EVALUATION OF CONCRETE PERMEABILITY BY ULTRASONIC TESTING TECHNIQUES

Phase IV

Final Report

MDOT
Michigan Department of Transportation

WAYNE STATE UNIVERSITY

I. Ozgur Yaman
Graduate Student

Hakan Karaca
Graduate Student

Haluk Aktan
Professor

Department of Civil and Environmental Engineering
Wayne State University

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16. Abstract
The nondestructive test procedure for the quantification of bridge deck concrete's future durability is based on the fundamental relationship between ultrasonic pulse velocity (UPV) and permeability of an elastic medium. An experimental study using standard concrete cylindrical specimens (ASTM C192) documented adequate sensitivity between UPV and permeability. The test procedure utilizes a parameter directly proportional to increase in field concrete permeability and called paste quality loss (PQL). The PQL is computed from UPV measurements on standard concrete specimens made from field concrete mixture (ASTM C31) and measurements on field concrete. Deck replacement projects on three NHS bridges are used as demo sites to implement the test procedure. The respective 56-day PQLs are calculated as 15%, 28% and 9% demonstrating a significant variability in the permeability of the three bridge decks. Field permeability tests are also conducted by Figg's apparatus for comparison purposes. PQL evaluation from post construction measurements proved to be an effective and reliable means of testing the bridge deck's future durability.

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Phase IV Final Report

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Michigan Department of Transportation

by

I. Ozgur Yaman
Graduate Student

Hakan Karaca
Graduate Student

Haluk Aktan
Professor

Wayne State University

Detroit, Michigan

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EXECUTIVE SUMMARY

Phase 1

The objective of the research was the evaluation of concrete permeability from the measured ultrasonic pulse velocity (UPV). The research design was based on casting specimens with different porosity by varying the water cement (w/c) ratio and testing the specimens at an age of 28 days for permeability and UPV. The relationship between permeability and UPV was established based on the 28-day measurements and the statistical significance was shown. The permeability of the concrete was measured using AASHTO T: 277 "Rapid Test for Permeability to Chloride Ions" and AASHTO T: 259 "Chloride Ion Penetration". The UPV was measured from direct through transmission measurements using a pair of narrow band transducers with a fundamental frequency of 50 kHz. The research results also show a correlation between the two permeability measurement methods.

The long-term goal of this research track was to provide a measure for durability of concrete bridge decks. The purpose of the durability measure is to provide quantification for quality control and quality assurance specifications (QC/QA). The purpose of QC/QA specifications is to include the performance of the constructed system as a parameter. Specifically, the value of the constructed system will be based on its service life expectancy and its life cycle cost as well as the initial cost.

The research goal was achieved by meeting the following objectives:

1. Document the existence of a significant relationship between permeability and UPV for the ranges of permeability and materials (coarse and fine aggregate, cement, admixtures) used for bridge decks.
2. Develop a procedure for field measurement for UPV and the base line relationship between permeability and UPV.
3. Develop an acceptance criterion for concrete permeability.
4. Develop a permeability-based life cycle cost model for concrete bridge decks.

The research described here responds to part of the issues described under the first objective. In this study the specimens consisted of concrete materials typically used by Michigan Department of Transportation (MDOT), except that air entraining agents and admixtures are not incorporated. Thus, the single variable in this study is the w/c ratios, which are 0.35, 0.40, 0.45, 0.50 and 0.55.

The research results present full documentation of concrete properties including strength, elasticity modulus, Poisson's ratio and density. The specimens for each different w/c ratio are tested for chloride permeability and UPV is measured. Calibration and measurement procedure is developed for UPV, which complements the ASTM C 597-83 "Standard Test Method for Pulse Velocity through Concrete".

The data obtained in this phase shows a clear relationship between UPV and concrete permeability. However, the concrete material used in this phase did not truly reflect Grade D concrete, since some w/c ratio is out of specification and since admixtures are not used.

The measured UPV range was from 15200 ft/sec for the highest w/c ratio of 0.55 to 16400 ft/sec for the lowest w/c ratio of 0.35 or an increase of 13%. A correlation coefficient of 0.95 was computed for a linear relationship between w/c ratio and UPV. A relationship between w/c ratio and permeability is developed. The rapid chloride permeability values were between 2540 coulombs and 8700 coulombs with increasing w/c ratio. The combined relationship between permeability and UPV was obtained with a linear regression yielding a correlation coefficient of 0.95.

The research plan described under the topic of use of UPV for estimation of concrete permeability will have two more phases for a total of three. The next two phases will deal with finalizing the UPV vs. permeability relationship inclusive of entrained air and admixtures and development of UPV field measurement procedure. In the second phase, the effect of entrained air and water reducing and superplasticizing (chemical) admixtures on UPV and/or permeability was investigated. During this phase concrete mix proportion and materials were the same of those used in phase one, except that air entraining, and necessary plasticizing admixtures will be added. The second phase also included UPV measurement procedure development. For this purpose large-scale (4.5 ft. by 3 ft) reinforced and nonreinforced specimens representative of portions of bridge decks were cast. Various UPV measurement techniques were tested and difficulties were identified using the large-scale deck specimens.

In the third phase, some of the field implementation issues were addressed and a prototype field UPV measurement system was manufactured. In this last phase a significant task was the development and implementation of the procedure during current deck replacement projects. Large-scale bridge deck specimens were cast and cured under various conditions to simulate inferior concrete properties. The durability was tested using UPV measurements. Trial implementation of the procedure was also conducted in the field using current bridge deck replacement property.

Phase 2

Earlier work on this topic consisted of casting concrete specimens with different porosity by varying the water-cement ratio and testing the specimens at an age of 28 days for permeability and UPV. The research results defined a statistically significant relationship between permeability and UPV.

This phase had the following three distinct objectives:

1. Document the effect of entrained air on the relationship between UPV and permeability.
2. Document effect of aggregate porosity on UPV.
3. Develop a field UPV measurement procedure for bridge decks.

In order to fulfill the first objective standard cylinder specimens were made from air entrained concrete with chemical admixtures. Water-cement ratio and the amount of entrained air were varied. The research results established a relationship with high statistical significance between permeability and UPV in terms of amount of entrained air. The permeability was measured using AASHTO T: 277 "Rapid Test for Permeability in Chloride Ions," direct measurement of gas permeability, and ASTM C642 "Standard Test Method for Specific Gravity, Absorption, and Voids in Hardened Concrete." The results show approximately 25 m/s decrease in UPV for each 1% of entrained air. Additionally, the use of superplasticizer admixture reduced the UPV by approximately 5%. The UPV measurement range was from a high of 15616.8 ft/s for 0.35 water-cement ratio with no air-entraining admixture to a low of 13385.8 ft/s for a water-cement ratio of 0.50 with 5% entrained air. The corresponding permeable voids were between 7.4% and 15.1 %.

