of 14.8 Kg/cu.m.(25 lbs/cu.yd.). No clogging or segregation was observed during the mixing and placing operations. However some unopened bundles (which led to balling) were observed during the placement operation. This was corrected by altering the mixing procedure. The same low slump dense concrete bridge deck overlay construction techniques and construction equipment without any modification were used in the construction. No difficulty was faced during transporting, placing or tining the concrete, and the workability was satisfactory. The fresh concrete properties recorded during construction were satisfactory, except that the air contents measured in two trucks were above the specified limit. The air content varied from 5.4 % to 8.2 %. The slump varied from 6.35 mm (0.25 inches) to 31.75 mm (1.25 inches). The mean 28 day compressive strength was 44.07 Mpa (6368 psi) for the casting done on May 16, 1997 and 37.76 MPa (5459 psi) for the casting done on June 3, 1997, which is above the minimum required compressive strength as specified by the DOT, 31.05 Mpa (4500 psi). There was significant increase in the impact strength, toughness, post-crack load carrying capacity and flexural strength. The toughness indices showed an increase in elasto-plastic behavior of the concrete in comparison to the plain concrete.

The unit cost of the concrete increased only slightly by $26 due to the addition of fibers. The only additional cost involved in the mixing, placing, and finishing operations was the expense incurred for adding the fibers to the concrete at the ready-mix plant. This additional cost was justified due to the achieved reduction in crack widths in the bridge deck overlay thus enhancing the durability of the structure.

Periodic inspections of the newly constructed bridge deck overlay were made. The post construction performance of the bridge deck overlay was satisfactory and as anticipated. It was observed that the polyolefin fibers helped to contain the crack propagation. Immediately after the curing period, no plastic shrinkage cracks were observed over the entire deck overlay. After a three month period, numerous cracks were observed on the east bound bridge deck overlay, but mostly of negligible widths 0.10 mm (0.004 inches). The pattern of a larger number of cracks with smaller harmless widths was observed and this was an anticipated desirable behavior.

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GLOSSARY

The following is a glossary of terms for fiber reinforced concrete (FRC) used in this report.

0.1 General Terms

Aspect Ratio - The ratio of length to diameter of the fiber. Diameter may be equivalent diameter.

Balling - When fibers entangle into large clumps or balls in a concrete mixture.

Collated - Fiber bundled together either by cross-linking or by chemical or mechanical means.

Equivalent Diameter - Diameter of a circle with an area equal to the cross-sectional area of the fiber.

Fiber content - The weight of fibers in a unit volume of concrete.

Fibrillated - A fiber with branching fibrils.

First Crack - The point on the flexural load-deflection or tensile load-extension curve at which the form of the curve first becomes nonlinear.

Hairline Crack – Cracks with widths less than 0.1 mm (0.0039 inches) are termed as hairline cracks.

First Crack Deflection - The deflection value on the load deflection curve at the first crack.

First Crack Strength - The stress obtained when the load corresponding to first crack is inserted in the formula for modulus of rupture given in ASTM Test Method C 78.

First Crack Toughness - The energy equivalent to the area of the load deflection curve up to the first crack.

Flexural Toughness - The area under the flexural load-deflection curve obtained from a static test of a specimen up to a specified deflection. It is an indication of the energy absorption capability of a material.

Toughness Indices - The numbers obtained by dividing the area under the load-deflection curve up to a specified deflection by the area under the load-deflection curve up to "First Crack" as given in ASTM C 1018.

Toughness Index, I_5 - The number obtained by dividing the area up to 3.0 times the first crack deflection by the area up to the first crack of the load deflection curve, as given in ASTM C 1018.

Toughness Index, I_{10} - The number obtained by dividing the area up to 5.5 times the first crack deflection by the area up to the first crack of the load deflection curve, as given in ASTM C 1018

Toughness Index, I_{20} - The number obtained by dividing the area up to 10.5 times the first crack deflection by the area up to the first crack of the load deflection curve, as given in ASTM C 1018

Residual Strength Factor $R_{5,10}$ - The number obtained by calculating the value of $20(I_{10}-I_5)$, as given in ASTM C 1018.

Residual Strength Factor $R_{10,20}$ - The number obtained by calculating the value of $10(I_{20}-I_{10})$, as given in ASTM C 1018.

Flexural Toughness Factor (JCI) - The energy required to deflect the fiber reinforced concrete beam to a mid point deflection of 1/150 of its span.

Equivalent Flexural Strength (JCI) - It is defined by

$$F_c = T_b \times s/\delta_{tb} \times b \times d^2$$

where

F_c = equivalent flexural strength, psi

T_b = flexural toughness, inch-lb

s = span, inches

δ_{tb} = deflection of 1/150 of the span, inches

b = breadth at the failed cross-section, inches

d = depth at the failed cross-section, inches

Impact Strength - The total energy required to break a standard test specimen of a specified size under specified impact conditions, as given by ACI Committee 544.

Monofilament - Single filament fiber.

Static Modulus - The value of Young's modulus of elasticity obtained from measuring stress-strain relationships derived from other than dynamic loading.

High Performance Concrete - In this report, High Performance Concrete is defined as a concrete with highly enhanced (or improved) desirable properties for the specific purpose and function for which it is used. It need not necessarily be high-strength concrete. High performance concrete may have one or more of the following properties enhanced: ductility, fatigue strength, durability, impact resistance, toughness, impermeability and wear resistance.

Whitetopping - Whitetopping is concrete placed over asphalt where the concrete thickness is 101 (4 inch) or more mm thick.

Ultra-Thin Whitetopping - Ultra-Thin Whitetopping is concrete placed over asphalt where the concrete is less than 101 mm (4 inch) thick.

0.2 Acronyms Used

ACI - American Concrete Institute

CFP - Collated Fibrillated Polypropylene

FRC - Fiber Reinforced Concrete

LS - Low Slump

NMFRC - Non-Metallic Fiber Reinforced Concrete. This acronym refers only to Polyolefin Fiber Reinforced Concrete. These fibers were manufactured and purchased from 3M for the purpose of this study.

NMFRS - Non-Metallic Fiber Reinforced Shotcrete

PFRC - Polypropylene Fiber Reinforced Concrete

PCC - Portland Cement Concrete

SFRC - Steel Fiber Reinforced Concrete.

SNFRC - Synthetic Fiber Reinforced Concrete

SIFCON - Slurry Infiltrated Fiber Concrete

SIMCON - Slurry Infiltrated Mat Concrete

0.3 ASTM Specifications

A 820 - Specification for Steel Fibers for Fiber Reinforced Concrete

C 31 - Practices for Making and Curing Concrete Test Specimens in the Field

C 39 - Test Method for Compressive Strength of Cylindrical Concrete Specimens

C 78 - Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-point Loading)

C 94 - Specification for Ready-Mixed Concrete

C138 - Test for Unit Weight, Yield and Air Content (gravimetric) of concrete

C 143 - Test Method for Slump of Portland Cement Concrete

C 172 - Method of Sampling Freshly Mixed Concrete

C 173 - Test Method of Air Content of Freshly Mixed Concrete by the Volumetric Method

C 231 - Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method

C 469 - Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression

C 995 - Test Method for Time of Flow of Fiber Reinforced Concrete Through Inverted Slump cone

C1018 - Test Method for Flexural Toughness and First Crack Strength of Fiber - Reinforced Concrete (Using beam with Third-point Loading)

C 1116 - Specification for Fiber Reinforced Concrete and Shotcrete

0.4 International Standards

A - American Concrete Institute Committée 544 Fiber Reinforced Concrete

ACI 544.2R.89 Flexural Fatigue Endurance

Impact Resistance

Toughness

B - British Standards Institute

BS1881: Part 2, Methods of Testing Concrete-Vebe Test

C - Japanese Society of Civil Engineers

JSCE Standard III-1, Specification of Steel Fibers for Concrete, Concrete Library, No. 50, March 1983.

- JSCE-SF4 Standard for Flexural Strength and Flexural Toughness, "Method of Tests for Steel Fiber Reinforced Concrete," *Concrete Library of JSCE,* No. 3, June 1984, Japan Concrete Institute (JCI), pp. 58-66.

- "Standard Test Method for Flexural Strength and Flexural Toughness of Fiber Reinforced Concrete, (Standard SF4),"*JCI Standards for Test Methods of Fiber Reinforced Concrete,* Japan Concrete Institute, 1983, pp. 45-51.

SECTION I

INTRODUCTION

The most widely used construction material in the world is concrete. Concrete has a low relative cost, is easily available, is an incorporation of local materials, is versatile in its use, has a strong strength capacity and adaptivity for different environments. However, concrete has the drawbacks of low tensile strength (8 - 10% of its compressive strength) and lack of adequate ductility. Temperature/moisture variations throughout the cross section of a concrete structure cause microcracking in concrete. These microcracks can develop as macro cracks under applied stress leading to the failure of the plain concrete structure. As plain concrete is mostly slab on grade, the service life will be effected by the frequency of loading and amount of loading.

Research on the brittleness of concrete and its lack of crack control before failure of the matrix had been done in great detail for years. In the past three decades the addition of fibers to the concrete matrix had been studied with interest. Various types of fibers were used to reinforce concrete and the performance characteristics of fiber reinforced concretes were studied. The fibers act as a three dimensional reinforcement and enhance quantifiable durability properties such as impact resistance, fatigue strength and modify the cracking mechanism. The presence of fibers in the concrete matrix resists the propagation of microcracking to macrocracking. This reduces the permeability of the matrix and the ultimate cracking strain of the concrete is increased. Plain concrete specimens fail at the point of ultimate flexural strength or at first crack, but fiber reinforced concrete has the applied stress transferred from the matrix to the fiber elements when the matrix cracks, thus enhancing the ductility, toughness, impact resistance, tensile strength, flexural strength, fatigue life, abrasion resistance, shrinkage, durability, and cavitation resistance.

The principle of reinforcing concrete with fibers has stayed the same over the years but the diversity in the fiber types, shapes, sizes, textures, volume, mode of addition etc. have been widely experimented. The workability of fiber reinforced concrete that facilitates the concrete to be placed, compacted and finished with ease and the uniform distribution of the fibers in the matrix had been the focus of attention as the possible problems to be encountered in this technology.

The increasing awareness and the enhancement of the fibers led to extended diversification of its applications. The numerous types of fibers that are presently being commercially employed are steel, glass, synthetic (polymeric) and carbon. A wide variety of natural fibers like coconut, sisal, jute, coir, wood pulp, bamboo, akwara, cotton, armid, and asbestos also find limited use in reinforcing concrete. Fiber reinforced concrete is employed in the construction of pavement overlays for airfields, highways, bridges, machine foundations, blast resistant structures, piles, pipes, sea protective structures, ship hulls, storage tanks and even concrete canoes. It is also utilized in shotcreting for rehabilitation of damaged structures, tunnel lining, and slope stabilization where it has proved to be more economical than the traditional steel mesh and plain concrete.

The property enhancement of the fiber reinforced concrete is found to be in direct proportion to the volume of fibers added to the mix. The amount of paste present in the mix controls the ability of the concrete matrix to incorporate fibers. The physical shape, aspect ratio and surface area of the added fibers are important properties to be considered to avoid the balling of the fibers and to ensure a good and workable mix. The 3M Company, St. Paul, Minnesota, USA, has developed polyolefin fibers - a synthetic fiber with low aspect ratio. Research is being continued on these fibers by varying their aspect ratios, texture, shape and other physical qualities and the volume of fibers added to the matrix. This study focuses on the performance characteristics of these polyolefin fibers in the construction of two low-slump dense NMFRC bridge deck overlays to extend the life of the existing bridges due to shortages of funds.

LITERATURE SURVEY

In its first state-of-the-art report on fibers used to reinforce concrete in 1973 the American Concrete Institute defines fiber reinforced concrete as "Concrete made of hydraulic cements containing fine, or fine and coarse aggregates and discontinuous discrete fibers". This definition was endorsed by the ACI again in 1982 (10). RILEM - the European counterpart of the ACI defines fiber concrete as "made from hydraulic cements without or with aggregates of various sizes and incorporating, in the main, discrete fiber reinforcements" (1).

The concept of reinforcing relatively brittle building materials with fibers has been conceived and applied since ancient times. Some primitive examples of the use of fibers to reinforce construction materials that date well back in history are mud huts constructed with baked clay reinforced with straw, and masonry mortar reinforced with animal hair. The present day history of fiber development and use in cementitious matrices dates from the late 1800's - manufacture of asbestos-cement sheeting by the Hatschek process. The basic idea in both the historic and recent examples is to enhance the properties of an inherently weak and brittle cementitious matrix to increase tensile strength and ameliorate brittleness by the addition of fibers giving improved ductility and toughness. The availability of different fiber types, shapes, sizes, and the chemical and mineral admixtures has increased greatly over the years to enhance matrix characteristics. Among the commonly available fiber types glass fibers have been available since about 1920 and received a boost in its application with the development of fiber glass in 1960's. Although a patent to use short pieces of steel in reinforcing concrete dates from 1913, it was only after 1964 that they were actively used in construction. Interest in the use of other fiber types has increased in the 1970's onwards and the types of natural and synthetic fibers in the market at present are numerous. Polyolefin fiber is a new entry in this family. This non-metallic fiber used to reinforce concrete is found to supersede all the previously known fibers in its performance and is in a relatively new stage in its field applications (4).

Polyolefin Fibers

The aspect ratio (defined as the fiber length divided by the fiber diameter) of a fiber is an important property to look for in terms of workability of the fresh concrete. Typical aspect ratios range from 30 to 150 with length dimensions of 7 to 76 mm (0.25 to 3.00 inches). If the aspect ratio is high (small diameter and great length) balling of the fibers in the mixing process will occur. Conversely a high aspect ratio is desirable for the finished product, the hardened concrete. The ability of a specimen to withstand load in the post crack region is highly dependent on the aspect ratio. Therefore the best performing FRC will then be a mix with fibers as long as possible, and still able to provide good workability so as to provide a good compaction. The performance of synthetic fibers would thus be similar if not superior to the steel fibers in terms of aspect ratio, workability and hardened concrete properties.

The Polyolefin fibers manufactured by the 3M company St. Paul MN has an aspect ratio similar to steel but superior qualities in terms of hardened concretè properties. It also satisfies the need for a chemically inert, non-corrosive, non-magnetic fiber to reinforce concrete. The low unit weight of polyolefin fiber (1/8 of steel) and a cost as low as $2.00/lbs strengthens the chances of polyolefin fibers to dominate the other types of fibers in the market. Polyolefin fibers out perform steel fibers at comparable quantities on an equal weight basis, and therefore, are more effective than steel fibers. These fibers can be incorporated in concrete with conventional equipment and procedures(5).

The proprietary delivery system developed by the 3M Company provides uniform distribution of even higher dosages of fibers into concrete composites without the loss of workability in the fresh concrete. The current synthetic fiber (nylon and polypropylene fibers) loading is typically 0.1 to 0.3 % by volume and steel fiber loading is typically up to 1.0 % by volume. The limiting factor in achieving higher loading was the challenge to mechanically incorporate fibers uniformly in concrete. Polyolefin fibers 0.63 mm (0.025 inch) diameter and 50 mm (2 inch) length could be added to concrete 1.0 % to 4.0 % by volume of the concrete using the new delivery system (5,8,9).

Extensive research has been done and is being continued by Ramakrishnan in the laboratories of South Dakota School of Mines and Technology to evaluate the performance qualities of the polyolefin fibers in reinforcing concrete (5,8,9).

Properties of polyolefin fiber reinforced concrete

Fresh concrete properties

The workability and finishability of this non-metallic fiber reinforced concrete is found to be satisfactory. No significant balling or segregation is observed. It abides by the fact that the amount of fiber allowed by a mix, without balling and segregation will always depend on the amount of paste in a cementitious mix versus volume and that the paste has to cover the total surface area of the fiber introduced in the mix. The slump decreases considerably due to the addition of the fibers in comparison to the plain concrete. This can be adjusted by the addition of admixtures such as superplascticizers. The unit weight of the NMFRC is found to be similar to that of plain concrete. The air content of the polyolefin fiber reinforced concrete is found not to exceed normal values of entrained air and varies within the variance for normal concrete (6,11,12).

Hardened Concrete Properties

Compressive Strength

The NMFRC cylinders tested for compressive strength and elastic modulus fail with a vertical crack appearing and extending gradually. Unlike plain concrete no shear failure (cylinders fail along about 45° line) occurs, when the NMFRC specimens fail they are held together by the fibers and can withstand further deformation without falling apart. The fibers are credited with the capability to hold the concrete from falling apart. The compressive strength or elastic modulus values do not differ much from that of the plain concrete specimens.

Flexural Strength

There is a significant increase in the flexural strength of concrete due to the addition of polyolefin fibers. The plain concrete specimens break completely at failure but the NMFRC specimens are held together by the evenly distributed polyolefin fibers. The specimens continue to take load after failure and the cracks continue to widen. With a higher quantitiy of fibers, a larger number of cracks with smaller widths form as loads increase as compared to plain concrete. The NMFRC specimens can even take more load after first crack depending on the fiber volume.

Toughness Indexes

The toughness indices and toughness ratios determined according to ASTM and Japanese (JCI) procedures prove that the NMFRC specimens have increased ductility as compared to plain concrete. The toughness ratio remains below 2.0 indicating that there is no perfect elasto-plastic behavior, however the ductile properties are greatly improved. The high values of I5, I10, I20 indicate that the NMFRC absorbs much more energy than plain concrete before failure.

Impact Strength

The impact strength of the NMFRC is improved very significantly when compared to any other types of fiber reinforced concrete or plain concrete. The fibers come into play significantly when the first crack forms and resist the propagation and widening of the cracks. The impact strength increases with an increase in the aspect ratio of the fibers. The increase in impact strength can be as high as 1500% of the impact strength of the plain concrete with same mixture proportions.

Fatigue Strength

When exposed to fatigue (dynamic loading) the NMFRC matrix clearly distinguishes itself from the plain concrete. Extensive research has shown that the flexural fatigue strength is significantly increased when fibers are added to the mix compared to the non-reinforced matrix (6,21).

The properties of polyolefin fiber concrete having a fiber addition rate of 14.8 kg/m^3(25lbs/yd^3) are compared with the properties of the two types of steel fiber reinforced concrete both having 39.1 Kg/m^3 (66 lbs/cu.yd.) fibers in the Table 1 (6).

