2004

Evaluation of concrete bridge deck overlays

Zhenhua Sun
West Virginia University

Recommended Citation

Sun, Zhenhua, "Evaluation of concrete bridge deck overlays" (2004). *Graduate Theses, Dissertations, and Problem Reports*. 1512.
https://researchrepository.wvu.edu/etd/1512

Evaluation of Concrete Bridge Deck Overlays

by

Zhenhua Sun

Thesis submitted to the
College of Engineering and Mineral Resources
At West Virginia University
In partial fulfillment of the requirements
For the degree of

Master of Science
In
Civil Engineering

Approved by

Julio F. Davalos, Ph.D., Chair
Indrajit Ray, Ph.D., Co-Chair
Xingbo Liu, Ph.D.

Department of Civil and Environmental Engineering
Morgantown, West Virginia
2004

Keywords: Concrete Overlay, Interface, Shear Bond Strength, Fractional Factorial Design of Experiment, Silica Fume, Latex, Slag, Fiber.

ABSTRACT

Evaluations of Concrete Bridge Deck Overlays

Zhenhua Sun

Advisors: Dr. Julio F. Davalos and Dr. Indrajit Ray

Overlay systems have been used by many states for the protection of bridge decks, but the premature delaminations and failures have been observed in many cases. A comprehensive study was recently defined to investigate overlay performance in collaboration with the West Virginia Department of Transportation-Division of Highways (WVDOH).

As part of a comprehensive program, the present study is concerned with the properties of several types of overlay mixtures and the interface bond strengths between them and substrate concrete. All the materials used are of interests to WVDOH. Both fresh and hardened concrete properties of seven different overlay types were characterized. Four of the seven were selected for the study of interface bond strength, which included latex modified concrete, silica fume modified concrete, fiber-reinforced concrete and slag modified concrete. With these four selected overlays, statistical design of experiments were conducted for the evaluation of the influences on bond strength of four factors: aggregate types, surface preparations, use of bonding slurry, and substrate age using a recently developed direct shear test apparatus.

Results show that except for bonding slurry, all the parameters had strong influence on shear bond strength. The results of this study will serve the purpose of screening and selection of overlays from a large number of variables, and will finally help to develop guidelines by WVDOH for future implementations of concrete overlays in the field.

ACKNOWLEDGEMENTS

I would first like to thank Dr. Julio F. Davalos, who as my advisor has provided valuable guidance and exhibited a great deal of patience throughout my graduate education process. I feel very privileged to have been able to study under him.

I am indebted to Dr. Ray, whose immense concrete knowledge has been essential to the accomplishment of this study. Thank you for your tremendous guidance and help throughout my research endeavor, from the experiment work to the writing of my thesis.

I would like to extend my thanks to Dr. Xingbo Liu for his friendship, review of my work and willingness to serve on my committee.

My thanks go to Justin Robinson, William Comstock, David Turner, and Doug Cutlip, for their valuable help with the laboratory work.

I want to thank my colleague, Tao Hong, for his support and patience during this research effort. I also want to thank Dayong Fan, Zhiguo Gong, and Aniruddha Chatterjee, from whom I have got a lot of help and friendship.

I gratefully acknowledge the financial support provided by West Virginia Department of Transportation- Division of Highways and WVU Research Corp. Incentive Grant Program. I also acknowledge Arrow Concrete Company for supplying limestone, gravel and cement, Martin Marietta Aggregates for gravel and sand, Holcim, Inc. for slag, Advanced Cement Technology for metakaolin, BASF and John Ahern Association for latex, Dow Chemicals for antifoam, and Master Builders Inc. for silica fume and chemical admixtures.

I want to thank my wife for her love, support, and encouragement whenever I need them. I love you so much.

To my unborn baby: You have already brought so much joy to my life. Daddy is looking forward to seeing you on time.

Especial thanks go to my parents for always supporting me. I love you both.

TABLE OF CONTENTS

CHAPTER 1 INTRODUCTION

LIST OF TABLES

LIST OF FIGURES

(c) Application of slurry

(d) Substrate ages

(e) Aggregate type

ABBREVIATIONS

ACI	**American Concrete Institute**
ASTM	**America Society of Testing and Materials**
LMC	**Latex Modified Concrete**
SFMC	**Silica Fume Modified Concrete**
FRC	**Fiber Reinforced Concrete**
SLMC	**Slag Modified Concrete**
LSDC	**Low Slump Dense Concrete**
PC	**Polymer Concrete**
MTMC	**Metakaolin Modified Concrete**
WVDOH	**West Virginia Department of Transportation Division of Highway**
ICRI	**International Concrete Repair Institute**
CSP	**Concrete Surface Profiles**
SDPC	**Superdense Plasticized Concrete**
SHRP	**Strategic Highway Research Program**

CHAPTER 1

INTRODUCTION

This chapter presents the background and objective of this project. It also describes the organization of this thesis.

1.1 Introduction

Deterioration of reinforced concrete decks is one of the main problems in life-cycle service of highway bridges. For this reason, overlay systems have been used by many states to protect bridge decks from deterioration. A significant amount of researches have been done recently, which showed that the overlay systems were useful in extending the life of the reinforced concrete bridge deck for both newly constructed and repaired old bridges thus reducing overall costs for the bridge structure.

The West Virginia Department of Transportation, Division of Highway (WVDOH) has been routinely using concrete deck overlay systems at different environmental conditions for many years. Details of the overlay system are defined by the WVDOH standard specifications for roads and bridges (Section 679, WVDOH, 2000). Normally, a 50 mm (2 in.) overlay is applied on the reinforced concrete deck, which acts as a protective layer to the substrate. The thickness of overlay shall not be less than 32 mm (1¼ in.) under any circumstances.

To achieve good performance, the overlay system must act compositely with the regular bridge deck during the service. Although there is much debate concerning the best type of overlay to choose, there is consensus that achieving a good bond to the existing deck is the key to overlay durability. The most important factor towards achieving a good bond is to properly prepare the surface of the bridge deck (Sprinkl

1997). Suprenant (1988) also mentioned that the surface preparation, selection and using of overlay materials and curing are three major factors which could affect the concrete-to-concrete bond. Other factors, such as the temperature of concrete, curing conditions and the maturity of concrete, can also affect the deck characteristics and eventually affect the overall performance of overlay.

Depending on the quality of construction and properties of materials, the failure can occur through overlay, interface, substrate or combinations of some of them. The failure can take place as spalling or even delamination in extreme cases. The overlay mixtures typically used in West Virginia are latex modified concrete (LMC) and silica fume modified concrete (SFMC). Spalling and delamination have been found in both using of them. There are evidences that the failure in the old concrete can be mostly eliminated by proper hydrodemolition of the bridge deck surfaces and using surface treatments routinely. However for newly constructed bridges, there are still no good ways to prevent the failures, which emphasizes the need for the development of specifications for proper applications of the technology.

Several types of overlay have been used in USA. The most commonly used ones are: latex modified concrete (LMC), silica fume or micro silica modified concrete (SFMC), low slump dense concrete (LSDC), fiber reinforced concrete (FRC), and polymer concrete (PC). Each overlay has its own advantages and limitations. Proper selection depends on many factors such as: substrate concrete, local aggregate availability, construction practices, construction costs and others. The WVDOH typically uses either LMC or SFMC. The specifications (WVDOH, 2000) provide the general mix requirements for both of them. The ACI 518 also gives the standard specification for LMC. But all the standards only provide the application of overlay under particular conditions. It is necessary to have more specific information on the suitability of a particular overlay on a concrete deck with certain maturity and surface condition. Also, the LMC and SFMC overlays used in new decks are showing premature cracks, spalling and delaminations due to surface shrinkage and strength failure at interfaces caused by moisture change, temperature change and mechanical stresses. All the problems mentioned above need to be addressed.

As for surface preparation, several techniques have been used in the US. For small areas, the decks are normally scrabbled, sandblasted or shot-blasted. For larger areas, concrete milling machine or hydrodemolition is used. There are some guidelines for surface preparations in the reports by ACI committee 345 (ACI 345R-91, 1991), and in WVDOH specifications. However, both of them are very general.

Therefore, from the discussions above, more specific construction standards are required on practices such as surface preparation, placement, curing and others to ensure better bonding between overlays and the reinforced concrete deck concrete, and to eliminate the crack development and get better resistance against different environmental conditions such as chloride penetration and freeze-thaw cycling.

Thus, the characterizations of overlay materials and evaluations of performance of two-layer system (overlay and deck) under different constructional and environmental condition is extremely important for developing modification to current specifications.

This study, as a part of a comprehensive program on concrete overlays, will focus on the characterization of several overlays and performance of interface between overlay and substrate. All the materials used were of interests to WVDOH. Initially seven different overlays were developed and characterized. Then four out of seven were selected for interface shear bond strength evaluation by using a newly developed shear tool. Fractional factorials design method was used as a statistical method for the design of experiment to evaluate the effects of several variables on interface bond strength.

1.2 Global Research Objectives

The objectives of the whole program are (i) to investigate current practices of concrete overlay construction prevalent in WV and in other states; (ii) to develop a research protocol and conduct a focused study in material characteristics and delaminations of overlay, particularly for selected materials of interest to the WVDOH; and (iii) to develop comprehensive specifications for the WVDOH for concrete overlay applications on both old and new concrete bridge deck construction.

The objectives were organized into the following three phases:

Phase I: To gather the current state-of-knowledge from review of technical literature and experiences of other departments of transportation, survey the concrete overlay projects in WV and identify problem areas from them. Then to select, develop and evaluate overlay materials of mixtures suitable for WVDOH.

Phase II: To investigate delamination issues related to materials and construction methods.

Phase III: To conduct field performance tests on selected groups of deck-overlay combinations and to prepare specifications for the implementation of the overlay systems in the field.

1.3 Present Research Objectives

The objectives of the present research was to gather the current state of knowledge from review of technical literature to select, develop and evaluate the materials of mixtures suitable for WVDOH and to investigate the delamination issues related to materials and construction methods.

The objectives are presented as follows:

1. To review the current state-of-knowledge;

2. To develop, evaluate and select different kinds of overlay mixtures;

3. To investigate the shear bond strengths of four overlay mixtures (LMC, SFMC, FRC, and SLMC) using a newly developed shear tool. In this part, fractional factorial design was used for experimental design to evaluate the effects of several variables on shear bond strength, such as surface preparation, substrate ages, using of bonding slurry and aggregate types.

1.4 Thesis Organization

Chapter 1 presents the background, the global objective and the task of this research. Chapter 2 gives the description of the overlay system. The detailed literature review is also given in this chapter. Chapter 3 describes the materials and the mixture proportion used for overlay evaluation. Chapter 4 presents the characterization of both fresh and hardened concrete for overlays and substrate. Chapter 5 introduces the specimens and shear test apparatus used in the study. Chapter 6 presents the design of experiment and the analysis of test results. Chapter 7 draws the conclusion from this research and makes recommendations for future study.

CHAPTER 2

DESCRIPTION OF OVERLAY SYSTEMS AND REVIEW OF LITERATURE

This chapter introduces the current status of research on overlay systems and gives a detailed literature review on this area.

2.1 Description of Different Types of Overlays

The application of overlays has been a major effort for the highway agencies in the United States to protect existing reinforced concrete bridge decks from premature deterioration. Concrete overlays can be bonded or unbonded to the existing bridge decks. Most of the overlays in the United States are bonded to the substrate. In some cases unbonded overlays are placed to protect waterproofing membranes. Common types of bonded overlays consist of LMC, SFMC, FRC, LSDC, PC and others. The following are brief descriptions of the most commonly used overlays.

2.1.1 Silica Fume Modified Concrete (SFMC)

Silica fume has been used to substitute part of the cement in concrete outside the United States since the 1970s. It has been used in bridge decks in the US since 1983 (Luther 1988). It is a byproduct of the silicon or ferrosilicon industry. In cementitious compounds, silica fume works both at chemical level and physical level. Research and practice showed that silica fume modified concrete had better resistance to penetration of chloride ions of the deck reinforcement, higher amount of abrasion-resistance in the surface, higher early and ultimate strength, and lower cost (Luther 1988 and Ozyldirum 1988). In a recent report by FHWA, it was shown that concrete repair mixes for slabs produced with micro silica and fly ash mineral admixtures performed exceptionally well for rebar corrosion. For typical concrete overlays, silica fume is added in the range of 5% to 15.5% by weight of portland cement. As for curing, the overlay surface shall be completely covered with clean and wet burlap, which shall be well drained and continuously wet for a period of at least 96 curing hours (WVDOH Standard Specifications, 2000) to avoid plastic shrinkage cracking. SFMC has been used in many states in USA, such as West Virginia, New York, Oregon, Ohio, Rhode Island and others.

2.1.2 Latex Modified Concrete (LMC)

LMC has been used for bridge overlays in the USA since 1956. The first LMC overlay was placed in West Virginia in 1961 (Steele and Judy 1977). In general, LMC shows a noticeable increase in the tensile, compressive, and flexural strengths when compared to the normal concrete. As a bridge deck overlay, LMC has higher adhesion or bond strength with any substrate, which significantly increases the interface bond strength. It has good resistance to impact, abrasion, water penetration and freezing-thawing cycling, which is also critical for bridge overlays (Ramachandran 1995). The curing for latex concrete is different from that for normal concrete. WVDOH suggests 48 hours saturated burlap covering immediately after the casting followed by air curing for another 48 hours. ACI developed a standard specification (ACI 548.4-93) for latex modified concrete overlays in 1993. WVDOH also gives general guidelines on LMC application on bridge decks (Section 679 of Supplemental Specifications 2003).

2.1.3 Fiber Reinforced Concrete (FRC)

Since the 1960s, FRC has been used to increase the durability of transportation structures. Virginia Department of Transportation used steel fibers in 1974 for a bridge deck overlay and recently used steel and plastic fibers in bridge deck and pavement overlays experimentally (Ozyildirim et al., 1997). The advantages of FRC for bridge overlay applications are as follows: (1) increased resistance to crack propagation due to plastic and drying shrinkage; (2) improved resistance to thermal and moisture stresses; (3) increased ductility; (4) higher impact and abrasion resistance, and (5) greater tensile, flexural, and fatigue strength. Currently in the United States, steel, glass, and synthetic fibers are the most widely used fiber types. Blends of steel and synthetic fibers are also available. Usually, certain admixtures are used with fibers to achieve better workability.

2.1.4 Low-Slump Dense Concrete (LSDC)

The LSDC was adopted by many states as overlay materials since 1970s. It has low or even no slump. The high cement content and low water content reduce the permeability if the concrete is well consolidated. A dense overlay mix was used in Kansas earlier in the 1960s (Halvorsen, 1993). Iowa extensively used LSDC overlay in several projects. Due to the low slump, the placement and consolidation of LSDC can be difficult. In some cases, mechanical tamping is used. In other cases, high-range water reducing admixture (HRWRA) was added in concrete to make the placing easier. The application of low-slump or high-density concrete has been incorporated in the specifications of several states, such as: Kentucky, Minnesota, New York, North Dakota and a few others.

2.1.5 Polymer Modified Concrete (PC)

PC is a composite material made with fillers and binders. It is variously known as synthetic resin concrete, plastic resin concrete or simply resin concrete. Polymer concrete composites have generally good resistance to attack by chemicals and other corrosive agents, very low water sorption properties, good resistance to abrasion and marked freeze-thaw stability. It appears to be very fast setting and no-shrinking. It is marketed as useful materials for overlay applications on reinforced concrete. Polymer overlays are becoming increasingly popular with state Department of Transportations (DOT) as protective barrier for bridge decks, especially when it is necessary to reopen the bridge to traffic as quickly as possible. Since PC is relatively expensive, they are mainly used in special applications such as skid-resistant overlays in highways. ASTM 881 requirements are used by various DOTs as a guideline for epoxy bridge deck overlay systems.

2.1.6 Other Types of Overlays

Several other overlays have been developed in the past years. In some of them, mineral admixtures such as fly ash and slag are added. In other cases, several admixtures or fibers are combined together. Here are some examples: Fiber Reinforced Polymer Concrete, High Early Strength Latex Modified Concrete, Steel Fiber Reinforced Micro-silica Modified Concrete, Steel Fiber Reinforced Superplasticized Dense Concrete and others.

2.2 Literature Review

According to the research objectives, the literature review was done mainly in two areas: (1) General evaluations of overlay systems, and (2) The evaluation of interface bond strength. They are presented in 2.2.1 and 2.2.2 respectively. Due to large number of literature on the general evaluations of overlay systems, the reviews are summarized in a tabular form. In case of interface evaluations, a detailed literature review is furnished.

2.2.1 Summary of Reviewed Literature on Overlay Materials

The summarized review of overlay systems are furnished in Table 2.1

Table 2.1−Summarized reviews on overlay mixtures

No.	Title	Author / Authors	Source	Objectives	Parameters evaluated	Selected Outcome/conclusions
1	Paving of roads and bridges with unsaturated polyesters	Estrada, N. S.	*25th annual technical conference, the society of plastics industry, Inc*., 1970, 20-F, 20p	To describe a progressive series of applications of polyester overlays on a variety of concrete road and bridge surfaces.	–	The polyester showed the potential to be developed as an overlay material.
2	Pavement applications for steel fibrous concrete	Lankard, D. R. and Walker, A. J.	*ASCE, Transportation Engineering Journal*, v 101, n 1, Feb, 1975, p 137-153	To discuss the suitability of SFC as an overlay material for bridge overlays and pavements.	Comprehensive evaluation	SFC was potentially a superior pavement overlay material.
3	Deck slab repaired by fibrous concrete overlay	Schrader, E. K. and Munch A. V.	*ASCE, Journal of the Construction Division*, v 102, n 1, Mar, 1976, p 179-196	To describe the mix design and construction of fibrous concrete overlays, and evaluate the results obtained.	–	It was possible to overlay concrete surfaces with steel fibrous concrete as thin as 1 in.
4	Polymer-modified concretes in bridge deck overlay systems	Steele, G. W. and Judy, J. M.	*ASTM Special Technical Publication*, n 629, 1977, p 110-115	To introduce the use of polymer-modified concretes for bridge overlay in WV.	Compressive strength, freeze-thaw resistance, bond to concrete, and chloride penetration.	Latex-modified concrete was the most satisfactory compared to other types of treatment under evaluation.
5	Shrinkage and creep characteristics of latex-modified concrete	Bishara, A. G.; Tose, J. D. and Youssef, M. A. R.	*Journal of The American Concrete Institute*, v 75, n 5, May, 1978, p 204-208	To study creep and shrinkage characteristics of LMM, LMC used for bridge deck overlays.	Creep and shrinkage.	Empirical equations based on test results were developed for predicting creep and shrinkage.

6	Properties of portland cement concrete containing fly ash and condensed silica-fume	Mehta, P. K. and Gjory, O. E.	*Cement and Concrete Research*, v 12, n 5, Sep, 1982, p 587-595	To investigate the effect of using a mixture of normal and highly reactive pozzolans to early strengths	Compressive strength	From the standpoint of early concrete strengths, it was better to use mixtures of low and high surface-area pozzolans (fly ash and silica fume) than using a normal pozzolan alone.
7	Construction of Thin Bonded Concrete Overlay	Obuchowski, R. H.	*Transportation Research Record*, 1983, p 10-15	To present the construction of a 3 in. thick overlay on a section of I-81 in 1981.	–	An adequate bond could be achieved by using surface preparation and a portland-cement and sand bonding grout.
8	A study on the effect of temperature variations on the bonding of concrete overlays	Dhir, M. P.	*Journal of The American Concrete Institute*, v 81, n 2, Mar-Apr, 1984, p 172-179	To assess the adverse effects of large temperature variations that occur when overlaying is done in intemperate weather.	Shear bonding strength	Overlaying done in weather with large temperature variations did not yield satisfactory bonding with conventional techniques. Using of insulation coverings could be a solution.
9	Rochbond: a new micro silica concrete bridge deck overlay material	Christensen, D. W.; Sorenson, E.V. and Radjy, F. F.	*Engineers' Soc of Western Pennsylvania*, 1984, p 151-160	To evaluate a new bridge deck overlay material, Rockbond, which is a high-strength micro-silica concrete, by comparing it with LMC and LSDC.	Compressive strength, flexural strength, chloride permeability, shear-bond strength, freeze-thaw and abrasion resistance.	High-strength micro silica concrete developed greater compressive, flexural and bond strengths, was less permeable to chloride ions, and had excellent freeze-thaw resistance.
10	Thin polymer concrete overlays for bridge deck protection	Sprinkel, M. M.	*Transportation Research Record*, v 1, 1984, p 193-201	To discuss the potential of thin PC overlays for extending the service life of bridge decks.	Shear bond strength, delamination, permeability, and shrinkage.	The PC overlay had the potential to be an economical alternative method of LMC, although it was still experimental.
11	Durability and compatibility of overlays and bridge deck substrate Treatment	Cady, P. D.; Weyers, R. E. and. Wilson, D. T.	*Concrete International: Design and Construction*, v 6, n 6, Jun, 1984, p 36-44	To provide ratings relative to durability and compatibility of combinations of a variety of potential substrate treatments and overlays	Freezing and thawing tests for LMC, LSDC and PC. Specimen weight and pulse velocity	Ratings relative to durability and compatibility of combinations of a variety of potential substrate treatments and overlays were provided.

12	Fibrous portland cement concrete overlay research in Greene county, Iowa	Betterton, R. M.; Knutson, M. J. and Marks, V. J.	*Transportation Research Record*, n 1040, 1985, p 1-7	To evaluate the performance of steel fiber-reinforced concrete overlay (fibrous concrete).	–	The thicker and no fibrous pavement overlay sections performed better than the fiber-reinforced concrete overlays.
13	Polymer concrete bridge overlays	Cremaschi, J.	*Concrete International: Design and Construction*, v 8, n 5, May, 1986, p 58-60	To discuss the use of polymer concrete bridge overlays as a faster, less expensive way to protect bridge decks while offering good wear resistance and skid resistance.	–	Polymer concrete polyester overlays had already been successfully applied in several states and they were beginning to be accepted and recognized as a means of economical bridge and pavement repair.
14	A polymer concrete overlay	Mendis, P.	*Concrete International: Design and Construction*, v 9, n 12, Dec, 1987, p 54-56	To evaluate the performance of the epoxy overlay on bridge.	Bond strength, wear, skid resistance, and electrical resistance.	The epoxy overlay was performing satisfactorily in terms of protection, bonding, and durability.
15	Laboratory investigation of concrete containing Silica fume for use in overlays	Ozyildirim, C.	*ACI Materials Journal*, v 84, n 1, Jan-Feb, 1987, p 3-7	To assess the suitability of SFMC for use in overlays having a minimum thickness of 32 mm.	Strength, permeability, and freeze-thaw resistance.	SFMC overlays with a minimum thickness of 32mm (1¼ in.) could provide a cost-effective protective system for bridge decks.
16	ODOT experience with Silica-fume Concrete	Bunke, D.	*Transportation Research Record*, n 1204, 1988, p 27-35	To evaluate the using of silica-fume concrete for bridge-deck-overlay in Ohio	Compressive and flexural strengths, resistance to freezing and thawing, and permeability.	The Ohio's 15 percent by mass of silica-fume requirement could be reduced. SFMC appears to be a satisfactory and cost-competitive material for bridge deck overlays.

17	Experimental installation of a concrete bridge-deck overlay containing silica fume	Ozyildirim, C.	*Transportation Research Record*, n 1204, 1988, p 36-41	To determine whether SFMC can be successfully used in thin overlays as a cost-effective alternative to the widely used LMC.	Compressive strength, flexural strength, bond strength, chloride permeability, and freezing and thawing.	SFMC could be a cost-effective alternative to LMC for use as thin bridge decks overlays. Concretes containing 7~10% SF exhibited satisfactory strengths and low chloride permeability.
18	High early strength latex-modified concrete overlay	Sprinkel, M. M.	*Transportation Research Record*, n 1204, 1988, p 42-51	To describe the condition of the first high early strength latex-modified concrete (LMC-HE) overlay constructed for the VDOT.	Compressive strength, shear bond strength, freeze-thaw, drying shrinkage, and skid resistance.	The LMC-HE overlay performed well. The LMC-HE was a good choice for overlay, which could be opened to traffic within 24 hr.
19	Bonding new concrete to old	Suprenant, B.	*Concrete Construction*, v 33, n 7, Jul, 1988, p 676-680	To introduce the factors affecting the bonding between new concrete and old.	–	Proper surface preparation, material choice and use, and curing should be ensured to achieve good bonding.
20	Field evaluation of steel fiber reinforced concrete overlay with various bonding mechanisms	Chanvillard, G.; Aitcin, P. -C. and Lupien, C.	*Transportation Research Record*, n 1226, 1989, p 48-56	To evaluate the performance of overlays of 18 different conditions.	–	The use of a thin, bonded fiber reinforced concrete overlay to rehabilitate old concrete pavements yielded encouraging results.
21	Chloride permeability of rigid concrete bridge deck overlays	Whiting, D. and Dziedzic W.	*Transportation Research Record*, n 1234, 1989, p 24-29	To study the chloride permeability of bridge deck overlays constructed with LMC, SDC, and CSFC.	Rapid chloride permeability test and 90-day chloride ponding test.	CSFC was the most impermeable to chloride ions, followed by LMC and SDC
22	Thin steel fiber cement mortar overlay for concrete pavement	FWA, T. F. and Paramasivam, P.	*Cement & Concrete Composites*, v 12, n 3, 1990, p 175-184	To examine the reasonability of using thin steel fiber cement overlay for the rehabilitation of surface-deteriorated concrete pavements.	Abrasion test and flexural test.	Fiber in the cement was effective in improving the abrasion resistance of concrete surface and load-carrying capacity of concrete.