To fulfill the second objective, concrete specimens were made using a coarse aggregate having an absorption in excess of 3%. The results show a 10% decrease in measured UPV from comparable specimens made with coarse aggregate with absorption less than 1.5%.

To fulfill the third objective, lab deck specimens of size 4.5 ft. by 3 ft. and 12 inches thick were cast representing portions of bridge decks. A UPV measurement procedure was developed for the arrangement when both receiver and pulser transducers are placed on the deck surface. The procedure includes recommendations for transducer spacing, number of measurements, effect of reinforcement on UPV and the influence of surface texturing on UPV.

It should be reiterated that the long-term goal of this research is to provide a measure for early age durability assessment of concrete bridge decks. The durability measure is defined as the measured providing the quantification of concrete permeability at an early age. The purpose is for incorporating durability as a performance measure. Currently, the use of permeability as a performance measure is being experimented with High Performance Concrete (HPC) bridge deck material in several states such as Virginia and Texas. In these states permeability is measured on standard specimen using RCPT procedure. The permeability measurement procedure based on UPV measurements will improve the implementations by allowing the permeability to be directly measured from the deck rather that from standard specimens.

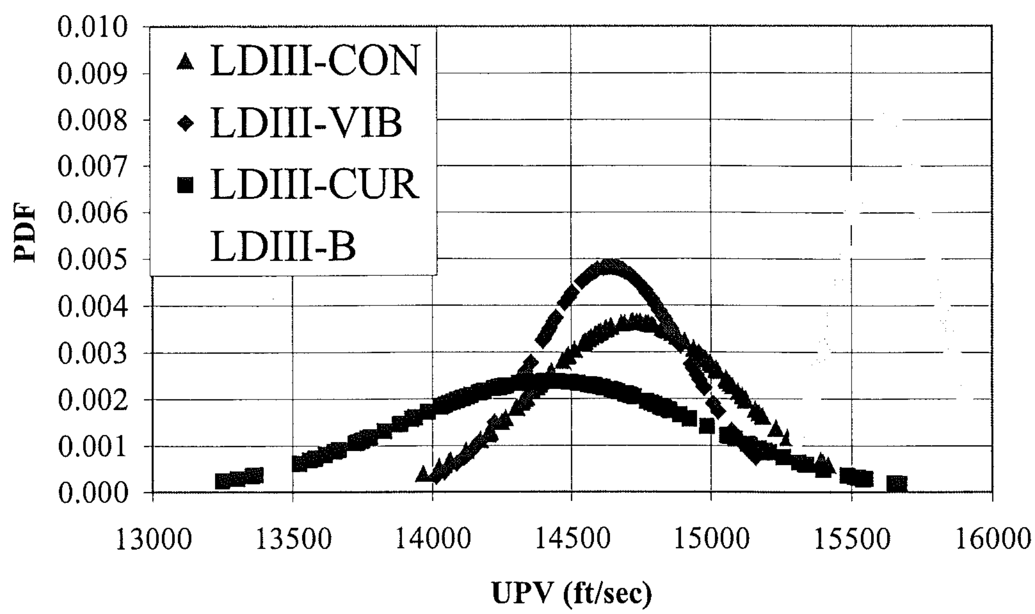
Phase 3

The methods and procedures developed during this research are specifically calibrated for concrete bridge deck durability assessment starting at an early age. Potential uses for these techniques are, first in the QC/QA specifications Level II as defined by FHWA as measurement of performance parameters from the constructed facilities and, second in timing the positive maintenance interventions for intelligent health monitoring.

The primary early finding in this phase was the quantification of concrete soundness using a relationship defined as the "Paste Quality Loss", (PQL). Soundness is defined as the deck permeability smeared measurement on the deck surface. The PQL relationship utilizes the ultrasonic pulse velocity measured on standard specimens and the ultrasonic pulse velocity measured on field concrete. The PQL gives in percent the loss of concrete soundness compared to standard specimens that were cured in ideal conditions.

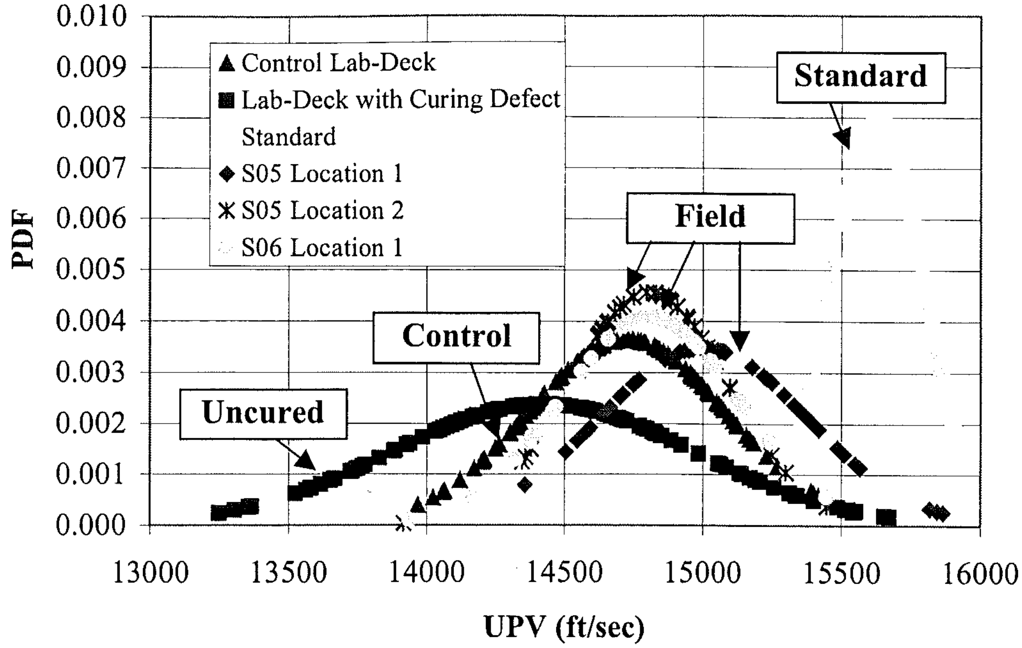
In this phase the sensitivity to the appraisal of UPV and the PQL relationships for unsound bridge deck concrete was tested. Samples of unsound concrete were obtained by deliberately avoiding proper curing practices and over-consolidation by excessively vibrating the concrete during casting. The samples were large portions of typical bridge decks and manufactured in the laboratory. Additional samples as control specimens were cast and cured according to specifications. The level of durability loss of the unsound concrete is established using various permeability tests. For example, the RCPT values measured on core specimens of over-consolidated decks were 8100 Coulombs and uncured decks were 10000 Coulombs whereas the control specimens were 7250 Coulombs. The RCPT obtained from moist cured standard cylinder specimens were 5900 Coulombs (RCPT values are elevated perhaps due to the use of chemical admixtures.) Similar results were obtained from the other permeability tests.