Table 1: Comparison of Properties of Steel and Polyolefin Fiber Concretes

	Steel Corrugated	Steel Hooked	3M Fiber 32M4
Compressive Strength (psi)	39.24 MPa 5687 psi	35.54 MPa 5150 psi	34.54 MPa 5006 psi
Static Modulus	34224 MPa 4.96×10^6 psi	34500 MPa 5.00×10^6 psi	29670 MPa 4.30×10^6 psi
First Crack Flexural Strength (psi)	3.93 MPa 570 psi	4.93 MPa 715 psi	4.88 MPa 707 psi
Max Flexural Strength (psi)	3.93 MPa 570 psi	5.76 MPa 835 psi	6.07 MPa 879 psi
ASTM Toughness I_5	3.63	4.76	3.94
ASTM Toughness I_{10}	6.19	9.31	7.47
ASTM Toughness I_{30}	-	23.18	21.97
Impact: Number of blows up to first crack	-	20	242
Number of blows for failure	-	107	1159

Applications of polyolefin fiber reinforced concrete

Based on the continuing research the polyolefin fibers are found to be more suited than steel fibers for the construction of certain types of structures like pavements, thin bridge-deck overlays, full depth bridge decks, barriers and overlays over asphalt pavements (whitetopping). As this fiber is new in the market very few projects have been constructed with this fiber. The most significant projects so far have been done by the SDDOT (6, 20).

The construction projects undertaken to evaluate the performance characteristics of the non-metallic fiber reinforced concrete were part of repair, rehabilitation and construction of the following structures:

1. Low-slump dense concrete bridge deck overlay on the bridge at Vivian (the bridge on the U.S.83 No. 43-026-195, over I-90, south of Pierre, SD.)
2. Jersey Barrier on the above referred bridge.

3. Whitetopping test section on the asphalt bridge approach road.

4. Full Depth fiber (both steel and polyolefin) - reinforced concrete pavement, on Sheridan Lake Road in Rapid City, SD (3).

5. Full Depth Bridge Deck and Jersey Barrier at Spearfish (the bridge on Exit 10, I-90).

6. Evaluation of NMFRC Whitetopping, Project SD 96-13.

7. Evaluation of Non-Metallic Fiber Reinforced Concrete in Full Depth PCC Pavement - SD 96-15.

Studies 6 and 7 are under progress and have not yet been completed.

The observations made during the construction of these seven projects are given below:

Workability

In all the five construction applications no balling or segregation was observed and the mixing, transporting, placing, consolidating, tining and finishing were done satisfactorily without any difficulties. The same construction techniques, and construction equipment as that of PCC without any major modification were used. All the SDDOT - standard specification for the mix were met such as low slump dense concrete with high cement content (section 560.A2) used for bridge deck overlays.

Structural Qualities

The polyolefin fibers were found to have the structural benefits of steel fibers in concrete and material benefits of polyolefin. In all the projects the addition of polyolefin fibers enhanced the structural properties of concrete. The improvement was higher with higher dosage. A slight increase in the flexural strength and a considerable increase in the toughness, impact and fatigue strengths, endurance limit and post-crack loading were observed. This enhancement was the same or in some cases (such as impact) better than the improvement that could be achieved with the addition of 39.1 kg/m^3 (66 lbs./cu.yd.) of the best available steel fiber in the market. The performance evaluation with periodic inspections showed that all five structures performed satisfactorily. The addition of fibers reduced the average shrinkage crack width to a level tolerable for its exposure. And, as expected, a larger number of uniformly distributed thinner cracks formed which is a more desirable crack distribution (6).

Polyolefin Fiber Reinforced Shotcrete (NMFRS)

Experimental investigations have shown that it is possible to add 1.0 and 2.0 % by volume of 25 mm (1 inch) long and 0.38 mm (0.015 inch) diameter polyolefin (3M) fibers directly to a ready-mix concrete truck and get a good distribution of the fiber throughout the mix, and to pump and shoot the mix without any difficulty. It should be noted that so far all commercially available synthetic fibers (both nylon and polypropylene) could not be successfully added to wet-mix shotcrete at 1 to 2 % by volume. Polyolefin fibers can be successfully added to wet-mix shotcretes at 8.9 Kg/m^3 (15 lb/cu.yd.) and 17.8 Kg/m^3 (30 lbs/cu. yd.). These shotcretes performed equivalent or better in toughness tests (both ASTM C 1018 and Japanese JSCE-SF4) than the best quality steel fibers added at an addition rate of 54.6 Kg/m^3 (92 lbs/cu. yd.) (0.7 % volume) and superior performance to lesser quality steel fibers added at the same dosage of 54.6 Kg/m^3 (92 lbs/cu. yd.) (0.7 % volume) (7).

BACKGROUND

Due to a decaying infrastructure and tightening budget constraints, transportation engineers are challenged to rehabilitate existing facilities economically with an increase in performance. However, simultaneous improvements in cost and performance are unlikely unless new material technology can be exploited.

Polyolefin fiber reinforced concrete is one material that promises to provide many advantages over steel and polymeric fibers while providing a practical approach to enhanced durability and cost-effectiveness in concrete compositions. Currently, polypropylene fibers are typically used at 0.1% to 0.3% by volume in concrete to reduce plastic shrinkage cracking. These fibers provide only minimal benefit to the mechanical properties of hardened concrete. Steel fiber, used more extensively in Europe, is typically incorporated in quantities up to 0.5% by volume, and while it does enhance the structural performance of hardened concrete, it poses other problems such as staining, inherent corrosion and potentially harmful protrusions.

Polyolefin fiber reinforced concrete incorporates 50 mm by 0.64mm (2" by 0.025") fibers into the concrete mix. These fibers are longer and stronger than plastic fibers previously used to reinforce concrete, and a proprietary packaging technology enables rapid and uniform mixing into the concrete matrix at quantities up to 2% by volume. These volumes of fiber significantly alter the concrete's physical properties, especially toughness, ductility and resistance to shrinkage cracking. The improved properties make polyolefin fiber reinforced concrete an attractive material for bridge deck overlays.

To be successful and long-lived, a deck overlay must be durable and resistant to fatigue, and must have only thin cracks (less than 0.178mm(0.007in)) and these cracks must be held tightly to resist intrusion of chlorides. In the past, transportation agencies throughout the nation have found these requirements (especially low cracking) are difficult to achieve. Several research projects have been undertaken to solve these problems, but with limited success. However, these challenges perfectly match polyolefin fiber reinforced concrete's characteristics.

The South Dakota Department of Transportation has sponsored research to investigate the properties and practicality of polyolefin fiber reinforced concrete. Through laboratory tests at the South Dakota School of Mines and Technology and construction of a segment of pavement, a bridge deck overlay, concrete barrier replacement, and a thin unbonded overlay of asphalt bridge approaches, the material proved to be workable and significantly more resistant to early cracking than ordinary concrete. The research results demonstrated increased fatigue capacity of 150%, crack width reductions below American Concrete Institute (ACI) recommendations for chloride intrusion, and skid resistant surface texture. In the opinion of the Department, the favorable research results warrant more widespread use of polyolefin fiber reinforced concrete in other applications, including bridge deck overlays.

PROJECT DESCRIPTION

Due to tightening budget constraints and reprogramming of construction funds, two badly deteriorated structures at Exit 32 on I-90 could not be reconstructed during fiscal year 1997 and may not be reconstructed for as many as seven more years. Since their replacement is delayed, their condition clearly indicated some form of rehabilitation was necessary. The possible types of rehabilitation were deck replacements and deck overlays. When considering the bridges will be reconstructed soon, deck overlays become more economical than deck replacements. Since each deck is badly deteriorated, minimal partial depth removal of concrete was done after a typical scarification. Therefore, for these bridges the SDDOT enhanced its present deck overlay system by reinforcing it with non-metallic fibers. Previous SDDOT research indicates that the performance of pavements, bridge decks, bridge deck overlays, and bridge barriers can be enhanced by utilizing non-metallic fiber reinforced concrete (NMFRC).

In a previous study, SD94-04, one aspect of the project was to construct an NMFRC deck overlay for the Vivian Interchange on I-90. Usually, for deck overlays, a plain low-slump dense (LSD) concrete is produced by a mobile-mixer. In this study, attempts were made to produce a LSD NMFRC with a mobile-mixer. However, after determining that the mobile-mixer could not meter the fiber addition rate and the mixing chamber could not evenly distribute the fibers, a different means of producing the LSD NMFRC had to be found. With some skepticism, testing was done to produce and deliver the necessary concrete with redi-mix trucks. This test proved that the desired product could be obtained.

Even though a LSD NMFRC deck overlay had successfully been constructed, research was necessary to give the Department additional experience with this method of producing and delivering a LSD NMFRC, to ensure that the desired concrete product is obtained, and to evaluate it's performance over the badly deteriorated bridge decks at Exit 32. The following information are some specifics about these bridges.

- Constructed in 1963.
- Girder Spacing is 2.7m(8' 10").
- Bridge skew is 47 degrees.
- Deck thickness prior to overlay was 165mm(6.5").
- Clear cover between the top layer of steel and the deck's top surface was 38mm(1.5").
- Span lengths are 17m(55' 9"), 19.8m(65'), and 17m(55' 9").
- Recent maintenance costs were about $3,000/year/bridge(this is a rough estimate).
- Deck reinforcing steel is black.
- These bridges experienced a heavy use of deicing chemicals.

RESEARCH OBJECTIVE

- To recommend LSD NMFRC mix design and construction methods which will enhance deck overlay performance.
- To evaluate performance and constructability of LSD NMFRC deck overlays.

RESEARCH PLAN

The following tasks which were clearly specified in the "Request for Research proposal" were performed in this project.

Task 1. Meet with Technical Panel to discuss the research topic and work plan.

Task 2. Review and summarize literature to identify previous work and procedures concerning FRC.

Task 3. Construct, monitor, and evaluate two bridge deck overlays at Exit 32 on I-90.

Task 4. Submit a final report summarizing relevant literature, research methodology, inspection procedures, test results, costs, specifications, design standards, conclusions, and recommendations.

Task 5. Make an executive presentation summarizing the findings and conclusions.

MATERIALS

Fibers

The non-metallic fibers (Polyolefin fibers) were supplied by 3M, St. Paul, MN. The non-metallic fibers type 50/63 were 50.0 mm (2.00 inch) long and 0.63 mm (0.025 inch) diameter. There were about 20,000 fibers per pound. Several hundred individual fibers were wrapped together in approximately 50 mm (2 inch) diameter bundle, and were packaged 11.3 kg (25 lbs.) per box. Typical physical properties of 3M polyolefin Type 50/63 are given below.

Specific Gravity	0.91
Tensile Strength	275 MPa (40,000 psi)
Modulus of Elasticity	2647 MPa (384,000 psi)
Elongation at Break	15 - 17 %
Ignition Point	593°C (1100°F)
Melt Point	160°C (320°F)
Chemical and Salt Resistance	Excellent
Alkaline Resistance	Excellent
Electrical Conductivity	Low

Materials Used In The Lab For The Trial Mixes

Cement: Type I/II normal Portland cement satisfying the requirements of ASTM C150, produced by Dacotah Cement, Rapid City, South Dakota was used.

Aggregate: The coarse aggregate was of 9.5mm(3/8 inches) maximum size crushed limestone, the fine aggregate used was natural sand with a fineness modulus of 2.89 and an absorption coefficient of 1.64 %. But the coarse and fine aggregate used, were within the gradation requirements of ASTM C33, and produced locally in Rapid City, South Dakota.

Water: The water used for the trial mixes was tap water from the Rapid City municipal water supply system and the temperature was maintained around 68 °F.

QUALITY CONTROL TEST

Tests for Fresh Concrete

The fresh concrete was tested for slump (ASTM C 143), air content (ASTM C 231), fresh concrete unit weight (ASTM C 138) and concrete temperature. The yield of the concrete was determined. The concrete from the unit weight container was washed and the fibers were separated and weighed to determine the actual fiber content in a cubic yard of concrete.

Tests for Hardened Concrete

Compressive Strength & Static Modulus

Cylinders were tested for compressive strength at ages of 7 and 28 days according to ASTM C 39. Prior to the compression test the cylinders were also tested for the static modulus of elasticity (ASTM C 469) and for dry unit weight. The dry unit weight was obtained by dividing the weight of the specimen by the measured volume of the specimen.

Static Flexure Test

The beams were tested for static flexural strength (ASTM C 1018) at ages of 7 and 28 days. According to ASTM C 1018, the beams were tested over a simply supported span of 300 mm (12 inch) and third point loading was applied to the beams. The deflection was measured at the mid-span by using a dial gage accurate to 0.00254 mm (0.0001 inch). The deflections were measured using a specially fabricated frame. It was possible to measure the actual deflections eliminating all extraneous deflections due to the crushing of concrete and testing machine deformations. This test was a deflection controlled test. The rate of deflection was kept in the range of 0.05 mm to 0.10 mm (0.002 to 0.004 inch) per minute as per ASTM C 1018. The loads were recorded at every 0.0254 mm (0.0001 inch) increment in deflection till the first crack appeared after which the loads were recorded at regular intervals. The load corresponding to first crack and the maximum load reached were noted for each specimen. From the test results, load-deflection curves were drawn and ASTM toughness indices were calculated. The flexural toughness factor and equivalent flexural strength were also calculated using the Japanese standard method.

Impact Test

The specimens were tested for impact strength at an age of 28 days by the drop weight test method (ACI Committee 544). In this method, the equipment consisted of a standard manually operated 4.54 kg (10 lbs) weight with a 457 mm (18 inch) drop (compactor), a 63.5 mm (2-1/2 inch) diameter hardened steel ball, a flat steel base plate with a positioning bracket and four positioning lugs. The specimen was placed on the base plate with its rough surface facing upwards. The hard steel ball was placed on the top of the specimen and within the four positioning brackets. The compactor was placed with its base on the steel ball. The test was performed on a flat rigid surface to minimize the energy losses. The hammer was dropped consecutively, and the number of blows required to cause the first visible crack on the specimens was recorded. The impact resistance of the specimen to ultimate failure was also recorded by the number of blows required to open the crack sufficiently so that the pieces of specimen were touching at least three of the four positioning lugs on the base plate.

SECTION II

This project was undertaken to extend the life of two badly deteriorated bridge decks through the enhancement of SDDOT's present low-slump dense (LSD) concrete overlay system by incorporating 3M's polyolefin fibers. SDDOT wanted to enhance their present LSD concrete overlay system because, the condition of these bridges was so poor that there was a question whether the normal LSD concrete would last.

Also, a LSD NMFRC would be more likely to hold together and minimize large cracks, spalling, and loss of material from the top of the deck. Therefore, the potential for hazards to the public would be reduced. The project involved two complete bridge deck overlays at Exit 32 over Interstate 90 near Sturgis, South Dakota. The entire bridge deck was overlaid using concrete reinforced with polyolefin fiber. The completed primary tasks of the project are given below:

Research Task 1 – Meet with Technical Panel to discuss the research topic and work plan.

The Principal Investigator (PI) met with the Technical panel to review the total project and made the necessary revisions in the procedures, methods and proposed tasks as per suggestions, comments, and instructions from the Technical Panel. The meeting with the Technical Panel was found to be very useful and very productive.

Research Task 2 – Review and summarize literature to identify previous work and procedures concerning FRC.

In a previous study, SD94-04, a comprehensive literature review concerning FRC was reported. Recently some additional publications were available. Therefore, the previous review was updated with particular reference to polyolefin fiber reinforced concrete in Section I.

Research Task 3 – Construct, Monitor, and Evaluate two bridge deck overlays at Exit-32 on I-90.

a) Design the concrete mix and conduct test to ensure desired properties.

The mixture proportion was selected based on the laboratory experience and field experience from the construction of the bridge deck overlay at the Vivian bridge prior to the start of the project. Actual aggregates to be used in the project were obtained from the contractor. Five trial mixes (TD1 to TD5) were made at the SDSMT Concrete Technology laboratory. The mix design was done for a polyolefin fiber addition of 14.8 kg/m^3 (25 lbs/cu.yd.) and to satisfy or exceed the SDDOT specifications for Roads and Bridges, Section 550.3 A-2. Based on the trial mixes and in consultation with the SDDOT engineer, the final mixture proportions were recommended.

The testing program included both fresh and hardened concrete properties. Appropriate ASTM and ACI standard test methods were used to determine:

* slump	* modulus of elasticity
* air content	* flexural strength
* unit weight	* impact strength
* yield	* toughness indices
* concrete temperature	* residual strength factor
* finishability	* flexural toughness factor by Japanese Standard
* compressive strength	* equivalent flexural strength by Japanese Standard

The trial mix designations, mixture proportions and fiber details are given Table A1, and the fresh concrete properties are given in Table A2, Appendix A. The effect of air entrainments was investigated in trial mixes TD1 to TD5. The air content varied from 3.8% to 5.4% for trial mixes TD1 to TD5. The slump also increased from 12.7mm (0.5 inches) to 15.87mm(0.625 inches). The 7-day, 28-day compressive strengths, unit weights, and static modulus values are given in Table A3, Appendix A. The average 7-day compressive strength for the mix TD4-5 was 33.1 MPa (4802 psi), the average 28-day compressive strength was 45.1 MPa (6539 psi). The compressive strengths are shown in Figure A1, Appendix A. First crack strengths and modulus of rupture values are given in Table A4, and shown in Figures A2 and A3 in Appendix A. The modulus of rupture for 7-days was 5.3 MPa (764 psi) and the 28 day strength was 5.9 MPa (858 psi). The First Crack Toughness values are shown in Figure A4, Appendix C. The ASTM toughness indices and toughness ratios are given in Table A5 and shown in Figures A5 and A6 in Appendix A. The Japanese Standard toughness and equivalent flexural strength values are given in Table A6, Appendix A. The JCI Toughness values obtained for the 7-day and 28-day were 19.3 Nm (171 inch-lbs). The JCI Equivalent flexural Strengths for 7-day and 28-day were 2.63 MPa (382 psi) and 2.60 MPa (378 psi). The comparison of JCI Toughness and Equivalent Flexural Strength is shown in Figures A7 and A8 in Appendix A. The ASTM residual strength factors are given in Table A7 and the comparison is shown in Figure A9 in Appendix A. The 28-day impact strengths are given in Table A8. The average number of blows for the first crack for TD4 mix was 77 and for TD5 mix it was 50. The average number of blows to failure for TD4 mix was 294 and for TD5 mix it was 282. The comparison graph is shown in Figure A10. Based on the results obtained from trial mixes the mix TD5 was selected for use on the project.