23	Performance of bridge deck concrete overlays	Babaei, K and Hawkins, N. M.	*ASTM Special Technical Publication*, n 1100, 1990, p 95-108	To document performance of 12 concrete bridge decks in Washington State which were rehabilitated and /or protected with LMC and LSDC overlays.	Freeze-thaw, surface wear and skid resistance, surface cracking, bond with substrate, and chloride and water intrusion.	Compared to LSDC, LMC bonded more strongly with substrate, had more scaling resistance. They both were resistant but not impermeable to salt intrusion.
24	Cracks in latex-modified concrete overlays	Kuhlmann, L.	*Transportation Research Record*, n 1301, 1991, p 17-21	To investigate the cause, effect, and prevention of cracks in latex-modified concrete.	Both internally caused and externally caused cracks	Cracks in LMC were not always detrimental to long term performance of the material and it could be controlled by proper attention to quality of materials and construction procedures.
25	Silica fume, latex-modified portland cement mortars and concretes	Walters, D. G.	*Transportation Research Record*, n 1301, 1991, p 12-16	To examine the combined use of silica fume and S-B latex.	Compressive strength, flexural strength, adhesion, tensile bond, and permeability	The combined use of SF and S-B latex yielded mortars and concretes that had superior properties to those using one or the other of them.
26	Performance of rehabilitated / protected concrete bridge decks	Babaei, K. and Hawkins, M.	*ASTM Special Technical Publication*, n 1137, 1992, p 140-154	To determine the relative effectiveness of three bridge deck protective systems: LMC, LSDC and CP	Field investigation.	LMC and LSDC seemed to be more cost effective than CP systems.
27	Compatibility of polyester-styrene polymer concrete overlays with portland cement concrete bridge decks	o'Connor, D. N. and Saiidi, M.	*ACI Materials Journal*, v 90, n 1, Jan-Feb, 1993, p 59-68	To evaluate the compatibility of polyester-styrene polymer concrete overlays with portland cement concrete	Compressive strength, modulus of elasticity, splitting tensile strength, and modulus of rupture.	The polymer concrete was good to be used as overlays for its high compressive strength, low Modulus of elasticity and high modulus of rupture. However, it had higher coefficient of thermal expansion, which was not good for the composite action between overlay and substrate.

28	Twenty-Year performance of latex-modified concrete overlays	Sprinkel, M. M.	*ASTM Special Technical Publication*, n 1176, 1993, p 141-154	To compare the performance of bridge deck overlays with latex and without latex	Permeability, rate-of-corrosion, and bond strength.	The LMC performed satisfactorily and much better than unmodified concrete.
29	Steel fiber-reinforced concrete bridge deck overlays: experimental use by Ohio Department of Transportation	Baun, M. D.	*Transportation Research Record*, n 1392, 1993, p 73-78	To evaluate SFR-MSC and SFR-SDC as two bridge deck overlay materials.	Comprehensive evaluations	SFR-MSC and SFR-SDC should be more closely examined as serious material candidates of overlay materials.
30	Using styrene-butadiene latex as a modifier to concrete for bridge deck and parking garage overlays	Kuhlmann, L. A.	*ASTM Special Technical Publication*, n 1176, 1993, p 125-140	To introduce the using of latex as a bridge deck and parking garage overlay material.	Properties of both fresh and hardened concrete.	Polymer-modified concrete was suitable for use as an overlay on bridge decks and parking garage.
31	Polyester concrete for bridge deck overlays	O'Connor, D. N. and Saiidi, M	*Concrete International: Design and Construction*, v 15, n 12, Dec, 1993, p 36-39	To determine the basic engineering properties of the polymer concrete and the effects of elevated temperature and temperature cycling on the strengths of concrete	Bond strength, compressive strength, and modulus of elasticity	The compressive strength of polyester concrete decreased when temperature increased, but the durability and integrity were not affected. Bond strength was satisfactory for all specimens and exceed the specified bond modulus of rupture of 3.4 MPa
32	Ohio evaluates reinforced concrete deck overlays	Baun, M. D.	*Better Roads*, v 63, n 5, May, 1993, p 16, 18-19	To analyze SFR-MSMC and SFR-SPDC as potential bridge deck overlay candidates.	Crack information	The addition of quality randomly dispersed deformed steel fibers could noticeably reduce early crack formation and propagation.

33	Laboratory investigation of low-permeability concretes containing slag and silica fume	Ozyildirim, C.	*ACI Materials Journal*, v 91, n 2, Mar-Apr, 1994, p 197-202	To evaluate the general range of combinations of slag and silica fume that could be expected to provide suitable strength and permeability at maximum economy	Chemical and physical analyses, compressive strength, chloride permeability	The combining using of slag and SF could reduce the chloride permeability significantly.
34	Use of conventional and high-performance steel-fiber reinforced concrete for bridge deck overlays	Krstulovic-Opara, N.; Haghayeghi, A. R.; Haidar, M. and Krauss P. D.	*ACI Materials Journal*, v 92, n 6, Nov-Dec, 1995, p 669-677	To present cement based composites, high-performance FRC and improved FRC, which could provide a long-term solution to bridge deck problems.	–	Both HPFRC and FRC bridge deck overlays would improve the ride ability of deteriorated bridge decks and protect underlying structures from influence of aggressive agents.
35	A latex-modified concrete overlay on plain-jointed concrete pavement	Glauz, D. L.	*Cement, Concrete and Aggregates*, v 17, n 2, Dec, 1995, p 201-204	To evaluate the potentially lower cost latex overlay system.	Cracks, bonding, joints, and long-term performance.	LMC bonded well to a dry clean substrate. Detailing of joint construction was important to prevent delaminations.
36	Construction applications of polyolefin fiber reinforced concrete	Strand D.; Macdonald, C.N.; Ramakrishnan V. and Rajpathak V. N.	*Proceedings of the Materials Engineering Conference*, v 1, *Materials for the New Millennium*, 1996, p 103-112	To present construction applications of Nonmetallic polyolefin fiber reinforced concrete.	–	The specially designed mix worked well. There was no difficulty or problem encountered during the mixing, transporting, placing, and consolidation.
37	Restrained shrinkage cracking in fiber reinforced concrete: a novel test technique	Banthia, N.; Yan C. and Mindess S.	*Cement and Concrete Research*, v 26, n 1, Jan, 1996, p 9-14	To present a novel experimental technique developed to assess the cracking potential of cement based materials used as a bonded overlay.	Crack due to shrinkage	Steel fibers reduced cracks better when applying 1% fibers by volume.

38	Thin bonded overlays	Granju, J. L.	*Advanced Cement Based Materials*, v 4, n 1, Jul, 1996, p 21-27	To research the role of fiber reinforcement on the limitation of the debonding of FRC overlays.	FE analysis and experimental tests	The major factor improving the durability of fiber-reinforced overlays was the capacity of fibers to restrain cracking development.
39	Investigation of fiber-reinforced concrete for use in transportation structures	Ozyildirim, C.; Moen, C. and Hladky, S.	*Transportation Research Record*, n 1574, Nov, 1996, p 63-70	To evaluate the effect of different fiber types and volumes on HCC used for pavements and bridge deck overlays.	Compressive strength, splitting tensile strength, impact resistance, first-crack strength, and flexural toughness.	FRC had higher compressive, splitting tensile and first-crack strength. The impact resistance and toughness of concrete improved with increases in fiber volume.
40	Design and construction of a bonded fiber concrete overlay of CRCP	Ahirazi, H. H.; Rasoulian, M. and King, B.	*Proceedings of the Materials Engineering Conference*, v 2, *Materials for the New Millennium*, 1996, p 1647-1658	To evaluate a bonded steel fiber reinforced concrete overlay on an existing 8-inch CRC pavement.	Compressive strength, flexural strength, modulus of elasticity, Poisson's ratio, and overlay bond strength.	The fiber concrete overlay had been successfully bonded to a 16 year old CRCP which had carried twice its design load.
41	Shrinkage of high performance concrete overlays on route 60 in Virginia	Sprinkel M. M. and Ozyildirim, C.	*Transportation Research Record*, n 1610, Aug, 1998, p 15-19	To demonstrate and evaluate 16 overlay systems for bridge rehabilitation.	Compressive strength, modulus of elasticity, flexural strength, tensile bond strength, and chloride permeability	HPC overlays that had low chloride permeability and satisfactory compressive, flexural, and bond strengths could be constructed with combinations of SF, FA, Latex and admixtures.
42	Field and laboratory evaluation of silica fume modified concrete bridge deck overlays in Ohio	Fitch, M. G. and Abdulshafi O. A.	*Transportation Research Record*, n 1610, Aug, 1998, p 20-27	To evaluate the SFMC used for bridge deck in Ohio under field and laboratory conditions	Direct tensile bond strength and field evaluation	The SFMC performed well as bridge deck overlays.

43	Durability of repaired bridge overlays.	Paulsson, J. and Silfwerbran, D. J.	*Concrete International*, v 20, n 2, Feb, 1998, p 76-82	To evaluate how the environment affects bridge decks repaired with bonded overlays	–	The research showed that the repair method used in the study was structurally sound, reliable, fast, and cost effective.
44	Polymers in concrete: a vision for the 21st century	Fowler, D. W.	*Cement and Concrete Composites*, v 21, n 5-6, Oct, 1999, p 449-452	To introduce polymer concrete as a promising materials for future use in repair and overlays	–	PIC, PC, and PMC had received considerable attention over the paste 25 years. Limitations included cost, odor, toxicity, and flammability.
45	Very-early-strength latex-modified concrete overlay	Sprinkel, M. M.	*Transportation Research Record*, n 1668, Sep, 1999, p 18-23	To evaluate an LMC-VE overlay system tat could be opened to traffic in approximately 3 hours	Compressive strength, permeability to chloride ion, bond strength, cracking, and cost.	LMC-VE overlay overlays could be placed and opened to traffic with 3 hours of curing time and the initial condition of them was as good as LMC-HE and LMC.
46	Overlay for concrete segmental box-girder bridges	Tang, F. F.	*Journal of Bridge Engineering*, v 5, n 4, Nov, 2000, p 311-321	To identify the major factors causing the cracks and delaminations on a concrete segmental box-girder bridge.	Analytical investigation and field and laboratory examinations.	The overlay delamination in the bridge was caused by the combination of shrinkage of the overlay, action of the nighttime temperature gradient, and inadequate bond strength.
47	Bond strength development with maturity of high-early-strength bonded concrete overlays	Delatte, N. J.; Williamson, M. S. and Fowler, D. W.	*ACI Materials Journal*, v 97, n 2, March/April, 2000, p 201-207	To discuss a method to estimate the bond strength between bonded concrete overlay and underlying substrate.	Compression and splitting tension test, tension bond test, and shear bond test.	For a given concrete, the strength may be predicted by the maturity method. Shear bond strength was found to be approximately twice the value of tension bond strength.
48	Influence of chloride permeability test parameters on results for silica fume and nonsilica fume concrete	Abou-Zeid, M. N.; Meggers, D. and McCabe, S. L.	*Transportation Research Record*, n 1775, 2001, p 90-96	To investigate the impact of the rapid chloride permeability testes (RCPT) parameters on concrete made with and without silica fume.	Rapid chloride permeability test	The relation between the coulomb charge and specimen thickness is nonlinear. The relation between the coulomb charge and time is linear generally. Specimen compaction technique had little effect on the measured coulomb charge.

49	Service life prediction of concrete bridge decks repaired with bonded concrete overlays	Paulsson-Tralla, J.	*Materials and Structures/Materials et Constructions*, v 34, n 235, January/February, 2001, p 34-41	To discuss and quantify the three topics related to service life prediction of bridge decks repaired by water jetting and bonded SFRP overlay: service life criterion, concrete cover and method to predict the chloride ingress rate.	–	The service life with respect to chloride initiated corrosion was found to be more than 100 years for the repaired concrete bridge decks. Bonded concrete overlays constituted a durable repair alternative for deteriorated concrete bridge decks.
50	Bond strength between sealed bridge decks and concrete overlays	Gillum, A. J.; Shahrooz, B. M. and Cole, J. R.	*ACI Structural Journal*, v 98, n 6, Nov/Dec, 2001, p 872-879	To evaluate the bond strength between overlays and bridge decks sealed with epoxy resin or high molecular-weight methacrylate.	Field and laboratory tests.	Extra surface preparation techniques were effective and simple methods for restoring a significant portion of the bond strength.
51	Increasing concrete durability with high-reactivity metakaolin	Gruber, K. A.; Ramlochan, T.; Boddy, A.; Hooton, R. D. and Thomas, M. D. A.	*Cement and Concrete Composites*, v 23, n 6, December, 2001, p 479-484	To discuss the laboratory evaluations to assess the long-term performance of concrete containing high-reactivity metakaolin for resistance to chloride penetration and reduction in expansion due to alkali-silica reactivity.	Bulk diffusion testing and expansion tests	HRM substantially reduced chloride ion penetration in concrete with w/cm of 0.30 or 0.40. The 15% HRM can prevent deleterious expansion due to alkali-silica reactivity (ASR).
52	Mechanical properties and durability of bonded-concrete overlays and ultra thin white topping concrete	Delatte, N. and Sehdev, A.	*Transportation Research Record*, n 1834, 2003, 03-2831, p 16-23	To analyze the mechanical properties and durability of several plain and fiber-reinforced concrete overlay mixes.	Compressive and splitting tensile strength, modulus of elasticity, bond to concrete, and durability.	The normal-strength concrete is more economical than the high-strength concrete but developed its design properties more slowly.
53	Alkali ash material: a novel fly ash-based cement	Rostami, H.; Brendley, W.	*Environmental Science and Technology*, v 37, n 15, Aug 1, 2003, p 3454-3457	To evaluate a new cementitious material -Alkali ash material (AAM) which could be used as overlay materials.	Strength and durability.	The advantages of AAM concrete included rapid strength gain, high ultimate strength, excellent acid resistance and freeze-thaw durability.

54	Shrinkage of latex-modified and micro silica concrete overlays	Buchanan, P. M.; Mokarem, D. W.; Weyers, R. E. and Sprinkel, M. M.	*Transportation Research Record*, n 1834, 03-3758, 2003, p 33-39	To examine the shrinkage of VDOT-approved LMC and SFMC.	Shrinkage and crack	LMC and SFMC had similar shrinkage, but SFMC cracked earlier and more frequently. The conditions and quality of construction and type and frequency of traffic had a greater effect on cracking than the overlay material
55	Properties of polymer concrete using fly ash	Rebeiz, K.S.; Serhal, S.P. and Craft, A.P.	*Journal of Materials in Civil Engineering*, v 16, n 1, January/February, 2004, p 15-19	To investigate the use of fly ash as a replacement for sand in PC.	Compressive strength and flexural strength	A replacement of sand with fly ash improved the compressive strength and the flexural strength. However, it did not seem to have an impact on the shear strength of PC. Potential applications of PC using fly ash were numerous, including thin overlays on bridges

2.2.2 Detailed Literature Review on the Evaluation of Interface Bond Strength

The delamination is the most common cause of overlay failure. Although there is much debate concerning the choice of best type of overlay, there is no doubt that achieving a good bond to the existing deck is the key to overlay durability. Currently there is still no standard method to evaluate the bond strength between overlay and substrate which can assess the interface character correctly. Also there are only few articles on overlay-substrate interface evaluations that have been published. The following are the review of these articles.

Dhir (1984) studied the adverse effects of large temperature variations on the bonding strength that occur when overlaying is done in intemperate weather. A direct shear test method to determine the shear bond strength was introduced in his research, as shown in Fig. 2.1. The testing specimens were made by two ways: (1) cast separately in laboratory and (2) cut out from a large overlaid panel at different locations in field. It was observed that the laboratory specimens developed high bond strengths ranging from 2.5 to 2.7 MPa (360 to 390 psi). For the overlaid field scale, the specimens cut from interior position performed well too (2.4 to 2.8 MPa or 250 to 405 psi), while those from edge and corner had low bond strength in some cases (as low as 0.4 MPa or 60 psi). He also found that overlaying done in intemperate weather could not make satisfactory bonding with conventional techniques, while using of insulation coverings for preventing temperature variations could be a solution.

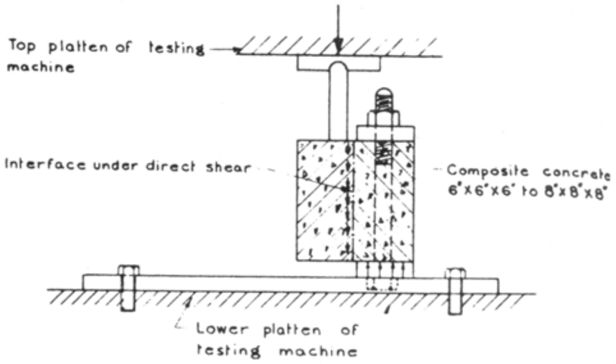


Fig. 2.1−Schematic view of shear testing apparatus by Dhir (1984)

Christensen, Sorenson and Radjy (1984) tested the interface shear bond strength of several overlays to the substrate. The tests were performed in a direct shear testing device (Fig. 2.2), which consists of two heavy steel yokes in which each end of the composite core are tightly mounted. The yokes are separated by brass spacers 6.4 mm (0.25 in.) thick and loosely held together by two steel channels, one on each side. The assembled device with a core in position was tested in compression, resulting in a shear failure at the region of the bond. The specimens consist of a base concrete about 44 mm (1.75 in) thick, upon which an overlay of equal thickness was cast. The base slab was sand blasted and saturated with water prior to casting the overlay. A cement-rich mortar was used as a grout-bond coat for the low-slump concrete. The LMC and SFMC were bonded to the base material by brushing the mortar directly from the overlay mixtures. The results showed the bond strength of silica modified concrete to existing concrete is very high; perhaps as much as 10.3 MPa (1300 psi) for high strength mix designs.

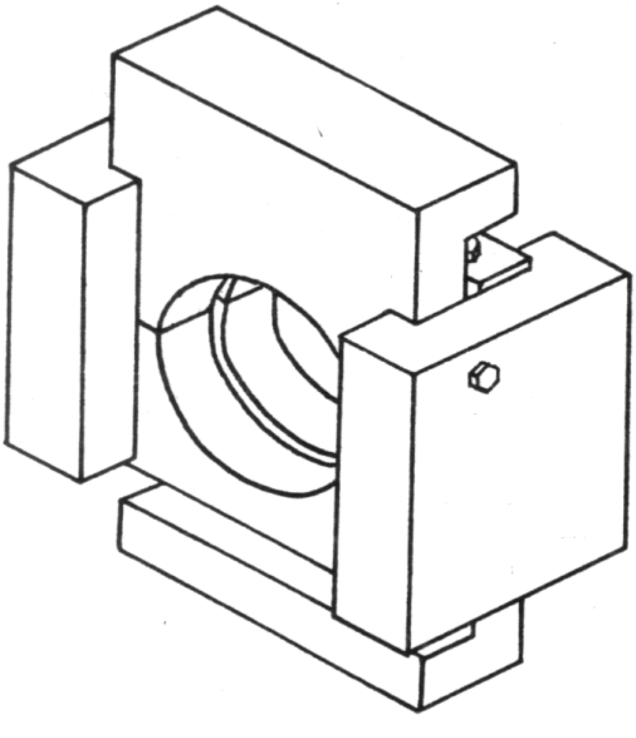


Fig. 2.2−Schematic view of shear testing apparatus by Christensen, Sorenson and Radjy (1984)

Sprinkel (1988) used the guillotine shear apparatus to evaluate the shear bond strength of LMC and LMC-HE overlays. The test apparatus are shown in the Fig. 2.3 below. A test value was determined by placing a 10 mm (4 in.) diameter core or specimen into the base, placing the top part of the apparatus over the overlay, and subjecting the apparatus to a compressive force that sheared the overlay from the base concrete. The average bond strength of the specimens was 2.41 MPa (350 psi) at 12 hours, 3.45 MPa (500 psi) at 24 hours, 4 MPa (580 psi) at 28 days, and 4.27 MPa (620 psi) after approximately 1 year in service.

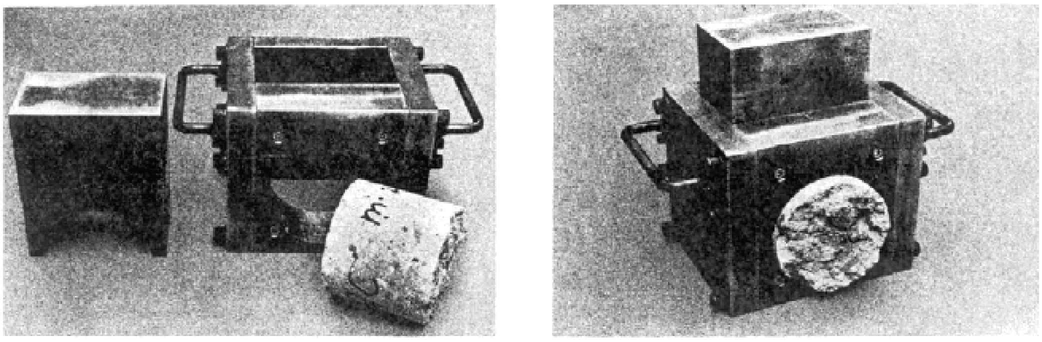
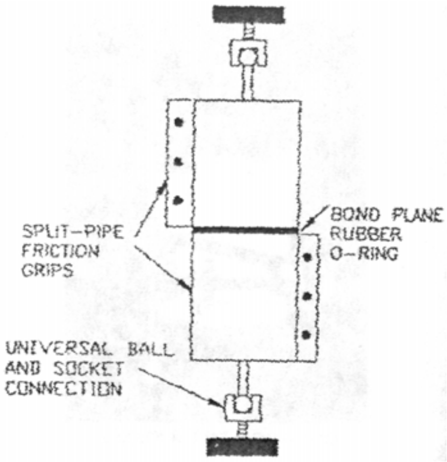
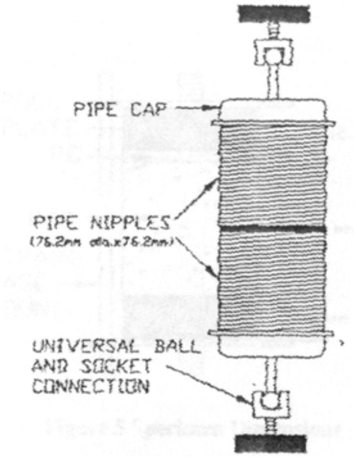


Fig. 2.3−Schematic view of shear testing apparatus by Sprinkel (1988)

Knab and Spring (1989) evaluated three bond strength test methods for use in screening and selecting repair materials in overlaying and patching portland cement concrete. The three methods evaluated were: (1) modified ASTM C 882 slant shear test, (2) friction grips uniaxial tension test and (3) pipe nipple grips unixial tension test. For friction grips, the required friction around the lateral surface area of the specimen was developed by closing together the sides of steel pipe which had been split parallel to its longitudinal axis. For pipe nipple grips, the specimen was bonded to the steel pipe by epoxy. Three repair materials were investigated, which were portland cement concrete, excessive air LMC and normal air LMC. The testing results showed that both slant shear test method and pipe nipple grips uniaxial tension test method were promising for screening and selecting repair materials. The slant shear test seemed to have smallest coefficient of variation, which meant it had relatively highest precision. For normal air LMC, they obtained the bond strength of 2 MPa (293 psi) for friction grips test, 2.7 MPa (393 psi) for pipe nipple tension test, and 14.5 MPa (2100 psi) for slant shear test.



(a) Friction grips uniaxial tension test

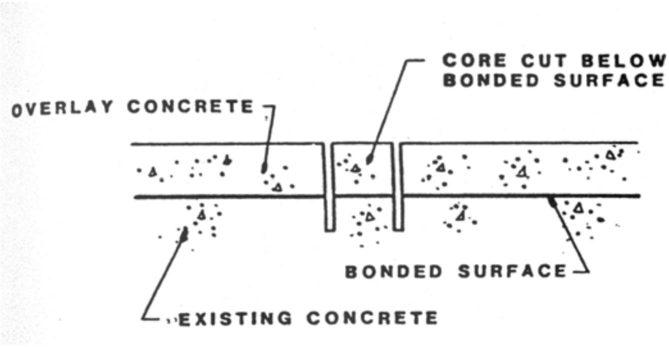


(b) Pipe nipple grips unixial tension test

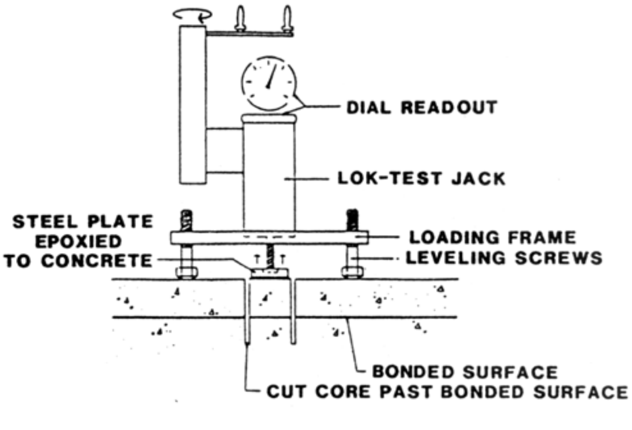
Fig. 2.4−Test methods evaluated by Knab and Spring (1989)

Kuhlmann (1990) described a test method that accurately measured the bond strength of latex-modified mortar and concrete to conventional concrete. Using 76 mm (3 in.) diameter cylinders of concrete as the base material and standard 76 mm (3 in.) diameter steel pipe nipples as molds, an overlay of the latex-modified material was applied and cured similar to field conditions and then tested in direct tension. The tests were conducted by pulling the specimens with both overlay and substrate contained in steel-pipe nipples. The results not only give values of the bond strength of the overlay tested but also clearly indicated whether the failure was in the bond or the materials tested. He concluded that the test method demonstrated a coefficient of variation of less than 10 percent. He obtained LMC bond strength of 0.48 MPa (70 psi) at 1 day, 2.34 MPa (340 psi) at 28 days and 3.1 MPa (450 psi) at 90 days.

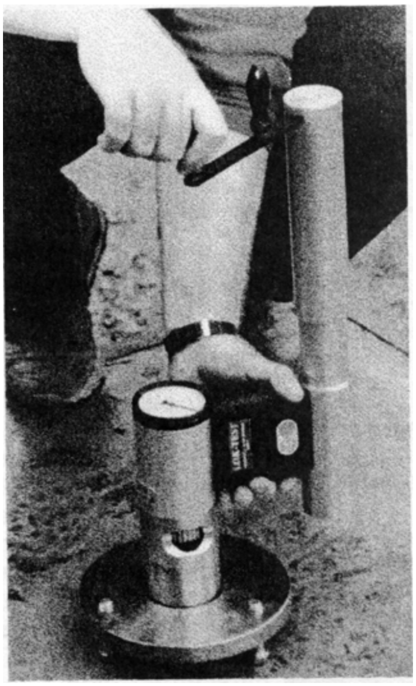
Hindo (1990) introduced a newly devised method to determine the bond strength directly. The device, which was called LOK-TEST pullout device, was developed to be used in field to measure the direct tensile strength. The schematic representation of the test preparation and apparatus is shown in Fig. 2.5.