The use of UPV in the appraisal of concrete soundness is demonstrated by plotting all 90-day UPV measurements against its probability density function (PDF) and shown below. Where: LDIII-CON is the control lab-deck, LDIII-VIB is the over consolidated lab-deck, LDIII-CUR is the uncured lab-deck, and LDIII-B are the standard cylinder specimens.



The flat and wide UPV distribution obtained on the uncured deck is typical of concrete less sound than UPV distribution obtained on the control deck, which is tall and narrow. The UPV distribution obtained on moist cured standard cylinder specimens is the example of soundness benchmark. In the quantification of soundness, PQL is defined as the change of field concrete from the UPV distribution relation obtained from standard cylinder specimens.

The UPV measurements were also performed on two four-year-old bridge decks. Visual inspection indicated that aside from minor cracking decks appear to be sound. The measurements in comparison to the laboratory deck tests are shown below in a similar relationship with measured UPV against its PDF.



The PQL procedures developed in this study are ready for use in further field studies. The use of the procedures in QC/QA will require significantly more testing with establishing the relationship between PQL and deck performance. During the testing period the PQL data can be used as a feedback procedure in appraising the practices used in casting and curing bridge decks.

Phase 4

This phase of the research deals with the field implementation procedure for the assessment of concrete permeability from ultrasonic pulse velocity measurements. The methods and procedures developed during this research that defined the relationship between UPV and soundness (permeability) of field concrete are applied to actual bridge decks for concrete bridge deck durability assessment at an early age.

In this phase, deck replacement projects were used in the implementation of concrete soundness assessment by PQL (paste quality loss) evaluation. The three bridges and the measured respective 56-day PQL's are as follows:

Bridge	PQL (%)
S04-82062	15
S17-82112	31
S26-82251	9

The PQL is a quantitative measure comparing the permeability of the concrete mixture to the field permeability. The PQL measure shows the aggregate of all factors adversely affecting concrete permeability between the time concrete delivered to site up until the final UPV measurements at 56 days of age of the bridge deck.

Our earlier goal was to develop the PQL relation suitable for use in "Performance Related Specifications". Further research and literature review demonstrated that this is not possible because the change in PQL cannot be narrowed down to a single distress and the change is not necessarily under contractor's control. The PQL value is affected by concrete placement, consolidation, curing, the structural system, materials, and most importantly the structural design and detailing. However, the PQL parameter is a powerful research tool for evaluating field procedures and changes to those field procedures. An example is establishing curing procedures for cure sensitive overlays containing silica fume and/or fly ash.

The research developed the following relationship between concrete permeability and ultrasonic pulse velocity:

$$k = \gamma \frac{\Delta V}{V_{lo}}$$

where

k : Intrinsic permeability
V_{lo} : UPV at zero porosity
ΔV : Decrease in UPV from V_{lo}
γ : Concrete mixture constant

This relationship gives the change in permeability in relation to a baseline permeability. The difficulty in using this equation in the past was due to a lack of baseline UPV for concrete. Unlike steel, where UPV is constant for all grades, UPV in concrete is affected by all mixture parameters such as coarse and fine aggregate contents and properties, w/c, air content, and moisture state. Thus field measurements of UPV are not useful unless its change from the baseline is known.

The initial impact of this research was first the development of a procedure for establishing a baseline UPV. This procedure established the baseline UPV from the measurements made on "standard specimens". "Standard specimens" were those prepared in the field from the concrete delivered to site. The standard specimens were kept in the lab in an ideal curing environment for 28 days. Knowing that the mixture parameter in the equation will remain constant between the standard specimens and field concrete, the ratio of change in UPV to baseline UPV is described as the paste quality loss (PQL). As described in the equation the PQL parameter is proportional to the change in permeability between standard specimens and field concrete.

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The opinions presented here are of the authors and do not necessarily represent the views of the Michigan Department of Transportation.

1.0. INTRODUCTION

1.1. Overview

This report describes the fourth and final phase of a research program on the development of non-destructive permeability measurement procedure using ultrasonic pulse velocity (UPV) during early age of concrete. In the first and second phases strong relationships between pulse velocity (UPV) and permeability were obtained for normal concrete. In these phases, concrete permeability was varied by changes in w/c ratio. The UPV-permeability relations developed were based on 28-day tests on moist cured standard cylinder specimens. Additionally, in the second phase, large concrete specimens that are representative of reinforced concrete bridge decks were cast and used for developing the field UPV measurement procedure. In the third phase, six lab-deck concrete specimens were cast using Grade D concrete as specified by MDOT simulating different field defects. The lab-decks were cast and cured deliberately with nonstandard procedures that will affect their soundness. The soundness of lab-deck concrete was quantified using the "Paste Quality Loss", (PQL) relationship.

The goal of this research study is to develop a rapid non-destructive concrete permeability test method for assessing the soundness of new concrete. The proposed test procedure is based on ultrasonic pulse velocity (UPV) methods. Specific objective of this phase was to apply the findings of the last three phases on actual field bridge decks.

1.2. Summary of Phase I

In phase one, a survey of selected literature culminated in a hypothesis that became the focal point of this study. That hypothesis was that UPV and permeability is related through the pore structure of the concrete. To test this hypothesis, an experimental program was designed in which UPV and permeability tests were conducted on concrete specimens.