The following are the fresh and hardened concrete properties for the selected concrete; slump 15.87 mm (0.625 inch), air content 5.4 percent, fresh concrete unit weight 86.62 kg/cu.m. (146 pcf), 1-day, 3-day, 7-day, 14-day, and 28-day compressive strengths were 17.6 MPa (2550 psi), 26.0 MPa (3770 psi), 33.1 MPa (4800 psi), 34.2 MPa (4955 psi), and 45.1 MPa (6540 psi). The 7-day, 14-day, and 28-day flexural strengths were 5.3 MPa (764 psi), 6.0 MPa (870 psi), and 5.9 MPa (858 psi). The ASTM toughness indices and the residual strength factors were highly satisfactory. The Japanese Standard toughness was 19.3 Nm (171 inch-lb), and the equivalent flexural strength was 2.6 MPa (378 psi). The impact strengths were 50 blows for first crack and 282 blows for final failure.

The tests conducted by the DOT during the construction of the overlays are included in the Appendix D. These results were similar to the results obtained for the trial mixes done at the Concrete Technology Laboratory, SDSM&T. They were also very close to the test results obtained from concrete samples taken during the construction by the research team.

b) Pre-construction Meeting

The research associate attended the pre-construction meeting and presented the test results of the trial mixes.

c) Pre-Condition Survey

The pre-construction condition surveys were done on May 15 and June 2, 1997 after deck slabs had been milled and all loose concrete had been removed. The exposed rebar had been sand blasted to remove the corrosion. There was severe map cracking on the bottom surface of the deck, as close as 75 to 100 mm(3 to 4 inches)(Photo 1). A number of partial and full-depth repair patches were also observed (photos 2 & 3). The final condition survey was done a few hours before the concrete was placed. The sketches of the pre-condition survey are shown in Appendix C. Photographs were also taken showing the milled decks, approach pavement surfaces and the exposed rebar (photos 3,4 & 5). In general more deterioration was observed on the west bound lanes than on the east bound lanes.

Shortly after deck scarification each deck was chained for delamination. Results of this process found roughly 90% of each deck to be delaminated. With the exception of several maintenance patches in various locations, both the driving and passing lanes were found to contain equal areas of delamination for each deck. Both bridge decks were found to be affected equally.

Chaining was conducted again on the east bound bridge deck after the overlay was applied and no delamination was found between the existing deck and the overlay. Although existing delamination areas were deep enough to be undetectable by chaining, they are still present in the deck. The west bound bridge was opened to traffic before it could be chained, but results similar to the east bound bridge were anticipated.

d) Overlay Construction

The PI was present and observed the construction on both deck overlays and recorded construction problems, weather conditions, and other construction variables. The west bound driving lane was constructed on May 15, 1997 and the east bound driving lane was constructed on May 16, 1997.

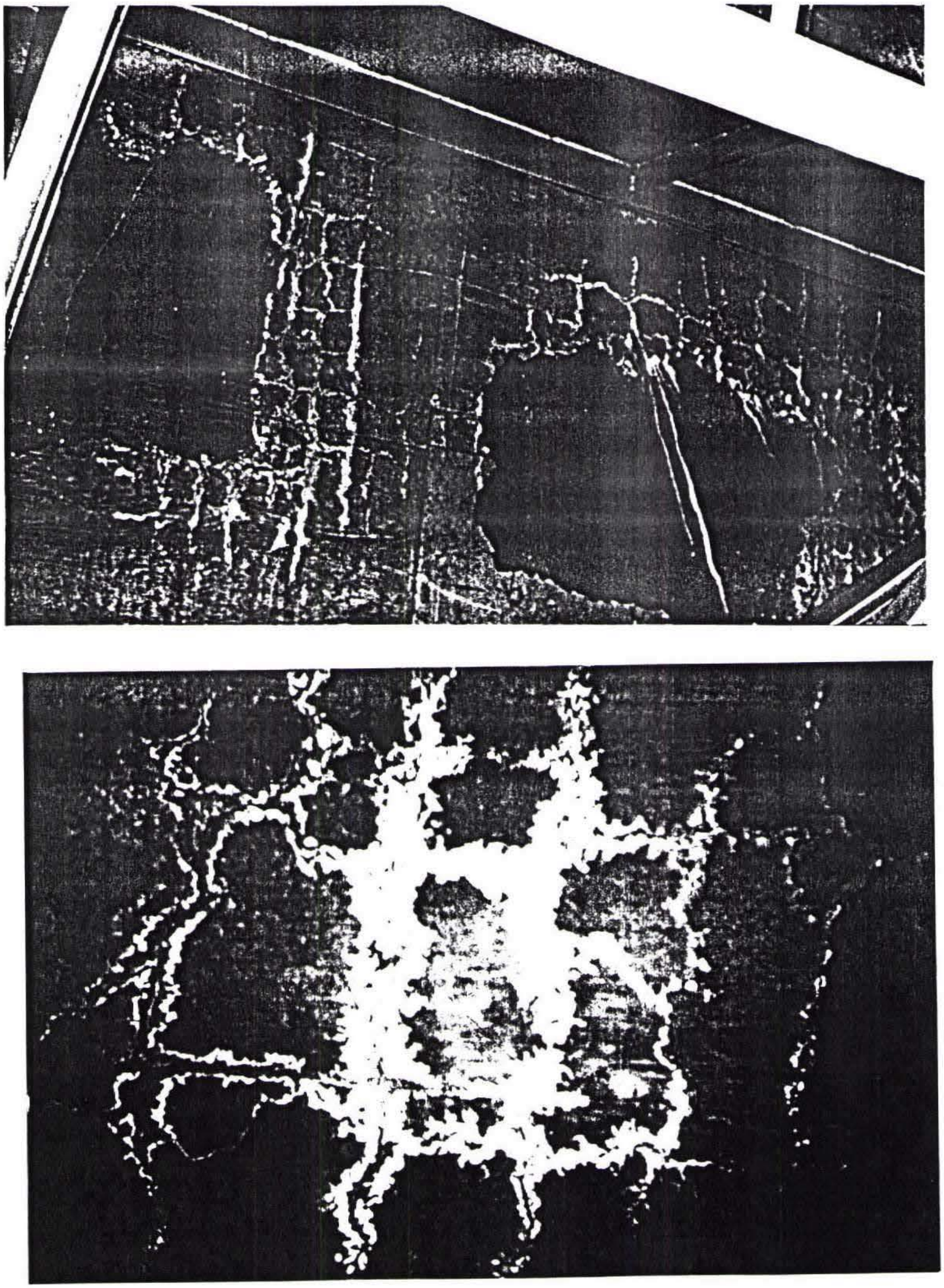

PHOTO 1: Severe Map Cracking and Leaching on the Bottom Surface of the Deck

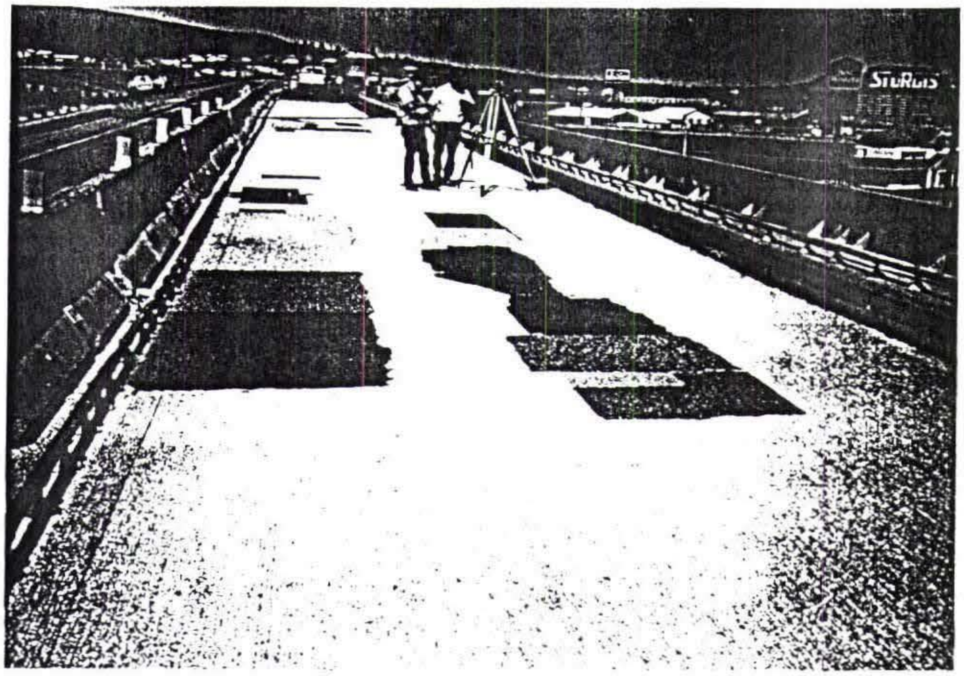

PHOTO 2: Maintenance Patches

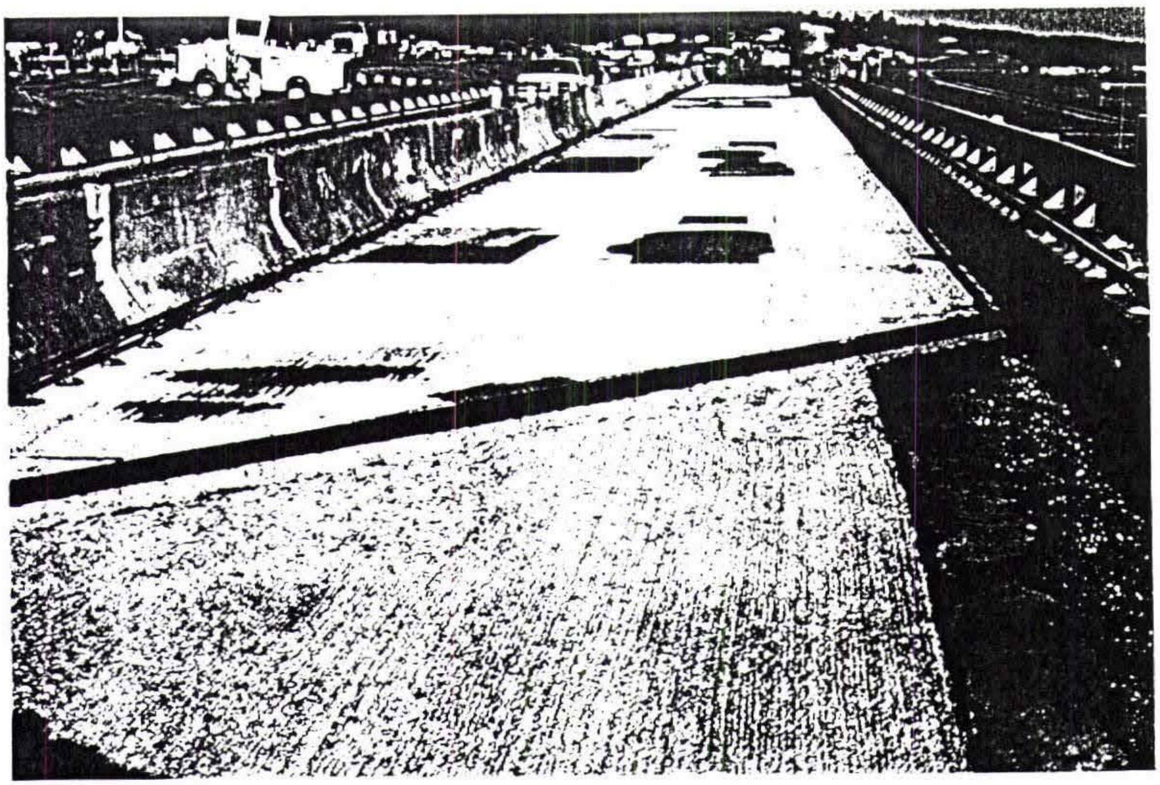

PHOTO 3: Maintenance Patches and Corroded Rebars

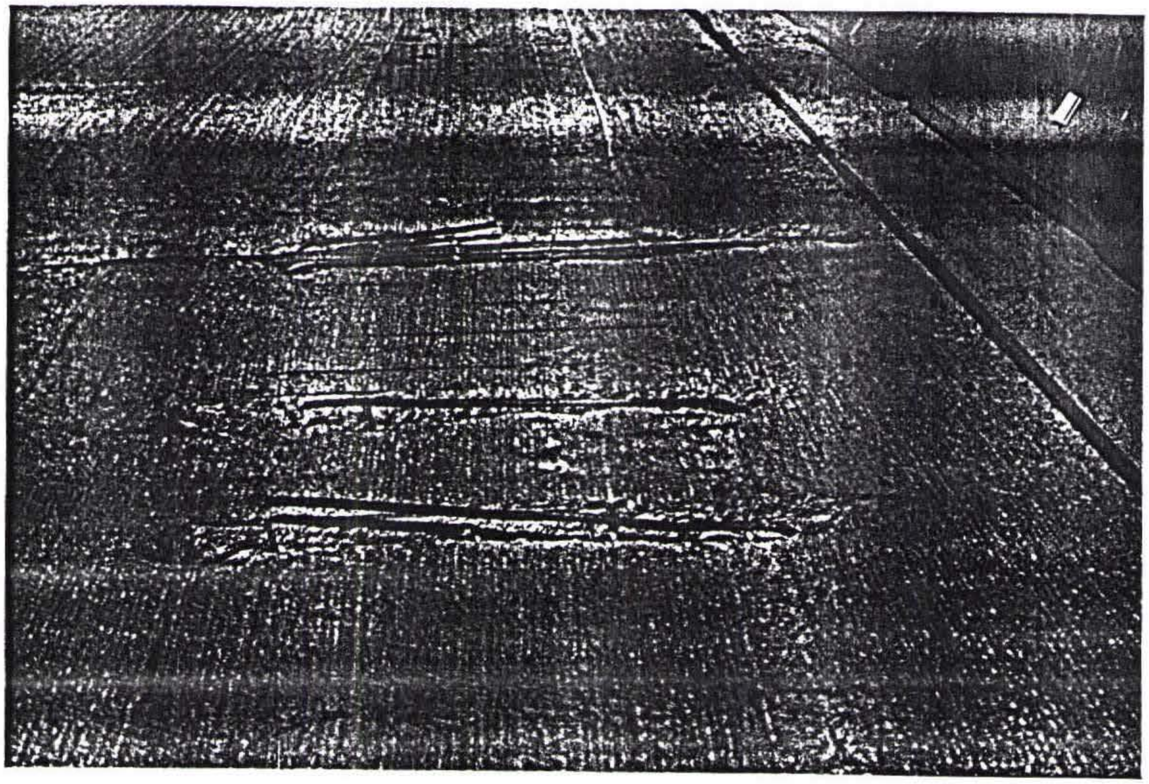

PHOTO 4: Exposed Rebars

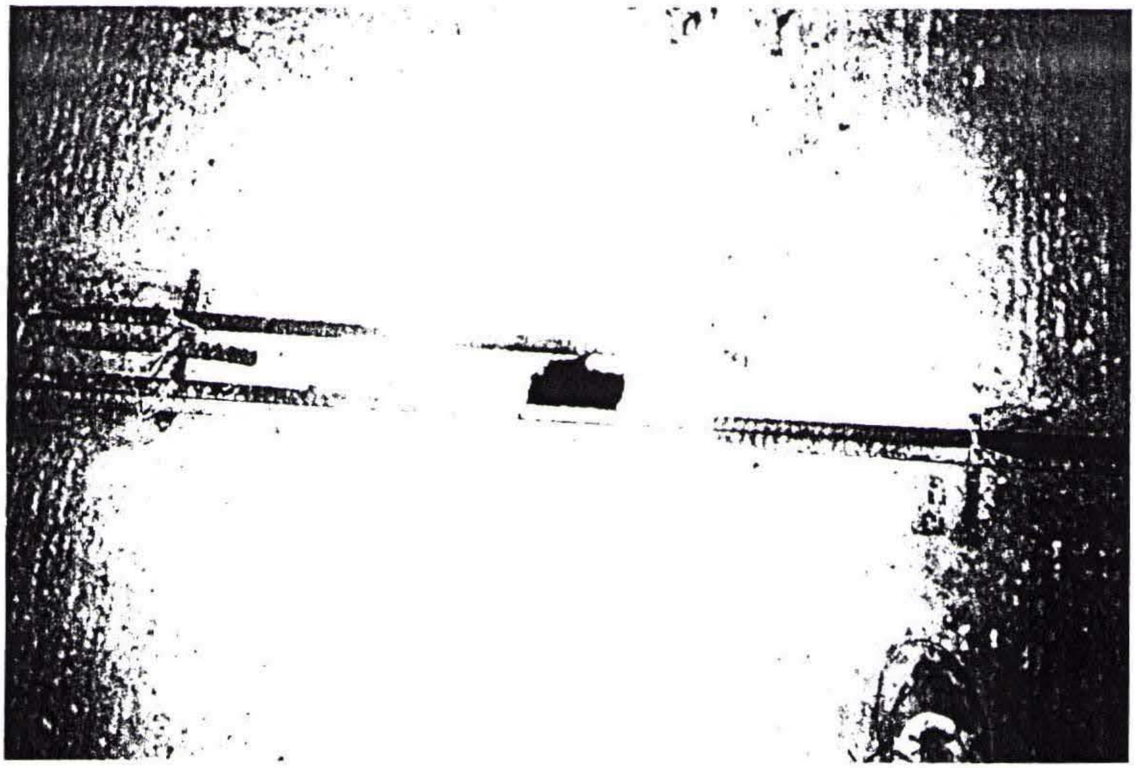

PHOTO 5: Exposed Rebars and a Full Depth Hole on the East Bound Passing Lane

A Bidwell bridge deck finishing machine was used. The ready mixed concrete was supplied in trucks from a plant in Sturgis, SD. The weather conditions were satisfactory for the concreting. The concrete placement started at 4 p.m. and ended at about 8 p.m.. There were no problems in the addition and mixing of fibers in the low-slump concrete. The fibers were mixed uniformly, however, few unopened bundles were seen during the placement. The mixing procedure used on the 15^{th} was as follows.

- Add all ingredients into the truck except the fibers.
- Mix until you have concrete.
- Add fibers at a rate of 14.8kg/m^3 (25lbs/yd^3).
- Mix for 5 additional minutes to ensure proper distribution of the fibers.