(a) Schematic representation of test preparation



(b) Schematic representation of test apparatus



(c) Testing in progress

Fig. 2.5−Schematic representations of test method by Hindo (1990)

According to his study, he concluded that the in-place bond strength test was a valuable tool to determine the bond strength and the quality of the prepared surface directly, which could be used for quality control during construction repairs. By comparing bond strength of two different surface preparations, he found that bond strength of the surface prepared by hydrodemolition could be double that of a surface prepared by a pneumatic hammer. For the preparation of hydrodemolition, he got the bond strength ranged from 1.21 to 1.46 MPa (175 to 212 psi).

O'Connor and Saiidi (1993) conducted the research to determine the basic engineering properties of the polymer concrete. Laboratory testing was conducted to determine the effects of elevated temperature and temperature cycling on the compressive strength of polyester concrete, the bond strength between overlay concrete and portland cement concrete, and the modulus of elasticity. California test 551 was used to determine the bond strength. The test measures the modulus of rupture of a beam specimen consisting of a half-span portland cement concrete beam, to which was bonded polymer concrete to form the other half-span. The beam was then loaded in flexure at the center of the span, directly onto the bond line, as shown in Fig. 2.6. The test provided baseline bond strength information. Test results showed that all the specimens met the California specifications which require a modulus of rupture greater than 3.4 MPa (500 psi).

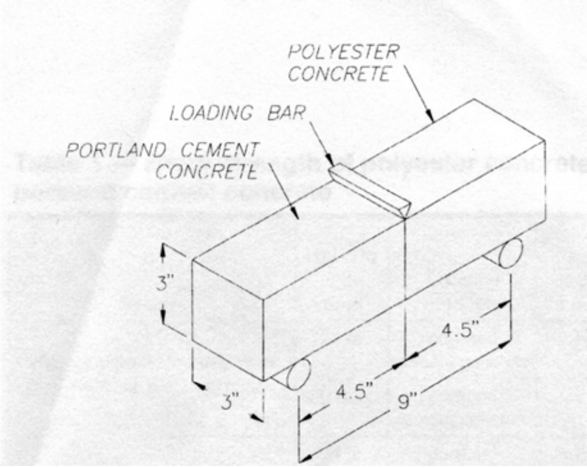


Fig. 2.6−California test 551 used by O'Connor and Saiidi (1993)

Deming, Aktan and Usmen (1994) developed a laboratory direct test procedure for evaluating the interface bond strength of polymer concrete to portland cement concrete. The objective of this development was to determine the interface tensile strength that can be used in design of PC overlays. The basic testing apparatus consisted of steel pull plates uniformly attached to the top and bottom of the specimen with structural adhesive. This type of bonding, instead of bonding two pipe nipples to the circumference of the specimen, could prevent the concentration of stress at the edge. Thus they obtained bond strength higher than those by Kuhlmann (1990) and Knab and Spring (1989). By analyzing the data, they concluded that the test produced relatively consistent results. The bond strength ranged from 2.47 to 3.51 MPa (358 to 510 psi).

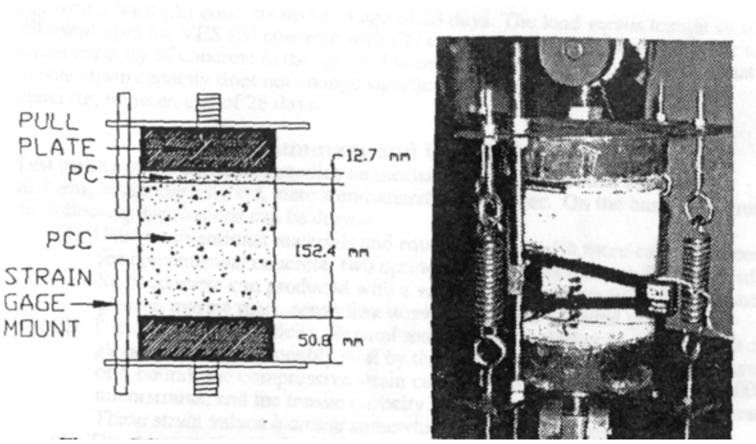


Fig. 2.7−Schematic view of bonding test by Deming, Aktan and Usmen (1994)

Shirazi, Rasoulian and King (1996) evaluated bonded steel fiber reinforced concrete overlays on an existing 200 mm (8 in.) concrete CRC pavement which was chosen for rehabilitation. Just before the casting of overlay, a stiff slurry grout was applied onto the cleaned dry concrete surface. The compressive strength of concrete cylinders was tested at 28 days. The interface bond strength was tested by two methods. One method was the Iowa DOT shear collar method. In this method, a core of the overlay was sheared at the bond interface using the collar device mounted in a laboratory compression tester. The other method was an ACI procedure which subjected the specimen to a direct pull attempting to debond the overlay. The latter was found to be more suitable for field test. The average bond strength measured with the shear collar was 6.50 MPa (943 psi) which significantly exceed the minimum value specified by Iowa DOT (1.38 MPa or 200 psi) minimum as specified by Iowa DOT. The average pull out strength was 0.88 MPa (128 psi) which exceeds 0.689 MPa (100 psi), minimum set forth by ACI for multi-component epoxy adhesives used to bond fresh concrete to hardened concrete.

Ali, Kurihara and Matsui (1998) studied the shear bonding strength at interface between old and new concrete by a new developed torque test instrument. They reviewed several test methods that had been developed to measure bonding strength, of which only pull-off tests could be carried out in-situ to test the conformity of the works. The instrument they used for the test is shown in Fig. 2.8. The relationship between the torque moment and shear stress was given by:

$$\tau_{\max} = \frac{16M_t}{\pi d^3}$$

The modes of failure, which was described by the percentage of cross-section area of the partial core where failure had occurred, were determined by visual inspection. They found the results of the testing were consistent and reliable. The test results showed that bonding agent improved the bonding shear strength greatly. For cases without bonding agents or with cement mortar, surface roughness was the main factor which affected the bonding strength. He also concluded that there might be linear relationship between shear bonding and tensile bonding strength, as well as between shear bonding strength and surface roughness.

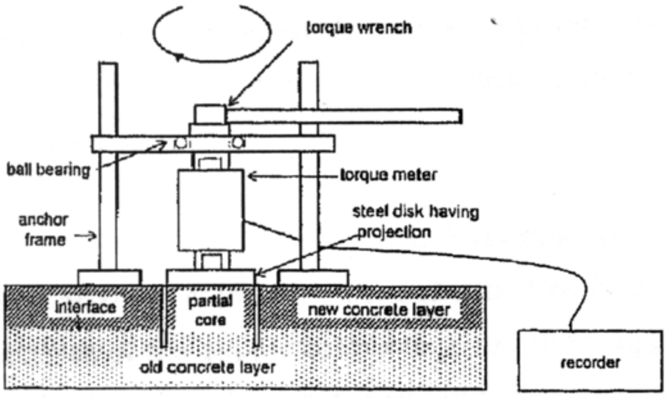


Fig. 2.8–Schematic view of torque test instrument and layout of specimen by Ali, Kurihara and Matsui (1998)

Wells, Stark and Polyzois (1999) studied the effects of surface preparations and bonding agents on the bonging strength between existing slabs and repair overlays. Four different methods of surface preparation and six different methods/materials for bonding agents were involved in the study. The bond strength between the base slab and overlays was measured using the uniaxial tension test in accordance with CSA A 23.2-6B (Canadian Standards Association, Methods of Test for Concrete, A23.2- M94). The failure mode was classified as overlay, bond interface, or substrate, depending on a visual judgment of the location of the plane of failure. The standard required a minimum bond strength of 0.90 MPa (130 psi) following a 28-day of cure of concrete. The authors got the conclusion that surface preparation was critical for achieving satisfactory bonding strength. A good surface preparation such as shot blasting could remove the dependency on the use of bonding agent. For shot blasting preparation, he got the bond strength of around 3 MPa (430 psi).

Delatte, Wade and Fowler (2000) evaluated the bond development for expedited bonded concrete overlays. He did both laboratory and field testing for the study. A HES (High Early Strength) concrete mixture proportion was developed for expedited bonded concrete overlay construction. In addition to attaining TxDOT specified compressive and flexural strengths within three days, the mixture could also develop bond strength rapidly. At the first stage of the study, the field push off test was performed. For the reason of cost and stability, guillotine test was used in stead in the second stage. He mentioned that guillotine test was useful for laboratory investigation of bond development, and was simpler to use than other available methods while it could not be used for field testing with thicker overlays because it was impossible to extract an undamaged core. Pull off test was useful in field although it provided a lower bound, rather than an actual measure, of interface strength. Thus he recommended that further study should be conducted to determine if a correlation of guillotine test to pull off tests exists. And finite element modeling could also be used to determine the magnitude of the shear and tensile stress that develop between the BCO and the base concrete.

Shahrooz et al. (2000) evaluated the effect of surface preparations for restoring the bond strength of interface when the substrate is sealed before casting the overlay. He used two methods to test the bond strength: direct shear test (guillotine test) and SHRP (Strategic Highway Research Program) 2025 test, Fig. 2.9 and Fig. 2.10 below show the testing. They evaluated LMC, SDC (Superdense Plasticized Concrete) and SFMC bonded with sealed and unsealed substrate. For those sealed, they divided them into two groups: Surface untreated and Surface treated. According to the Guillotine test results, LMC possessed the highest bond strength followed by SDC and SFMC (5 to 7.5 MPa or 725 to 1088 psi). But a clear trend could not be established on the basis of SHRP specimens (3.5 MPa or 508 psi).The tests results showed that the use of sealer can reduce the bond strength appreciably, while the surface preparation on the sealed substrate can restore the bond strength 80~85%.

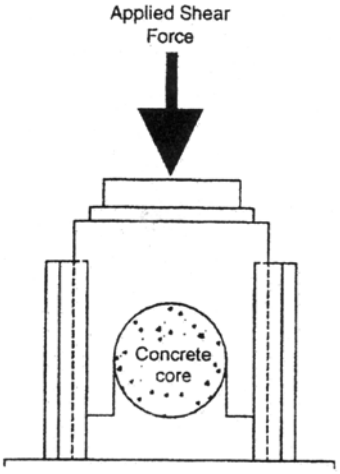


Fig. 2.9−Shear testing apparatus used by Shahrooz et al., 2000

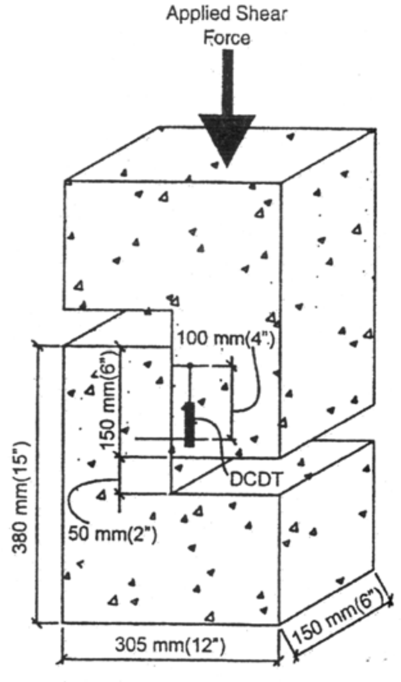


Fig. 2.10−SHRP test specimen

Delatte and Sehdev (2003) analyzed the mechanical properties and durability of several plain and fiber-reinforced concrete-overlay mixes. He investigated the strength of concrete mixes at 1, 3, 7, and 14 days. Eight candidate concrete overlay designs were involve in the evaluation. All the high-strength concrete overlay mixture design appeared to have satisfactory strength, stiffness, bond properties, and durability for use in bonded overlay construction. Tension tests were used for bond testing. Concrete base slabs (0.3 × 0.3 m or 11.8 × 11.8 in.) were made in the laboratory with overlays cast on after 2 months curing. Before test, the specimens were cored 32 mm (1.5 in.) deep into the base concrete slab. An aluminum disk was attached to the top of the overlay with a high-strength epoxy. Then a pull-off tester with 16 kN (3.6 kips) capacity was used to apply tension to the disks until specimens failure. The bond testing was subject to considerable scatter due to the variable nature of bond and the test. They got 14 days bond strength from 1.4 to 2.1 MPa (200 to 300 psi)

Some other researchers also conducted the bond strength test in their studies. Ozyildirim (1987) tested the shear bond strength between overlay and substrate. The 50mm (2 in.) thick overlays with and without SF were placed over cylinders made of base concrete. The samples were subjected to shear at the interface after 28-day moist curing of the overlays. The base concrete was kept at least 3 months in the moist room when the overlays were placed. He obtained the shear bond strength ranging from 5.1 to 6.0 MPa (740 to 870 psi). In another article Ozyildirim (1988) conducted the shear test of SFMC and LMC and in which the shear bond strength was from 2.6 to 4.8 MPa (383 to 697 psi). Sprinkel (1999) conducted direct tensile testing to evaluate the bond strength of very early strength LMC overlay. He got the tensile strength ranging from1.05 to 1.90 MPa (153 to 276 psi). Babaei and Hawkins (1990) tested the bond strength of LMC and LSDC, they got the tensile strength of 1.38 MPa (203 psi) for LMC and 0.96 MPa (141 psi) for LSDC, the shear bond strength were about 3 times that of tensile bond strength.

2.3 Significance of the Research

In West Virginia, there have been many cases that the bridge deck overlay may experience delamination problems. However, there is only some guidelines which are very general for the application of overlays, such as ACI committee 345 (ACI 345 R-91,

1991) and WVDOH standard specifications for roads and bridges (Section 679, WVDOH, 2000). More specific construction standards are required on practices such as surface preparation, placement, curing condition to ensure better bonding between overlays and the reinforced concrete deck concrete, elimination of crack development, better resistance against chloride ion permeability, and freeze-thaw durability. Thus, a comprehensive research on the delamination issue is needed.

According to the literature reviewed, currently, there are no standards or specifications on the evaluation of interface performance. A large number of researches have been done on overlay issues, but most of them were focused on the properties of the overlays themselves, only a small fraction of them investigated the composite performance of overlay and substrate. It has been accepted that shear stress might be the main reason of the interface failure. The shear strength of the interface depends not only on the properties of interface itself, but also on the test methods. Several methods have been used to test the direct and indirect shear strength of interface, such as: ACI field test, ASTM slant shear test, Pipe nipple grip test, Friction grip test, Guillotine shear test, and SHRP 2025 test. Most of these tests have their own limitations. Guillotine test is inexpensive, but cannot reliably measure the adhesion bond strength. It is highly dependent on the placing of test specimen in the machine. If the bond line is not centered, the machine will measure the shear strength of either the repair materials or the substrate, not the strength of the bond (Sprinkel, 1997). SHRP test is not sensitive enough to assess the overlay performance where different kinds of overlays are used (Shahrooz et al. 2000). Shear-compression or slant-shear tests have also been used, but considerable scatter has been found in the test results (Delatte et al., 2000). Pipe nipple grip test and friction grip test measure the pull out strength at interface, not shear strength. Other information about the test methods can be found in (Luo 2002).

A new direct shear test apparatus was developed in WV by a research team led by Dr. Davalos and has been used by Luo (2002) to evaluate performance of overlay-substrate interface of medium or low strength. The results showed that this apparatus was reliable and had the potential to be used for the shear strength evaluation. A more comprehensive evaluation on overlay-interface strength was conducted by using this apparatus. However, for high bond strength capacity interface, the apparatus needed further modifications.

Considering the needs discussed above, this study is focused on to develop and evaluate number of possible overlays using various locally available materials, and then to evaluated interface shear bond strength of overlay-substrate bi-layer composite system. The interface bond strengths in the current study are much higher than previous study due to improved surface preparation and material gravity, which will need upgrading and modifying the previously developed shear apparatus at WVU. Results can be used for screening and selecting of overlay types and the use of local sources of materials will help WVDOH to update their specifications for overlays.

CHAPTER 3

MATERIALS AND MIXTURE PROPPORTIONS

This chapter describes the materials and the mixture proportions used for substrate and overlays evaluated in this study.

3.1 Materials

3.1.1 Cement

Commercially available Type I portland cement was used in this study. The cement conformed to ASTM C150 (Standard Specification for Portland Cement).The basic physical properties and compound composition of cement are presented in Table 3.1 and 3.2 respectively.

Table 3.1─Physical properties of type I portland cement used

Specific Gravity	Fineness	Setting time	
		Initial (min.)	Final (min.)
3.15	320 m^2/Kg	90	260

1 m^2/Kg = 578.6 $in.^2$/lb

Table 3.2─Compound compositions of portland cement

Compounds	Percentage by mass
Tricalcium Silicate	49
Dicalcium Silicate	25
Tricalcium Aluminate	12
Tetracalcium Aluminoferrite	8
Calcium Sulfate	2.2
Calcium Oxide	0.8
Magnesium Oxide	2.0
Others	1.0

3.1.2 Coarse Aggregate

For overlays, two types of coarse aggregates from WV source were used. Both the aggregates conformed to ASTM C33 (Standard Specification for Concrete Aggregates). One type was crushed limestone, and the other was crushed gravel. Table 3.3 shows the properties of the coarse aggregates used.

Table 3.3—Properties of coarse aggregates

Items		**Crushed Limestone**	**Crushed Gravel**
Source		Cave In Rock Quarry	Joe Lucas dredge
SSD Bulk Specific Gravity		2.68	2.57
Absorption		1.17 %	2.5 %
Sieve analysis data	12.7 mm	100	100
	9.5 mm	94	96
	6.4 mm	29	27
	3.2 mm	6	3
	1.6 mm	1	1

Note: 1 mm = 0.039 in.

3.1.3 Fine Aggregate

Only one type of fine aggregate was used in this study, the sand was from Joe Lucas Dredge, which conformed to ASTM C33 (Standard Specification for Concrete Aggregates). Table 3.4 shows the properties of sand.

Table 3.4—Properties of sand

Source and Basic Properties	
Facility source	Joe Lucas Dredge
Type	Natural silica sand
SSD bulk specific gravity	2.61
Absorption	1.5%
Fineness Modulus	2.958
A-BAR	6.056

Sieve Analysis (% passing)	
9.5 mm	100
4.75 mm	99
3.2 mm	84
1.6 mm	59
0.8 mm	38
0.6 mm	-
0.5 mm	18
0.3 mm	6
0.1 mm	1.6

Note: 1 mm = 0.039 in.

3.1.4 Mineral Admixtures

3.1.4.1 Silica fume

The silica fume used in the study conformed to ASTM C 1240 (Standard Specification for Silica Fume for Use in Hydraulic-Cement Concrete and Mortar). It was a commercially available compacted silica fume manufactured by Master Builders, Inc. The specific gravity of the silica fume was 2.2.

3.1.4.2 Slag

The slag used in the study was commercially available ground granulated blast-furnace slag from local source in Weirton, WV. Table 3.5 shows the properties of the slag.

Table 3.5─Properties of slag

Items	Values/Description
Grade	100
Appearance	White powder
Odor	No distinct odor
Physical State	Solid(powder)
pH Value (in water)	10.5 to 12.7
Solubility in Water (%)	Slightly (0.1 to 1.0)
Melting Point (°C)	1300-1350
Specific Gravity	2.7 – 3.1

3.1.4.3 Metakaolin

The metakaolin used in the study was commercial kaolin clay manufactured by W.R. Grace & Co.-Conn. It was an extremely fine and off-white powder with the specific gravity of 2.6. Table 3.6-1 and 3.6-2 furnish the properties of metakaolin used in this study.

Table 3.6 -1—**Properties of metakaolin used**

Items	Values/Description
Grade	100
Appearance	Fine, off-white powder
pH in 5% Slurry	4.8
Odor	none
Specific Gravity	2.6
Solubility	400 to 432 Kg/m^3

Note: 1 Kg/m^3 = *0.0625* lb/ft^3.

Table 3.6 -2—**Compound composition of metakaolin**

Compounds Analysis	Mass (%)
Kaolin	81.21
Quartz	2
Oxides (Iron and others)	3.79
Loss on Ignition	13

3.1.5 Latex and Antifoam

Both latex and antifoam used in this study were commercial products manufactured by BASF and Dow Chemical Company respectively. The latex was proprietary styrene/butadiene latex supplied as a white liquid with suspended solids. Table 3.7 shows the properties of latex used in this study.

Table3.7─Typical properties of latex

Properties	Values
Specific Gravity	1.04
Solids (%)	47.0-49.0
pH	9.0-11.0
200 Mesh Residue, per 900 ml	0.50 Max
Particle Size, red filter (Angstrom)	1900-2200
Surface Tension (dyn/cm)	22-31
Freeze Thaw Stability, after 2 cycles (g)	0.1 Max
Butadiene Content (%)	30-40
Weight per Gallon (Kg/m^3)	62.9 to 64.4

Note: 1 Kg/m^3 = *0.134* lb/gal

The DOW Corning Antifoam 2210 was also used in this study to control the excessive foaming due to latex. The properties of the product are presented in the Table 3.8.

Table 3.8─Typical properties of antifoam

Items	Description
Appearance	White
Active Ingredient (%)	10
Specific Gravity, at 25^{o}C (77^{o} F)	1
Consistency at 25^{o}C (77^{o}F)	Medium
Viscosity, cps	2,500
pH	7
Emulsifier Type	Nonionic

3.1.6 Fiber

The fiber used in this study was steel polypropylene hybrid fiber produced by SI concrete system. It was a blend of ASTM A820 steel and 100% virgin homopolymer graded multifilament. The fiber complied with national building codes ASTM C-1116 Type III and ASTM A820.

3.1.7 Chemical Admixtures

3.1.7.1 Shrinkage-reducing admixture

A commercial shrinkage-reducing admixture (SRA) was used in the study. It was supplied by Master Builders, Inc.

3.1.7.2 High-range water reducing admixture

The commercially available high-range water reducing admixture (HRWRA) used in this study was produced by Master Builders, Inc. It conformed to ASTM C 494 Type A and F requirements.

3.1.7.3 Water-reducing and retarding admixture

The water-reducing and retarding admixture (WRA) used in this study was produced by Master Builders, Inc. It conformed to ASTM C 494 requirements for Type A water-reducing, Type B retarding and Type D water-reducing and retarding admixtures

3.1.7.4 Air-entraining admixture

The air-entraining admixture (AEA) used in the mixtures was produced by Master Builders, Inc. It conformed to the requirements of ASTM C 260.

3.2 Mixture Proportions for Specialized Overlays and Substrate

Eleven mixtures of specialized overlays and a mixture of normal concrete substrate were prepared for this study. Out of the eleven mixtures, seven were with limestone aggregate and four were with gravel aggregate. Overlay types were selected according to the published information by various DOTs, literature and WV state requirements. The mixture proportions used in the study are provided in the Table 3.9.

Table 3.9−Mixture proportions of overlays and substrate (For each cubic meter of concrete)

Ingredient	Substrate	Overlay (Limestone)							Overlay (Gravel)			
	NC	SFMC (L)	LMC (L)	FRC (L)	SLMC (L)	LMC + SF (L)	SFMC + SRA (L)	MTMC (L)	SFMC (G)	LMC (G)	FRC (G)	SLMC (G)
Cement (kg)	337	377	415	410	266.5	377	377	377	377	415	410	266.5
Silica fume (kg)		33				33	33		33			
Slag (kg)					143.5							143.5
Metakaolin (kg)								33				
Latex (kg)			126			126				126		
Antifoam (kg)			1.182			1.182				1.182		
Fiber (kg)				24.5							24.5	
Water (kg)	168.5	164	145	164	164	143.5	164	164	164	145	164	164
Coarse Aggregate (kg)	1043	574	592	679	678	590	716	693	679	562	651	650
Sand (kg)	718	832	858	982	984	856	937	1005	984	850	982	984
HRWRA (ml)	1860	3180		1670	1250		2390	1030	3180		2120	1250
WRA (ml)				1250							1250	
SRA (ml)							8200					
AEA (ml)	300	680		275	680		680	680	680		275	680
w/cm	0.5	0.4	0.35	0.4	0.4	0.35	0.4	0.4	0.4	0.35	0.4	0.4

Notes:

- *1 Kg = 2.205 lb 1 ml = 0.0338 oz 1 Kg/m^3 = 0.062 lb/ft^3*
- *SRA was used 2% by weight of cementitious materials;*
- *In LMC and LMC+SF overlay, solid latex used was 15% by weight of cement and cementitious materials respectively.*
- *NC = normal concrete, SFMC = Silica fume modified concrete, LMC = Latex modified concrete, FRC = Fiber reinforced concrete, SLMC = Slag modified concrete, LMC+ SF = Latex modified concrete with silica fume, SFMC + SRA = Silica fume modified concrete with 0.2% SRA, MTMC= Metakaolin modified concrete, w/cm = water to cementitious material ratio.*

3.3 Mixing Procedure

All the mixings were performed in the laboratory using the standard rotary drum mixer. The mixing procedures for different mixtures are listed below.

3.3.1 NC

1. Added coarse aggregate and approximately 3/4th of water to the mixer and rotated the mixer until uniformly mixed.
2. Sand premixed with the AEA was added to mixer and mixed thoroughly until small air bubbles are visible.
3. Cement and remaining water were added and mixed for 3 minutes.
4. Stopped the mixer for 3 minutes.
5. Remixed for 2 minutes.
6. Added the HRWRA and mixed until the desired slump was obtained.

3.3.2 SFMC

1. Added coarse aggregate and approximately 3/4th of water to the mixer and rotated the mixer until uniformly mixed.
2. Added silica fume and continued to rotate.
3. Sand premixed with the AEA was added to mixer and mixed thoroughly until small air bubbles are visible.
4. Cement and remaining water were added and mixed for 3 minutes.
5. Stopped the mixer for 3 minutes.
6. Remixed for 2 minutes.
7. Added the HRWRA and mixed until the desired slump was obtained.

3.3.3 LMC

1. Added latex premixed with antifoamer and coarse aggregate to the mixer and rotated the mixer until uniformly mixed.
2. Added sand to mixer and mixed uniformly for about 1.5minutes.
3. Cement and remaining water were added and mixed for 3 minutes.
4. Stopped the mixer for 3 minutes.

5. Remixed for 2 minutes.

3.3.4 FRC

1. Added coarse aggregate and approximately 3/4th of water mixed with WRA to the mixer, and rotated the mixer until uniformly mixed.
2. Sand premixed with the AEA was added to mixer and mixed thoroughly until small air bubbles are visible.
3. Cement and remaining water were added and mixed for 3 minutes
4. Stopped the mixer for 3 minutes
5. Remixed for 2 minutes.
6. Added fiber and HRWRA and mixed until the desired slump was obtained.