Varying the w/c ratio and keeping all other ingredients constant resulted in concrete with changing permeability. Five groups of specimens were made from w/c ratio between 0.35 and 0.55 increasing by 0.05. Specimens were moist cured and the change in porosity was primarily due to increasing amount of water used in the mixture. Permeability and UPV tests were performed on five groups of concrete specimens obtained by varying the w/c ratio at 28- and 90-days. The data collected includes those of compressive strength, elastic properties, UPV, RCPT, and Chloride Infiltration (CIP) tests. For each w/c ratio UPV measurements were made on sixteen specimens. For each specimen, four UPV measurements were performed in order to evaluate equipment and procedure related variability. For example, UPV measurements for the group of specimens with w/c ratio of 0.45 showed the equipment and procedure related variability as 0.25 percent, while the variability across the 16 specimens as 1.83 percent. This gives a variability of UPV measurements for the specimen groups under 2 percent (calculated by the root mean square of the two error terms). The UPV-Permeability data showed that UPV decreases with increasing w/c ratio. Measured UPV values show sufficient resolution to detect relative differences in the characteristics of the concrete microstructure within this range of w/c ratio. On the basis of statistical analysis of experiment results, it is concluded that there is a stable and measurable relationship between UPV and RCPT measured at 28- days. The relationship between UPV and RCPT is given by the following equation:

$$K=2000+5(16400-V_l) \tag{1}$$

where,

K : Charge passed (coulombs)

V_l : UPV (ft/s)

The relationship with RCPT was verified for UPV values between 15100 ft/s and 16400 ft/s. The form of the above regression equation is chosen to reflect typical values of RCPT and UPV, measured in low permeability concrete. In this equation, the RCPT test value of 2000 coulombs is the upper bound of the charge that would pass through a low permeability concrete, while a UPV of 16400 ft/s, is typical of low permeability concrete specimens of this study made and cured by standard procedures.

1.3. Summary of Phase II

The second phase objectives were two fold. The first objective was the evaluation of the effects of entrained air, chemical admixtures, and aggregate type on UPV and permeability. The second objective was the development of a field UPV measurement procedure.

The entrained air and chemical admixture effects on UPV were evaluated by varying the water-cement (w/c) ratio with chemical air entraining admixtures to produce concrete materials of air entrainment between 5% to 9%. Standard specimens were made from fifteen mix variations corresponding to w/c ratios of 0.35, 0.40, 0.45, 0.50, and chemically induced target air entrainment of none, 5%, and 9%. The mix design was the Grade D specified by the Michigan Department of Transportation and commonly used for bridge decks. The permeability was measured using several methods: AASHTO T: 277 "Rapid Test for Permeability to Chloride Ions", direct measurement of gas permeability, and measurement of permeable voids from ASTM C642 "Standard Test Method for Specific Gravity, Absorption, and Voids in Hardened Concrete".

A multiple regression equation between the 28-day UPV measured 8-inch standard cylinder specimens, 28-day porosity, and entrained air data is shown below:

$$V_l = 5104 - 24.0 \text{ (Air Content)} - 24.5 \text{ (Porosity)} \qquad (2)$$

In this relation, porosity is the as volume of permeable voids. A coefficient of determination of 0.80 was computed for this regression equation where UPV is reduced from a reference value of 16750 ft/s for each percentage of entrained air and porosity. Total volumes of voids (entrained air and open porosity) in these specimens were between 9.4% and 21.1%.

Another objective of the second phase was the development of UPV measurement procedures. In developing these procedures a practical and efficient transducer arrangement was determined on the surface of concrete deck for measuring UPV. Transducer arrangements were established by comparing UPV measurements obtained from indirect and direct transducer arrangements. Adequacy of transducer contact on the concrete surface was also evaluated using the lab-deck specimens.

The transducer arrangement for the indirect UPV measurement was similar to a scanning procedure of the surface concrete along an axis. The scanning procedure refers to a measurement technique where the transmitting transducer is at a fixed position and the receiving transducer is gradually moved away with each measurement. The indirect UPV is computed from the slope of the wave transit time versus spacing between transmitting and receiving transducers. Indirect UPV measured on the two lab-deck specimens was 14862 ft/s and 14829 ft/s with a COV of 1.01% and 1.13% versus a direct velocity of 14717 ft/s. Statistical analysis demonstrated that indirect and direct velocities measured on the lab-deck specimens were equivalent. The minimum number of receiving transducer locations in measuring indirect UPV (to improve the speed of UPV testing) was investigated. Four receiver transducer locations starting with an initial separation of 8 inches from the pulser with distances increasing at 2 inch increments was determined to be a reliable transducer arrangement.

1.4. Summary of Phase III

The phase three objectives were to investigate the effects of two field quality problems, namely poor compaction and substandard curing on UPV, and to develop a field UPV measurement system. Accordingly, 6 lab-deck specimens were prepared which have the dimensions of 60 x 40 x 9 inch. Additionally, 32 standard cylindrical specimens of dimensions 4 x 8 inch, and 36 standard cylindrical specimens of dimensions 6 x 12 inches were prepared. Concrete lab-decks specimens were cast. In two of the lab-deck specimens proper curing practices were avoided, and in another two specimens were purposely over-consolidated by excessively vibrating the concrete during casting. The assumption was to increase permeability by using a nonstandard procedure during placement and curing. Two lab-decks were made as control specimens. The control specimens were moist cured for seven days by wrapping in burlap and covering with a plastic sheet.

The durability lost by nonstandard curing and over-consolidation was measured using various permeability tests. For example, the RCPT performed on core specimens of over-consolidated decks and uncured decks gave values of 8100 coulombs and 10000 coulombs, respectively. The RCPT performed on the control specimens gave a value of 7250 coulombs, and the RCPT performed on the standard cylinder specimens gave a value of 5900 coulombs (RCPT readings are assumed elevated uniformly across all specimens perhaps due to the use of chemical admixtures, as documented in the literature.) Results were consistent with the gas permeability and permeable void volume measurements. Permeability of the bridge decks measured on a large segment is defined as soundness. With the loss of soundness, permeability of the deck is increased. The soundness of concrete is quantified using a relationship defined as the "Paste Quality Loss", (PQL). The PQL relationship utilizes the ultrasonic pulse velocity measured on moist cured standard specimens and the ultrasonic pulse velocity measured on field concrete. The PQL gives the relative loss of concrete soundness compared to standard specimens.

As for the second objective, field UPV measurements were performed on two 4-year-old bridge decks. Visual inspection indicated minor cracking on deck surface otherwise they appeared to be sound. The field test setup encountered minor problems. The minor problems were resolved in the field, and field-testing demonstrated that rapid field UPV measurements are feasible.