The standard practice was followed for placing, consolidating, and finishing of the concrete. Then bull-floating, broom-finishing, and tining were done.

On May 16, the east bound south lane was overlaid with NMFRC. The concrete placement started at 2 p.m. and ended about 6.30 p.m.. This day was hotter than the previous day, however the concrete temperature was within the allowable limits.

In order to reduce the additional mixing time required by the fibers and to increase each trucks turn around time, the contractor used the following mixing procedure.

- Pre-wet the fiber bundles.
- Add all ingredients into the truck except the fibers.
- Begin mixing.
- Prior to having sufficiently mixed the concrete, add the pre-wetted fibers.
- Mix for two to three additional minutes.

There were some partly opened bundles in the first two trucks because the contractor had changed the procedure for adding and mixing the fibers. He had presoaked the fiber bundles and reduced the time of mixing. This might have contributed to the unopened bundles. A few partly opened bundles were also noticed on the finished surface. For the remaining trucks the procedure was changed following the same procedure as used on May 15. Then there were no problems. Beams, cylinders and impact test specimens were made from the mix used in the construction of the overlay in order to determine the hardened concrete properties. All these hardened concrete properties are given in Tables B1 to B5, in Appendix B.

The east bound passing lane was constructed on June 3 and the west bound passing lane was constructed on June 4, 1997.

The concrete placement started at 11.30 a.m. and finished at 4 p.m. The first and second trucks had a minor problem with unopened bundles. Then they were corrected. On June 4, the last truck had a number of unopened bundles, which were also seen on the finished surface. This concrete was placed in the approach road. We could not understand why the fibers were mixed into concrete correctly most of the time and then suddenly one truck had a number of unopened bundles. The contractor said that he was using the same procedure all the time.

For concreting on June 3 and 4, the rails for the paver were laid within the deck slab. After the paver passed the rails, the rail supports were removed and the concrete was consolidated with a poker(spud) vibrator and hand finished. The rest of the procedure used for concrete placement, consolidating, finishing, broom finish, and tining were the same as before. Two power buggies were used to transport the concrete from the truck to the placement site. Plastic sheets were placed on the decks so the buggies could drive on the plastic which kept the decks clean. A few minutes after tining, the surface was covered with wet burlap for curing, later the burlap was covered with polyethylene sheets. The curing was continued for 3 days minimum.

On June 3, beams, cylinders, and impact test specimens were made from the actual concrete used in the construction. These specimens were tested to determine the properties of hardened concrete at 7, 14, 28 days. Test results are tabulated in Tables B6 to B10 in Appendix B.

e) Inspection

Following the construction of the bridge deck overlay using the fiber reinforced concrete, the performance of the bridge deck overlay was evaluated. For this purpose inspection had been done at predetermined time intervals. The survey included, mapping of the cracks, measurement of crack lengths, and widths, visual observation to see any spalling, pop-outs, fiber protrusions, and any other distress in the newly constructed overlays. The condition survey was performed according to ACI 201.3R-86, *Guide for Making a Condition Survey of Concrete Pavements* and ACI 201.1R-68, *Guide for making a Condition Survey of Concrete in Service (Revised 1984).* These inspections were to record the cracks formed on the bridge deck and their growth or multiplication with time. The widths of the cracks were measured by a crack comparator which can measure width accurate to 0.05mm (0.002 in.). The inspections were done on May 21, May 31, June 12, July 16, September 6, November 19, 1997 and March 13, 1998. During the inspection done on May 21, 1997, the bridge deck overlay was inspected, after the curing had stopped and the burlap removed. There was no plastic shrinkage cracking on either bridge except where the expansion joints were located. There was extensive cracking along the expansion joints, which was expected.

During the inspection done on May 31, 1997, no shrinkage cracks were observed along the entire bridge deck overlay. Some unopened bundles were visible at the surface both on the approaches and the decks. The bond between the old concrete and overlay was good as indicated by hammer tapping at various locations.

During the inspection done on June 12, 1997, cracks were not found throughout the bridge deck on both the sides. There was some cracking at the expansion joint, but the concrete at those joints was to be replaced latter.

Inspection done on June 16, 1997 also showed no cracks along the entire bridge deck overlay.

During the inspection done on September 6, 1997, both the south and north lanes of the west bound lane were carefully observed. No cracks were observed in these lanes. The south lane, i.e. the driving lane of the east bound lane showed numerous cracks along the bridge deck. These cracks were carefully located and the crack widths measured using a crack comparator. The cracks are tabulated in Table C1-C2 and cracks mapped in Figure1, in Appendix C. There were only a couple of exposed bundles on the west bound lane, but the bundles were properly bonded to the concrete and were holding good; there were eight exposed bundles on the east bound lane, with a cluster of six bundles on the driving lane. The unopened bundles were found both on the approaches and the decks. All the bundles were holding good and showed no possibility of getting washed away. There were numerous cracks and spalling occurring at the junction of the new and old construction on the driving lane of the east bound lane.

During the inspection done on November 19, 1997, both the north and south lanes of the west bound lane were carefully observed. No cracks were observed on the north lane. The south lane showed one crack about four feet long and less than 0.08mm(0.003in) width along the bridge deck, the cracks are tabulated in Table C3, in Appendix C. The cracks on the east bound lane were carefully located and the crack widths measured. The cracks are tabulated and compared with the previous inspection in Table C1-C2, in Appendix C, the cracks are mapped and shown in Figure1, Appendix C.

During the inspection done on March 13, 1998, both the south and north lanes of the west bound lane were observed for cracks. No cracks were observed on the north lane. The south lane had developed a couple of new longitudinal cracks about six feet from the edge and also a new crack at the expansion joint about 610 mm (2ft) long, 0.35 mm (0.014 inch) in width. The cracks located during previous inspections did not increase in width. A new transverse crack had developed on the approach road on the east side of the driving lane. There were no cracks on the west side in the approach road. A few bundles were also seen along the deck but they were held very firmly and there was no spalling or depression at the bundle surface. The details of the cracks are given in the Table C3, Appendix C.

The east bound lane was also carefully observed for any new cracks. One new transverse crack was observed on the north lane about 7.92 m (26 ft.) from the west edge. Multiple cracks about 50.8 mm (2 in.) long, parallel to the road were observed on the junction of the overlay and the approach road on the east side. The previous cracks were observed for any increase in width. The cracks were measured with the crack comparator. The details of the cracks are given in Table C1 and C2, Appendix C. A summary of all inspections is given in Table C4 in Appendix C.

Cost Information

The average unit bid cost in 1997 for deck overlay LSD concrete was $\$210/yd^3$, whereas, the cost for the LSD NMFRC for the Exit 32 deck overlays was $\$236/yd^3$. Therefore, based on the average unit cost for 1997, we can say that the fiber cost was $\$26/yd^3$ for the Exit 32 structures. Other prospective bidders bid this item at $\$250/yd^3$, however, they did not get the job because their total contract price was not the low bid.

The total contract cost for both deck overlays was $342,329. This cost included costs for the overlays, traffic control, guardrail work, etc. (all aspects of the job). The plans quantity indicated that a total of 193.8 yd^3 of concrete was needed to complete both deck overlays (a total of 360.8 lineal feet of paving for the bridges) as well as the approach slabs (a total 450 lineal feet of paving for the approach slabs). By multiplying 193.8 yd^3 by $26/$yd^3$ we see that the fiber cost for this project was $5,040. Now by comparing this to the total cost of the job we see that the fiber cost was 1.5% of the total contract cost. So, it might be fair to say if the fibers can extend the life of the bridge deck overlay (and therefore the bridge) by 1.5%, they have more than paid for themselves. The same comparison could be made if the cost were $50/$yd^3$ (which is the purchase price of the fibers from 3M-$2 at 25lbs/$yd^3$). Therefore, multiplying 193.8 yd^3 by $50/$yd^3$ gives a fiber cost of $9,690 which is only 2.8% of the cost of the total contract.

Conclusions

The performance characteristics of the bridge deck overlay constructed with the polyolefin fiber reinforced concrete proves the efficiency of this new construction material. The fresh and hardened concrete properties obtained from testing the concrete confirm the results obtained in prior research and trial mixes. Based on the observation made during the trial mixing, the actual construction, and the performance evaluation of the fiber reinforced concrete of the bridge deck overlay, the following conclusions are made:

1. It is possible to incorporate the newly developed non-metallic polyolefin fibers in concrete at 14.8 kg/m^3 (25 lbs/cu.yd.) without causing any balling, clogging and segregation. The addition of fibers did not cause any additional bleeding or cause any other construction problems during mixing, placing, consolidating, finishing and tining operations.
2. The polyolefin fibers are superior to the best available steel fiber in the market in terms of workability. They are non-corrosive, non-magnetic, and non-hazardous, and can be burnt off if found to protrude from the surface.
3. The addition of fibers at 14.8 kg/m^3 (25 lbs/cu.yd.) enhanced the structural properties of concrete. There was an increase in the flexural strength, and a considerable increase in toughness, impact, and post-crack load-carrying capacity.
4. The same construction techniques and equipment without modifications could be used in the construction of bridge deck overlays. The consolidation, finishing and tining operations were the same as for plain concrete.

Based on the periodic inspections over a period of 10 months, the following conclusions are made:

1. The post construction performances of the deck slab overlay were satisfactory, there was no plastic shrinkage cracking immediately after the curing period was over.
2. Once the cracks formed, the polyolefin fibers helped to contain the crack propagation and restrict the widening of cracks.

Recommendations

Polyolefin fiber reinforced concrete is a high performance concrete because it has enhanced desirable structural properties needed for transportation structures such as increased flexural, impact and fatigue strengths, and increased toughness and ductility.

1. It is recommended that LSD NMFRC be used for deck overlays when an overlay will be placed over badly deteriorated bridge decks. This will improve the performance of the overlay by minimizing large cracks, spalling, and loss of material from the top of the deck. Therefore, the potential for hazards to the public will be reduced.
2. It is recommended that the LSD NMFRC follow the same specifications as that for SDDOT's plain LSD with the exception of the inclusion of 3M's polyolefin fibers at a rate of 14.8kg/m^3(25lbs/yd^3). The LSD specification is in SDDOT's *Standard Specifications for Roads and Bridges.*

   It is suggested that the slump of the concrete after the addition of fibers (LSD NMFRC) should satisfy the specification requirement. Therefore the concrete before the addition of fibers should have a slump of 50mm(2 in).

Limitation

The addition of polyolefin fibers at 14.8 kg/m^3 (25 lbs/cu.yd.) only slightly increased (by $26) the unit price of concrete. However, the enhanced structural properties and the resulting better long-term performance of the structure could fully justify the use of polyolefin fibers

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APPENDIX – A
(Details of Laboratory Mixes)

Table A1: Mixture Proportions used for the trial mixes

Mixture #	Mixture Proportions Kg/m^3 (lb/cu.yd.)					AEA (oz/cu.yd)
	Cement	Coarse Aggregate	Fine Aggregate	Water	Fiber	
TD 1	823	1394	1394	271	25	16.9
TD 2	823	1394	1394	271	25	16.9
TD 3	823	1394	1394	271	25	21.6
TD 4	823	1394	1394	271	25	22.6
TD 5	823	1394	1394	271	25	29.4

Table A2: Fresh Concrete Properties of the trial mixes

Mixture #	Conc. Temp (°F)	Humidity (%)	Air Entrainment (c.c.)	Unit Weight (pcf)	Air Content %	Slump (inches)
TD 1	68	34	37	146.0	3.8	0.500
TD 2	65	34	37	146.0	4.0	0.500
TD 3	66	35	47	144.0	5.2	0.500
TD 4	62	35	100	144.0	5.0	0.750
TD 5	62	35	130	146.0	5.4	0.625

AEA – Air Entraining Agent

Conversions:

1 inch = 25.4 mm

1 lb/cu.yd. =0.5933 kg/cu.m

1 oz/cu.yd = 0.026 mL/cu.m

1 pcf = 16.02 kg/cu.m

°F to °C: T(°C) = [T(°F) - 32]/1.8

Table A3: Compressive Strength of the trial mixes

Specimen #	Age (days)	Length (in)	Diameter (in)	Area (sq.in.)	Unit Weight (pcf)	Static Modulus (psi)	Compressive Strength (psi)
TD1 - C1	1	12.052	5.954	27.84	149.33	---	2443
TD2 - C2	1	12.028	5.986	28.14	145.5	---	2665
						Average=	**2554**
TD1 - C2	3	12.085	6.025	28.51	142.93	---	3858
TD1 - C3	3	12.092	5.985	28.13	144.76	---	3573
TD2 - C2	3	12.104	5.992	28.19	144.28	---	3547
TD2 - C3	3	12.110	6.011	28.37	145.81	---	4106
						Average=	**3771**
TD4 - C1	7	12.020	5.978	28.07	145.98	4.28×10^6	4489
TD4 - C2	7	12.105	6.012	28.39	145.83	4.23×10^6	4967
TD5 - C1	7	12.178	6.000	28.27	148.05	4.24×10^6	4951
						Average=	**4802**
TD4 - C3	14	12.213	6.031	28.57	143.63	4.20×10^6	4551
TD5 - C2	14	12.289	6.020	28.46	143.27	4.21×10^6	5358
						Average=	**4955**
TD4 - C4	28	12.086	5.976	28.03	145.37	5.35×10^6	6600
TD5 - C3	28	12.082	6.006	28.33	143.88	5.29×10^6	6477
TD5 - C4	28	12.025	5.985	28.13	145.59	5.33×10^6	6541
						Average=	**6539**

--- Test not conducted

Conversions:

1 inch = 25.4 mm   1 sq. in. = 645.2 sq. mm.   1 lb = 4.448 N

1 pcf = 16.02 kg/cu.m   1 psi = 0.006895 Mpa

Table A4: First Crack Strength and Maximum Flexural Strength of the trial mixes

Specimen #	Age (days)	Load (lbs)	First Crack Deflection (inches)	Stress (psi)	Maximum Load (lbs)	Flexural Strength (psi)
TD4 - B1	7	4298	0.0012	764	4298	764
TD4 - B2	7	4308	0.0007	760	4318	762
TD5 - B1	7	3535	0.0006	642	4216	766
					Average =	**764.0**
TD4 - B3	14	4437	0.0005	811	4842	885
TD5 - B2	14	3525	0.0004	612	4926	856
					Average =	**870.5**
TD4 - B4	28	3601	0.0008	627	5367	934
TD5 - B3	28	3672	0.001	678	4416	815
TD5 - B4	28	3695	0.0006	636	4792	825
					Average =	**858**

TABLE A5: ASTM Toughness Indices of the trial mixes

Specimen #	Age (days)	First Crack Toughness (inch-lbs)	Toughness Indices			Toughness Ratios	
			I 5	I 10	I 20	I 10/ I 5	I 20/ I 10
TD4 - B1	7	3.91*	3.53	6.37	11.01	1.81	1.73
TD4 - B2	7	2.05	3.91	7.39	13.85	1.89	1.87
TD5 - B1	7	1.29	4.78	9.47	18.09	1.98	1.91
Average =		**2.42**	**4.07**	**7.74**	**14.31**	**1.89**	**1.84**
TD4 - B3	14	1.54	4.10	7.86	14.89	1.92	1.89
TD5 - B2	14	1.02	4.62	9.32	18.31	2.02	1.96
Average =		**1.28**	**4.36**	**8.59**	**16.6**	**1.97**	**1.93**
TD4 - B4	28	1.81	5.15	10.11	16.39	1.96	1.62
TD5 - B3	28	2.44	4.52	8.82	16.81	1.95	1.90
TD5 - B4	28	1.38	4.96	10.08	19.91	2.03	1.98
Average =		**1.88**	**4.88**	**9.67**	**17.70**	**1.98**	**1.83**

* Outlier (not included in computations)

Conversions:

1 inch = 25.4 mm   1 sq. in. = 645.2 sq. mm.   1 in-lb = 0.113 Nm

1 lb = 4.448 N   1 psi = 0.006895 MPa

Table A6: Japanese Standard - Toughness & Equivalent Flexural Strength of the trial mixes

Specimen #	Age (days)	JCI- Toughness (inch-lbs)	JCI- Equivalent Flexural Strength (psi)
TD4 – B1	7	164	364
TD4 – B2	7	185	408
TD5 – B1	7	165	374
	Average=	**171**	**382**
TD4 – B3	14	161	368
TD5 – B2	14	211	458
	Average=	**186**	**413**
TD4 – B4	28	163	354
TD5 – B3	28	166	382
TD5 – B4	28	185	397
	Average=	**171**	**378**

Table A7: Residual Strength Factors of the trial mixes

Specimen	$R_{5,10}$		$R_{10,20}$	
#	7 Days	28 Days	7 Days	28 Days
TD4 - B1	56.8	---	46.4	---
TD4 - B2	69.6	---	64.6	---
TD5 - B1	93.8	---	86.2	---
TD4 - B4	---	99.2	---	62.8
TD5 - B3	---	86.0	---	79.9
TD5 - B4	---	102.4	---	98.3

--- Test not conducted

Conversions:

1 in-lb = 0.113 Nm 1 psi = 0.006895 MPa

Table A8: Impact Strength (28 Days) of the trial mixes

Specimen #	Number of Blows	
	First Crack	Failure
TD4 - I1	63	281
TD4 - I2	82	326
TD4 - I3	111	270
TD4 - I4	51	372
TD4 - I5	78	222
Average=	**77**	**294**
TD5 - I1	45	227
TD5 - I2	58	293
TD5 - I3	36	302
TD5 - I4	24	233
TD5 - I5	86	356
Average=	**50**	**282**