3.3.5 SFMC + SRA

1. Added coarse aggregate and approximately 3/4th of water to the mixer and rotated the mixer until aggregate was uniformly mixed.
2. Added silica fume and continued to rotate.
3. Sand premixed with AEA was added to mixer and mixed thoroughly until small air bubbles are visible.
4. Cement and remaining water were added and mixed for 3 minutes.
5. Stopped the mixer for 3 minutes
6. Added SRA and remixed for 2 minutes.
7. Added the HRWRA and mixed until the desired slump was obtained.

3.3.6 LMC + SF

1. Added coarse aggregate to the mixer
2. Added latex and silica fume to the mixer and rotated the mixer until uniformly mixed.
3. Added sand to mixer and mixed thoroughly for about 1.5 minutes.
4. Cement and remaining water were added and mixed for 3 minutes.
5. Stopped the mixer for 3 minutes
6. Remixed until the desired slump was obtained

.

3.3.7 SLMC (or MTMC)

1. Added coarse aggregate and approximately 3/4th of water to the mixer and rotated the mixer until aggregate was well mixed.
2. Sand premixed with AEA was added to mixer and mixed thoroughly until small air bubbles are visible.
3. Slag(or Metakaolin) ,cement and remaining water were added and mixed for 3 minutes
4. Stopped the mixer for 3 minutes
5. Remixed for 2 minutes.
6. Added the HRWRA until the desired slump was obtained.

3.4 Preparation of Specimens

3.4.1 Casting

All specimens were prepared according to relevant ASTM standards. Table 3.10 shows the details of specimen preparations.

Table 3.10─Details of specimen preparation

Specimens	Sizes of Specimens	Brief Casting Description
Compressive strength	Cylinder Ø = 101.6 mm (4in.) h = 203.2 mm (8in.)	Fresh concrete was cast in the plastic molds in three layers, and each layer was compacted by steel rod and plastic hammer.
Flexural strength	Beam 50.8×50.8×279.4 mm (2×2×11 in.)	Fresh concrete was cast in the steel beam molds fitted with pins and vibrated on a vibration table for a short time.
Free shrinkage	Gage studded beam, 76.2×76.2×254 mm (3×3×10 in.)	Fresh concrete was cast in the steel beam molds fitted with pins and vibrated on a vibration table for a short time.
Elastic modulus	Cylinder Ø = 152.4 mm (6 in.) h = 304.8 mm (12 in.)	Fresh concrete was cast in the plastic molds in three layers and each layer was compacted by steel rod and plastic hammer.

Chloride permeability	Cylinder Ø = 101.6 mm (4 in.) h= 203.2 mm (8 in.)	Fresh concrete was cast in the plastic molds in three layers and each layer was compacted by steel rod and plastic hammer. After certain curing time, it was cut into disc shape by diamond cutter. The middle two discs were selected for test.

3.4.2 Curing

3.4.2.1 Specimens for compressive, flexural strength, elastic modulus and chloride permeability

(A)LMC and LMC+SF

Soon after casting the specimens were covered with wet burlap and plastic sheet at temperature of 23±2°C. After 24±1 hours, the specimens were demolded. 1-day specimens were tested and the rest of the specimens were allowed to air dry at temperature of 23±2°C. Then 3-day and 7-day specimens were tested and rest of the specimens were transferred to a curing room at 50% relative humidity and temperature of 23±2°C until the testing at 28-day and 90-day. The curing method was according to guidelines by BASF (the producer of latex) with necessary modifications for early age tests

(B)NC, SFMC, FRC, SLMC, SFMC+SRA, and MTMC

Soon after casting, the specimens were covered with wet burlap and plastic sheet at temperature of 23±2°C. After 24±1 hours, the specimens were demolded. 1-day specimens were tested and the rest of the specimens were kept under water at 23±2°C. The 28-day specimens were tested and the rest of the specimens were transferred to a curing room at 50% relative humidity and temperature of 23±2°C until the day of testing at 90-day.

3.4.2.2 Specimens for free shrinkage test

Soon after casting, the specimens were covered with wet burlap and cured in a curing room at 23±2°C. The specimens were demolded after 24±1 hours. After demolding, all specimens were transferred to the environmental room at 50% relative humidity and

23±2°C temperature with the provisions of adequate air circulation through the specimens.

CHAPTER 4

PROPERTIES OF OVERLAYS AND NORMAL CONCRETE USED AS SUBSTRATE

This chapter presents the characterization of different overlays and normal concrete (NC) used as substrate. Both fresh and hardened concrete properties were evaluated. Results and analysis are provided in the following paragraphs.

4.1 Testing of Fresh Concrete

Fresh concrete properties such as slump, air content and unit weight were measured. The slump was measured according to ASTM C 143 (Standard Test for Slump of Hydraulic Cement Concrete) immediately after the mixing. The air content of fresh concrete was measured by using the Press-UR-Meter which meets ASTM C-231 (Standard Test Method for Air Content of Fresh concrete by the Pressure Method). The unit weight was also measured according to ASTM C 138 (Standard test Method for Unit Weight, Yield, and Air Content of Concrete). Table 4.1 shows the properties of fresh concrete tested:

Table 4.1—Properties of fresh concrete

Mixtures		Slump in mm	Air Content (%)	Unit Weight (kg/m^3)
Substrate	NC	90	5	2220
Overlay mixtures	SFMC (L)	125	7	2230
	LMC (L)	215	3.5	2310
	FRC (L)	110	6.5	2225
	SFMC-SRA (L)	75	6.5	2255
	LMC+SF (L)	225	3.5	2284
	SLMC (L)	90	6	2305
	MTMC (L)	115	6	2270

Notes: 1. Properties of NC are averages of 16 batches.

2. Properties of overlay mixtures are averages of 2 to 3 batches.

3. 1 mm = 0.00394 in.   1 Kg/m^3 = 0.0624 bl/ft^3

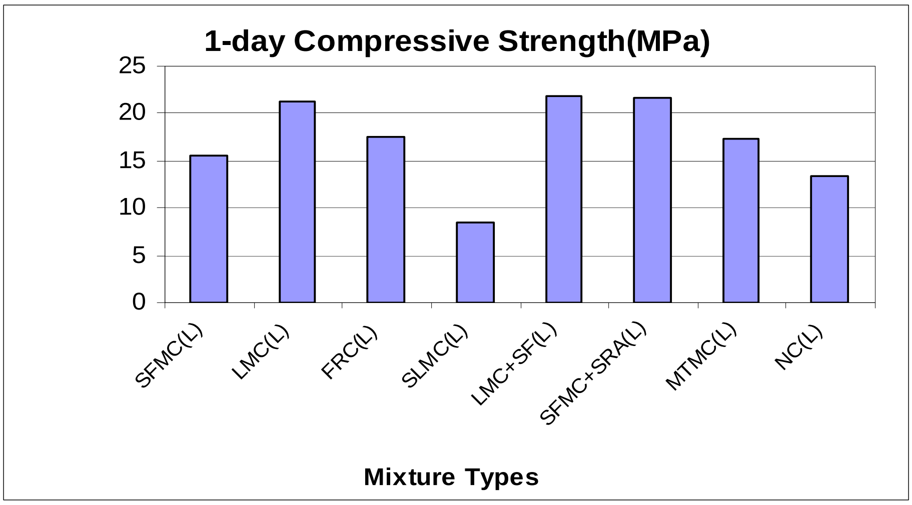
Results show that LMC and LMC+SF had the highest slump of 215mm (8.5 in.) and 225 mm (9 in.), respectively. They also had the lowest air content (3.5%) and relatively higher unit weights. Knab and Spring (1989) reported that high-air content in LMC could affect the bond strength between overlay and substrate. From this point of view, the low air content of LMC in the current study was desirable. In our case, use of about 15 % of latex by weight of cement enhanced the workability remarkably even with a w/cm material ratio as low as 0.35. However slight higher quantity of defoamer caused reductions in air contents. Latex modified concrete (LMC and LMC +SF) being more crack resistant due to inherent latex properties, these lower values of air content will not be of concern for freeze-thaw damage. NC substrate had the slump of 90 mm (3.5 in.), which was little lower than the others. SLMC also had the low slump of 90 mm (3.5 in.) and the maximum unit weight, which might have occurred due to addition of slag. The properties of fresh concrete of SFMC, FRC, SFMC+SRA and MTMC were close to each other. The slump ranged from 115 mm (4.5 in.) to 125 mm (5 in.), the air content from 5% to 7%, and the unit weight from 2225 to 2270 kg/m^3(138.8 to 141.6 lb/ft^3).

4.2 Testing of Hardened Concrete

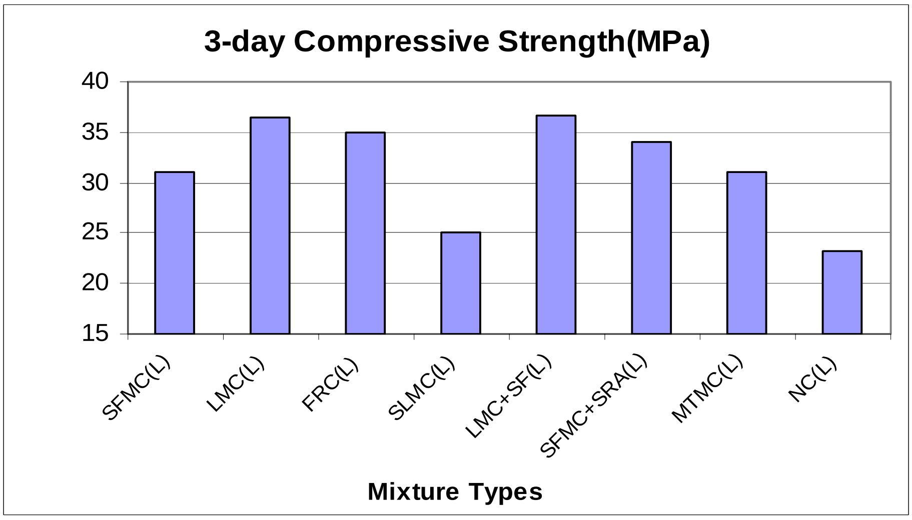
The testing of hardened concrete includes compressive strength, flexural strength, modulus of elasticity, free shrinkage and chloride permeability test. Following paragraphs provide the details.

4.2.1 Compressive Strength

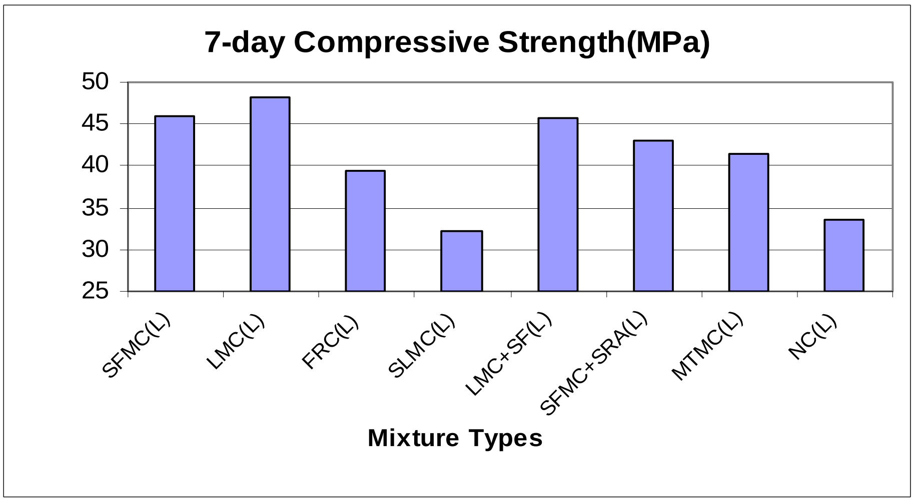
Compressive strength tests were conducted according to ASTM C 39 (Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens). Specimens used were cylinders with the dimension Ø101.6 mm (4 in.) × 203.2 mm (8 in.). A standard hydraulic machine was used for the tests. Tests were conducted at 1, 3, 7, 28 and 90 days. For each age, two batches of concrete were tested. For each batch, two specimens were tested and the overall average was calculated for presentation of data. Fig. 4.1 shows the results of compressive strengths for all the mixtures tested.


1-day Compressive Strength(MPa)
25
20
15
10
5
0
SFMC(L)
LMC(L)
FRC(L)
SLMC(L)
LMC+SF(L)
SFMC+SRA(L)
MTMC(L)
NC(L)
Mixture Types

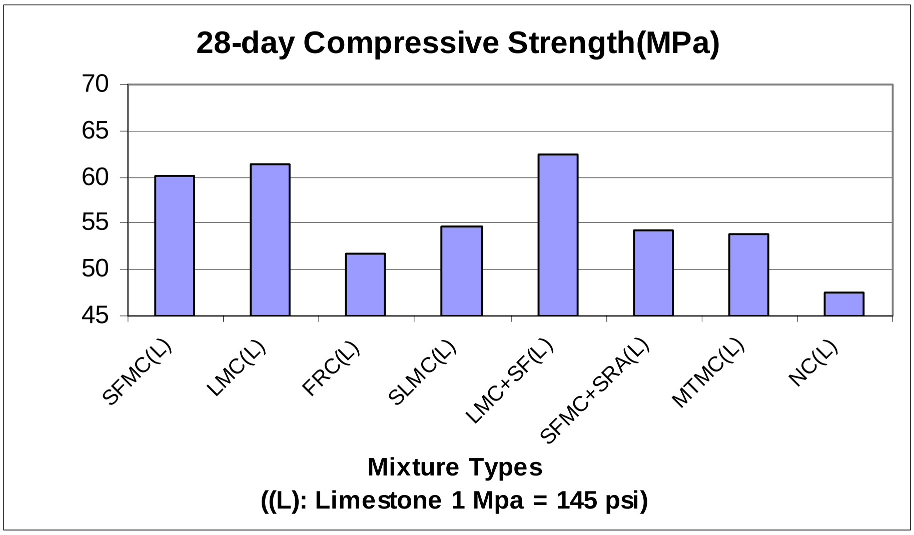
(a)


3-day Compressive Strength(MPa)
40
35
30
25
20
15
SFMC(L)
LMC(L)
FRC(L)
SLMC(L)
LMC+SF(L)
SFMC+SRA(L)
MTMC(L)
NC(L)
Mixture Types

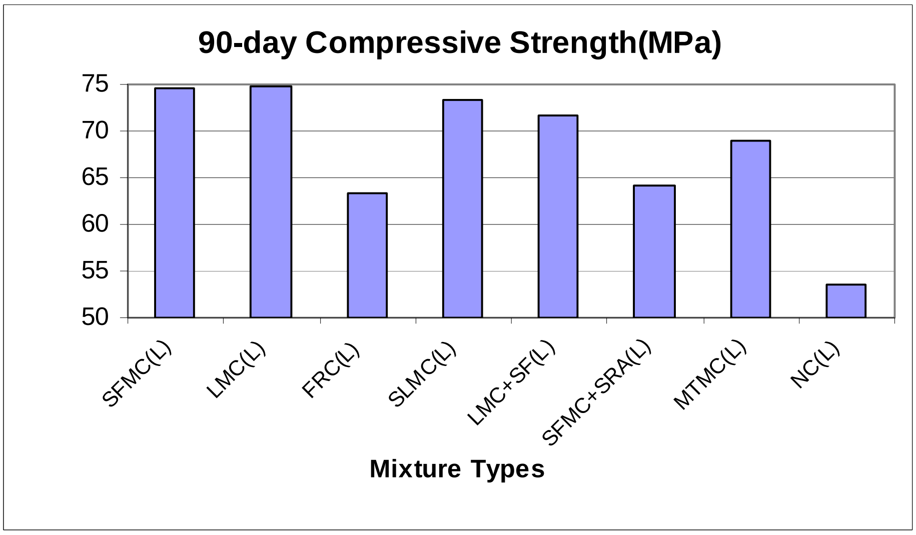
(b)


7-day Compressive Strength(MPa)
50
45
40
35
30
25
SFMC(L)
LMC(L)
FRC(L)
SLMC(L)
LMC+SF(L)
SFMC+SRA(L)
MTMC(L)
NC(L)
Mixture Types

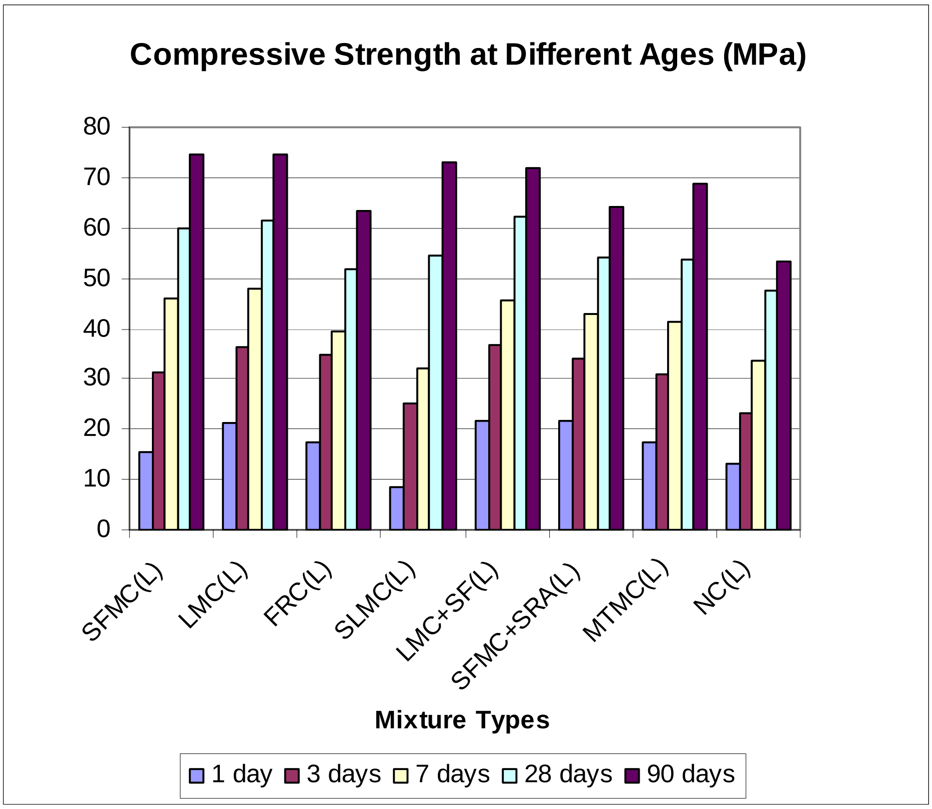
(c)


28-day Compressive Strength(MPa)
70
65
60
55
50
45
SFMC(L)
LMC(L)
FRC(L)
SLMC(L)
LMC+SF(L)
SFMC+SRA(L)
MTMC(L)
NC(L)
Mixture Types
((L): Limestone 1 Mpa = 145 psi)

(d)


90-day Compressive Strength(MPa)
75
70
65
60
55
50
SFMC(L)
LMC(L)
FRC(L)
SLMC(L)
LMC+SF(L)
SFMC+SRA(L)
MTMC(L)
NC(L)
Mixture Types

(e)



(f)

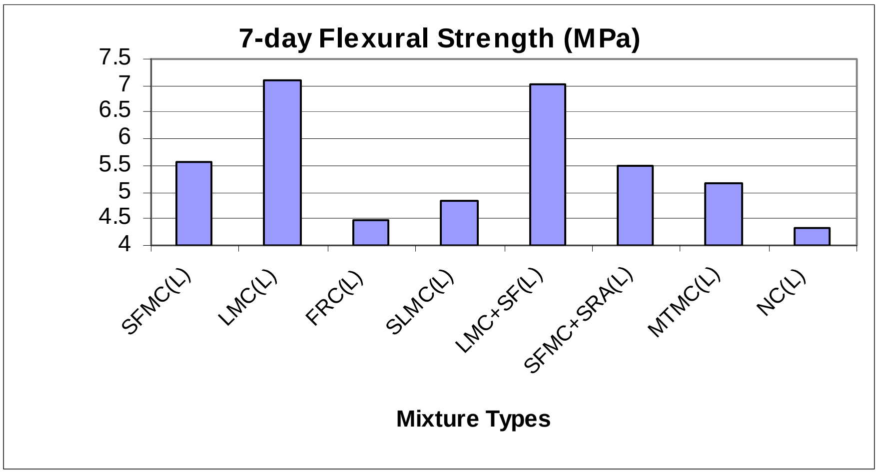
Fig 4.1−Compressive strength at different ages (1 MPa = 145 psi)

Test results show that all overlay mixtures had higher compressive strengths than NC substrate. The difference however depends on overlay types. Among overlays, LMC had the highest compressive strength at almost all ages. The early age strength of SFMC was not as high as LMC, but it increased quickly and was almost the same as LMC at 28 and 90 days. The early age strength of FRC was comparatively higher, but it increased slowly and the strengths after 28 days were lower than the others. Hybrid fiber used to prepare FRC in this study did not contribute to the compressive strength of the concrete. This fact is also mentioned in the data sheet of the fiber. SLMC had the lowest early age strength, but the strengths after 28 days were high, even close to those of SFMC and LMC. The strengths achieved by using the combination of latex and silica fume were similar to what was obtained by using each of them separately. By comparing the strengths of SFMC and SFMC+SRA, it is observed that the SRA slightly decreased the compressive strength of concrete. The compressive strength of MTMC was a little higher than FRC and NC, but lower than LMC and SFMC. All overlay mixtures satisfied the strength requirements of WVDOH, which is 27.5 MPa or 4000 psi (Luo 2002). The 3-day strengths of almost all the overlay types except SLMC were even greater than the 28-day strength requirement of WVDOH. This high early strength will allow the bridge to open to traffic only after 3 days of curing, which is highly advantageous.

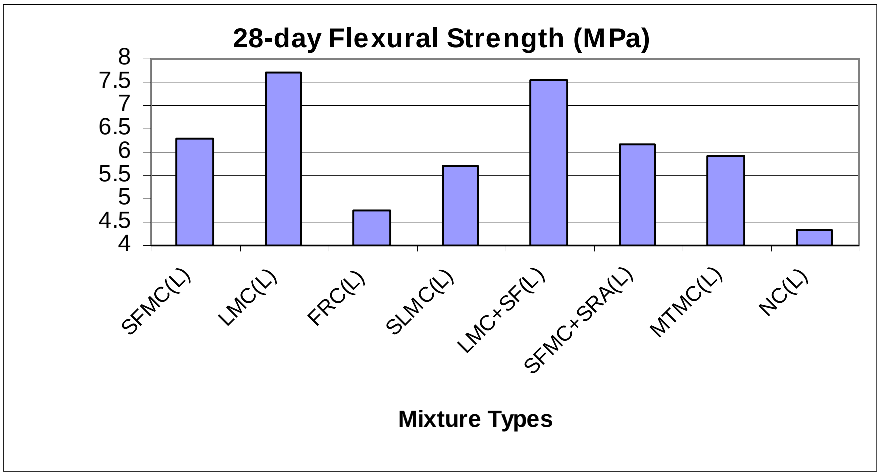
4.2.2 Flexural Strength

The flexural strength of 50.8 × 50.8 × 280 mm (2 × 2 × 11 in.) long concrete beam specimens of overlay mixtures was measured under four-point bending in accordance with ASTM C 78 (Standard Test Method for Flexural Strength of Concrete). The spans of the beams were 229 mm (9 in.). Fig. 4.2 shows the test system. The specimens were tested in a MTS machine at a constant displacement rate of 0.1mm /min according to ASTM C 1018 (Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete). For each mixture, two batches were tested. Each batch contained two specimens. Overall average was calculated for presentation of data. Tests were conducted at 7, 28 and 90 days. Fig. 4.3 shows the results of flexural tests.

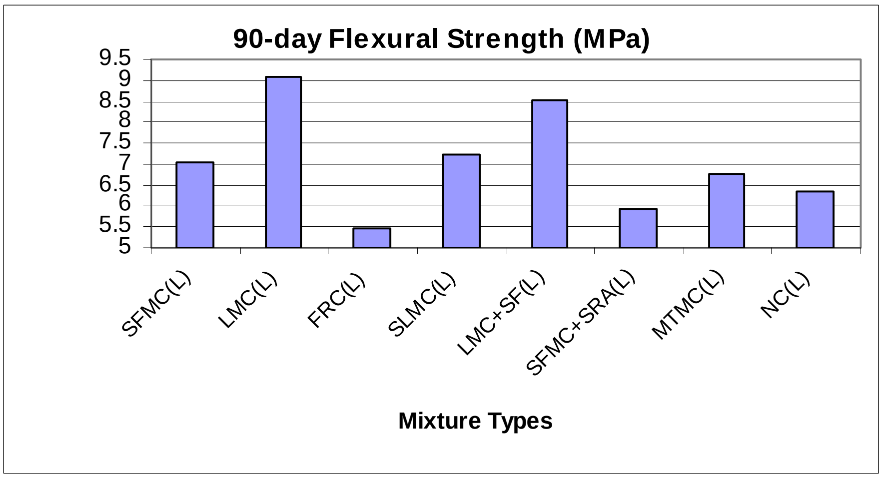
Fig 4.2−Flexural strength test


7-day Flexural Strength (MPa)
7.5
7
6.5
6
5.5
5
4.5
4
SFMC(L)
LMC(L)
FRC(L)
SLMC(L)
LMC+SF(L)
SFMC+SRA(L)
MTMC(L)
NC(L)
Mixture Types

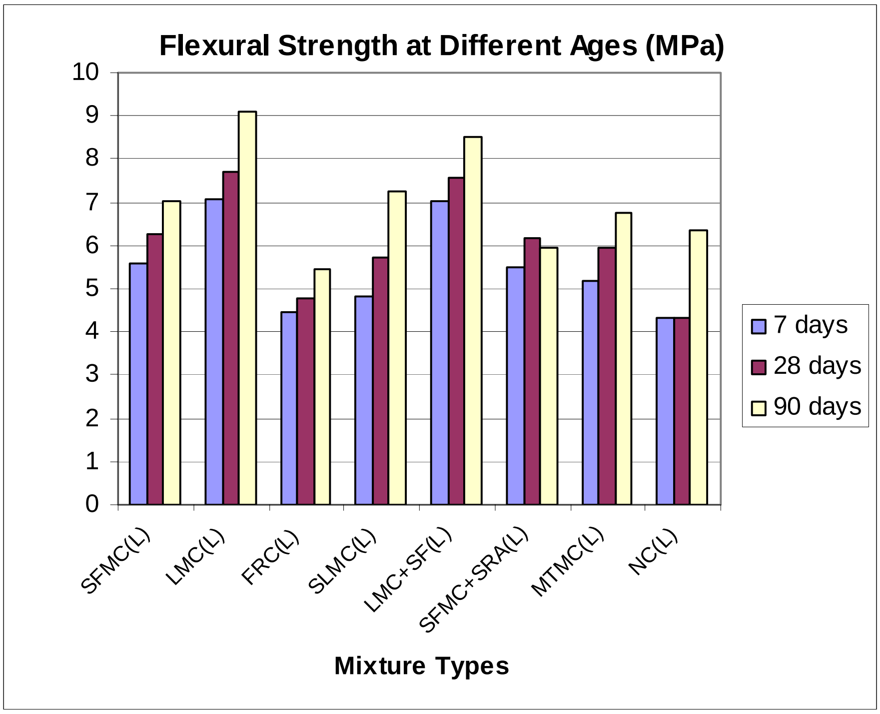
(a)


28-day Flexural Strength (MPa)
8
7.5
7
6.5
6
5.5
5
4.5
4
SFMC(L)
LMC(L)
FRC(L)
SLMC(L)
LMC+SF(L)
SFMC+SRA(L)
MTMC(L)
NC(L)
Mixture Types

(b)


90-day Flexural Strength (MPa)
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
SFMC(L)
LMC(L)
FRC(L)
SLMC(L)
LMC+SF(L)
SFMC+SRA(L)
MTMC(L)
NC(L)
Mixture Types

(c)



(d)

Fig 4.3−Flexural strength at different ages (1 MPa = 145 psi)

Fig. 4.3 shows that all overlay mixtures had higher flexural strengths at different ages than NC substrate. Among all overlay mixtures, LMC and LMC+SF had the highest flexural strengths. Silica fume increased the flexural strengths of concrete significantly as it increased the compressive strengths. The addition of SRA reduced flexural strengths slightly as it reduced compressive strengths. Both slag and metakaolin increased the flexural strengths, while slag did it marginally. The influence of fiber on flexural strength was not distinct. This agreed with the data sheet of the fiber by the company. However, all the FRC specimens have shown no disintegration after failures.