1.5. Summary of Phase IV

The field implementation of evaluation of concrete soundness using UPV was conducted. The field implementation consisted of implementing the paste efficiency principle procedure on four bridge deck replacement projects. On the bridge decks UPV measurements were performed at 14, 28 and 56 days following concrete placement. Figg gas and water permeability tests were performed on 28 and 56 days. Standard 4 x 8 in.

and 6 x 12 in. cylindrical specimens were prepared during deck casting and were used to document lab specimen properties.

The field implementation objectives are:

- Refine the implementation of the "Paste Efficiency Principle"
- Document and compare the "Paste Quality Loss (PQL)" obtained from the lab (Phase III) and field implementation study
- Evaluate the feasibility of using PQL as a feedback parameter in assessing the factors influencing concrete deck durability
- Test rapid measurement procedures using the field UPV measurement system

Work tasks for this research did consisted of:

- Selecting bridge decks for testing
- Preparing standard cylinder specimens during casting
- Perform strength, mechanical property, UPV, RCPT and other permeability tests (porosity, Figg) on standard specimens
- Conduct 14-, 28-, and 56-day field UPV measurements
- Conduct 28- and 56-day field Figg tests
- Prepare reports

A total of 36 large (6 x 12 in.) and 32 small (4 x 8 in.) specimens were fabricated during each deck concrete placement project. Large specimens were used for strength, elasticity modulus and Figg's tests. Small specimens were used for UPV measurements and permeability tests.

2.0. LITERATURE REVIEW

2.1. Performance Related Durability Specifications

Literature indicates that concrete durability is one of the performance parameter being emphasized for use in Performance Related Specification (PRS). Current implementations of PRS are reportedly used for high performance concrete (HPC) on Federal Highway Administration (FHWA) "showcase" projects. Common performance parameters and measures utilized in the HPC PRS are listed in Table 1 (Goodspeed et al. 1996).

Table 1. Common Performance Measures

Performance Parameter	Performance Measure	Standard Test Method
Durability	Freeze-thaw durability	AASHTO T 161 ASTM C 666
	Scaling resistance	ASTM C 672
	Abrasion resistance	ASTM C 944
	Chloride Ion penetration	AASHTO T 277 ASTM C 1202
Strength	Compressive strength	AASHTO T 2 ASTM C 39
	Elasticity	ASTM C 469
	Shrinkage	ASTM C 157
	Creep	ASTM C 512

In Table 1, concrete durability is characterized by its ability to resist penetration of chloride ions. Some of the most commonly used laboratory test methods for determining concrete permeability include hydraulic permeability, air or gas permeability, capillary suction, CIP and RCPT (Kropp 1995). Common on site test methods includes capillary suction, initial surface absorption test, Figg test, etc. A careful review of test procedures, specimens, and variability of results indicate that most are not suitable as acceptance tests of cast in place concrete structures such as bridge decks. In the current implementation of performance based specifications only RCPT and CIP are used for establishing concrete permeability. In the current implementations of performance-related specifications are strictly for material acceptance purposes. The field performance of concrete is assumed to be controlled by placement and curing specifications.

In moving towards full implementation of performance-related specifications the FHWA proposed a two level approach (FHWA 1997). Level I consists of the utilization of current acceptance tests by the State Highway Agencies. Level II consists of developing and implementing in-situ acceptance testing. The Level I permeability procedures employed by various state departments of transportations in PRS for defining high performance concrete durability is summarized below:

- The Virginia Department of Transportation (VDOT) uses permeability provisions for bridge concrete (Ozyildirim 1999). This special provision uses AASHTO T 277 or ASTM C 1202 as the standard test procedure for permeability. In this provision, specimens prepared in a standard fashion are tested at 28 days after moist curing for one week at room temperature followed by three weeks of curing at 38 °C. Acceptance criteria for concrete material is 1500 coulombs or less for prestressed, 2500 coulombs or less for the deck, and 3500 coulombs or less for the substructure.
- The New Hampshire Department of Transportation (NHDOT) requirements include strength and durability as performance parameters (Waszczuk and Juliano 1999). The durability characteristic of high performance concrete is permeability as measured by RCPT testing using the AASHTO T 277 method. Acceptance requires a maximum chloride permeability of 1000 coulombs at 56 days.
- The Texas Department of Transportation (TxDOT) also uses durability specifications for bridge concrete acceptance (Ralls 1999). The current durability

specification for bridge deck requires a maximum of 2000 coulombs measured using the RCPT at a specimen age of 28 days, with 5 to 7 percent in situ total air content.

- The Nebraska Department of Roads (NDOR) uses durability provisions for the acceptance of bridge deck concrete (Beacham 1999). A chloride ion permeability of 1800 coulombs by the RCPT at a specimen age of 56 days, or 1900 coulombs at an age of 28 days is required for acceptance.
- Florida Department of Transportation (FDOT) initiated a research program to develop durability specifications and a rating system for concrete mixtures and structures (Armaghani and Bloomquist 1992). The research goals were to develop durability specification for concrete mixtures based on strength and permeability as performance characteristics and to devise performance grades for concrete structures.

The properties that control concrete permeability and those that control ultrasonic pulse velocity (UPV) of concrete have both been the subjects of extensive research. Review of those articles shows a link between permeability and UPV, as both parameters are largely dependent on the pore structure of the concrete material (Udegbunam et al. 1999). The approach used to develop the relationship between permeability and UPV is to establish the theoretical relationship and to conduct a parametric experimental study to verify and calibrate the theoretical relationship.

In implementing the permeability measurement procedure to field concrete British Standards, BS 4408, Part 5 "The condition assessment for field concrete using UPV" (Tomsett 1980) was adopted. The BS 4408 standard contains six uses for UPV in relationship to concrete properties or defects; one of which is the estimation of concrete quality in relation to a standard quality. The field concrete quality is estimated by measuring the reduction in UPV for field concrete from specimens prepared using the ingredients of the field concrete but cured in a standard manner. For the permeability measurement procedure, the reduction in UPV measured in the field represents the increase in permeability. The procedure is described as the "principle of paste efficiency". Using the concept of "paste efficiency" the hypothesis of this investigation is that the change in permeability is proportional to the decrease in UPV. The decrease in

UPV in ratio to the UPV measured from standard specimens is described as "paste quality loss".