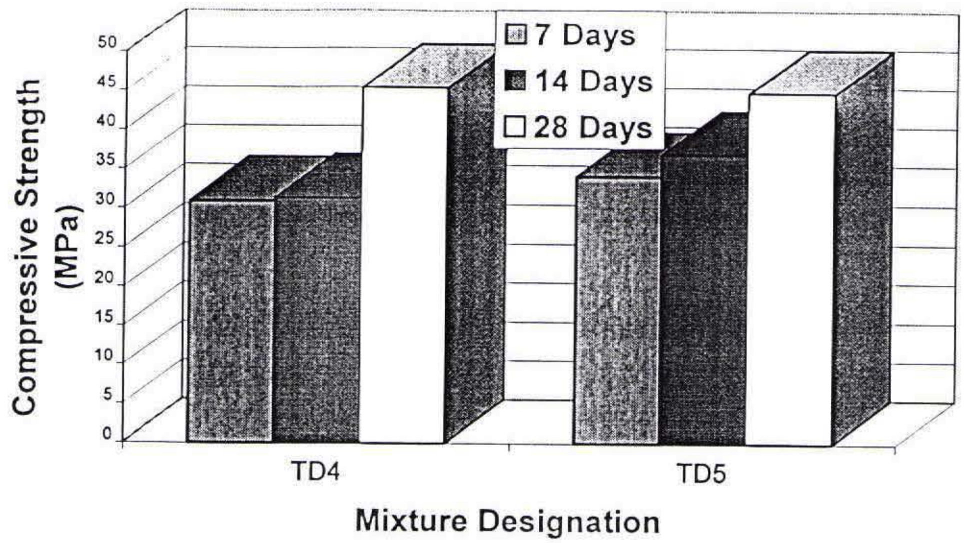


Fig A1: Compressive Strength for trial mixes

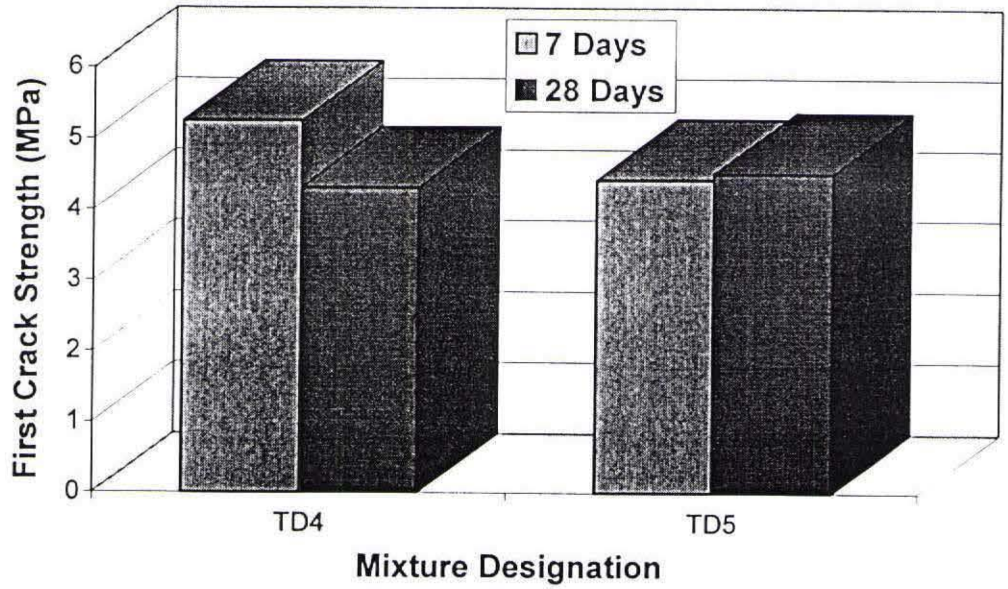


Fig A2: First Crack Strength for trial mixes

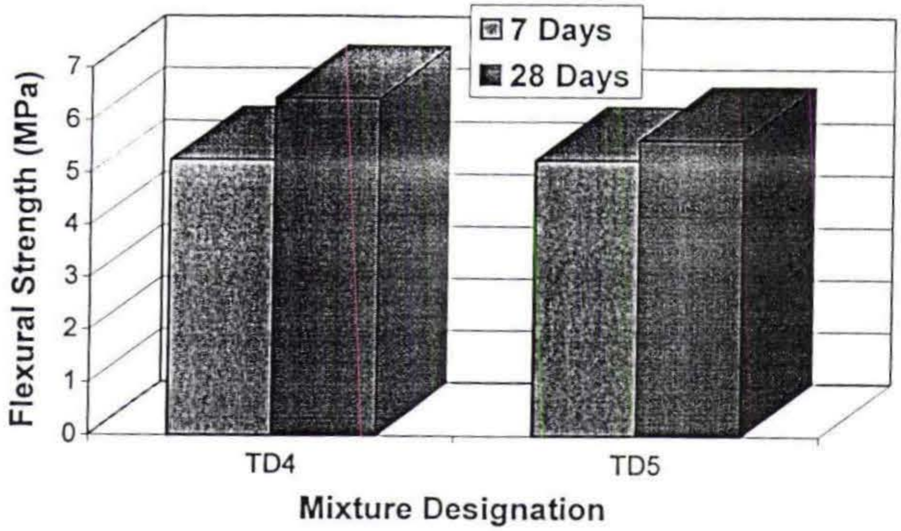


Fig A3: Flexural Strength for trial mixes

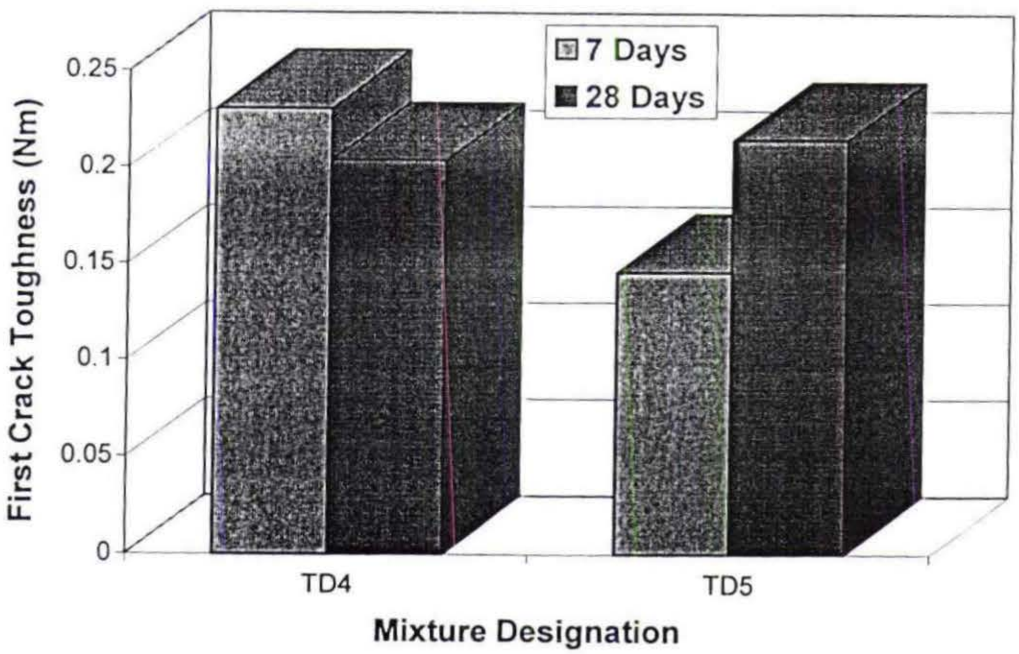


Fig A4: First Crack Toughness for trial mixes

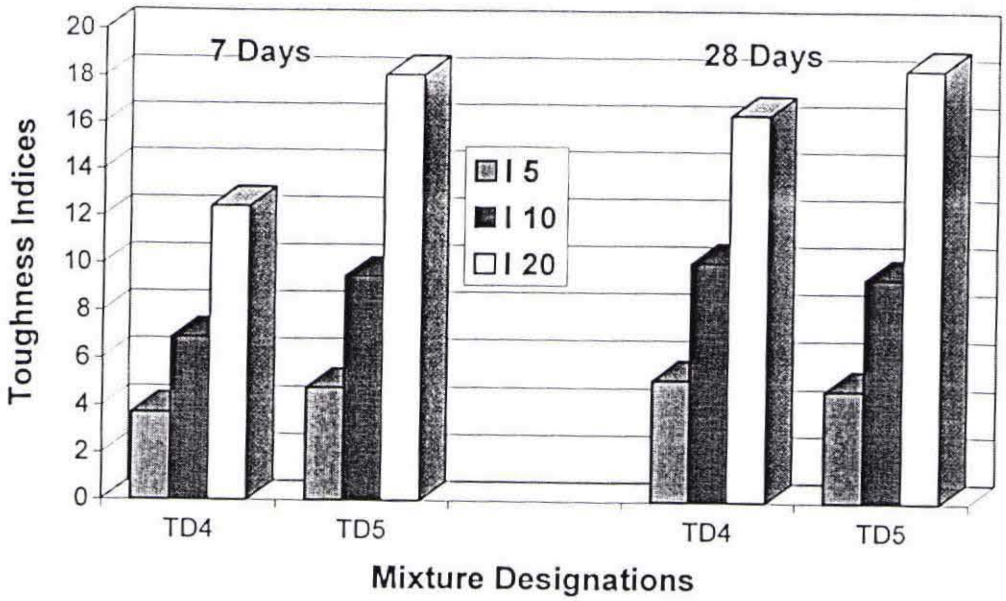


Fig A5: ASTM Toughness Indices for trial mixes

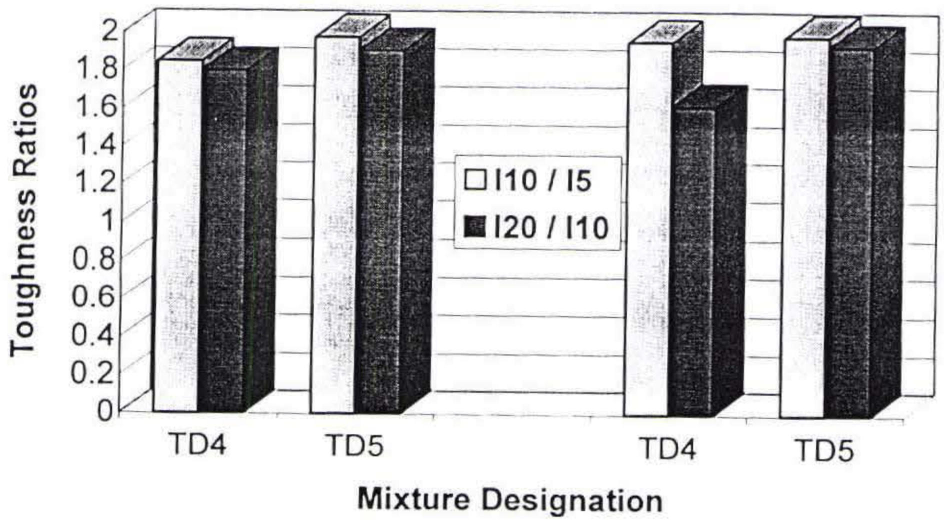


Fig A6: ASTM Toughness Ratios for trial mixes

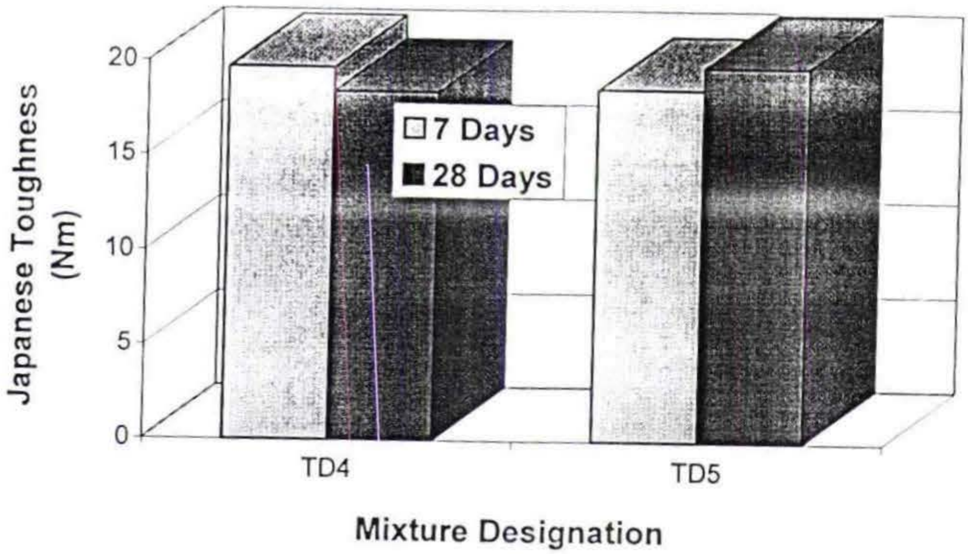


Fig A7: Japanese Toughness for trial mixes

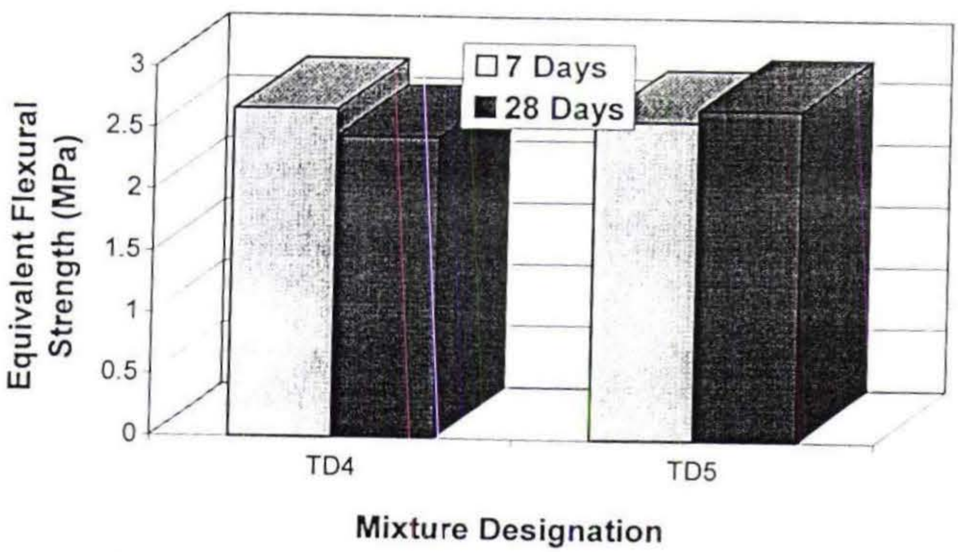


Fig A8: Japanese Standard Equivalent Flexural Strength for trial mixes

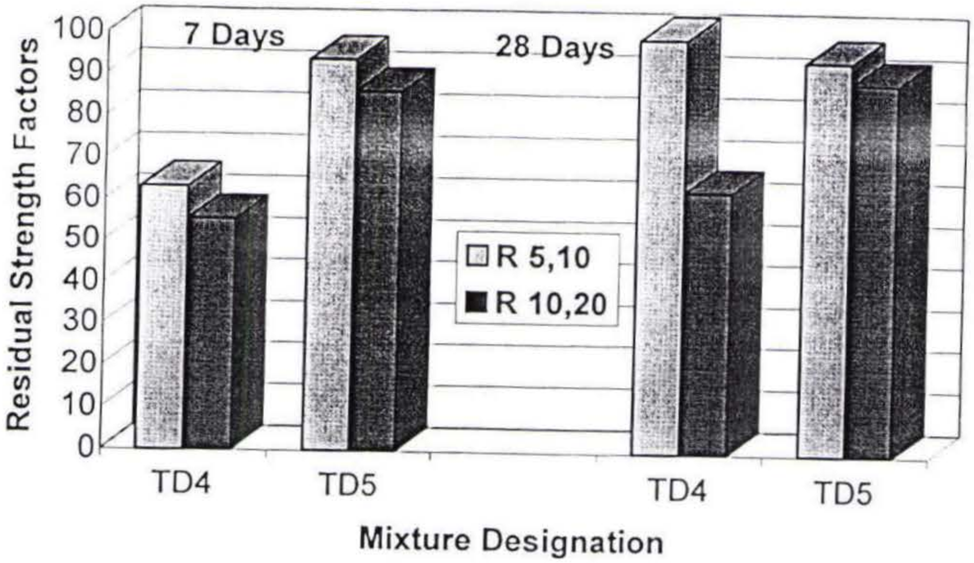


Fig A9: Residual Strength Factors for trial mixes

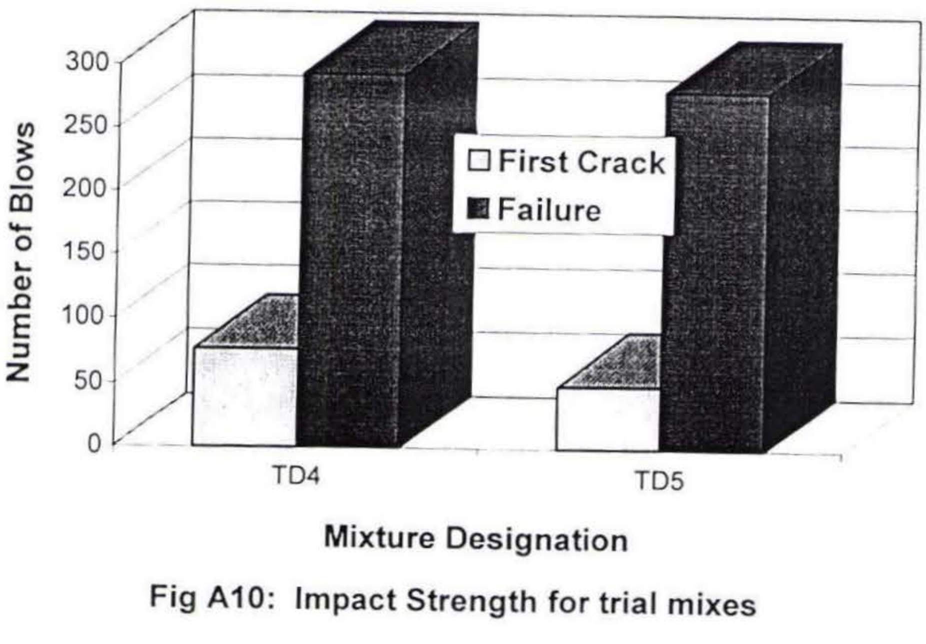


Fig A10: Impact Strength for trial mixes

APPENDIX – B
(Details of Field Mixes)

SB – Field mix made on May 16, 1997
STU – Field mix made on June 3, 1997

Table B1: Compressive Strength (Bridge deck overlay, Sturgis, 5-16-97)

Specimen #	Age (days)	Length (in)	Diameter (in)	Area (sq.in.)	Unit Weight (pcf)	Static Modulus (psi)	Compressive Strength (psi)
SC - 1	7	12.301	6.059	28.81	141.4	4.45×10^6	5432
SC - 2	7	12.261	6.009	28.36	144.1	4.23×10^6	4954
						Average=	**5193**
SC - 3	14	12.221	5.985	28.13	142.7	5.33×10^6	6292
SC - 4	14	12.249	6.022	28.48	140.6	4.21×10^6	5600
						Average=	**5946**
SC - 5	28	12.231	6.022	28.48	139.9	6.48×10^6	5829
SC - 6	28	12.270	5.985	28.13	143.1	6.09×10^6	6948
						Average=	**6388**