ACI 363R (State-of-the-art Report on High-strength Concrete) presents a relationship between compressive strength (fc') and modulus of rupture (fr'). The slope of the relationship between fr' and $(fc')^{1/2}$ represents the flexural strength capacity for a given compressive strength of the material. Based on current experimental data, these slopes are provided in Table 4.2 to get an idea of relative flexural strength capacity.

Table 4.2−Relationship of flexural strength and compressive Strength based on experiment

	fc' (MPa) 28 days	fr' (MPa) 28 days	$fr'/(fc')^{1/2}$
SFMC(L)	60	6.3	0.81
LMC(L)	61	7.7	0.99
FRC(L)	52	4.8	0.66
SLMC(L)	55	5.7	0.77
LMC + SF(L)	62	7.6	0.96
SFMC+SRA(L)	54	6.2	0.84
MTMC(L)	54	5.9	0.81
NC(L)	47	4.3	0.63

Note: 1 MPa = 145 psi

Table 4.2 shows that LMC and LMC+SF had the maximum flexural strength capacity, followed by SFMC+SRA, SFMC and MTMC. SLMC had lower flexural strengths capacity than the above mixtures, but still more than NC substrate. Due to the type of fibers added, FRC could not show higher flexural strength capacity. However the testing of FRC beam shows that the specimens did not break into pieces even after it reached its maximum load. After it reached maximum flexural load, it has undergone continuous deformation for a long time. The higher flexural strength for a given compressive strength is advantageous for overlays as bridge subject to bending under the wheel loads of moving traffic.

4.2.3 Modulus of Elasticity

The modulus of elasticity was tested according to ASTM C 469-94 (Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression). For each mixture type, two specimens were tested. Averages were calculated and presented in Table 4.3. ACI 363(State-of-the-Art Report on High-Strength Concrete) gives the following equation (4-1) to express the modulus of elasticity of concrete:

$$E_C = 3320\sqrt{f_c'} + 6900 \text{ MPa} \quad \text{for } 21 \text{ MPa} < fc' < 83 \text{ MPa} \ldots\ldots \quad (4\text{-}1)$$

Where fc' is compressive strength in MPa.

And ACI 318 expressed the Ec as:

$$E_C = 57{,}000 \sqrt{f_c^{'}} \quad \ldots\ldots \quad (4\text{-}2)$$

Where fc' is compressive strength in MPa.

Table 4.3 presents the experimental results and the predicted values of E_C by both ACI 363 and ACI 318 equations.

Table 4.3—Modulus of elasticity (E_c) and Poisson's ratio

Mixture	Experimental Value (MPa)	ACI 318 (MPa)	ACI 363 (MPa)	Experimental Poisson's Ratio (υ)
NC	30909	36669	32623	0.22
SFMC(L)	28132	37044	32886	0.21
LMC(L)	26292	34011	30758	0.22
FRC(L)	33919	34955	31420	0.24
SFMC-SRA(L)	30619	37375	33118	0.20
LMC+SF(L)	26416	34823	31327	0.23
SLMC(L)	29420	34729	31262	0.21
MTMC(L)	32266	32589	29760	0.24

Note: 1 MPa = 145 psi

By comparing the results, it is seen that the FRC had the highest E_c value, which might be due to the high Ec value of steel fiber. It is also seen that LMC and LMC+SF had the lowest values, even lower than NC. Table 4.3 also shows that ACI 318 expression overestimates the modulus of elasticity for concretes, while ACI 363 predicts the Ec much closer to the experimental value. The Poisson's ratios were all within the range mentioned in ACI 363 (section 5.4), which is 0.20 to 0.24 for 28 days compressive strengths ranging from 55 to 80 MPa (8000 to 11,600 psi).

4.2.4 Free Shrinkage

The length change of 76.2 × 76.2 × 254 mm (3 × 3 × 10 in.) long concrete prism specimens was measured in accordance with ASTM C 157 (Standard Test Method for

Length Change of Hardened Hydraulic-Cement Mortar and Concrete). The specimens were stored at 50 ± 2% relative humidity and 23±2°C (73±4°F) temperature with adequate air circulation through the specimens. For each mixture, three specimens were tested. The length changes were recorded by a standard length change comparator at 1, 4, 7, 14, 28, 56 and 112 days. From the values of length change, the free shrinkage of prism specimens was calculated in 10^{-6} mm/mm (in./in.). Fig. 4.4 shows the comparisons of free shrinkage of all mixtures at different ages.

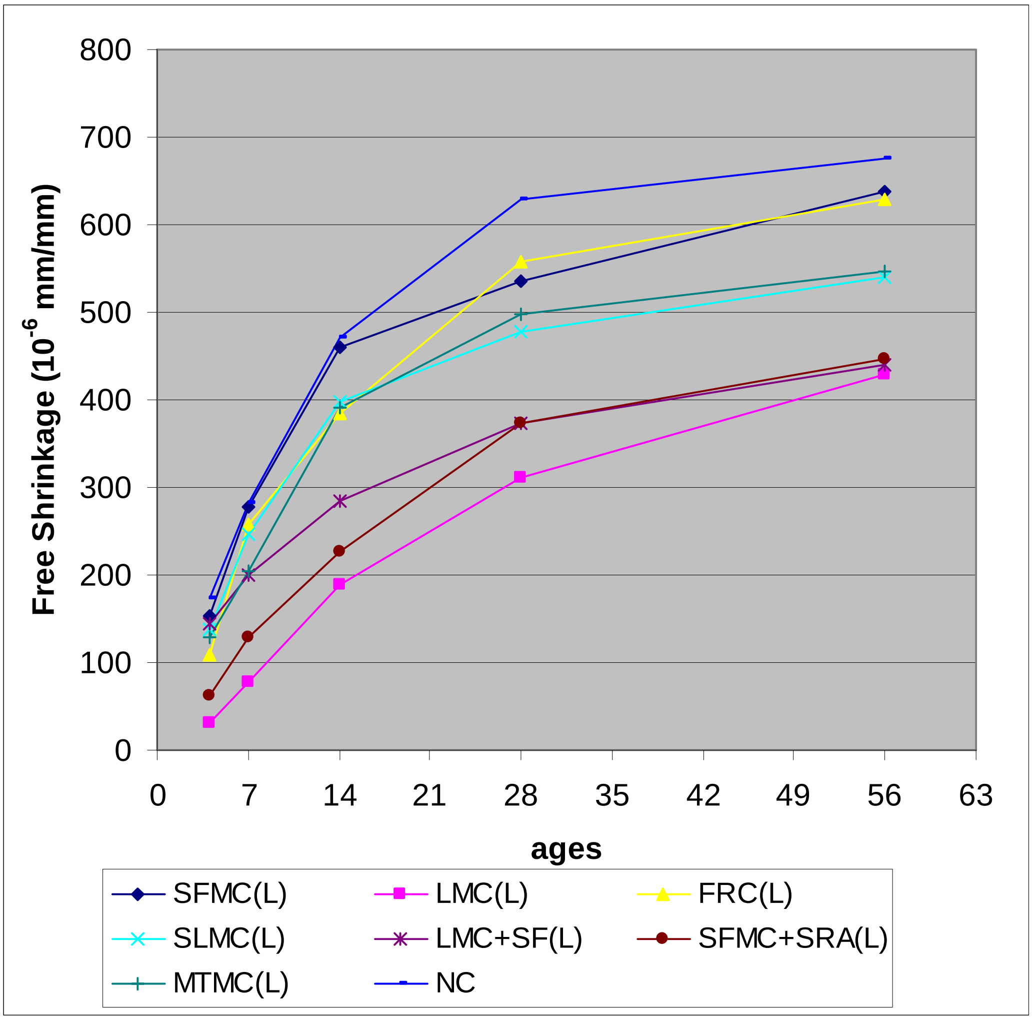


Fig. 4.4−Development of free shrinkage strain with time

From the comparisons above, it is seen that all the overlay mixtures had lower free shrinkage values compared to NC substrate. Except LMC, LMC+SF, and SFMC+SRA, all other overlay mixtures had similar free shrinkage. Silica fume did not affect the shrinkage much at early age, but it decreased the shrinkage after 28 days. LMC had the lowest shrinkage among all the overlays. SFMC+SRA also had very low free shrinkage compared to others, which means that SRA decreased shrinkage effectively. The LMC+SF had the shrinkage close to NC at early age, but the shrinkage after 7 days was close to those of LMC and SFMC+SRA. In general, those with latex and SRA had low shrinkage and the rest of the mixtures had high shrinkage. The difference of shrinkage between NC substrate and all other overlays was mainly due to the use of higher water-cement ratio for NC substrate (w/cm = 0.5) compared to the overlays (w/cm = 0.35 to 0.40). However the values do not provide adequate information of differential shrinkage under restrained conditions at different humidity and temperature existing in the field.

4.3 Selection of Overlay Types

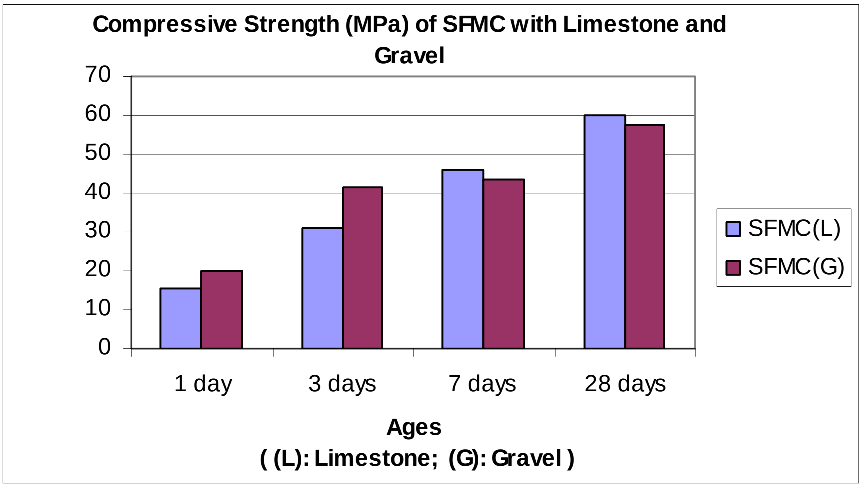
According to the properties discussed above and the literature reviewed, four types of overlays were finally selected for further evaluation for interface strength. Those were SFMC, LMC, FRC and SLMC. SFMC, LMC and SLMC had highest compressive as well as flexural strengths. LMC, SLMC, and FRC had the low free shrinkage, which will reduce the chance of shrinkage cracking at interface. FRC had highest modulus of elasticity. It has also good impact, abrasion and shatter resistance though not measured in this study. The fiber could also reduce the plastic cracking of fresh concrete.

4.4 Comparisons of Properties of Selected Overlay Mixtures Using Gravel and Limestone

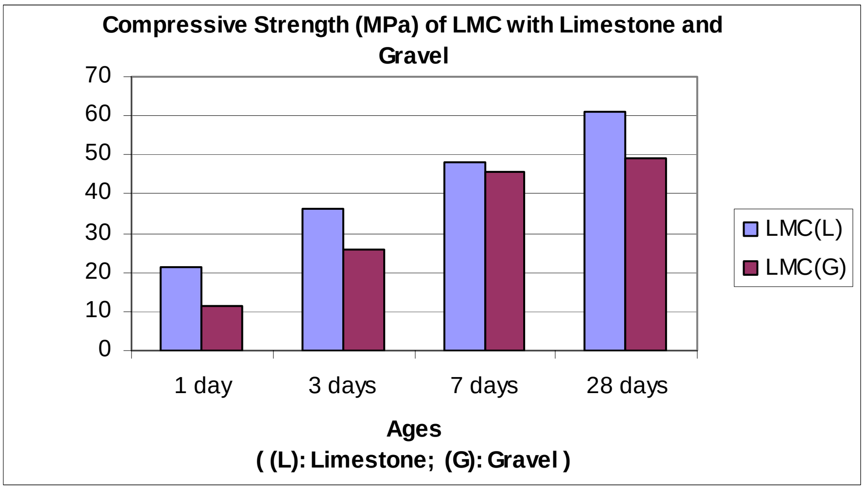
The compressive strength and chloride permeability of above four selected overlay mixtures (SFMC, LMC, FRC and SLMC) were further evaluated using another kind of coarse aggregate (gravel). Following paragraphs show the comparisons of overlays using two different aggregates (limestone and gravel).

4.4.1 Compressive Strength

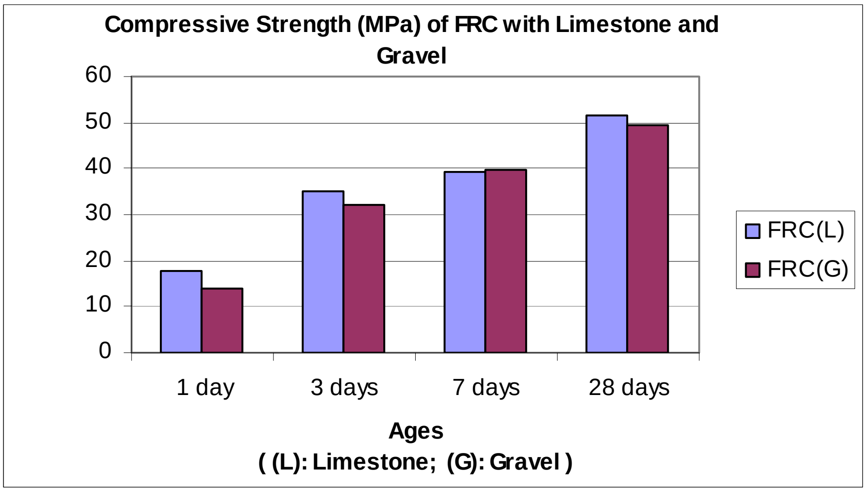
The strengths of overlay mixtures with two different coarse aggregates are presented in Fig. 4.5.


Compressive Strength (MPa) of SFMC with Limestone and Gravel
70
60
50
40
30
20
10
0
1 day
3 days
7 days
28 days
SFMC(L)
SFMC(G)
Ages
((L): Limestone; (G): Gravel)

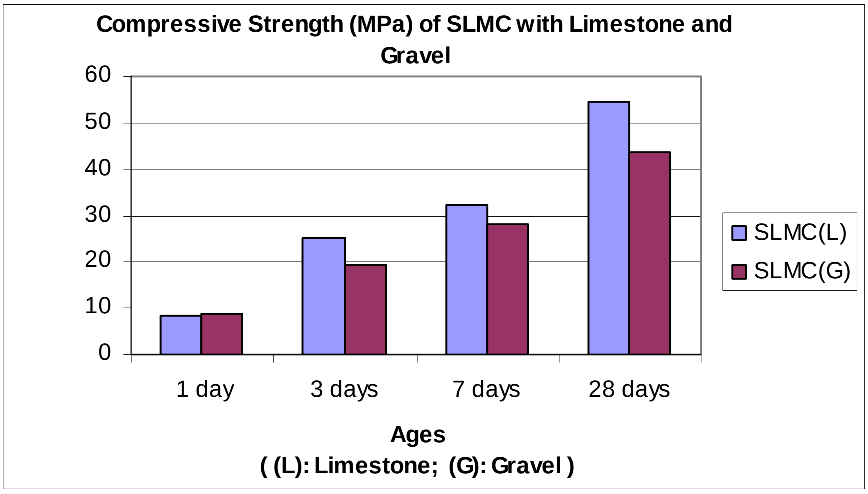
(a)


Compressive Strength (MPa) of LMC with Limestone and Gravel
70
60
50
40
30
20
10
0
1 day
3 days
7 days
28 days
LMC(L)
LMC(G)
Ages
((L): Limestone; (G): Gravel)

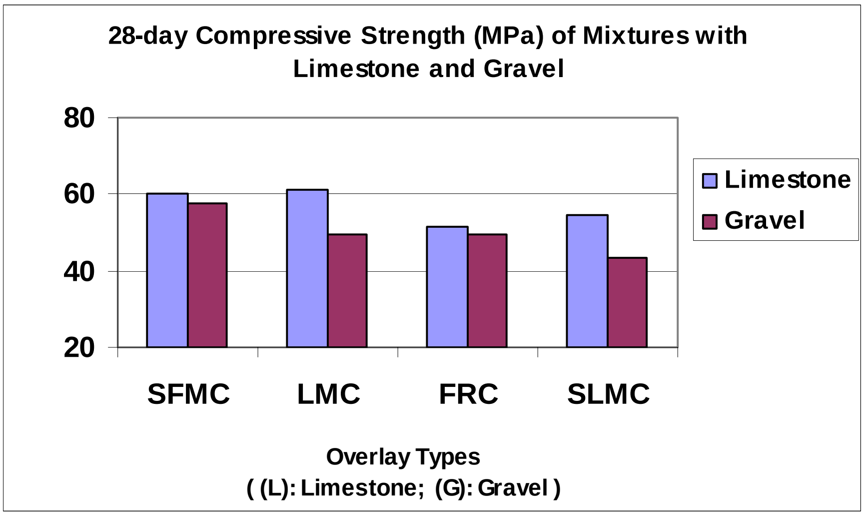
(b)


Compressive Strength (MPa) of FRC with Limestone and Gravel
60
50
40
30
20
10
0
1 day
3 days
7 days
28 days
FRC(L)
FRC(G)
Ages
((L): Limestone; (G): Gravel)

(c)



(d)



(e)

Fig. 4.5−Compressive strength of overlay types with limestone and gravel (1 MPa =145 psi)

From Fig. 4.4 it is evident that for all the mixture types, the compressive strengths of concrete with gravel are lower than those with limestone. The most likely reason for this is the greater mechanical bond developed in case of angular limestone particles (ACI 363, Section 2.5.2.2). Another possibility is that limestone being more angular compared to gravel had more surface area. This created a larger aggregate mortar interfacial zone and these zones being relatively stronger due to lower pores for the use of various mineral and chemical admixtures and latex increased the compressive strength values at almost all ages.

4.4.2 Rapid Chloride Permeability

The rapid chloride permeability test was conducted in accordance with ASTM C 1202 (Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration).The disc specimens with the dimension of ∅ 101.6 mm (4 in.) × 50.8 mm (2 in.) thickness were cut from cylinders The test was conducted on properly cured 28 to 35 days old specimens. For each mixture, two specimens were tested and the average was calculated for presentation of data. Table 4.4 shows the result of tests.

Table 4.4−Results of rapid chloride permeability test (coulombs)

Mixtures	**Limestone**	**ASTM Rating**	**Gravel**	**ASTM Rating**
SFMC	461	Very low	750	Very low
LMC	806	Very low	1432	Low
FRC	3532	Moderate	2534	Moderate
SLMC	1285	Low	1300	Low

It is seen from the results that among the four selected overlay mixtures, SFMC, LMC, and SLMC all had good resistance to chloride permeability, while SFMC performed the best. The charge passed through FRC seems particularly large. This might be caused by the steel fibers through which the charge could pass. From the result, it can be seen that SFMC and LMC with limestone had better chloride resistance than those with gravel, while there is almost no differences between mixtures with limestone and gravel for SLMC. According to the above result, no clear influence of aggregate type on chloride permeability could be seen.

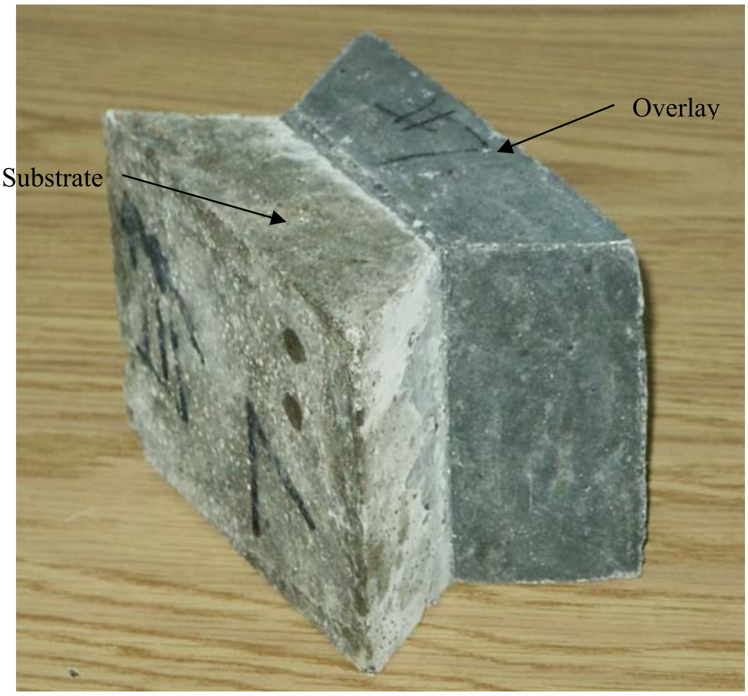
CHAPTER 5

BI-LAYER SPECIMENS AND DIRECT SHEAR TEST

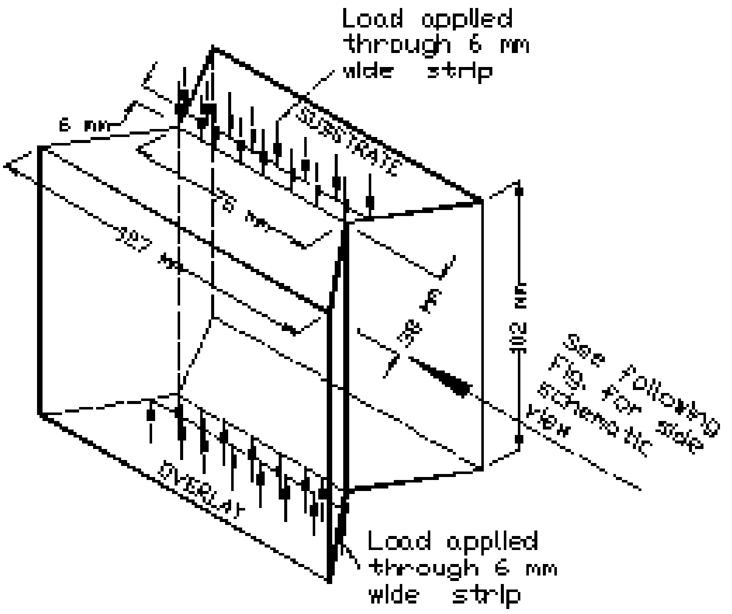
This chapter describes manufacturing of bi-layer specimens, modification of the shear testing apparatus, and the shear tests conducted.

5.1 Manufacturing of Bi-layer Specimens

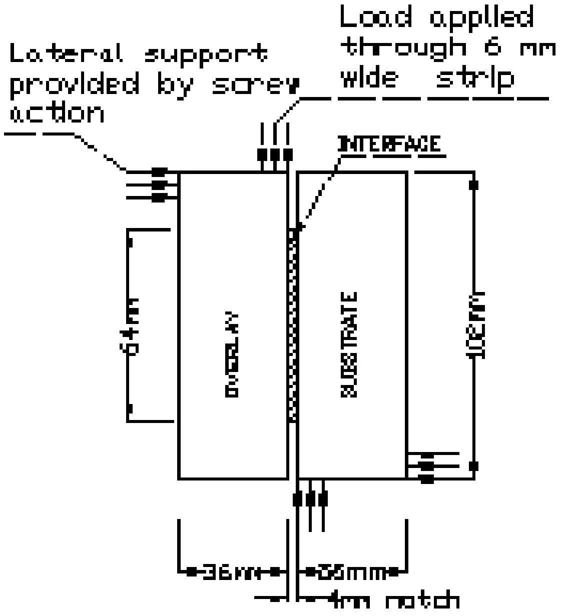
In this study, the butterfly shaped bi-layer specimens used by Luo (2000) were used with some modifications. The shape and dimension of a typical specimen are shown in Fig. 5.1 (a) ~ (c).