The use of UPV in concrete acceptance specifications was also proposed for strength assessment (Phoon et al. 1999). Phoon presented a probabilistic model to predict compressive strength from UPV using linear regression analysis (Phoon et al. (1999). In the proposed approach the first step was to determine an empirical relationship between UPV and strength from either representative core samples, or standard compressive strength specimens. Using the UPV data of the concrete section in question and an acceptable probability of exceedance, the characteristic strength corresponding to the measured UPV can be determined. The proposed statistical quality assurance criterion was shown to be an extension of the characteristic strength concept that is widely used in practice.

2.2. The Concerns and Need for Durable Bridge Deck Concrete

According to ACI Committee 201, the durability of concrete is considered as its ability to resist weathering action, chemical attack, abrasion or other processes of deterioration. In other words, durable concrete will retain its form (integrity), quality, and serviceability when exposed to its environment. If subjected to attacks from aggressive elements in the environment, concrete microstructure is adversely affected, and the concrete quality progressively deteriorates. The deterioration processes for reinforced concrete can be broadly classified into three categories: physical deterioration, chemical deterioration, and reinforcement corrosion. These physical and chemical deterioration can be as a result of the interaction of the member with the environment, as well as interaction of the material constituents, like alkali silica reaction.

According to a cooperative study sponsored by the Portland Cement Association with the cooperation from the Bureau of Public Roads and ten state highway departments (California, Illinois, Kansas, Michigan, Minnesota, Missouri, New Jersey, Ohio, Texas, Virginia), common defects include scaling, cracking, and surface spalling. Except for Kansas and Missouri, surveys were made in eight states on a large number of bridge decks. Scaling is the disintegration that occurs on a concrete surface exposed to freeze-thaw cycles. It is reported that scaling is produced with de-icing agents with specific chemical compositions. Even though scaling was encountered in all of the surveyed states, Texas and Virginia ranked highest. Transverse cracking of the deck was the mostly observed defect type. The spalling of the deck surface was described as the most serious and troublesome kind of bridge deck distress. Surface spalling is defined as the separation and removal of relatively large concrete segments from the deck surface area.

Poston presented the forms of distress and deterioration and the typical causes (Poston et al. 1995). Among the seven distress types, cracking, scaling, and spalling were listed as distresses that are typically controlled by concrete permeability. Mehta (1997) listed the principle causes of deterioration of concrete structures in decreasing order of importance as: corrosion of reinforcing steel, exposure to freezing and thawing, alkali-silica reaction, and sulfate attack. These four deterioration mechanisms are also controlled by concrete permeability. Thus, it is surmised that durability is improved by using low permeability concrete.

3.0. EXPERIMENTAL INVESTIGATION – FIELD APPLICATION

3.1. Overview

The field implementation consists of execution of the paste efficiency principle on four bridge decks, which were called the "test-decks". UPV measurements were performed on the test-decks at 14, 28,and 56 days following field concrete placement. Figg's air and water permeability tests were performed at 28- and 56-days on the test-decks. Standard 4 in. and 6 in. cylindrical specimens were fabricated during deck placement to establish the concrete properties.

The four bridges with scheduled deck replacement were selected based on the project schedule and their proximity to Wayne State University. However, due to traffic control concerns of B2 (Table 2), field-testing couldn't be completed and subsequently an alternate bridge was selected. Table 2 below shows the list of the bridges selected, their locations and the deck concrete placement dates.

Table 2. Test-Deck Location and Pouring Dates

WSU Bridge ID	MDOT Bridge Number	Location	Deck Placement Date
B1	S04-82062	Scotten St. over Michigan Ave.	July 24, 2000
B2	S03-82024	Woodward Ave. over I-94	August 4, 2000
B3	S17-82112	Oakman Ave. over Lodge Fwy (M-10)	August 11, 2000
B4	S26-82251	I-75 NBD to I-94 EBD	September 8, 2000
B5	S26-82251	I-75 NBD to I-94 EBD	September 14, 2000

The experiments planned on the test decks and on the standard specimens are tabulated in Table 3. At each bridge 32 small (4 x 8 in.) and 39 large (6 x 12 in.) cylinder specimens were fabricated for tests of strength, modulus of elasticity and Poisson's ratio, UPV, RCPT, absorption, gas permeability, and Figg's permeability. The UPV and Figg's permeability testing were conducted at four different locations on each deck surface. Four Figg's permeability tests and sixty UPV measurements were performed at each of these locations. The project schedule is included in the appendix.

Table 3. Tests for Phase IV

Test Name	Test Age	Number of tests		
		Cylindrical Specimens		Test-Deck
		4 x 8 in.	6 x 12 in.	
Strength	7	-	6	-
	14	-	6	-
	28	-	6	-
	56	-	6	-
E, μ	28	-	6	-
	56	-	6	-
Figg	28	-	3 +	4 x 4
	56	-	3 +	4 x 4
UPV	7	24 *	-	-
	14	24 *	-	4 x 60
	28	24 *	-	4 x 60
	56	12 *	-	4 x 60
RCPT	28	4 **	-	-
	56	4 ***	-	-
Absorption	28	4 **	-	-
	56	4 ***	-	-
Gas permeability	28	4 **	-	-
	56	4 ***	-	-
Total of specimens		**32**	**39**	**4**

*, **, ***, + These tests will utilize the same specimen

The specimens were cast at the construction site by the WSU team and representative members from the MDOT Research Advisory Team. Air content and slump tests were performed by the WSU team and verified against the properties obtained by the contractors testing consultant.

The following day the specimens were transported to the lab, removed from their molds, and labeled with the respective bridge designation. The 6 x 12 in. cylindrical specimens were labeled as "A" and 4 x 8 in. specimens were labeled as "B". The label format is as follows: B(WSU bridge #)-(A or B)(#). For example, the specimen label B4-B23 represents the 23rd 4 x 8 in. specimen of the 4th bridge and B5-A40 represents 40th 6 x 12 in. cylinder specimen of the 5th bridge. The specimens were cured for 28 days submerged in water and kept in ambient laboratory air after that.