Table B2: First Crack Strength and Maximum Flexural Strength (Bridge deck overlay, Sturgis, 5-16-97)

Specimen #	Age (days)	Load (lbs)	First Crack Deflection (inches)	Stress (psi)	Maximum Load (lbs)	Flexural Strength (psi)
SB - 1	7	4423	0.0008	805	4849	883
SB - 2	7	3713	0.0008	676	3927	715
					Average =	**799**
SB - 3	14	3839	0.0009	674	4341	762
SB - 4	14	3659	0.0006	619	4419	748
					Average =	**755**
SB - 5	28	4299	0.0008	717	4975	830
SB - 6	28	3890	0.001	744	4420	845
SB - 7	28	3740	0.0012	675	4988	901
					Average =	**859**

Conversions:

1 inch = 25.4 mm   1 sq. in. = 645.2 sq. mm.   1 lb = 4.448 N

1 pcf = 16.02 kg/cu.m   1 psi = 0.006895 MPa

Table B3: ASTM Toughness Indices (Bridge deck overlay, Sturgis, 5-16-97)

Specimen #	Age (days)	First Crack Toughness (inch-lbs)	Toughness Indices			Toughness Ratios	
			I 5	I 10	I 20	I 10/ I 5	I 20/ I 10
SB - 1	7	2.49	1.75	4.03	7.59	2.30	1.88
SB - 2	7	1.92	4.21	8.08	15.25	1.92	1.89
Average =		**2.21**	**4.07**	**7.74**	**14.31**	**2.11**	**1.89**
SB - 3	14	2.22	4.44	8.59	16.21	1.93	1.88
SB - 4	14	1.40	4.68	9.05	16.91	1.93	1.86
Average =		**1.81**	**4.56**	**8.82**	**16.56**	**1.93**	**1.87**
SB - 5	28	2.11	4.61	8.61	14.89	1.87	1.73
SB - 6	28	2.44	4.48	8.48	15.12	1.89	1.78
SB - 7	28	2.92	4.90	9.33	16.42	1.91	1.76
Average =		**2.49**	**4.67**	**8.80**	**15.47**	**1.89**	**1.75**

Table B4: Japanese Standard -Toughness & Equivalent Flexural Strength (Bridge deck overlay, Sturgis, 5-16-97)

Specimen #	Age (days)	JCI- Toughness (inch-lbs)	JCI- Equivalent Flexural Strength (psi)
SB – 1	7	226	515
SB – 2	7	192	437
	Average=	**209**	**476**
SB – 3	14	176	386
SB – 4	14	188	397
	Average=	**182**	**392**
SB – 5	28	192	400
SB – 6	28	168	401
SB – 7	28	146	330
	Average=	**169**	**377**

Conversions:

1 inch = 25.4 mm   1 sq. in. = 645.2 sq. mm.   1 in-lb = 0.113 Nm

1 lb = 4.448 N   1 psi = 0.006895 MPa

Table B5: Residual Strength Factors
(Bridge deck overlay, Sturgis, 5-16-97)

Specimen	$R_{5, 10}$			$R_{10, 20}$		
#	7 Days	14 Days	28 Days	7 Days	14 Days	28 Days
SB - B1	45.6	---	---	35.6	---	---
SB - B2	77.4	---	---	71.7	---	---
Average =	61.5			53.6		
SB - B3	---	83.0	---	---	76.2	---
SB - B4	---	87.4	---	---	78.6	---
SB - B5	---	---	80.0	---	---	62.8
SB - B6	---	---	80.0	---	---	66.4
SB - B7	---	---	88.6	---	---	70.9
Average =			82.9			66.7

Conversions:

1 in-lb = 0.113 Nm --- Test not conducted

1 psi = 0.006895 MPa

Table B6: Compressive Strength (Bridge deck overlay, Sturgis, 6-3-97)

Specimen #	Age (days)	Length (in)	Diameter (in)	Area (sq.in.)	Unit Weight (pcf)	Static Modulus (psi)	Compressive Strength (psi)
STU - C1	7	12.112	6.022	28.48	137.2	3.95×10^6	4635
STU - C2	7	12.096	5.981	28.09	139.3	3.71×10^6	4529
						Average=	**4582**
STU - C3	14	12.031	6.010	28.37	137.7	3.52×10^6	5005
STU - C4	14	12.322	6.038	28.63	136.2	4.19×10^6	5098
						Average=	**5052**
STU - C5	28	12.166	6.025	28.51	137.5	4.20×10^6	5384
STU - C6	28	12.073	6.022	28.48	137.2	4.21×10^6	5723
STU - C7	28	12.100	5.979	28.08	138.8	4.28×10^6	5270
						Average=	**5459**

Table B7: First Crack Strength and Maximum Flexural Strength (Bridge deck overlay, Sturgis, 6-3-97)

Specimen #	Age (days)	Load (lbs)	First Crack Deflection (inches)	Stress (psi)	Maximum Load (lbs)	Flexural Strength (psi)
STU - B1	7	3244	0.0008	573	3580	633
STU - B2	7	3147	0.0006	499	3745	594
					Average =	**614**
STU - B3	14	4361	0.0005	771	4361	771
STU - B4	14	3468	0.0006	599	3561	615
					Average =	**693**
STU - B5	28	3365	0.001	618	3908	718
STU - B6	28	3700	0.0006	670	3879	703
STU - B7	28	3638	0.001	632	3978	691
					Average =	**704**

Conversions:

1 inch = 25.4 mm　　1 sq. in. = 645.2 sq. mm.　　1 lb = 4.448 N

1 pcf = 16.02 kg/cu.m　　1 psi = 0.006895 MPa

Table B8: ASTM Toughness Indices
(Bridge deck overlay, Sturgis, 6-3-97)

Specimen #	Age (days)	First Crack Toughness (inch-lbs)	Toughness Indices			Toughness Ratios	
			I 5	I 10	I 20	I 10/ I 5	I 20/ I 10
STU - B1	7	1.66	4.44	8.76	17.26	1.97	1.97
STU - B2	7	1.24	4.37	7.57	12.39	1.73	1.64
Average =		**1.45**	**4.40**	**8.16**	**14.82**	**1.85**	**1.80**
STU - B3	14	1.23	4.41	8.34	15.05	1.89	1.81
STU - B4	14	1.28	3.75	7.07	13.31	1.89	1.88
Average =		**1.25**	**2.04**	**7.70**	**14.18**	**1.89**	**1.84**
STU- B5	28	2.11	4.60	8.97	16.97	1.95	1.89
STU - B6	28	1.52	4.03	7.72	14.74	1.92	1.91
STU - B7	28	2.22	4.46	8.45	15.15	1.89	1.79
Average =		**1.95**	**4.36**	**8.38**	**15.62**	**1.92**	**1.86**

Table B9: Japanese Standard - Toughness & Equivalent Flexural Strength (Bridge deck overlay, Sturgis, 6-3-97)

Specimen #	Age (days)	JCI- Toughness (inch-lbs)	JCI- Equivalent Flexural Strength (psi)
STU - B1	7	206	456
STU - B2	7	180	358
	Average=	**193**	**407**
STU - B3	14	195	432
STU - B4	14	146	316
	Average=	**171**	**374**
STU - B5	28	187	429
STU - B6	28	222	503
STU - B7	28	167	362
	Average=	**192**	**431**

Conversions:

1 inch = 25.4 mm
1 sq. in. = 645.2 sq. mm.
1 in-lb = 0.113 Nm
1 lb = 4.448 N
1 psi = 0.006895 Mpa

Table B10: Residual Strength Factors

(Bridge deck overlay, Sturgis, 6-3-97)

Specimen #	$R_{5,10}$ 7 Days	$R_{5,10}$ 14 Days	$R_{5,10}$ 28 Days	$R_{10,20}$ 7 Days	$R_{10,20}$ 14 Days	$R_{10,20}$ 28 Days
STU - B1	86.4	---	---	85.0	---	---
STU - B2	64.0	---	---	48.2	---	---
Average =	75.2			66.6		
STU - B3	---	78.6	---	---	67.1	---
STU - B4	---	66.4	---	---	62.4	---
STU - B5	---	---	87.4	---	---	80.0
STU - B6	---	---	73.8	---	---	70.2
STU - B7	---	---	79.8	---	---	67.0
Average =			80.3			72.5

Conversions:

1 in-lb = 0.113 Nm --- Test not conducted

1 psi = 0.006895 MPa

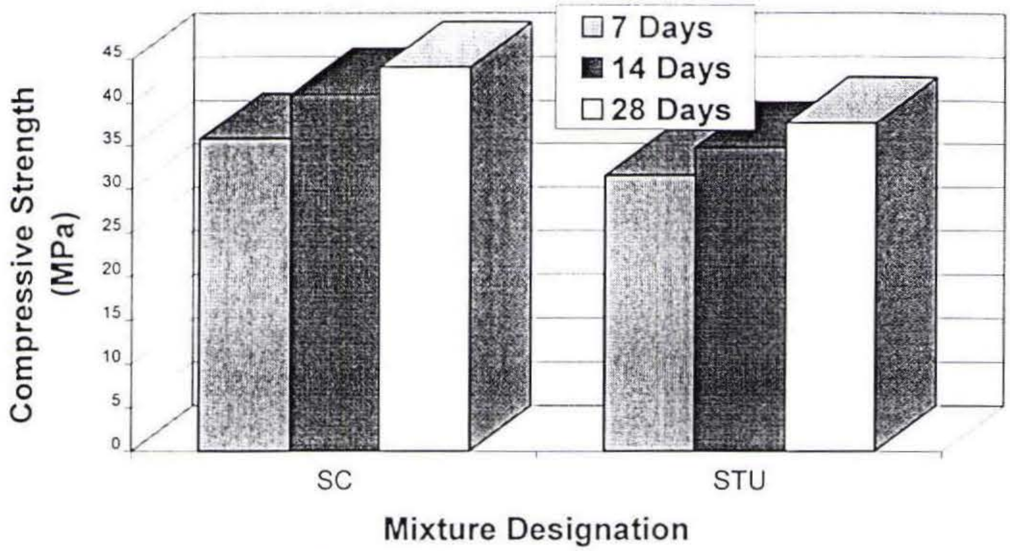


Fig B1: Comparison of Compressive Strength for field mixes

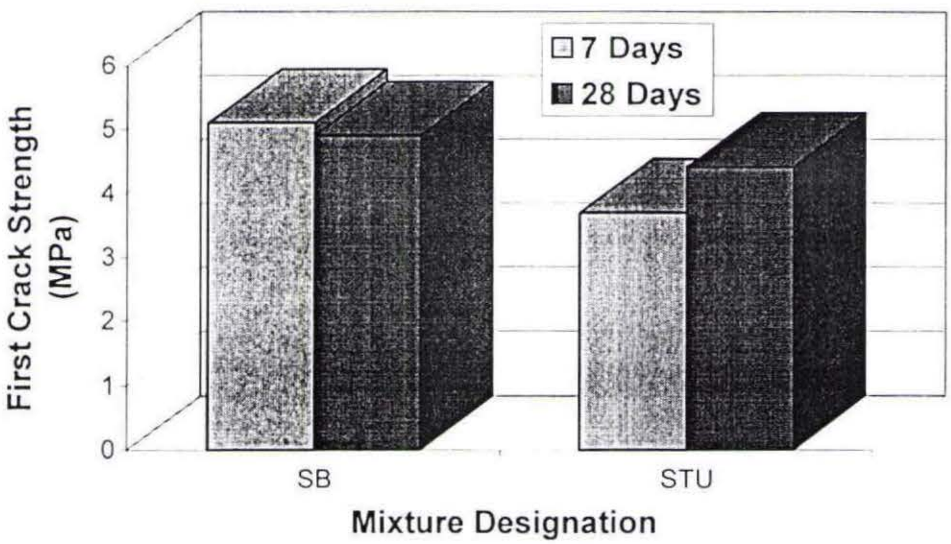


Fig B2: Comparison of First Crack Strength for field mixes

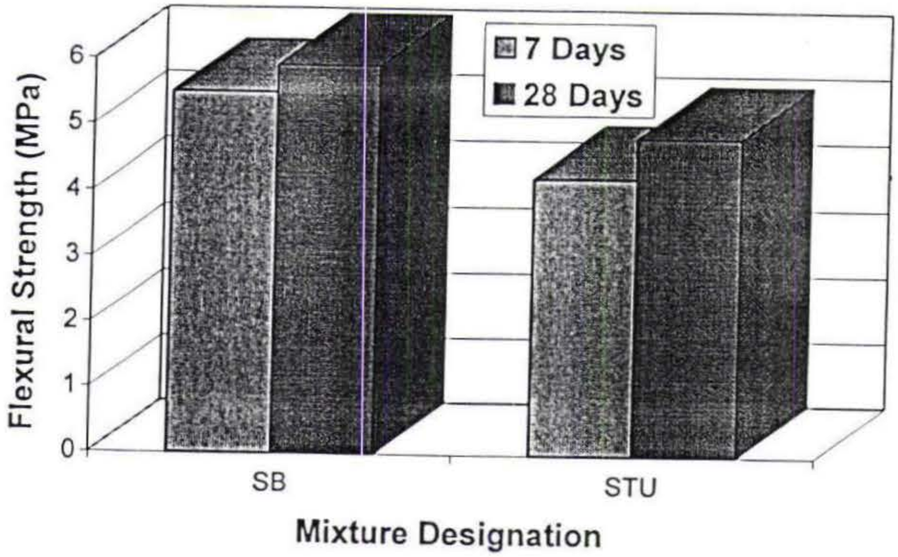


Fig B3: Comparison of Flexural Strength for field mixes

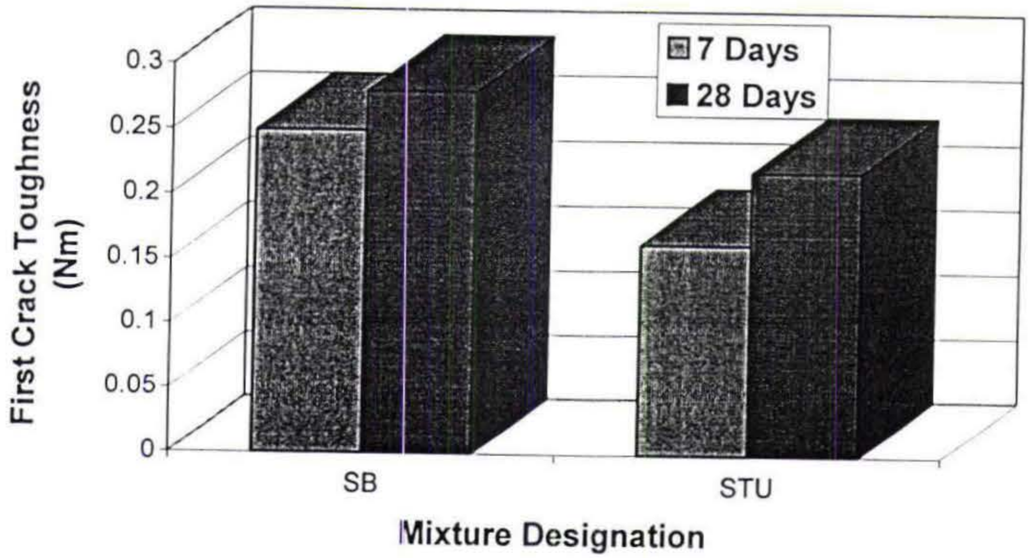


Fig B4: Comparison of First Crack Toughness for field mixes

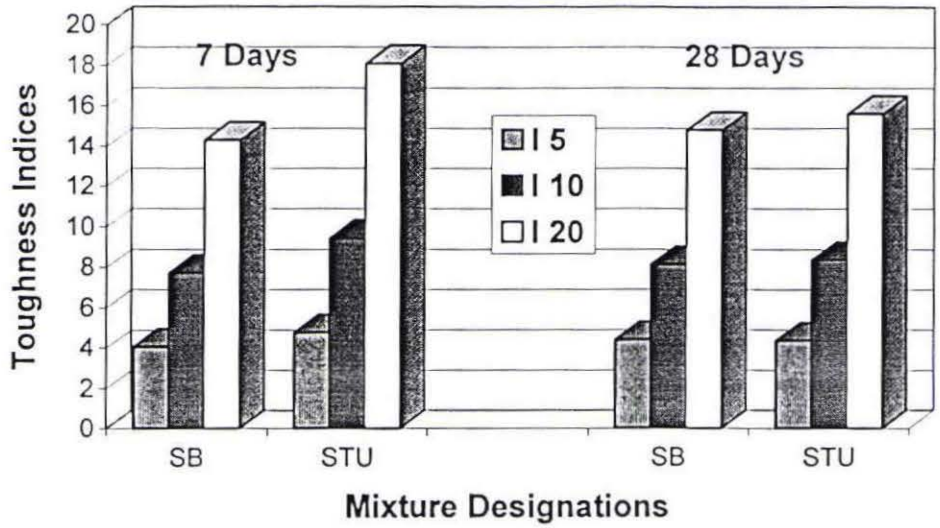


Fig B5: Comparison of ASTM Toughness Indices for field mixes

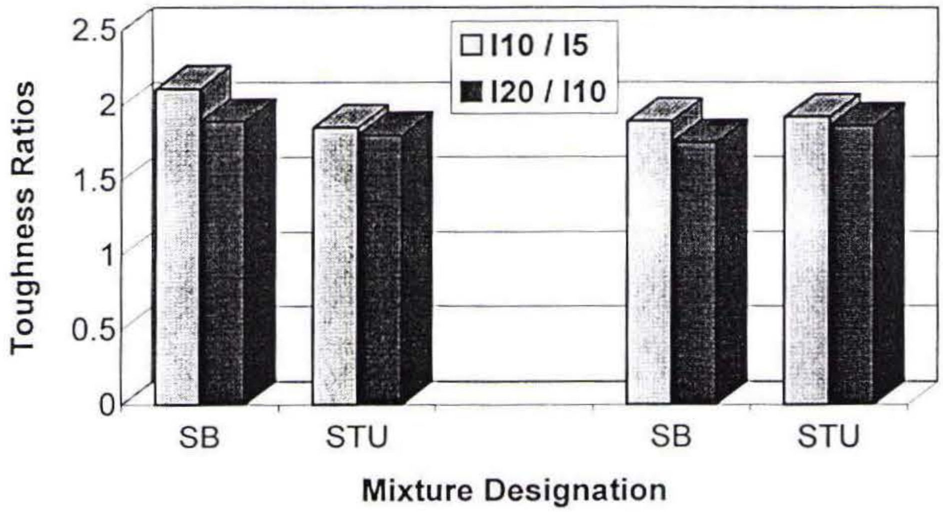


Fig B6: Comparison of ASTM Toughness Ratios for field mixes

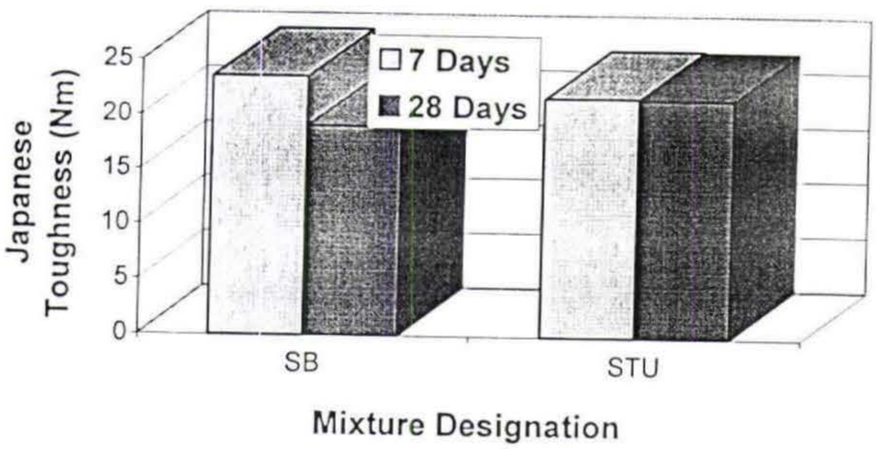


Fig B7: Comparison of Japanese Toughness for field mixes

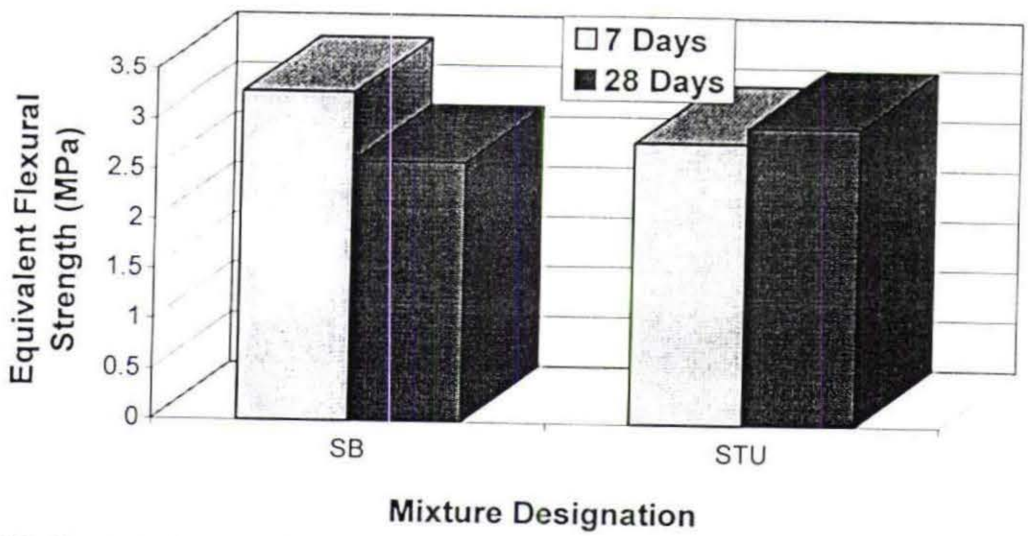


Fig B8: Comparison of Japanese Standard Equivalent Flexural Strength for field mixes

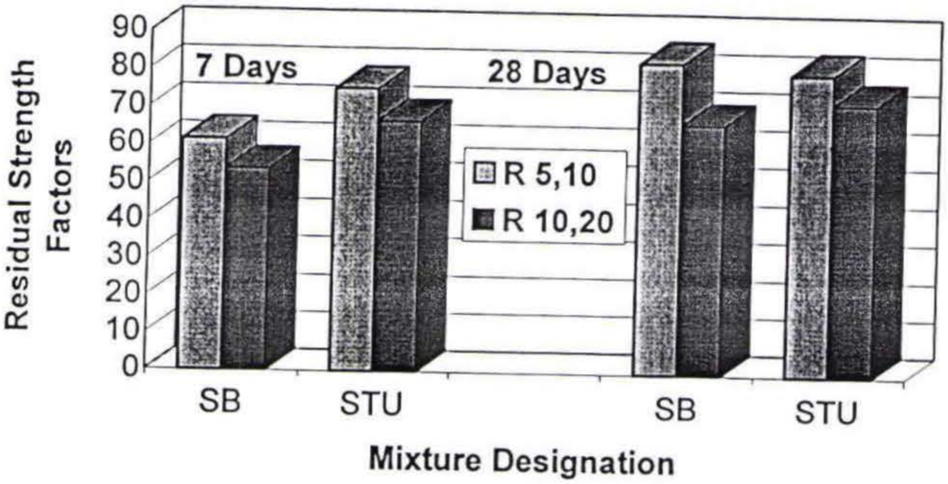
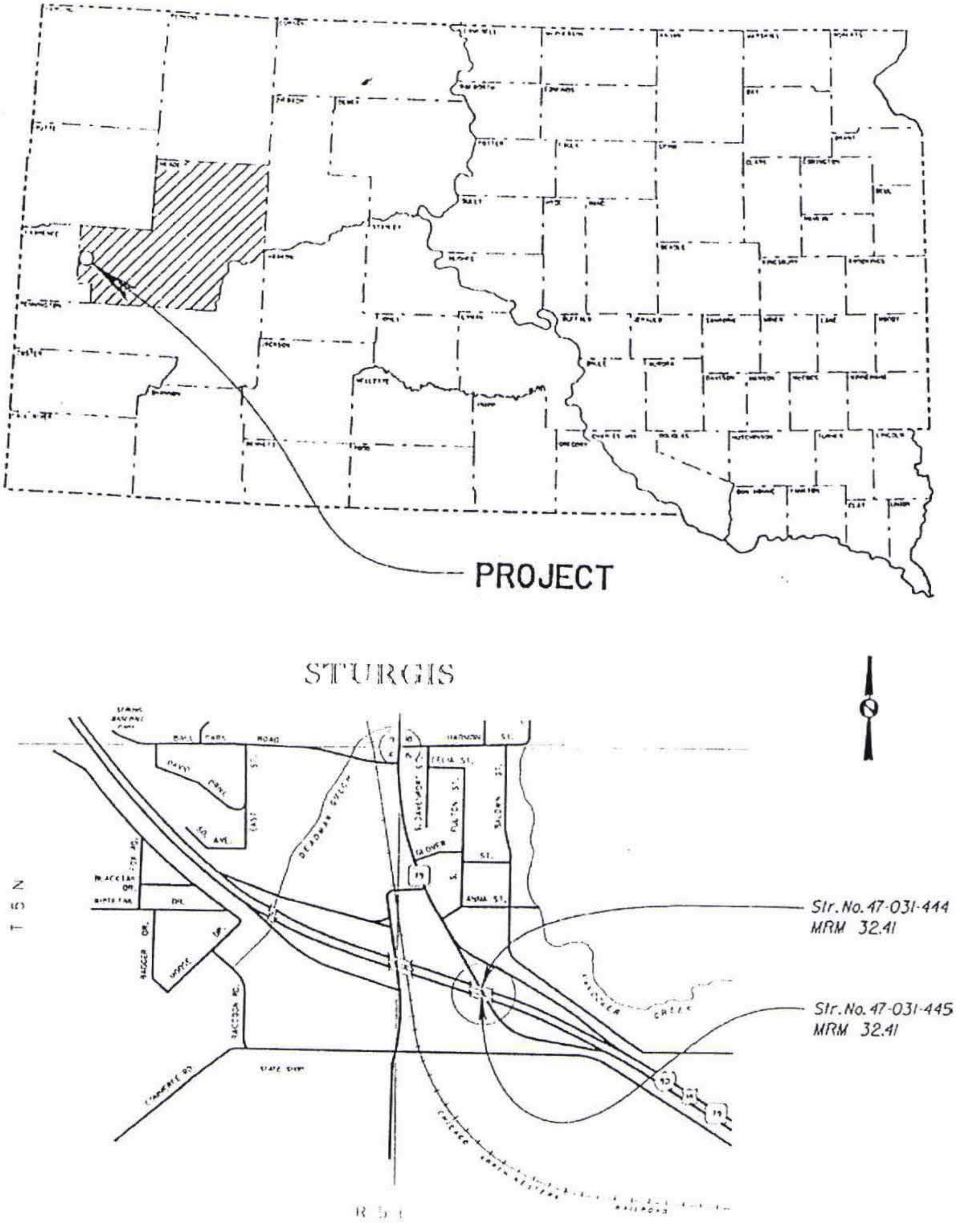


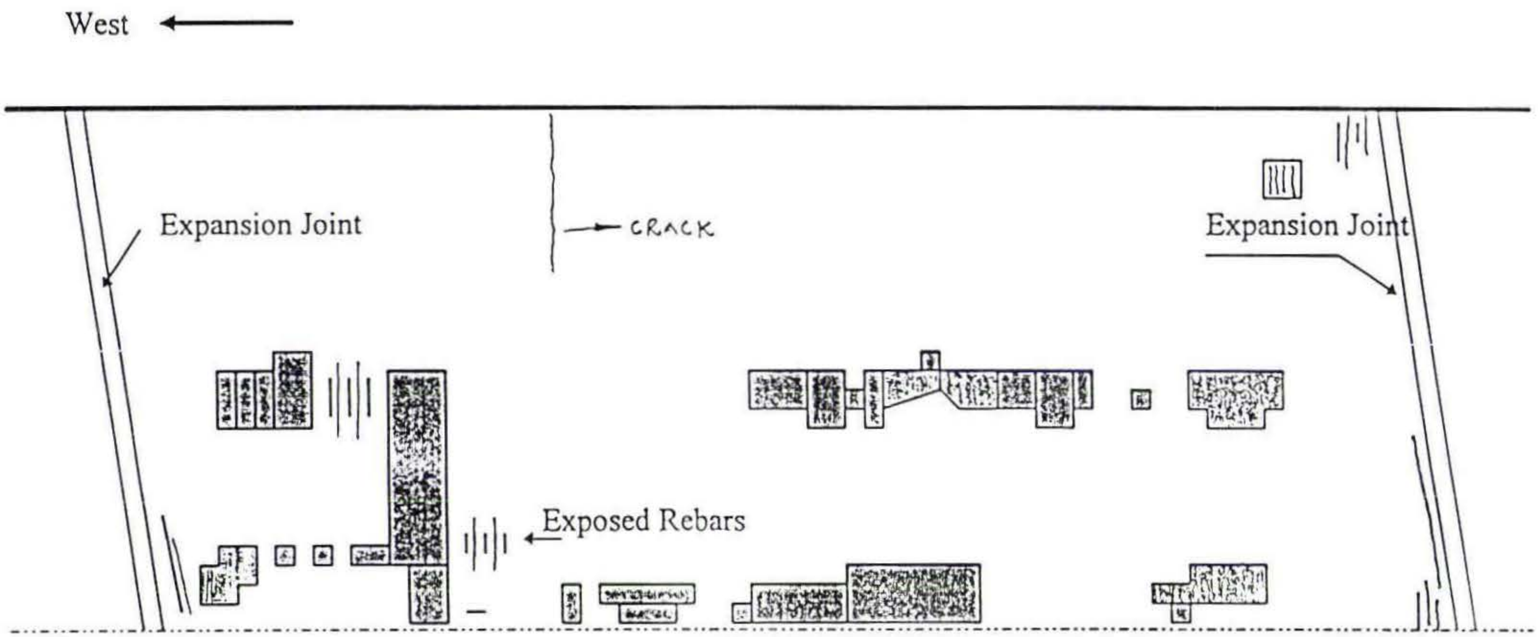
Fig B9: Comparison of Residual Strength Factors for field mixes

APPENDIX – C
(Inspection Details)



Project Location

Pre-Conditional Survey of the west bound, Driving lane.

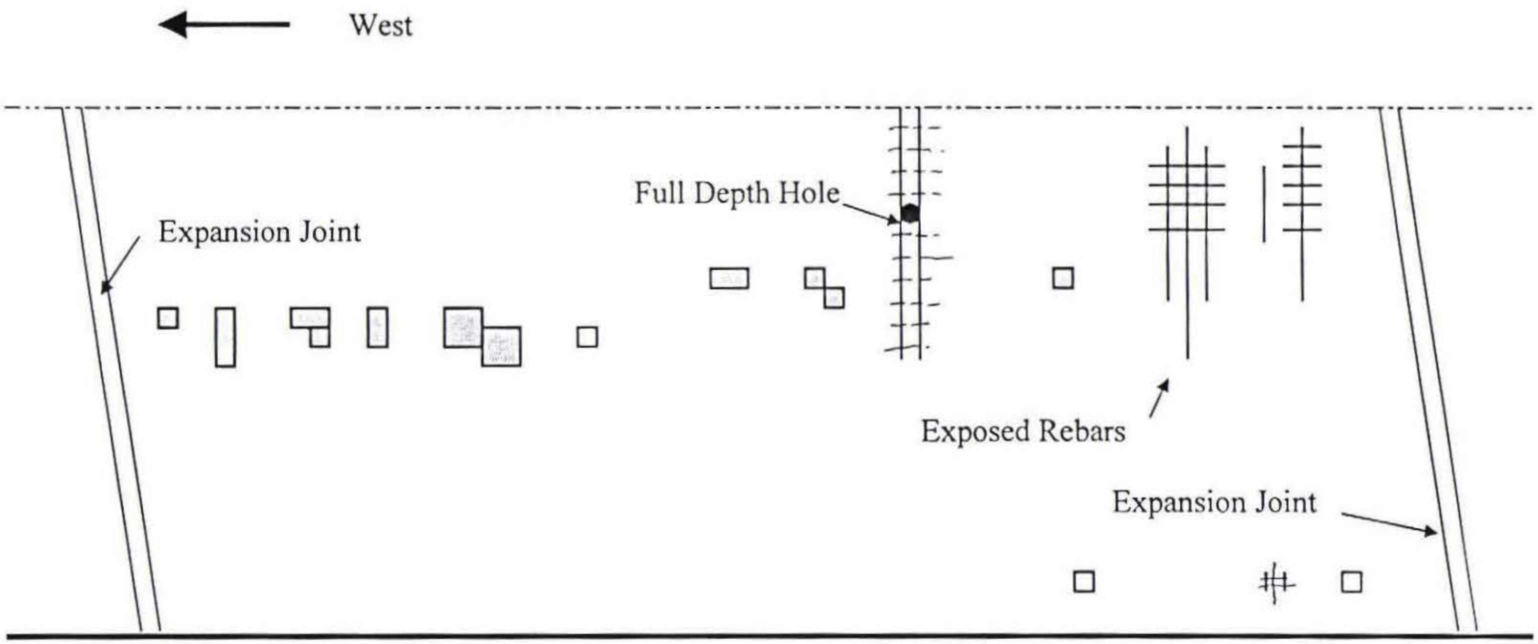


Full- Depth Patches

Exposed Rebars

Not to Scale

Pre-Conditional Survey of the West bound, Passing lane.