(a) Typical specimen



(b) Dimensions of specimen with applied load (schematic 3-D view)



(c) Schematic side view

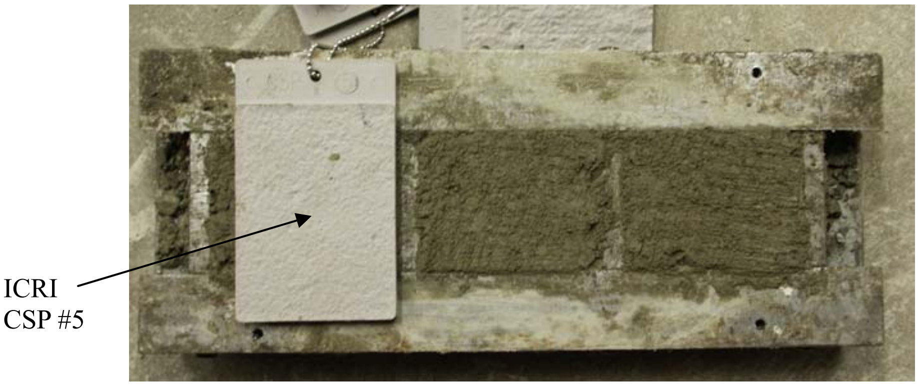
Fig. 5.1−Shear test specimen

The specimens were cast in partitioned steel molds in two layers. The bottom layer was substrate and the top layer was overlay. The substrate was made of NC as mentioned and the overlays were made of SFMC, LMC, FRC and SLMC mixtures, as selected before. All the specimens were fabricated according to the following steps:

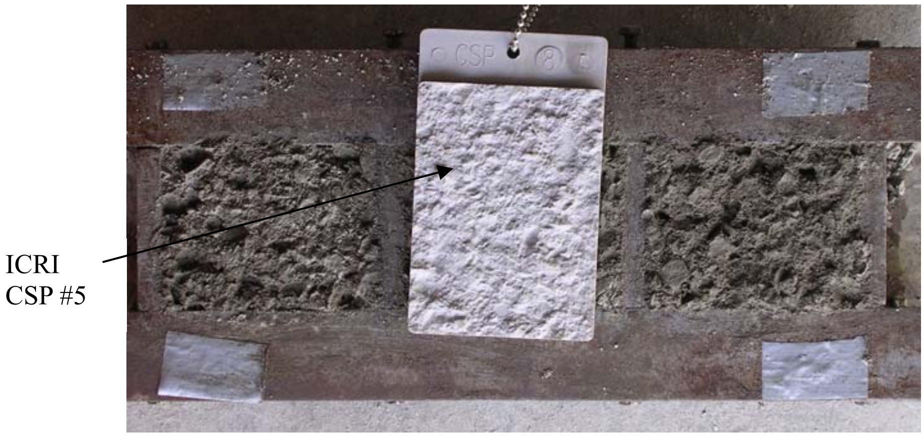
1. The substrates of thickness 38 mm (1.5 in.) were cast in the 3-specimen capacity steel molds and vibrated in a table vibrator. The specimens were then covered with wet burlap at a temperature of 23±2°C (73±4 °F) until surface preparation. Fig. 5.2 shows the casting of substrate in a typical 3-specimen gang mold.

Fig. 5.2−Casting of substrate

2. After curing for 5 to 6 hours, the surface was prepared according to International Concrete Repair Institute Technical Guidelines (ICRI 03732 Surface Preparation Guide & Surface Profile Chips). Two different types of surface preparations were followed in this study: CSP #5 and CSP #8. Fig. 5.3 shows the specimens with each of the surface preparations. For comparison, the corresponding ICRI profiles are displayed in the figures below.



(a) Surface preparation CSP # 5



(b) Surface preparation CSP# 8

Fig. 5.3−Substrate surface preparation

3. The substrates were demolded after 24 hours (Fig. 5.4), and cured in water at a temperature of 23±2°C (73±4 °F) for 28 days (4 weeks). Half of the substrates were further air cured in curing room at 50% relative humidity and 23±2°C (73±4 °F) temperature for another 6 weeks. Therefore substrates of two different ages were formed: 4 weeks and 10 weeks.

Fig. 5.4−Demolded substrates

4. At the age of 4 weeks (or 10 weeks), the substrates were reinstalled into the molds. The surfaces were cleaned and moistened thoroughly before the second layers of molds were set for casting of overlay (Fig. 5.5).

Fig. 5.5−Install the substrates back to molds

5. Bonding slurries made of the same type of overlay mixtures with coarse aggregate removed were applied thoroughly and scrubbed into the surface according to the guidelines provided by the WVDOH for half of the specimens. In case of FRC, the fiber was not included in the slurry used. No slurry was used in other half of the specimens.

6. Now, the overlay of thickness 38mm (1.5 in.) was cast within the top molds. Fig. 5.6 shows the casting of overlays. After casting, the specimens were covered under wet burlap at a temperature of 23±2°C (73±4 °F) for 48 hours.

Fig. 5.6−Casting of overlay

7. After 48 hours of curing, the specimens were demolded carefully and cured for another 26 days before testing. Thus the overlay concrete became 28 days (4 weeks) matured before testing.

8. Before shear testing, a notch around the interface periphery of each bi-layer specimen was formed by a diamond saw. The notch helped to propagate the crack through the interface. The notch was about 13 mm (1/2 in.) deep on 102 mm (4 in.) side and 19 mm (3/4 in.) deep on 76 mm (3 in.) side, which made the effective bond area 3300 mm^2 (50mm × 64 mm) or 5 in.^{2} (2 in. x 2.5 in.). Fig. 5.7 shows the typical bi-layer shear specimen with notches all around.

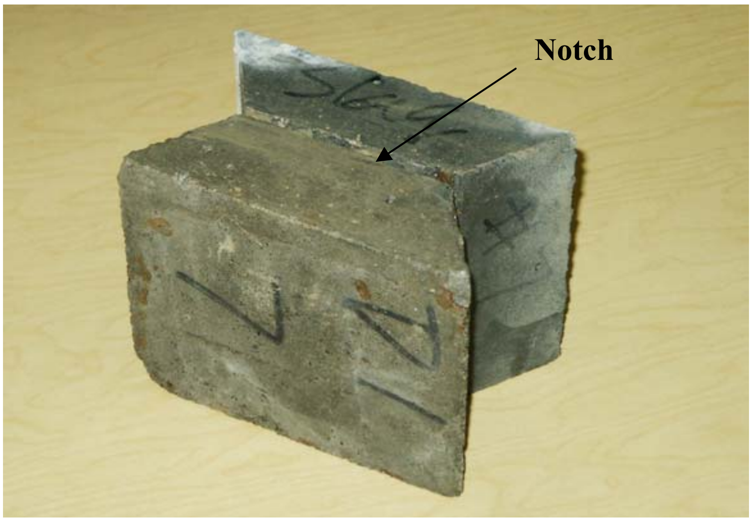


Fig. 5.7−Bi-Layer specimen with notches all around

5.2 Design and Fabrication of Shear Testing Apparatus

In this study, the shear tool used by Luo (2002) was used after necessary modifications. Modification was needed due to high shear strength capacity of the specimens used in this study. Shear strength of specimens of current study was much higher because of better surface preparation and improvement in the interface quality.

5.2.1 Description of Original Apparatus

Fig. 5.8 shows the shear apparatus used by Luo (2002). The apparatus was made of high quality steel and was designed to accommodate the bi-layer specimens. It was capable of fitting into the compression grips of an MTS machine.

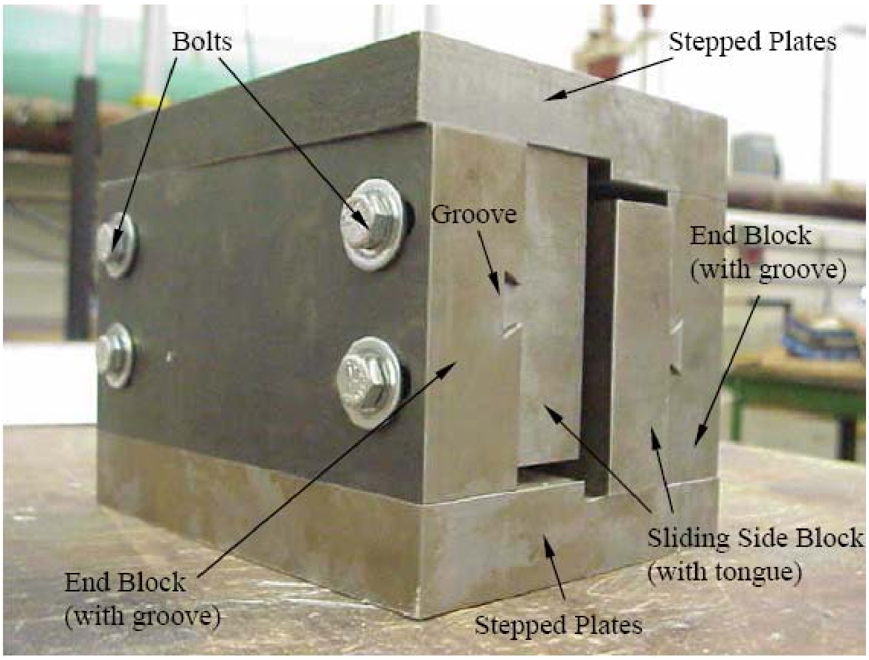


Fig. 5.8−Shear testing apparatus (1)

When the specimen was installed into the apparatus, the two sliding type side blocks could be adjusted to hold the specimen tightly. Also, the specimen was supported by the end blocks because the distance between two end blocks is very close to the thickness of the specimen. Thus the specimen was confined well from both side and back. The compressive load induced by the MTS machine (Fig. 5.9) was applied to the stepped plates and then transferred to the interface.

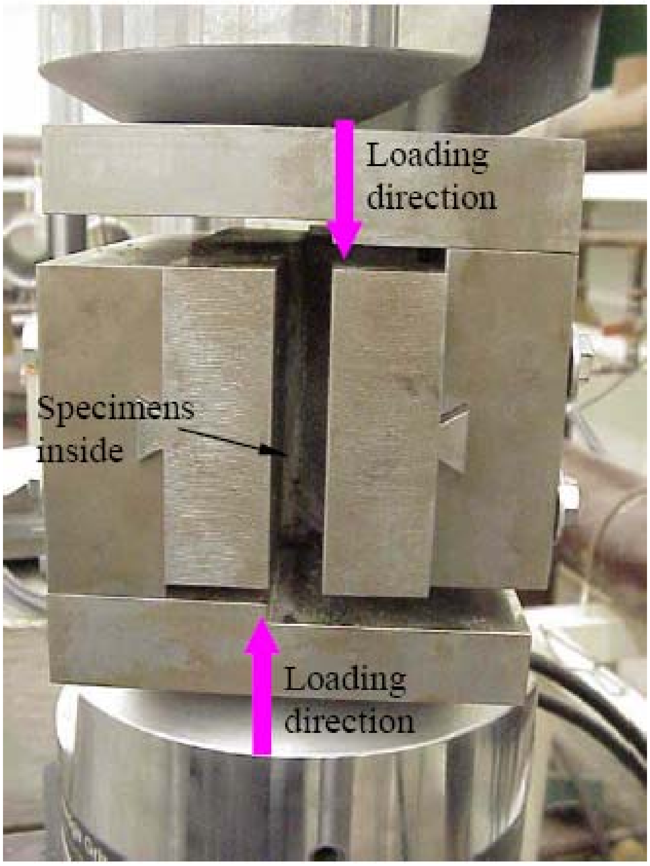


Fig. 5.9−Shear testing apparatus (2)

A more detailed description of the apparatus was presented by Luo (2002)

5.2.2 Modification of Apparatus

The shear strength in this study was much higher than studies by Luo (2002) got. This was due to much improved surface preparation and use of bonding slurry with low water-cementitious material ratio or without bonding slurry at the interface. This higher load carrying capacity (5000 lbs to 7000 lbs) caused higher moment even with the small eccentricity. Because of such moment, the specimens rotated about the horizontal axis. As it was confined tightly by holding from two sliding side blocks, it induced tension at the interface (Fig. 5.10). In case of Luo (2002), the small moment did not cause any problem, however in this present study much higher moment caused high tensile strength resulting into premature diagonal cracking or pull-out snapping in the NC substrate (weaker concrete in the bi-layer specimen).

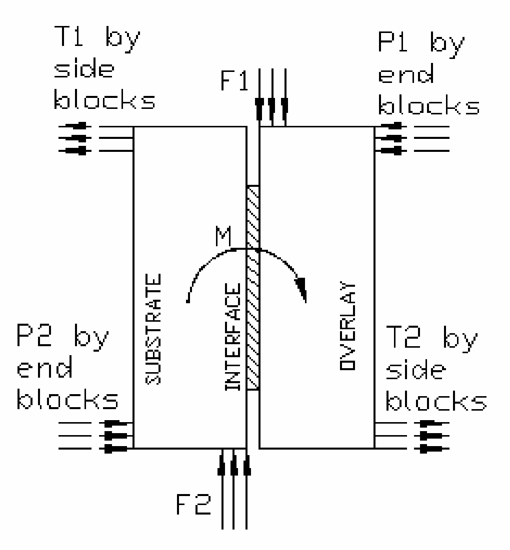


Fig. 5.10−Sketch for tension caused by side blocks
(F1 and F2 are loads applied by MTS machine. T1 (T2) and P1 (P2) are induced by side blocks and end blocks respectively to balance the M caused by F1 and F2. T1 and T2 will cause the tension in interface.)

In order to avoid this premature cracking during tests, the apparatus was modified as follows:

1. A 22.2 mm (14/16 in.) diameter hole was drilled and threaded for a screw. By driving the screw, a counterbalancing moment was developed by the steel plates to neutralize the moment due to load (see Fig. 5.11).

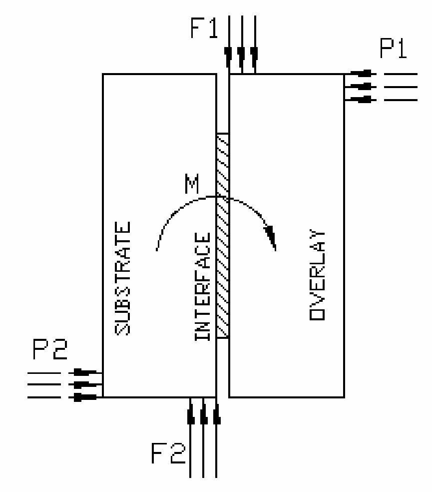


Fig. 5.11−Sketch for shear test after modification
(F1 and F2 are loads applied by MTS machine. P1 and P2 are induced by screw and steel plate to balance the moment)

2. The sliding side blocks were removed so that the specimens were not hold from the side, which prevented the occurring of tension in interface.
3. Since thickness of the specimens was slightly more than those of Luo (2002), both the end blocks were ground by 25.4 mm (½ in.). Whenever necessary, a thin steel plate and rubber pad were used as a packing between end blocks and specimens.
4. Load was applied through a thin steel strip of width 6 mm (1/4 in.). This strip reduced the eccentricity and consequently the moment induced by the load.

Through the modifications mentioned above, a pure shear conditions was achieved. Fig. 5.12 shows the apparatus after modification.

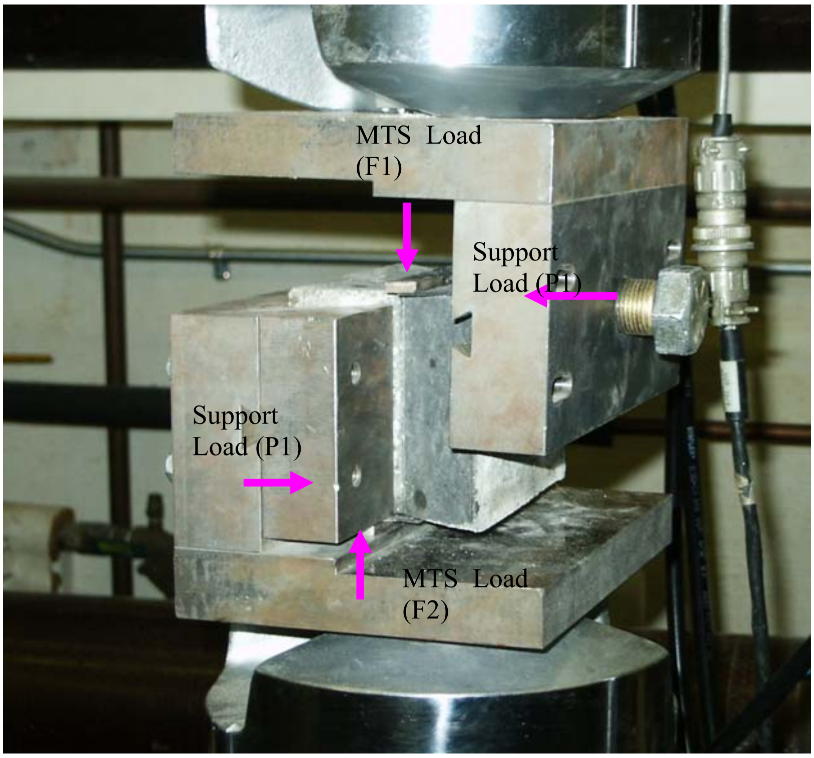


Fig. 5.12−Testing in progress after modification

5.3 Direct Shear Testing of Specimens

The tests were conducted in a MTS machine of 98 kN (22,000 lb) load-cell capacity. Fig. 5.12 shows the testing is in progress. A uniaxial vertical compressive load was applied through a steel strip of 6 mm (¼ in.) width. All the surfaces of the specimen touching the apparatus were covered by a neoprene rubber strip for transferring load evenly and thus protecting the specimen from local failure. The support from the back of the specimen was applied through a steel plate of 3 mm (1/8 in.) thickness tightened by the screw, which could prevent the specimen from rotation as mentioned before. Since there was still a very small rotation due to the flexibility of MTS machine, only one edge of the specimen was supported by the steel plate, which could guarantee there is no compression induced by the support (See Fig. 5.11 and 5.13)

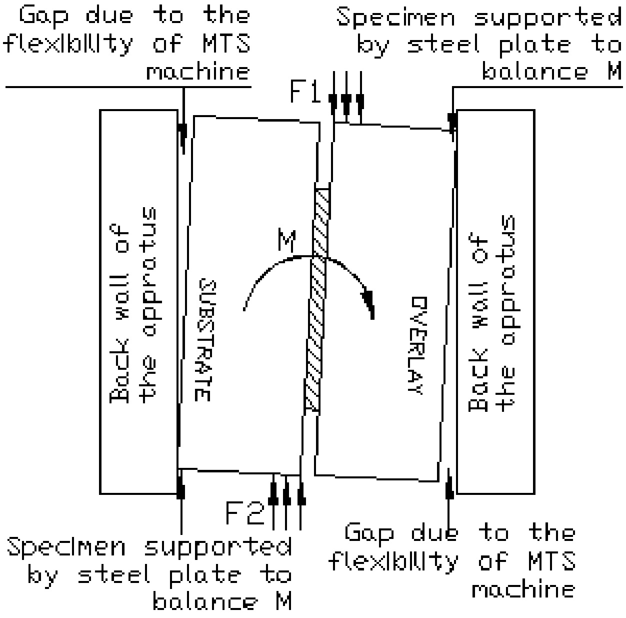
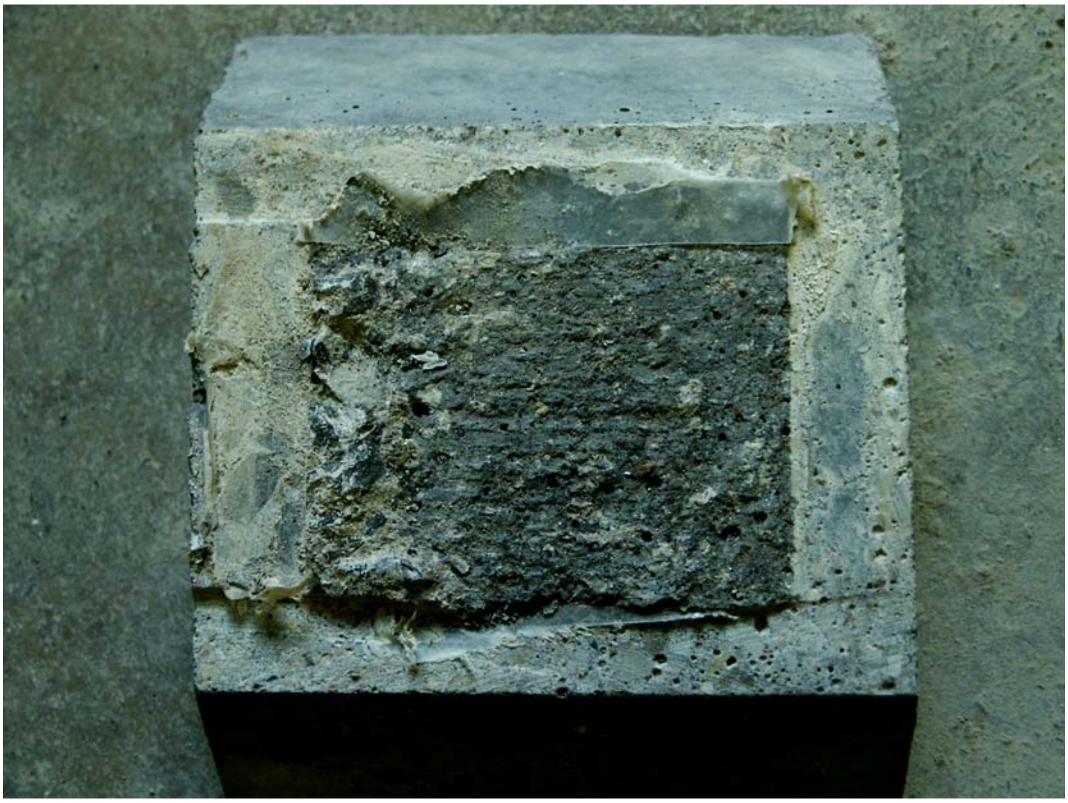


Fig. 5.13−Sketch for shear test

The load was applied at a constant displacement rate of 0.5 mm/min. (0.02 in. /min.), which was finalized after number of trials. The maximum load at failure and nature of failure of the specimens were recorded in each case. Fig. 5.12 shows the typical failures of the interface.

(a) Failure of Surface Preparation CSP #5



(b) Failure of Surface Preparation CSP #5 (Enlarged View)

(c) Failure of Surface Preparation CSP #8

(d) Failure of Surface Preparation CSP #8 (Enlarged View)

Fig. 5.14−Typical interface failures

The test results showed that the present test method and testing apparatus were appropriate for the evaluation of interface shear bond strength. The detailed results and analysis are presented and discussed in Chapter 6.

CHAPTER 6

DESIGN OF EXPERIMENT AND STATISTICAL ANALYSIS OF SHEAR TEST RESULTS

This chapter presents the design of experiments and statistical analysis of shear test results. A brief introduction of the design of experiment concept and analysis method is also provided at the beginning.

6.1 Introduction to Design of Experiment and Analysis of Data

6.1.1 Design of Experiment

There are many factors that can affect the interface shear bond strength of concrete. Based on the comprehensive literature review, overlay performance of various overlays of state DOTs, and previous research (Luo 2002) several parameters were selected for the evaluation of bond. Table 6.1 shows the factors which were considered in this study.

Table 6.1—Factors considered in present study

Factors Considered	Number of Levels	Details of Levels
Overlay mixtures type	4	(1) SFMC; (2) LMC; (3) FRC; (4) SLMC
Surface preparation	2	(1) CSP #5; (2) CSP #8
Bonding slurry	2	(1) With slurry; (2) Without slurry
Substrate age	2	(1) 4 weeks; (2) 10 weeks
Coarse aggregate types	2	(1) Limestone; (2) Gravel

The surface preparations were made according to Technical Guidelines prepared by the International Concrete Repair Institute, January 1997 (Guideline No. 03732). Two of the nine different concrete surface profiles (CSP) were selected in this study, which were CSP #5, described as medium shotblast and CSP #8, described as scabbled. CSP #5 could be achieved in field by several methods such as abrasive (sand) blasting, steel shot blasting, scarifying and needle scaling, while CSP #8 could be achieved by more aggressive steel shot blasting, scarifying, needle scaling, high/ultra high-pressure water jetting, scabbling, and flame blasting.

The number of all the possible combinations of the levels of factors mentioned above is 4×2×2×2×2 = 64. Taking eight specimens for each case, a total of 512 specimens need to be tested. Compared to the number of parameters studied this is an extremely large number. Running such a large number of tests is not only unrealistic, but may introduce experimental error.

To reduce the number of the experiment, we selected some of the combinations to represent all of them. This selection needs to be done carefully to ensure that they are representative. Thus the fractional factorial design method was conducted in this study. Detailed descriptions of this method can be found in many books (Montgomery 1991) on the topic of experimental design.

For the application of design of experiment, the following model was assumed to express the shear bond strength under different levels of factors:

$$Y_{ijklm} = \mu + (\tau 1)_i + (\tau 2)_j + (\tau 3)_k + (\tau 4)_l + (\tau 5)_m + \epsilon_{ijklm} \qquad (6\text{-}1)$$

Where, Y_{ijklm} is the $(ijklm)^{th}$ observation of shear strength, μ is a parameter common to all treatments called the overall mean, $(\tau 1)_i$ is a parameter unique to the i^{th} level of factor $\tau 1$. In our case, $\tau 1$ is overlay mixture type, $\tau 2$ is surface preparation, $\tau 3$ is application of slurry, $\tau 4$ is substrate age and $\tau 5$ is coarse aggregate type. ϵ_{ijklm} is the random error component.

It is seen from Table 6.1 that $i = 1,2,3,4$

$j, k, l, m = 1, 2$

Here, the assumption was made that the factors (overlay mixture type, surface preparation, bonding slurry, substrate age, and coarse aggregate type) were independent to each other, which means there was no interactions among the factors. Thus the interaction parameters such as $(\tau 1 \tau 2)$, $(\tau 1 \tau 2 \tau 3)$ were not included in the model. This assumption was reasonable according to the previous researches and published results. Based on the assumption, the coded $4 \times 2^{4-3}$ matrix was used for the design, and furnished in Table 6.2.