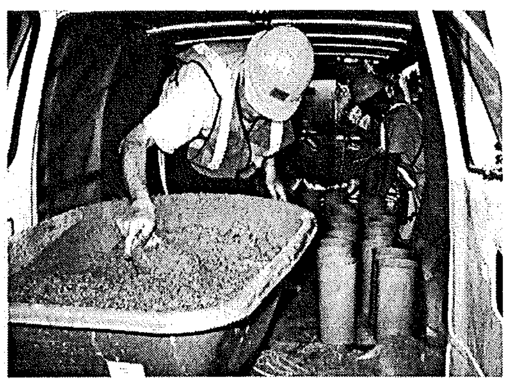


Photo 1. Casting of Cylinder Specimens

3.2. Test-Decks

3.2.1. Scotten St over Michigan Ave (B1)

The structural system of this bridge is composed of two plate girders continuous over two spans as shown in the photo below. The plate girders are supported by two abutments and at the mid-span. The plate girders are laterally supported by rolled cross beams and the deck is supported by a set of rolled I-section joists sitting on the crossbeams. For composite action shear studs were welded on the joists supporting the deck (as shown in the Photo 3).

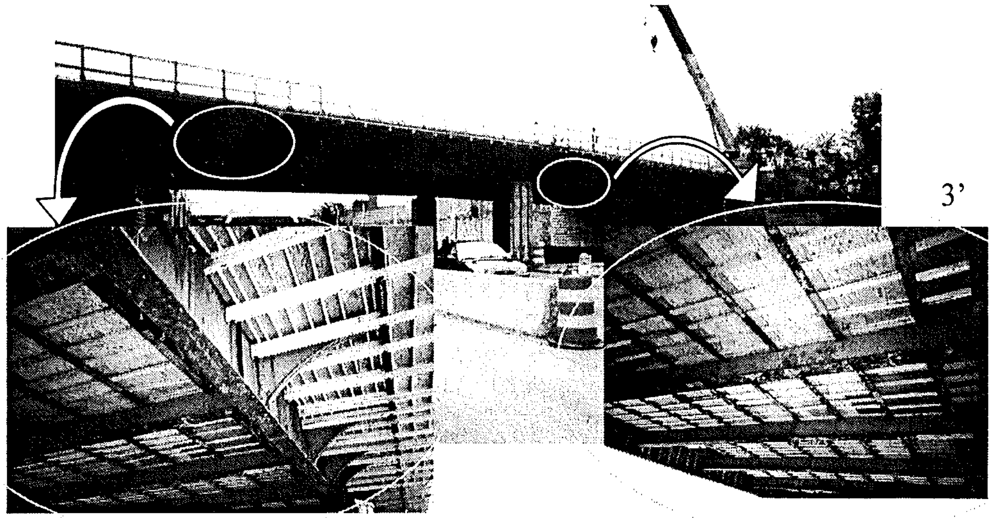


Photo 2. Scotten St over Michigan Ave (B1)

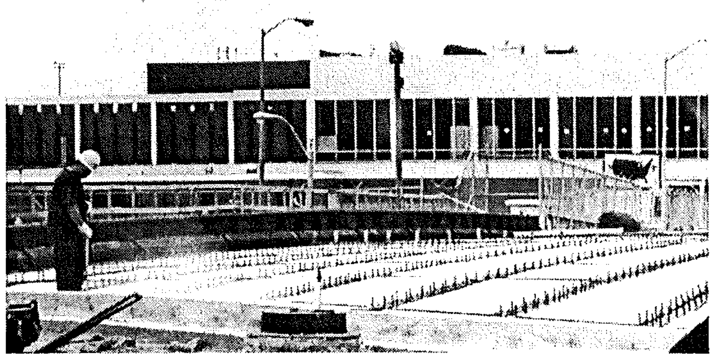


Photo 3. Shear Studs for Composite Action

The plan and the cross-section of the structural system are given in figure 1. As seen in the figure, the bridge is approximately 62' wide and 140' long. The deck consists of two lanes and two shoulders. Plate girders rise above the deck surface in between the sidewalks and the traffic lanes. Also shown in the figure are the UPV and Figg permeability measurement locations.

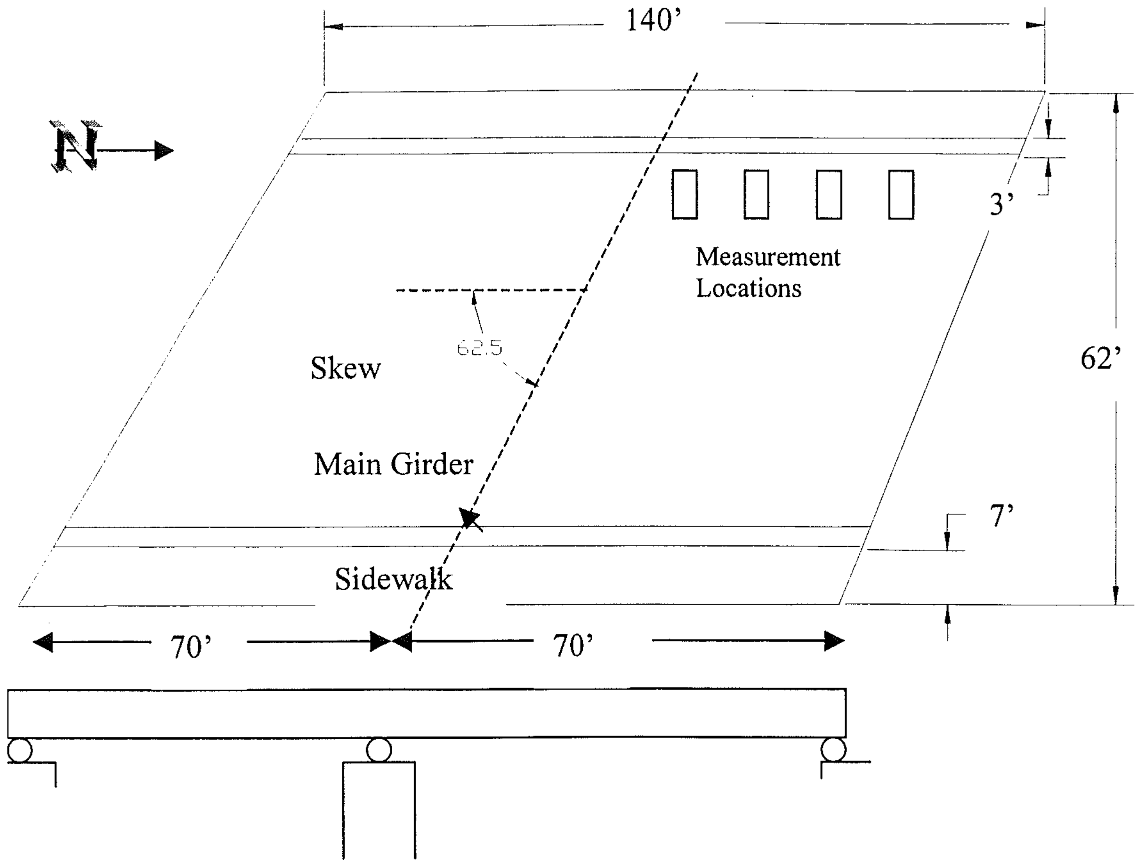


Figure 1. Plan and Cross-Section of Scotten over Michigan (B1)

Bridge deck concrete was placed in two consecutive nights. The lab specimens were prepared during the first night, when one side of the bridge deck was cast along with the opposite sidewalk. The concrete mix-design is shown in figure 2.