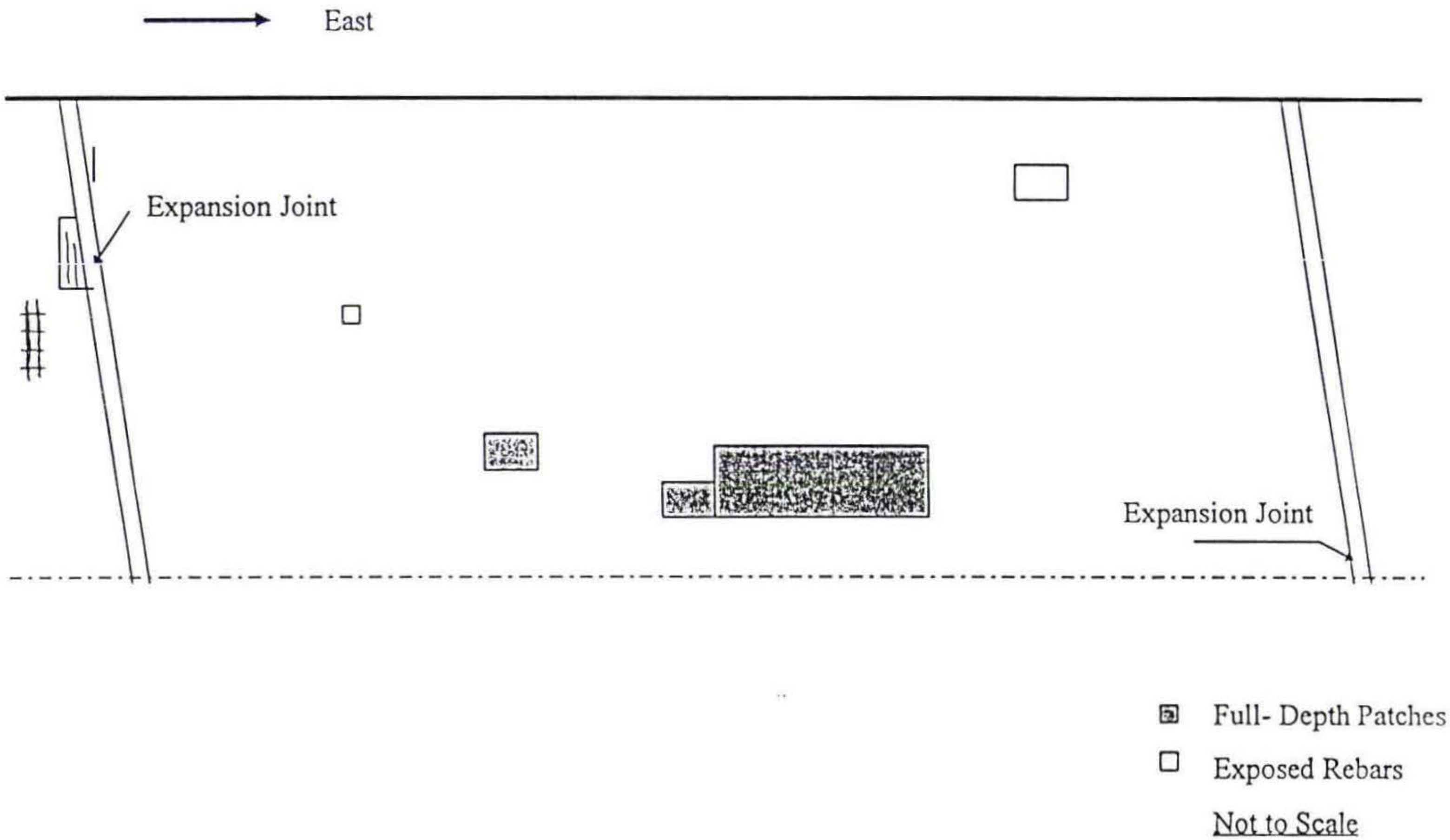


☐ Full- Depth Patches

☐ Exposed Rebars

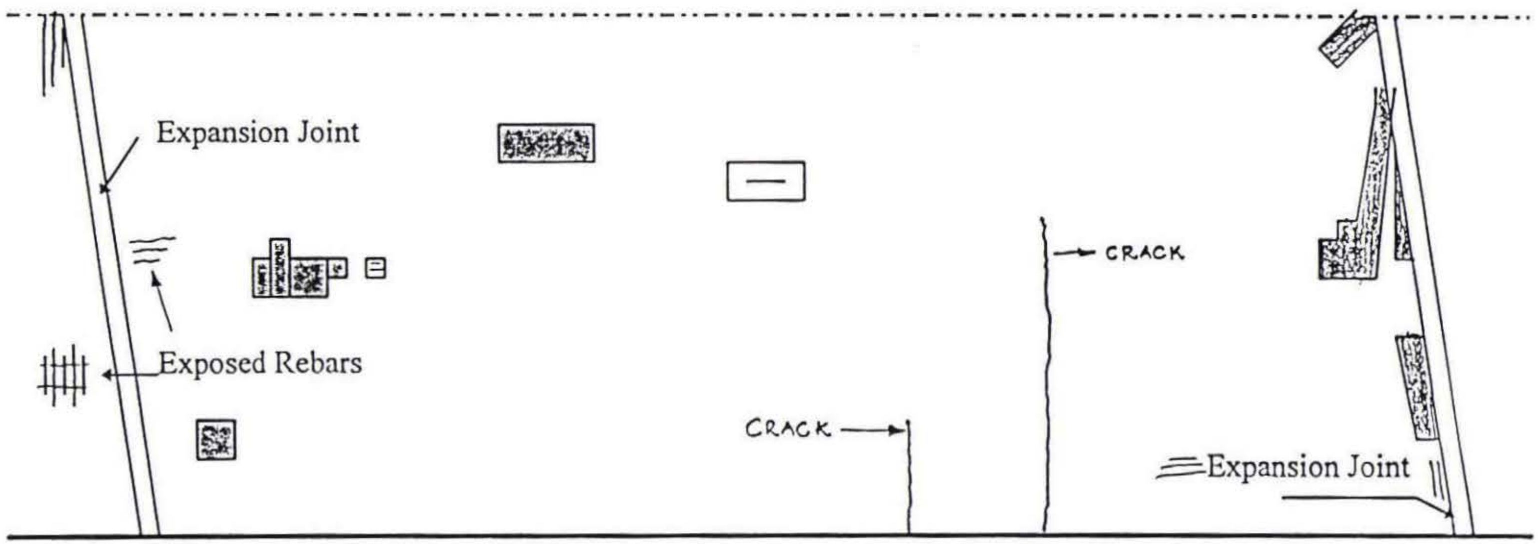
Not to Scale

Pre-Conditional Survey of the East bound, Passing Lane.



Pre-Conditional Survey of the East bound, Driving lane.

East



Full- Depth Patches

Exposed Rebars

Not to Scale

Table C1: Crack Details on the Driving lane of the East Bound lane.
(Distance measured from the expansion joint, east end)

Crack No	Distance from the east end m (ft.)	Length of Crack m (ft.)	Width of Crack mm (inches) 9/06/97	Width of Crack mm (inches) 11/19/97	Width of Crack mm (inches) 3/13/98	Status of Crack (width)
1	10.67 (35)	2.74 (9.00)	0.10 (0.004)	0.10 (0.004)	NV	
2	14.94 (49)	2.44 (8.00)		0.08 (0.003)	NV	
3	16.77(55)	3.35 (11.0)	0.20 (0.008)	0.20 (0.008)	0.10(0.004)	Decreased
4	19.82 (65)	1.15 (4.75)	0.10 (0.004)	0.10 (0.004)	0.10 (0.004)	Same
5	22.56 (74)	1.52 (5.00)	0.15 (0.006)	0.15 (0.006)	0.15 (0.006)	Same
6	26.22 (86)	1.37 (4.50)	0.25 (0.010)	0.25 (0.010)	0.25 (0.010)	Same
7	31.71 (104)	2.44 (8.00)	0.15 (0.006)	0.15 (0.006)	0.15 (0.006)	Same
8	42.38 (139)	3.58 (11.75)	0.20 (0.008)	0.20 (0.008)	0.20 (0.008)	Same
9	44.82 (147)	4.27 (14.00)	0.25 (0.010)	0.25 (0.010)	0.25 (0.010)	Same
10	46.05 (151)	1.52 (5.00)		0.1 (0.004)	0.1 (0.004)	Same
11	48.48 (159)	3.66 (12.00)	0.20 (0.008)	0.20 (0.008)	0.20 (0.008)	Same
12	51.54 (169)	1.37 (4.50)		0.08 (0.003)	0.08 (0.003)	Same
13	53.35 (175)	4.27 (14.00)	0.15 (0.006)	0.15 (0.006)	0.15 (0.006)	Same
14		1.52 (5.00)	0.10 (0.004)	on approach road	NV	

Table C2: Crack Details on the Passing lane of the East Bound lane.

Crack No	Distance from the west end m (ft.)	Length of Crack m (ft.)	Width of Crack mm (inches) 9/06/97	Width of Crack mm (inches) 11/19/97	Width of Crack mm (inches) 3/13/98	Status of Crack (width)
1	6.40 (21)	2.44 (8.00)	0.15 (0.006)	0.15 (0.006)	0.15 (0.006)	Same
2	7.92 (26)	0.91 (3.00)			0.25(0.010)	New crack

Table C3: Crack Details on the Passing lane of the West Bound lane.

Crack No	Distance from the east end m (ft.)	Length of Crack m(ft.)	Width of Crack mm (inches) 9/06/97	Width of Crack mm (inches) 11/19/97	Width of Crack mm (inches) 3/13/98	Status of Crack (width)
1	9.15 (30)	1.22 (4.00)		<0.08 (<0.003)	NV	
2*	32.92 (108)	6.70 (22.0)			0.25 (0.01)	New crack
3*	40.85 (134)	3.05 (10.0)			0.25 (0.01)	New crack
4**		0.45 (1.5)			0.25 (0.01)	New crack

Note:
NV – Not Visible
* - Longitudinal crack ** At the expansion joint west end

Table C4: Results of Periodic Inspection

Inspection Date	Description of Observation
May 21, 1997	No plastic shrinkage was observed on both the bridges except where the expansion joints were located.
May 31, 1997	No shrinkage cracks were observed along the entire bridge deck. Some unopened fiber bundles were observed. These bundles held tight to concrete.
June 12, and 16, 1997	No shrinkage cracks were observed throughout the deck overlay.
Sept. 6, 1997	No cracks were observed on the west bound lane. The driving lane of the east bound lane showed numerous cracks, but most of negligible thickness. The exposed bundles were holding good and showed no possibility of getting washed away. Numerous cracks and spalling were observed at the junction of the new and old construction on the driving lane of the east bound lane.
Nov. 19, 1997	No cracks were observed on the driving lane of the west bound lane. Only one crack of negligible width was observed on the passing lane. The cracks on the driving lane of the east bound lane showed no increase in widths and a couple of new cracks were observed. The exposed fiber bundles were also held firmly to the concrete.
March 13, 1998	No cracks were observed on the driving lane of the west bound lane. The previously observed crack on the passing lane was not visible. Longitudinal cracks were observed about 6ft from the edge along the passing lane. The exposed fibers held firmly to the concrete, there was no spalling or depression at the exposed surface. On the east bound lane only one crack was observed on the passing lane. The cracks on the driving lane showed no increase in widths. Multiple cracks about 2 inches long parallel to the road were observed on the junction of the overlay and the approach road on the east side.

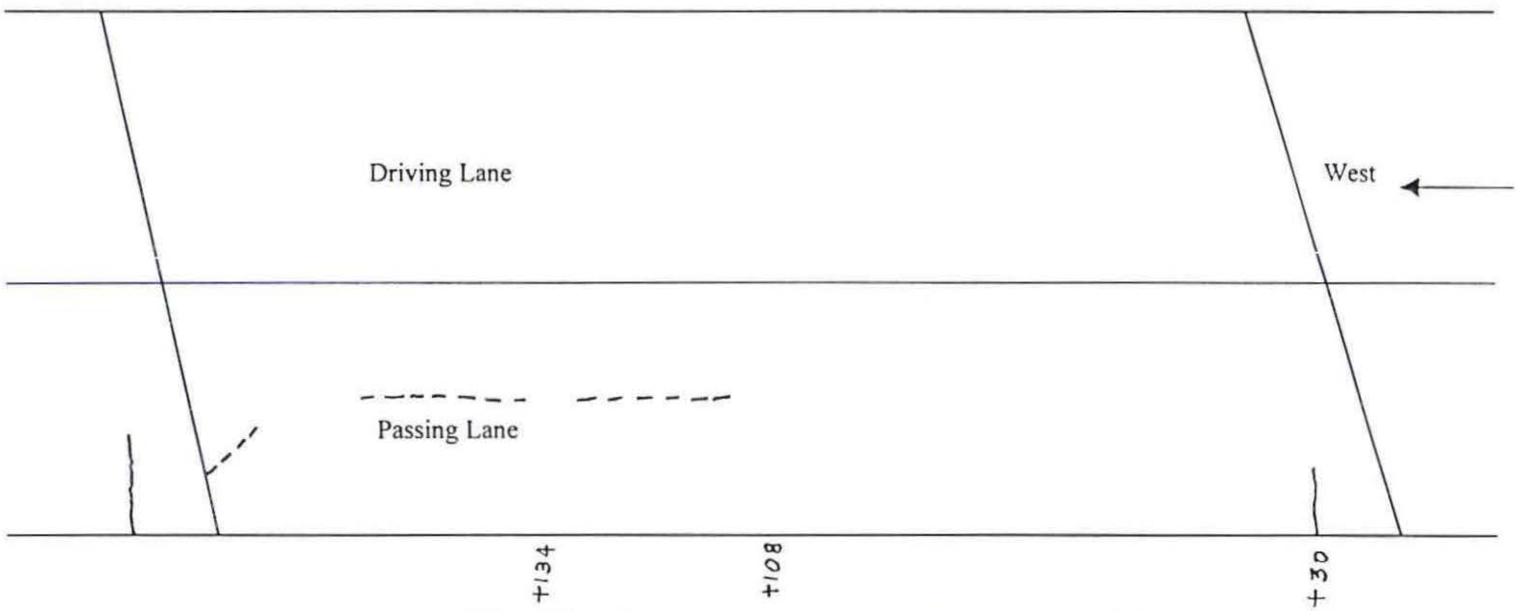


Fig C1: Crack details on the West bound Lane
(---New Cracks observed on 13th March 1998)

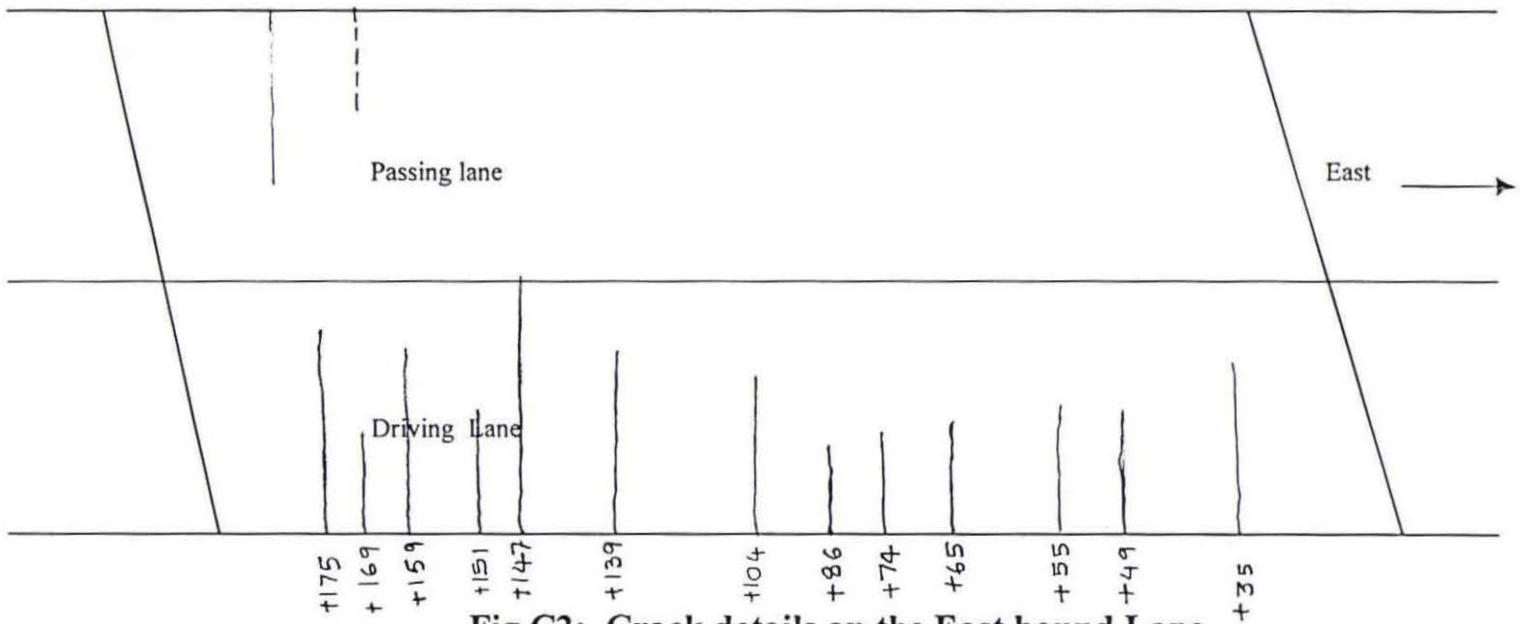


Fig C2: Crack details on the East bound Lane

(--- New cracks observed on 13th March 1998)

APPENDIX – D

(Details of data provided by DOT)

Table D1 - Compressive Strength (Data given by DOT)

Specimen #	Date of Casting	Age (Days)	Unit Weight (lbs/cu.ft.)	Air Content (%)	Slump (inches)	Compressive Strength (psi)
P1	5/15/97	4	139.5	6.90	0.75	4630
P2	5/16/97	11	142.6	5.80	1.25	4740
P3	5/23/97	4	146.7	6.20	1.75	3170
P3	6/3/97	6	139.0	6.3	0.50	4060
P4	6/4/97	5	140.5	6.2	0.50	4410

Table D2 – Compressive Strength (Data given by DOT)

Specimen #	Date of Casting	Age (Days)	Unit Weight (lbs/cu.ft.)	Area (sq. in)	Load (Kips)	Compressive Strength (psi)
P1	5/15/97	28	143.1	28.27	195	6900
P2	5/16/97	28	142.6	28.27	173	6120
P3	6/3/97	28	140.0	28.27	167	5900
P4	6/4/97	28	141.5	28.27	189	6690

Table D3 - Density Report – PC Concrete (Data given by DOT)

Test #	Date	Standard Density	Percentage of Standard Density Required (%)	Percentage of Standard Density Obtained (%)
1	5/15/97	141.2	98	99
2	5/16/97	139.9	98	99
3	6/3/97	138.9	98	102
4	6/4/97	138.8	98	100.5

Table D4 – Swiss Hammer Test Results (Data given by DOT)

Test #	Location	Date	Age	Reading (Average)	PSI From Chart	Corrected PSI
1	West Bound Driving lane	5/15/97	4	33.4	4750	5250
2	East Bound Driving Lane	5/19/97	3	31.9	4500	5000

Table D5 - Fresh Concrete Properties of the concrete on 5/15/97

Test #	Air Temp. (F)	Concrete Temp. (F)	Air Content (%)	Slump (inches)	Unit Weight (lbs/cu.ft)	Cylinders taken for this test
1	75	76	5.4	0.5	---	P1
2	75	76.9	7.6	---	---	P1
3	73	75.6	8.1	---	---	P1
4	68	72.4	6.9	0.75		P1
5	62	76.0	6.3	0.5		P1

Table D6 - Fresh Concrete Properties of the concrete on 5/16/97

Test #	Air Temp. (F)	Concrete Temp. (F)	Air Content (%)	Slump (inches)	Unit Weight (lbs/cu.ft)	Cylinders taken for this test
1	82	80.0	5.8	1.25	138.2	P2
2	80	82.7	5.3	0.25	140.5	P2
3	80	81.7	6.1	0.50	139.8	P2
4	78	82.1	8.2	0.50	138.7	P2

Table D7- Fresh Concrete Properties of the concrete on 6/3/97

Test #	Air Temp. (F)	Concrete Temp. (F)	Air Content (%)	Slump (inches)	Unit Weight (lbs/cu.ft)	Cylinders taken for this test
1	72	82.0	6.3	0.50	138.2	P3
2	76	81.3	5.2	0.50	139.6	P3
3	78	81.0	6.1	1.25	134.8	P3

Table D8 - Fresh Concrete Properties of the concrete on 6/4/97

Test #	Air Temp. (F)	Concrete Temp. (F)	Air Content (%)	Slump (inches)	Unit Weight (lbs/cu.ft)	Cylinders taken for this test
1	75	80	6.2	0.25	140.2	P4
2	76	80	6.2	0.5	140.3	P4
3	74	80	5.3	0.75	139.4	P4
4	76	80	5.3	0.5	140.0	P4