Table 6.2—The $4 \times 2^{4-3}$ table used for experimental design

	Basic Design							
			Surface Preparations	**Overlay Types**		**Application of Slurry**	**Substrate Age**	**Aggregate Type**
Run	A	B	C	X=(A,B)	AB	AC	BC	ABC
1	-1	-1	-1	x1	1	1	1	-1
2	-1	1	1	x2	-1	-1	1	-1
3	1	-1	-1	x3	-1	-1	1	1
4	1	1	1	x4	1	1	1	1
5	1	1	-1	x4	1	-1	-1	-1
6	1	-1	1	x3	-1	1	-1	-1
7	-1	1	-1	x2	-1	1	-1	1
8	-1	-1	1	x1	1	-1	-1	1

Notes:

- *Overlay mixture type:* ***x1****: LMC;* ***x2****: SFMC;* ***x3****: FRC;* ***x4****: SLMC*
- *Surface preparation:* ***-1****: CSP # 8;* ***1****: CSP #5*
- *Bonding slurry:* ***-1****: without slurry;*
  1*: with slurry.*
- *Substrate age:* ***-1****: 4 weeks;* ***1****: 10 weeks*
- *Coarse aggregate type:* ***-1****: Limestone;* ***1****: Gravel*

Table 6.3—Matrix for the design of experiment (based on fractional factorial design)

Number of Runs	**Overlay Types OT(4)**	**Surface Preparation SP(2)**	**Bonding Slurry AS(2)**	**Substrate Age SA(2)**	**Aggregate Type AT(2)**
	OT1: SFMC **OT2:** LMC **OT3:** FRC **OT4:** SLMC	**SP1:** CSP # 5 **SP2:** CSP # 8	**AS1:** With Slurry **AS2:** Without Slurry	**SA1:** 4 Weeks **SA2:** 10 Weeks	**AT1:** Gravel **AT2:** Limestone
1	OT1 (LMC)	SP2 (# 8)	AS1 (With)	SA1 (10 w)	AT2 (L)
2	OT2 (SFMC)	SP1 (# 5)	AS2 (Without)	SA1 (10 w)	AT2 (L)
3	OT3 (FRC)	SP2 (# 8)	AS2 (Without)	SA1 (10 w)	AT1 (G)
4	OT4 (SLMC)	SP1 (# 5)	AS1 (With)	SA1 (10 w)	AT1 (G)
5	OT4 (SLMC)	SP2 (# 8)	AS2 (Without)	SA2 (4 w)	AT2 (L)
6	OT3 (FRC)	SP1 (# 5)	AS1 (With)	SA2 (4 w)	AT2 (L)
7	OT2 (SFMC)	SP2 (# 8)	AS1 (With)	SA2 (4 w)	AT1 (G)
8	OT1 (LMC)	SP1 (# 5)	AS2 (Without)	SA2 (4 w)	AT1 (G)

6.1.2 Data Analysis for the Design of Experiment

Tests were conducted strictly following the design of experiment plan furnished in Table 6.3. The results were analyzed using analysis of variance (ANOVA) and analysis of main effects. A residual analysis was performed to ensure that the model used for the design of experiment is adequate before the results of ANOVA and analysis of main effects were accepted. A concise introduction of these three analyses is presented below.

6.1.2.1 Model adequacy checking

As stated in section 6.1.1, the assumption underlying the design of experiment and the analysis of both variance and main effects is that the data are adequately described by the model (6-1).To make sure the assumption was met, a model adequacy checking is then necessary. The primary diagnostic tools are based on the residuals. The residuals for this model are

$$(\mathrm{e}_{\mathrm{eijklm}})_{\mathrm{n}} = (\mathrm{Y}_{\mathrm{ijklm}})_{\mathrm{n}} - (\overline{\mathrm{Y}}_{\mathrm{ijklm}})$$

$(\mathrm{Y}_{\mathrm{ijklm}})_{\mathrm{n}}$ is n$^{\mathrm{th}}$ data in treatment $\mathrm{Y}_{\mathrm{ijklm}}$, $(\overline{\mathrm{Y}}_{\mathrm{ijklm}})$ is the average of that treatment. In our study, n=8 (see section 6.2).

A residual which is much larger than others is called outlier. The presence of one or more outliers can seriously distort the ANOVA. To examine the existence of outliers, standardized residuals are calculated as follows,

$$(\mathrm{d}_{\mathrm{ijklm}})_{\mathrm{n}} = \frac{(e_{ijklm})_n}{\sqrt{MS_E}}$$

The calculation of $\mathrm{MS_E}$ is presented in section 6.1.2.2. A residual bigger than 3 or 4 standard deviations from zero is a potential outlier.

Usually if the distribution of standard deviations residuals conforms to N (0, 1), the adequacy of model could be guaranteed. Thus, about 68 percent of the standardized residuals should fall within ±1, about 95 percent of them should fall within ±2, and virtually all of them should fall within ±3. If the data meets this rule, we can confidently say that the model is adequate and the analysis can be adopted.

6.1.2.2 Analysis of variance (ANOVA)

The ANOVA is probably the most useful technique in the field of statistical inference, especially when testing the equality of several means (Montgomery 1991). Thus, to see whether there is a significant difference between levels of the factors, the ANOVA was performed in this study, which is presented below in Table 6.4.

Table 6.4−ANOVA table for our research (refer to table 6.2)

Source of variation in Table 6-2	**Corresponding Factors**	**Sum of Squares**	**Degrees of Freedom**	**Mean Square**	**F_0**
X	Overlay mixture types	$SS_X = SS_A+SS_B+SS_{AB}$	3	MS_X	$F_0 = MS_X/MS_E$
C	Surface preparations	SS_C	1	MS_C	$F_0 = MS_C/MS_E$
AC	Bonding slurry	SS_{AC}	1	MS_{AC}	$F_0 = MS_{AC}/MS_E$
BC	Substrate age	SS_{BC}	1	MS_{BC}	$F_0 = MS_{BC}/MS_E$
ABC	Aggregate type	SS_{ABC}	1	MS_{ABC}	$F_0 = MS_{ABC}/MS_E$
Error		SS_E	2×2×2×(8-1) =56	MS_E	
Total		SS_T	2×2×2×8-1 =63	MS_T	

The computing formulas for the sums of squares in Table 6.4 are as follows:

$$SS_T = \sum_{a=1}^{2}\sum_{b=1}^{2}\sum_{c=1}^{2}\sum_{n=1}^{8} Y_{abcn}^2 - \frac{Y_{....}^2}{2\times2\times2\times8}$$

$$SS_A = \sum_{a=1}^{2}\frac{Y_{a...}^2}{2\times2\times8} - \frac{Y_{....}^2}{2\times2\times2\times8}$$

$$SS_B = \sum_{b=1}^{2} \frac{Y_{.b..}^2}{2\times2\times8} - \frac{Y_{....}^2}{2\times2\times2\times8}$$

$$SS_C = \sum_{c=1}^{2} \frac{Y_{..c.}^2}{2\times2\times8} - \frac{Y_{....}^2}{2\times2\times2\times8}$$

$$SS_{AB} = \sum_{a=1}^{2}\sum_{b=1}^{2} \frac{Y_{ab..}^2}{2\times8} - \frac{Y_{....}^2}{2\times2\times2\times8} - SS_A - SS_B$$

$$SS_{AC} = \sum_{a=1}^{2}\sum_{c=1}^{2} \frac{Y_{a.c.}^2}{2\times8} - \frac{Y_{....}^2}{2\times2\times2\times8} - SS_A - SS_C$$

$$SS_{BC} = \sum_{b=1}^{2}\sum_{c=1}^{2} \frac{Y_{.bc.}^2}{2\times8} - \frac{Y_{....}^2}{2\times2\times2\times8} - SS_B - SS_C$$

$$SS_{ABC} = \sum_{a=1}^{2}\sum_{b=1}^{2}\sum_{c=1}^{2} \frac{Y_{abc.}^2}{8} - \frac{Y_{....}^2}{2\times2\times2\times8} - SS_A - SS_B - SS_C - SS_{AB} - SS_{AC} - SS_{BC}$$

$$SS_E = SS_T - \left(\sum_{a=1}^{2}\sum_{b=1}^{2}\sum_{c=1}^{2} \frac{Y_{abc.}^2}{8} - \frac{Y_{....}^2}{2\times2\times2\times8}\right)$$

The mean square is computed by dividing sum of squares by degree of freedom. The F tests were then performed to see whether there were significant differences between the effects of levels of factors.

6.1.2.3 Analysis of main effects

The main effect for each factor is the difference between the averages of two levels:

$$\text{Main effect} = \overline{Y}_1 - \overline{Y}_2,$$

Where $\overline{Y}_1$ and $\overline{Y}_2$ are averages of two levels compared.

For overlay mixture types, all the levels were compared with each other.

The standard errors for effects were also calculated from the replicated testing results:

$$\sigma = \sqrt{\left(\frac{1}{16}+\frac{1}{16}\right)\times s^2}$$ for overlay mixture types and

$$\sigma = \sqrt{\left(\frac{1}{32}+\frac{1}{32}\right)\times s^2}$$ for other factors.

In the above expression, s^2 is the pooled estimate of run variance given by:

$$s^2 = \frac{\sum_{i=1}^{8}(8-1)\times s_i^2}{(8-1)\times 8}$$

Where i is the number of runs, s_i^2 is the variance of the testing results of i^{th} run.

6.1.2.4 Estimation of model parameters

As stated in section 6.1.1, the shear bond strength of our specimens was assumed to be expressed by model (6-1). This means if all the parameters in the model are known, the strength of those runs we did not perform (For example in dry conditions only 8 test run were made out of 4×2×2×2×2 = 64 run) can then be predicted. The estimation formulas for those parameters were given by Montgomery (1991) as follows:

$$\hat{\mu} = \overline{Y}_{.....}$$

$$(\hat{\tau}1)_i = \overline{Y}_{i.....} - \overline{Y}_{.....}$$

$$(\hat{\tau}2)_j = \overline{Y}_{.j....} - \overline{Y}_{.....}$$

$$(\hat{\tau}3)_k = \overline{Y}_{..k...} - \overline{Y}_{.....}$$

$$(\hat{\tau}4)_l = \overline{Y}_{...l.} - \overline{Y}_{.....}$$

$$(\hat{\tau}5)_m = \overline{Y}_{....m} - \overline{Y}_{.....}$$

6.2 Shear Bond Test Results and Discussions

Table 6.5 shows all testing results. Each run had 8 replicates.

Table 6.5−Testing results for dry condition

Number of Runs	Bond Strength (MPa) (8 Replicates For Each Run)								Average ($\bar{x}$)	Variance (s^2)	Coefficient Of Variance (COV = s / $\bar{x}$)
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**			
1	7.36	8.16	7.27	6.98	8.07	7.57	8.38	7.36	7.63	0.26	6.70%
2	7.53	8.20	6.71	8.14	6.48	8.28	7.90	7.53	7.58	0.47	9.04%
3	7.19	7.78	6.44	4.99	7.51	5.99	7.16	7.19	6.74	0.82	13.47%
4	5.51	4.89	6.17	5.06	6.01	4.43	4.68	5.51	5.21	0.39	11.97%
5	7.08	6.40	7.08	6.09	7.69	7.12	5.87	7.08	6.62	0.52	10.92%
6	5.21	6.69	4.83	5.95	4.68	5.27	5.42	5.21	5.54	0.50	12.72%
7	7.07	7.80	7.17	6.84	6.38	6.51	6.70	7.07	6.92	0.20	6.40%
8	4.92	5.24	4.66	5.70	5.31	5.58	6.15	4.92	5.38	0.21	8.58%

Note: 1 MPa = 145 psi

The coefficient of variance (COV) values were also calculated and presented in the Table. It represents how precisely the tests were performed each time. The COVs in this study ranged from 6.40% to 13.47%, which was reasonable considering the manufacturing complexity and variations in material properties. Knab and Sprinkel (1989) observed COV values of 4.7% to 10.1% on similar materials when tested by friction grip tension test, pipe nipple tension test and slant shear tests. The result in Table shows the consistency of the test method and test performance.

6.2.1 Model Adequacy Checking

As stated in section 6.1.2.1, the standardized residuals and summarization of them are calculated and presented in Table 6.6 and Table 6.7, respectively.

Table 6.6−Standardized Residuals Calculated from Table 6.5

Number of Runs	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	-0.42	0.82	-0.55	-1.00	0.68	-0.09	1.16	-0.60
2	-0.09	0.95	-1.34	0.86	-1.70	1.08	0.50	-0.26
3	0.69	1.61	-0.45	-2.69	1.19	-1.14	0.65	0.15
4	0.46	-0.50	1.47	-0.24	1.23	-1.19	-0.81	-0.42
5	0.71	-0.34	0.71	-0.82	1.64	0.77	-1.15	-1.51
6	-0.50	1.77	-1.09	0.63	-1.33	-0.42	-0.18	1.14
7	0.23	1.36	0.39	-0.12	-0.82	-0.63	-0.33	-0.07
8	-0.71	-0.22	-1.10	0.49	-0.11	0.32	1.18	0.14

Table 6.7−Summary of Standardized Residuals

Range	**Number of Residuals within the Range**	**Total number of Residuals**	**Percentage**	**Percentage for N(0,1) Distribution**
± 1	42	64	66 %	68 %
± 2	63		98 %	95 %
± 3	64		100 %	100%

From the above analysis, we can see that there is no indication of outliers. Furthermore, the largest standardized residual is d = 2.69, which is not severe enough to have a significant impact on the analysis and conclusions, and thus should cause no concern.

The distribution of standardized residuals is also very close to N (0, 1) distribution. All these give us much confidence that the data are adequately described by the assumed model. Thus the analysis of variance and main effects can be performed, which are presented in section 6.3.2 and 6.3.3, respectively.

6.2.2 Analysis of Variance (ANOVA)

The calculation of sums of squares were described in section 6.1.2.2, the results of calculation are presented in Table 6.8 and Table 6.9

Table 6.8−Calculation of Sum of Squares-1 (Refer To Table 6.2)

SS_A	SS_B	SS_C	SS_{AB}	SS_{AC}	SS_{BC}	SS_{ABC}	SS_E	SS_T
11.54	1.09	17.57	3.76	1.04	7.29	9.79	23.60	75.66

Table 6.9−Calculation of Sum of Squares-2 (Refer To Table 6.2 and Table 6.4)

Source of Variation	**Corresponding Factors**	**Sum of Squares**	**Degree of Freedom**	**Mean Square**	**F_0**	**Level of Significance**
X	Overlay mixture types	11.54+1.09+3.76 = 16.38	3	5.46	12.96	< 1%
C	Surface Preparations	17.57	1	17.57	41.70	< 1%
AC	Bonding slurry	1.04	1	1.04	2.46	> 10%
BC	Substrate age	7.29	1	7.29	17.29	< 1%
ABC	Aggregate type	9.79	1	9.79	23.23	< 1%
Error		23.60	56	0.42		
Total		75.66	63			

From summarized analysis in Table 6.9, it is seen that the overlay mixture types, surface preparations, substrate ages and aggregate types influenced the interface shear strength significantly (significant at 1 percent), while the effect of presence or absence of bonding slurry on shear strength is not clearly understood by this study (significant at 10 percent). This indicates that influence of bonding slurry on interface shear strength is less certain.

Also from comparing the value of F, we could see that the surface preparation affect the bond strength most significantly.

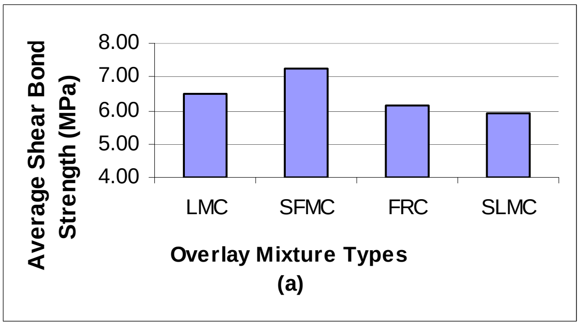
6.2.3 Analysis of Main Effects

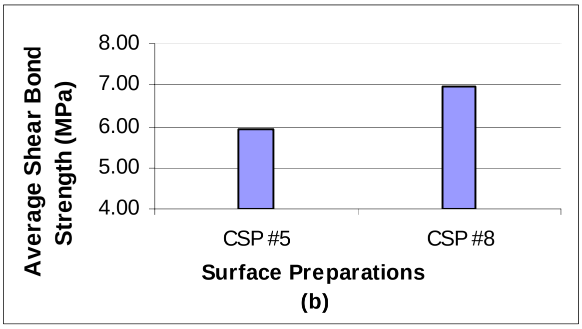
The average of each level for all factors are calculated and presented in the Table 6.10. Fig. 6.1 presents the plots of the average strengths at levels of all the factors, which will help to compare the results easily.

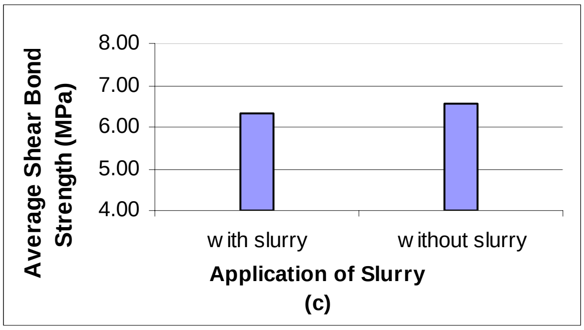
Table 6.10−Average Strength of Levels of Factors

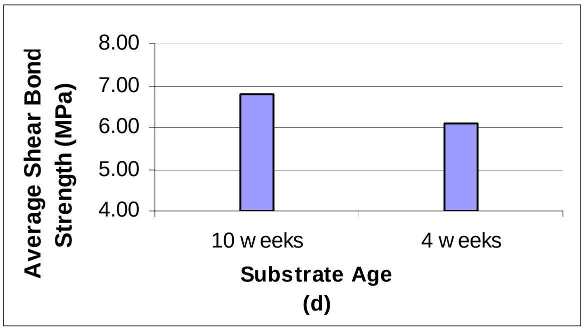
Factors Considered	Levels	Average Strength ± Standard Errors (MPa)
Overlay mixture types	LMC	6.50 ± 016
	SFMC	7.25 ± 0.16
	FRC	6.14 ± 0.16
	SLMC	5.92 ± 0.16
Surface preparations	CSP # 5	5.93 ± 0.11
	CSP # 8	6.98 ± 0.11
Bonding slurry	With slurry	6.32 ± 0.11
	Without slurry	6.58 ± 0.11
Substrate age	10 weeks	6.79 ± 0.11
	4 weeks	6.11 ± 0.11
Aggregate types	Limestone	6.84 ± 0.11
	Gravel	6.06 ± 0.11

Note: 1 MPa = 145 psi


Average Shear Bond Strength (MPa)
8.00
7.00
6.00
5.00
4.00
LMC
SFMC
FRC
SLMC
Overlay Mixture Types
(a)


Average Shear Bond Strength (MPa)
8.00
7.00
6.00
5.00
4.00
CSP #5
CSP #8
Surface Preparations
(b)


Average Shear Bond Strength (MPa)
8.00
7.00
6.00
5.00
4.00
with slurry
without slurry
Application of Slurry
(c)


Average Shear Bond Strength (MPa)
8.00
7.00
6.00
5.00
4.00
10 weeks
4 weeks
Substrate Age
(d)

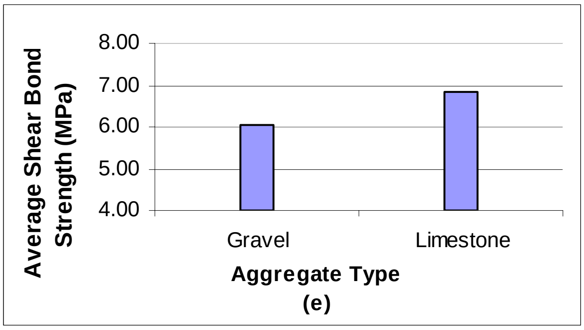


Fig. 6.1 Average Strength of Levels of Different Factors

The differences of shear bond strength between levels of the factors (which are called main effects) and the standard errors for them are listed in Table 6.11.

Table 6.11−Calculated Main Effects and Standard Errors

Related factors considered	**Main effects**	**Estimate ± standard error (MPa)**	**Main effects / average**
	Average	6.45 ± 0.08	
Overlay mixtures	$\sigma_{SFMC} - \sigma_{LMC}$	0.74 ± 0.23	11.5%
	$\sigma_{LMC} - \sigma_{FRC}$	0.36 ± 0.23	5.7%
	$\sigma_{LMC} - \sigma_{SLMC}$	0.59 ± 0.23	9.1%
	$\sigma_{SFMC} - \sigma_{FRC}$	1.11 ± 0.23	17.2%
	$\sigma_{SFMC} - \sigma_{SLMC}$	1.33 ± 0.23	20.7%
	$\sigma_{FRC} - \sigma_{SLMC}$	0.22 ± 0.23	3.5%
Surface preparation	$\sigma_{CSP\ \#8} - \sigma_{CSP\ \#5}$	1.05 ± 0.16	16.2%
Bonding slurry	$\sigma_{without} - \sigma_{With}$	0.25 ± 0.16	3.9%
Substrate age	$\sigma_{10w} - \sigma_{4w}$	0.67 ± 0.16	10.5%
Aggregate types	$\sigma_{Limestone} - \sigma_{Gravel}$	0.78 ± 0.16	12.1%

Note: 1 MPa = 145 psi

Results in Table 6.11 shows that all the overlay types have different effects on shear strengths though the magnitude of difference between any two overlays varied. Table

6.11 further shows that all the factors except the application of bonding slurry affected the interface strength significantly. Presence or absence of bonding slurry influenced the shear strength to a smaller extent.

6.2.4 Influence of Parameters on Shear Bond Strength

The result of main effects analysis matches those of ANOVA. The former is more direct and provides the quantitative difference between levels, while ANOVA can reflect the fact more representatively. Combining both the analyses, the following conclusions were made on the influence of various parameters on shear strength.

1. The effect of overlay types is significant. Among the overlay mixtures evaluated, SFMC had the highest strength, followed by LMC, FRC, and SLMC. The strength differences between SFMC and the others are relatively high, while the strength of FRC and SLMC are close to each other. Compared with findings of previous researchers (Spinkel 1988), the strength of LMC is relatively low, while still within the reasonable range. This might be due to different curing protocol in this study.
2. Surface preparation is one of the most important factors that affected the shear bond strength. This has been mentioned by many researchers (Suprenant 1988, Sprinkel 1997 and Gullum 2001). In this study, the surface preparation CSP # 8 exhibited 16.2% more strength than CSP #5.
3. Bonding slurry seemed to have little effect on the interface bond. In fact slurry lowered the bond strength slightly. The elimination of coarse aggregate in bonding slurry reduced interlocking with substrate surface which consequentially affected the strength.
4. In our study, the substrate ages also played an important role in shear bond strength. The specimens with the substrate age of 10 weeks had 10.5% more strength compared to those with the substrate age of 4 weeks. The reason for this was the maturity of substrate concrete. Substrate age of 10 weeks was more matured due to longer curing than substrate age of 4 weeks, thus had more strengths.

5. The types of coarse aggregates affected shear bond strength at a significant level (< 1% from ANOVA and 12.1% in main effects analysis) in which limestone performed better than gravel. These results agreed well with the report of Dewar (1964), who observed that the tensile splitting strength was about 8 percent higher for crushed-rock-aggregate concrete than for gravel-aggregate concrete.

6.2.5 Calculation of Parameters of Model

As stated in section 6.1.1.4, the parameters of model are calculated and presented in Table 6.12

Table 6.12−Parameters of Model

parameters	Corresponding considered factors	Parameters suffixes	Corresponding factor levels	Estimated value (MPa)
μ	--	--	--	6.45
$(\tau 1)_i$	Overlay mixture types	i = 1	LMC	0.05
		i = 2	SFMC	0.80
		i = 3	FRC	-0.31
		i = 4	SLMC	-0.54
$(\tau 2)_j$	Surface preparation	j = 1	CSP # 5	-0.52
		j = 2	CSP # 8	0.52
$(\tau 3)_k$	Bonding slurry	k = 1	With slurry	-0.13
		k = 2	Without slurry	0.13
$(\tau 4)_l$	Substrate age	l = 1	10 weeks	0.34
		l = 2	4 weeks	-0.34
$(\tau 5)_m$	Coarse aggregate types	m = 1	Gravel	-0.39
		m = 2	Limestone	0.39

Thus, the expected shear bond strength of specimens for other combinations of factors can be predicted by the following formula:

$$Y_{ijklm} = \mu + (\tau 1)_i + (\tau 2)_j + (\tau 3)_k + (\tau 4)_l + (\tau 5)_m$$

The values of parameters on the right hand side of above equation can be found from Table 6.12. From which the interface shear strength can be estimated for any combination of variables. For example, the highest shear bond strength can be achieved by SFMC with

#8 surface preparations, without bonding slurry, with for 10 weeks substrate age, and the limestone aggregate. Although it was not performed in this study, we can predict the expected value by using the above equation and values in Table 6.12.

$$
\begin{aligned}
Y_{max} &= \mu + (\tau 1)_2 + (\tau 2)_2 + (\tau 3)_2 + (\tau 4)_1 + (\tau 5)_2 \\
&= 6.45 + 0.80 + 0.52 + 0.13 + 0.34 + 0.39 \\
&= 8.63 \text{ MPa}
\end{aligned}
$$

While the lowest shear bond strength can be achieved by SLMC with #5 surface preparations, with bonding slurry, with for 4 weeks substrate age, and the gravel aggregate. The predicted value is:

$$
\begin{aligned}
Y_{min} &= \mu + (\tau 1)_4 + (\tau 2)_1 + (\tau 3)_1 + (\tau 4)_2 + (\tau 5)_1 \\
&= 6.45 - 0.54 - 0.52 - 0.13 - 0.34 - 0.39 \\
&= 4.53 \text{ MPa}
\end{aligned}
$$

We can see that for the factors we considered, the difference between two overlay systems with different materials and construction could be as great as 8.63 – 4.53 = 4.1 MPa.

Table 6.13 shows the predicted shear bond strength for all the combinations, among which, No. 4, 15, 22, 25, 37, 42, 51 and 64 were conducted in this study.

Table 6.13−Predicted shear bond strength for all the combinations

Runs	Overlay Types OT(4)	Surface Preparation SP(2)	Bonding Slurry AS(2)	Substrate Age SA(2)	Aggregate Type AT(2)	Predicted shear bond strength (MPa)
	OT1: SFMC **OT2:** LMC **OT3:** FRC **OT4:** SLMC	**SP1:** # 5 **SP2:** # 8	**AS1:** With Slurry **AS2:** Without Slurry	**SA1:** 4 Weeks **SA2:** 10 Weeks	**AT1:** Gravel **AT2:** Limestone	
1	OT1 (LMC)	SP1 (# 5)	BS1 (with)	SA1 (10 w)	AT1 (G)	5.80
2	OT2 (SFMC)	SP1 (# 5)	BS1 (with)	SA1 (10 w)	AT1 (G)	6.55
3	OT3 (FRC)	SP1 (# 5)	BS1 (with)	SA1 (10 w)	AT1 (G)	5.44
4	**OT4 (SLMC)**	**SP1 (# 5)**	**BS1 (with)**	**SA1 (10 w)**	**AT1 (G)**	**5.21**
5	OT1 (LMC)	SP2 (# 8)	BS1 (with)	SA1 (10 w)	AT1 (G)	6.84
6	OT2 (SFMC)	SP2 (# 8)	BS1 (with)	SA1 (10 w)	AT1 (G)	7.59
7	OT3 (FRC)	SP2 (# 8)	BS1 (with)	SA1 (10 w)	AT1 (G)	6.48
8	OT4 (SLMC)	SP2 (# 8)	BS1 (with)	SA1 (10 w)	AT1 (G)	6.25
9	OT1 (LMC)	SP1 (# 5)	BS2 (without)	SA1 (10 w)	AT1 (G)	6.06
10	OT2 (SFMC)	SP1 (# 5)	BS2 (without)	SA1 (10 w)	AT1 (G)	6.81
11	OT3 (FRC)	SP1 (# 5)	BS2 (without)	SA1 (10 w)	AT1 (G)	5.70
12	OT4 (SLMC)	SP1 (# 5)	BS2 (without)	SA1 (10 w)	AT1 (G)	5.47
13	OT1 (LMC)	SP2 (# 8)	BS2 (without)	SA1 (10 w)	AT1 (G)	7.10

14	OT2 (SFMC)	SP2 (# 8)	BS2 (without)	SA1 (10 w)	AT1 (G)	7.85
15	**OT3 (FRC)**	**SP2 (# 8)**	**BS2 (without)**	**SA1 (10 w)**	**AT1 (G)**	**6.74**
16	OT4 (SLMC)	SP2 (# 8)	BS2 (without)	SA1 (10 w)	AT1 (G)	6.51
17	OT1 (LMC)	SP1 (# 5)	BS1 (with)	SA2 (4 w)	AT1 (G)	5.12
18	OT2 (SFMC)	SP1 (# 5)	BS1 (with)	SA2 (4 w)	AT1 (G)	5.87
19	OT3 (FRC)	SP1 (# 5)	BS1 (with)	SA2 (4 w)	AT1 (G)	4.76
20	OT4 (SLMC)	SP1 (# 5)	BS1 (with)	SA2 (4 w)	AT1 (G)	4.53
21	OT1 (LMC)	SP2 (# 8)	BS1 (with)	SA2 (4 w)	AT1 (G)	6.16
22	**OT2 (SFMC)**	**SP2 (# 8)**	**BS1 (with)**	**SA2 (4 w)**	**AT1 (G)**	**6.91**
23	OT3 (FRC)	SP2 (# 8)	BS1 (with)	SA2 (4 w)	AT1 (G)	5.80
24	OT4 (SLMC)	SP2 (# 8)	BS1 (with)	SA2 (4 w)	AT1 (G)	5.57
25	**OT1 (LMC)**	**SP1 (# 5)**	**BS2 (without)**	**SA2 (4 w)**	**AT1 (G)**	**5.38**
26	OT2 (SFMC)	SP1 (# 5)	BS2 (without)	SA2 (4 w)	AT1 (G)	6.13
27	OT3 (FRC)	SP1 (# 5)	BS2 (without)	SA2 (4 w)	AT1 (G)	5.02
28	OT4 (SLMC)	SP1 (# 5)	BS2 (without)	SA2 (4 w)	AT1 (G)	4.79
29	OT1 (LMC)	SP2 (# 8)	BS2 (without)	SA2 (4 w)	AT1 (G)	6.42
30	OT2 (SFMC)	SP2 (# 8)	BS2 (without)	SA2 (4 w)	AT1 (G)	7.17
31	OT3 (FRC)	SP2 (# 8)	BS2 (without)	SA2 (4 w)	AT1 (G)	6.06
32	OT4 (SLMC)	SP2 (# 8)	BS2 (without)	SA2 (4 w)	AT1 (G)	5.83
33	OT1 (LMC)	SP1 (# 5)	BS1 (with)	SA1 (10 w)	AT2 (L)	6.58
34	OT2 (SFMC)	SP1 (# 5)	BS1 (with)	SA1 (10 w)	AT2 (L)	7.33
35	OT3 (FRC)	SP1 (# 5)	BS1 (with)	SA1 (10 w)	AT2 (L)	6.22
36	OT4 (SLMC)	SP1 (# 5)	BS1 (with)	SA1 (10 w)	AT2 (L)	5.99
37	**OT1 (LMC)**	**SP2 (# 8)**	**BS1 (with)**	**SA1 (10 w)**	**AT2 (L)**	**7.62**
38	OT2 (SFMC)	SP2 (# 8)	BS1 (with)	SA1 (10 w)	AT2 (L)	8.37
39	OT3 (FRC)	SP2 (# 8)	BS1 (with)	SA1 (10 w)	AT2 (L)	7.26
40	OT4 (SLMC)	SP2 (# 8)	BS1 (with)	SA1 (10 w)	AT2 (L)	7.03
41	OT1 (LMC)	SP1 (# 5)	BS2 (without)	SA1 (10 w)	AT2 (L)	6.84
42	**OT2 (SFMC)**	**SP1 (# 5)**	**BS2 (without)**	**SA1 (10 w)**	**AT2 (L)**	**7.59**
43	OT3 (FRC)	SP1 (# 5)	BS2 (without)	SA1 (10 w)	AT2 (L)	6.48
44	OT4 (SLMC)	SP1 (# 5)	BS2 (without)	SA1 (10 w)	AT2 (L)	6.25
45	OT1 (LMC)	SP2 (# 8)	BS2 (without)	SA1 (10 w)	AT2 (L)	7.88
46	OT2 (SFMC)	SP2 (# 8)	BS2 (without)	SA1 (10 w)	AT2 (L)	8.63
47	OT3 (FRC)	SP2 (# 8)	BS2 (without)	SA1 (10 w)	AT2 (L)	7.52
48	OT4 (SLMC)	SP2 (# 8)	BS2 (without)	SA1 (10 w)	AT2 (L)	7.29
49	OT1 (LMC)	SP1 (# 5)	BS1 (with)	SA2 (4 w)	AT2 (L)	5.90
50	OT2 (SFMC)	SP1 (# 5)	BS1 (with)	SA2 (4 w)	AT2 (L)	6.65
51	**OT3 (FRC)**	**SP1 (# 5)**	**BS1 (with)**	**SA2 (4 w)**	**AT2 (L)**	**5.54**
52	OT4 (SLMC)	SP1 (# 5)	BS1 (with)	SA2 (4 w)	AT2 (L)	5.31
53	OT1 (LMC)	SP2 (# 8)	BS1 (with)	SA2 (4 w)	AT2 (L)	6.94
54	OT2 (SFMC)	SP2 (# 8)	BS1 (with)	SA2 (4 w)	AT2 (L)	7.69
55	OT3 (FRC)	SP2 (# 8)	BS1 (with)	SA2 (4 w)	AT2 (L)	6.58
56	OT4 (SLMC)	SP2 (# 8)	BS1 (with)	SA2 (4 w)	AT2 (L)	6.35
57	OT1 (LMC)	SP1 (# 5)	BS2 (without)	SA2 (4 w)	AT2 (L)	6.16
58	OT2 (SFMC)	SP1 (# 5)	BS2 (without)	SA2 (4 w)	AT2 (L)	6.91
59	OT3 (FRC)	SP1 (# 5)	BS2 (without)	SA2 (4 w)	AT2 (L)	5.80
60	OT4 (SLMC)	SP1 (# 5)	BS2 (without)	SA2 (4 w)	AT2 (L)	5.57
61	OT1 (LMC)	SP2 (# 8)	BS2 (without)	SA2 (4 w)	AT2 (L)	7.20
62	OT2 (SFMC)	SP2 (# 8)	BS2 (without)	SA2 (4 w)	AT2 (L)	7.95
63	OT3 (FRC)	SP2 (# 8)	BS2 (without)	SA2 (4 w)	AT2 (L)	6.84
64	**OT4 (SLMC)**	**SP2 (# 8)**	**BS2 (without)**	**SA2 (4 w)**	**AT2 (L)**	**6.61**

CHAPTER 7

CONCLUSIONS

This chapter draws the conclusions on both material characterizations and interface evaluations. Based on the study, recommendations on future work are also presented.

7.1 Material Properties

From the test results discussed in Chapter 4, it is seen that overlay mixture with latex had largest slump and lowest air content. All the other overlay mixtures except SLMC had the similar air content and slump. The addition of slag might be the reason that SLMC had the lowest slump (90 mm). But it did not affect the air content much.

Among all the overlay mixtures evaluated, concrete modified by latex and/or silica fume had the highest compressive and flexural strength, followed by SLMC, MTMC, and FRC. According to manufacture's data sheet, the fiber used in this study had little influence on compressive and flexural strength. The current study agreed with this fact.

However, FRC had the highest modulus of elasticity in this study. It was possibly caused by the addition of steel fiber, which has much higher modulus of elasticity than concrete. Concrete modified by latex had the lowest modulus of elasticity. It can be concluded from this study that addition of cementitious materials such as silica fume, slag and metakaolin did not affect the modulus of elasticity of concrete at a significant level. Not much difference was observed among the Poisson's ratio values of different mixtures.

From the study of free shrinkage of all mixtures, it is seen that those mixtures with latex and SRA had much lower shrinkage compared to others. NC substrate had the highest shrinkage, which was expected due to the high w/cm ratio. Since NC substrate was allowed to cure for a period of 4 weeks longer than overlays, the differential shrinkage between substrate and overlays could be reduced.

From the comparison among overlay mixtures using limestone and gravel, it is seen that the mixtures with gravel had the lower compressive and flexural strength than mixtures with limestone. This may be due to the greater mechanical bond and larger aggregate mortar interfacial zone developed in case of angular limestone particles. It is also observed that for SFMC and LMC, mixtures with gravel had larger chloride permeability than mixtures with limestone, while this was not true for FRC and SLMC. Further study needs to be conducted to clearly know the effects of coarse aggregate types on the chloride permeability.

7.2 Interface Evaluations

The test result and discussion in Chapter 6 show that statistical design of experiment used this study was highly useful, which indicate that the design of experiment could be a potential tool for further study on issues about interface bond.

It is seen that overlay mixture types could affect bond strength significantly. SFMC had the highest bond strength to substrate, followed by LMC. The bond strengths of FRC and SLMC to substrate were close to each other, which were also lowest among all the four evaluated overlay mixtures.

Surface preparation was another very important factor that affected the bond strength significantly. Generally, the rougher and cleaner the surface is, the stronger the bond strength will be. In case of current study, substrates prepared according to CSP #8 achieved 16% more shear bond strength than substrates prepared according to CSP #5.

The analysis further shows that substrates with the age of 10 weeks had 10% more bond strength than substrates with the age of 4 weeks. This may be due to the fact that substrate with the age of 10 weeks age had higher strength than substrate with 4 weeks age as concrete matures with time.

It is shown in this study that the types of coarse aggregates in overlay mixtures also affected bond shear strength significantly. Overlay mixtures with limestone achieved 12.1% higher shear bond strength than those with gravel. The reason may be that limestone aggregate increased the mechanical bond at interface due to its angularity and with more improved interfacial zone.

Results show that the bond strength of the interface with slurry was a little lower than that of the interface without slurry. From current study, however, it is not possible to conclude whether slurry affected the interface strength. It may be suggested that use of bonding slurry is not a requirement for good bond of interface. Rather during overlay construction, instead of using bonding slurry, if a thin overlay (say 12.5 mm or 0.5 in.) is laid and compacted as first layer on the prepared substrate surface followed by final layer of overlay up to required thickness, the bond performance will be certainly better.

Table 7.1 lists the comparison of the test results of this study with the previous work. It can be assumed from the table that the shear strength depends not only on the materials and constructions, but also on the testing methods. Thus a standard test method of bond strength needs to be established for more comprehensive evaluation of overlay issues. The results of this shear test have shown the consistency and dependability. It may be reasonably concluded that this test method has the potential to be used as a standard test for shear bond strength evaluation for the purpose of screening and selection of overlays.

Table 7.1−Comparison of the test results of this study with the previous work

Researchers	Test Type	Bonding Strength (MPa)
Current Study	Butterfly specimen (Shear)	5.21 ~ 7.62
Luo (2002)	Butterfly specimen (Shear)	1.79 ~ 2.31
Dhir, 1984	Cylinder specimen (Shear)	0.41 ~ 2.83
Christensen, Sorenson and Radjy (1984)	Cylinder specimen (Shear)	10.3
Sprinkel (1988)	Guillotine shear	4
Shahrooz et al. (2000)	Guillotine test	5 ~ 7.5
	SHRP test	3.5

7.3 Recommendations for Future Work

The main emphasis of this research is shear bond strength, while there are many aspects which should be considered in future work to define the acceptance criteria of overlays. Further studies on durability of overlays and interface bond strengths are recommended. This may include: freeze-thaw and salt attack, temperature effect, moisture change, sulfate attack and alkali-aggregate reactions.

The definition of interface is not very clear. In this study, we consider the interface as a 3-D region, which a plate with the thickness of about 3 mm in the middle of the specimen. In the future work, this could be addressed in more details.

Interactions between factors were not considered in this study for the reason of simplification. For a more comprehensive study with more variables, some of the interactions between factors can be preselected and considered in the design of experiment. And also there is a necessity of checking the validity of predicted shear bond strength for the cases not tested by conducting tests on bi-layer specimens.

The shear bond strength obtained by this methods should be compared with the field data to be collected on cored specimens, and finally correlation are to be made between current laboratory tests and the samples collected from field.

REFERENCES

1. Abou-Zeid, M. N.; Meggers, D. and McCabe, S. L., "Influence of chloride permeability test parameters on results for silica fume and non-silica fume concrete", *Transportation Research Record*, n 1775, 2001, p 90-96.
2. Ali, M.; Kurihara, S. and Matsui, S., "Bonding shear strength at the interface between old and new concrete", *Technology Reports of the Osaka University*, v 48, n 2319-2337, Oct 15, 1998, p 237-246.
3. Babaei, K and Hawkins, N. M., "Performance of bridge deck concrete overlays", *ASTM Special Technical Publication*, n 1100, 1990, p 95-108.
4. Babaei, K. and Hawkins, N. M., "Performance of bridge deck concrete overlays", *ASTM Special Technical Publication*, n 1100, 1990, p 95-108.
5. Babaei, K. and Hawkins, M., "Performance of rehabilitated / protected concrete bridge decks", *ASTM Special Technical Publication*, n 1137, 1992, p 140-154.
6. Banthia, N.; Yan C. and Mindess S., "Restrained shrinkage cracking in fiber reinforced concrete: a novel test technique", *Cement and Concrete Research*, v 26, n 1, Jan, 1996, p 9-14.
7. Baun, M. D., "Steel fiber-reinforced concrete bridge deck overlays: experimental use by Ohio Department of Transportation", *Transportation Research Record*, n 1392, 1993, p 73-78.
8. Baun, M. D, "Ohio evaluates reinforced concrete deck overlays", *Better Roads*, v 63, n 5, May, 1993, p 16, 18-19.
9. Betterton, R. M.; Knutson, M. J. and Marks, V. J., "Fibrous Portland cement concrete overlay research in Greene county, Iowa", *Transportation Research Record*, n 1040, 1985, p 1-7.
10. Bishara, A. G.; Tose, J. D. and Youssef, M. A. R., "Shrinkage and creep characteristics of latex-modified concrete", *Journal of The American Concrete Institute*, v 75, n 5, May, 1978, p 204-208.
11. Buchanan, P. M.; Mokarem, D. W.; Weyers, R. E. and Sprinkel, M. M., "Shrinkage of latex-modified and micro silica concrete overlays", *Transportation Research Record*, n 1834, 03-3758, 2003, p 33-39.
12. Bunke, D., "ODOT experience with Silica-fume Concrete", *Transportation Research Record*, n 1204, 1988, p 27-35.
13. Box, G. E. P.; Hunter, W. G. and Hunter, J. S., *Statistics for Experimenters*, 1978.
14. Cady, P. D.; Weyers, R. E. and. Wilson, D. T., "Durability and compatibility of overlays and bridge deck substrate Treatment", *Concrete International: Design and Construction*, v 6, n 6, Jun, 1984, p 36-44.

15. Chanvillard, G.; Aitcin, P. -C. and Lupien, C., "Field evaluation of steel fiber reinforced concrete overlay with various bonding mechanisms", *Transportation Research Record*, n 1226, 1989, p 48-56.
16. Christensen, D. W.; Sorenson, E.V. and Radjy, F. F., "Rochbond: a new micro silica concrete bridge deck overlay material", *Engineers' Soc of Western Pennsylvania*, 1984, p 151-160.
17. Cremaschi, J, "Polymer concrete bridge overlays", *Concrete International: Design and Construction*, v 8, n 5, May, 1986, p 58-60.
18. Delatte Jr., N. J.; Wade, D. M. and Fowler, D. W., "Laboratory and field testing of concrete bond development for expedited bonded concrete overlays", *ACI Materials Journal*, v 97, n 3, May/June, 2000, p 272-280
19. Delatte, N. J.; Williamson, M. S. and Fowler, D. W., "Bond strength development with maturity of high-early-strength bonded concrete overlays", *ACI Materials Journal*, v 97, n 2, March/April, 2000, p 201-207.
20. Delatte, N. and Sehdev, A., "Mechanical properties and durability of bonded-concrete overlays and ultra thin white topping concrete", *Transportation Research Record*, n 1834, 2003, 03-2831, p 16-23.
21. Deming, B. M.; Aktan, H. and Usmen, M., "Test for polymer overlay interface on concrete", *Proceedings of the Materials Engineering Conference*, n 804, Oct, 1994, *Infrastructute: New Materials and Methods of Repair*, p 709-715.
22. Dewar, J. D., "The indirect tensile strength of concretes of high compressive strength," *Technical Report No. 42.377, Cement and concrete association, Wexham Springs,* Mar. 1964, p 12.
23. Dhir, M. P., "A study on the effect of temperature variations on the bonding of concrete overlays", *Journal of the American Concrete Institute*, v 81, n 2, Mar-Apr, 1984, p172-179.
24. Estrada, N. S., "Paving of roads and bridges with unsaturated polyesters", *25th annual technical conference, the society of plastics industry, Inc*., 1970, 20-F, 20p.
25. Fitch, M. G. and Abdulshafi O. A., "Field and laboratory evaluation of silica fume modified concrete bridge deck overlays in Ohio", *Transportation Research Record*, n 1610, Aug, 1998, p 20-27.
26. Fowler, D. W., "Polymers in concrete: a vision for the 21st century", *Cement and Concrete Composites*, v 21, n 5-6, Oct, 1999, p 449-452.
27. FWA, T. F. and Paramasivam, P., "Thin steel fiber cement mortar overlay for concrete pavement", *Cement & Concrete Composites*, v 12, n 3, 1990, p 175-184.
28. Gillum, A. J.; Shahrooz, B. M. and Cole, J. R., "Bond strength between sealed bridge decks

and concrete overlays", *ACI Structural Journal*, v 98, n 6, Nov/Dec, 2001, p 872-879.

29. Glauz, D. L., "A latex-modified concrete overlay on plain-jointed concrete pavement", *Cement Concrete and Aggregates*, v 17, n 2, Dec, 1995, p 201-204.
30. Granju, J. L., "Thin bonded overlays", *Advanced Cement Based Materials*, v 4, n 1, Jul, 1996, p 21-27.
31. Gruber, K. A.; Ramlochan, T.; Boddy, A.; Hooton, R. D. and Thomas, M. D. A., "Increasing concrete durability with high-reactivity metakaolin", *Cement and Concrete Composites*, v 23, n 6, December, 2001, p 479-484.
32. Halvorsen, G. T., "Bridge Deck Overlays", *Aberdeen's Concrete Construction*, v 38, n 6, Jun, 1993, p 415-419
33. Knab, L. and Spring C. B., "Evaluation of test methods for measuring the bond strength of Portland cement based repair materials to concrete", *Cement, Concrete and Aggregates*, v 11, n 1, summer, 1989, p 3-14.
34. Krstulovic-Opara, N.; Haghayeghi, A. R.; Haidar, M. and Krauss P. D., "Use of conventional and high-performance steel-fiber reinforced concrete for bridge deck overlays", *ACI Materials Journal*, v 92, n 6, Nov-Dec, 1995, p 669-677.
35. Kuhlmann, L. A., "Test method for measuring the bond strength of latex-modified concrete and mortar", *ACI Materials Journal (American Concrete Institute)*, v 87, n 4, Jul-Aug, 1990, p 387-394
36. Kuhlmann, L. A., "Cracks in latex-modified concrete overlays", *Transportation Research Record*, n 1301, 1991, p 17-21.
37. Kuhlmann, L. A, "Using styrene-butadiene latex as a modifier to concrete for bridge deck and parking garage overlays", *ASTM Special Technical Publication*, n 1176, 1993, p 125-140.
38. Lankard, D. R. and Walker, A. J., "Pavement applications for steel fibrous concrete", *ASCE, Transportation Engineering Journal*, v 101, n 1, Feb, 1975, p 137-153.
39. Luo, S., "Evaluations of Concrete Overlays for Bridge Deck Applications", 2002.
40. Mehta, P. K. and Gjory, O. E., "properties of Portland cement concrete containing fly ash and condensed silica-fume", *CEM CONCR RES*, V 12, N 5, Sep, 1982, p 587-595.
41. Mendis, P., "A polymer concrete overlay", *Concrete International: Design and Construction*, v 9, n 12, Dec, 1987, p 54-56.
42. Montgomery, D. C., *Design and Analysis of Experiments*, Third Edition, 1991.
43. Obuchowski, R. H., "Construction of Thin Bonded Concrete Overlay", *Transportation Research Record*, 1983, p 10-15.

44. O'Connor, D. N. and Saiidi, M., "Compatibility of polyester-styrene polymer concrete overlays with portland cement concrete bridge decks", *ACI Materials Journal*, v 90, n 1, Jan-Feb, 1993, p 59-68.
45. O'Connor, D. N. and Saiidi, "Polyester concrete for bridge deck overlays", *Concrete International: Design and Construction*, v 15, n 12, Dec, 1993, p 36-39.
46. O'Connor, D. N. and Saiidi, M, "Polyester concrete for bridge deck overlays", *Concrete International: Design and Construction*, v 15, n 12, Dec, 1993, p 36-39.
47. Ozyildirim, C., "Experimental installation of a concrete bridge-deck overlay containing silica fume", *Transportation Research Record*, n 1204, 1988, p 36-41.
48. Ozyildirim, C., "Laboratory investigation of concrete containing Silica fume for use in overlays", *ACI Materials Journal*, v 84, n 1, Jan-Feb, 1987, p 3-7.
49. Ozyildirim, C., "Laboratory investigation of low-permeability concretes containing slag and silica fume", *ACI Materials Journal*, v 91, n 2, Mar-Apr, 1994, p 197-202.
50. Ozyildirim, C.; Moen, C. and Hladky, S., "Investigation of fiber-reinforced concrete for use in transportation structures", *Transportation Research Record*, n 1574, Nov, 1996, p 63-70.
51. Paulsson, J. and Silfwerbran, D. J., "Durability of repaired bridge overlays", *Concrete International*, v 20, n 2, Feb, 1998, p 76-82.
52. Paulsson, J., "Service life prediction of concrete bridge decks repaired with bonded concrete overlays", *Materials and Structures/Materials et Constructions*, v 34, n 235, January/February, 2001, p 34-41.
53. Ramachandran, V.S., Concrete Admixtures Handbook - Properties, Science, and Technology (2nd Edition) © 1995.
54. Rebeiz, K.S.; Serhal, S.P. and Craft, A.P., "Properties of polymer concrete using fly ash", *Journal of Materials in Civil Engineering*, v 16, n 1, January/February, 2004, p 15-19.
55. Rostami, H.; Brendley, W., "Alkali ash material: a novel fly ash-based cement", *Environmental Science and Technology*, v 37, n 15, Aug 1, 2003, p 3454-3457.
56. Schrader, E. K. and Munch A. V., "Deck slab repaired by fibrous concrete overlay", *ASCE, Journal of the Construction Division*, v 102, n 1, Mar, 1976, p 179-196.
57. Shahrooz, B. M.; Gillum, A. J.; Cole, J. and Turer, A., "Bond characteristics of overlays placed over bridge decks sealed with high-molecular-weight methacrylate", *Transportation Research Record*, n 1697, 2000, p 24-30.
58. Shirazi, H. H.; Rasoulian, M. and King, B., "Design and construction of a bonded fiber concrete overlay of CRCP", *Proceedings of the Materials Engineering Conference*, v 2, *Materials for the New Millennium*, 1996, p 1647-1658.

59. Sprinkel, M. M., "Thin polymer concrete overlays for bridge deck protection", *Transportation Research Record*, v 1, 1984, p 193-201.
60. Sprinkel, M. M., "High early strength latex-modified concrete overlay", *Transportation Research Record*, n 1204, 1988, p 42-51.
61. Sprinkel, M. M., "Twenty-Year performance of latex-modified concrete overlays", *ASTM Special Technical Publication*, n 1176, 1993, p 141-154.
62. Sprinkel, M. M., "Preparing bridge deck for overlays", *Aberdeen's Concrete Repair Digest*, v 8, n 5, Oct-Nov, 1997, p 242-247
63. Sprinkel M. M. and Ozyildirim, C., "Shrinkage of high performance concrete overlays on route 60 in Virginia", *Transportation Research Record*, n 1610, Aug, 1998, p 15-19.
64. Sprinkel, M. M., "Very-early-strength latex-modified concrete overlay", *Transportation Research Record*, n 1668, Sep, 1999, p 18-23.
65. Steele, G. W. and Judy, J. M., "Polymer-modified concretes in bridge deck overlay systems", *ASTM Special Technical Publication*, n 629, 1977, p 110-115.
66. Strand D.; Macdonald, C.N.; Ramakrishnan V. and Rajpathak V. N., "Construction applications of polyolefin fiber reinforced concrete", *Proceedings of the Materials Engineering Conference*, v 1, *Materials for the New Millennium*, 1996, p 103-112.
67. Suprenant, B., "Bonding new concrete to old", *Concrete Construction*, v 33, n 7, Jul, 1988, p 676-680.
68. Tang, F. F., "Overlay for concrete segmental box-girder bridges", *Journal of Bridge Engineering*, v 5, n 4, Nov, 2000, p 311-321.
69. Walters, D. G., "Silica fume, latex-modified portland cement mortars and concretes", *Transportation Research Record*, n 1301, 1991, p 12-16.
70. Wells, J. A.; Stark, R. D. and Polyzois, D., "Getting better bond in concrete overlay", Concrete international, March, 1999.
71. Whiting, D. and Dziedzic W., "Chloride permeability of rigid concrete bridge deck overlays", *Transportation Research Record*, n 1234, 1989, p 24-29.