KOENIG - CONCRETE MIX DESIGN 2/3/2000

97 CONTRACTOR

DAN'S EXCAVATING, INC.
12955 TWENTY-THREE MILE RD.
SHELBY TWP., MI 48315
ATTN: MARK PEYERK

PROJECT

BRN 82062-48338A
SCOTTEN ST. OVER MICHIGAN AVE.
DETROIT, MI

ENGR: MDOT

MIX # D

CHART 97-0175

MIX DESCRIPTION:	MDOT D LIMESTONE AE + RET
CONTRACTORS' INTENDED USE:	D BRIDGE SUPERSTRUCTURE
28 DAY STRENGTH:	4500 PSI 31.0 MPa

SOURCE OF MATERIALS:

CEMENT:	TYPE I	ASTM C-150	LAFARGE CEMENT CO.
FLY ASH:	NONE		
FINE AGG:	2NS	ASTM C-33	KOENIG OXFORD (#63-7) or SHELBY BAY THESSALON (#95001)
CSE. AGG:	6AA LIMESTONE	ASTM C-33	PRESQUE ISLE (#71-47)
WATER:	POTABLE	ASTM C-94	CITY OF DETROIT
AEA:	CATEXOL AE-260	ASTM C-260	AXIM CONCRETE TECH.
RET:	CATEXOL 1000N	ASTM C-494	AXIM CONCRETE TECH.

MATERIAL WEIGHTS	SSD lbs.	kg	SP. G.	ABS. VOL. cu.ft.	cu.m.
CEMENT	658	390	3.15	3.35	0.124
FLY ASH	0	0	2.15	0.00	0.000
SAND	1112	660	2.65	6.72	0.249
C AGG	1778	1055	2.62	10.88	0.403
WATER	266	158	1.00	4.26	0.158
ADMIXTURES /cwt.					
AEA	1.6 oz	104 ml		1.81	0.067
RET	4.0 oz	261 ml			
TOTALS	3814	2263 kg		27.02	1.000

ANTICIPATED FIELD RESULTS:

SLUMP	3.5 "	MAX.	89 maximum	
AIR	6.5%	(+/- 1.5%)	6.5%	(+/- 1.5%)
WEIGHT	141.2	(+/- 1#)	2263	(+/- 25 kg/cu.m.)
YIELD	27.00	(+/- .3)	1.0	(+/- .01 cu.m.)
W/CM RATIO	0.40		0.40	

ABSORBTION:		7 DAY PSI	4675	32 MPa
FINE AGG.	1.3	28 DAY PSI	5844	40 MPa
CSE.AGG.	1.13			

CSE. AGG. UNIT WT:
DRY LOOSE 1490 kg
B/Bo 0.70

KOENIG FUEL & SUPPLY
Neil Crocker

STRICT ADHERANCE TO ASTM CYLINDER SPECIMEN CURING AND TESTING ARE REQUIRED (BY M.D.O.T.). KOENIG FUEL & SUPPLY CANNOT BE RESPONSIBLE FOR SAMPLED CYLINDER TEST RESULTS IF ASTM PROCEDURES ARE NOT STRICTLY FOLLOWED AND/OR IF SLUMP AND AIR CONTENTS ARE OUTSIDE OF SPECIFIED LIMITS.

Figure 2. Concrete Mix-Design of Scotten St. over Michigan Ave. (B1)

3.2.2. Woodward Ave over I-94 (B2)

Northbound Woodward Ave. bridge consists of four spans simply supported with spread prestressed box beams, shown in photo 4.

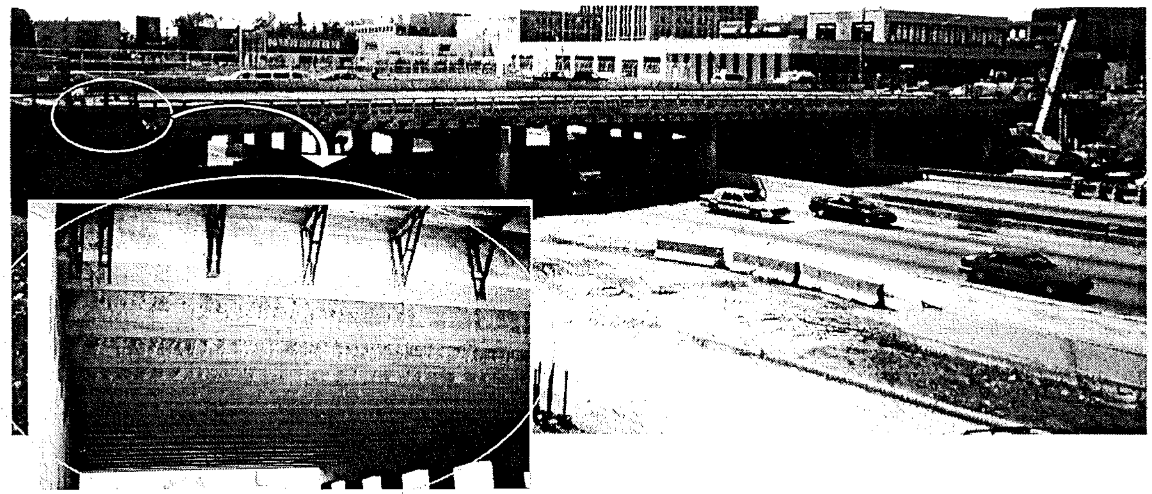


Photo 4. Woodward Ave. over I-94 (B2)

The plan and the cross-section of the structural system are shown in figure 3. As seen in this figure, the bridge is approximately 90' wide and 330' long. The deck surface consists of four lanes and one shoulder. Although, the girders are simply supported, the deck is cast with construction joints only and designed as a continuous plate for the full length of the bridge.

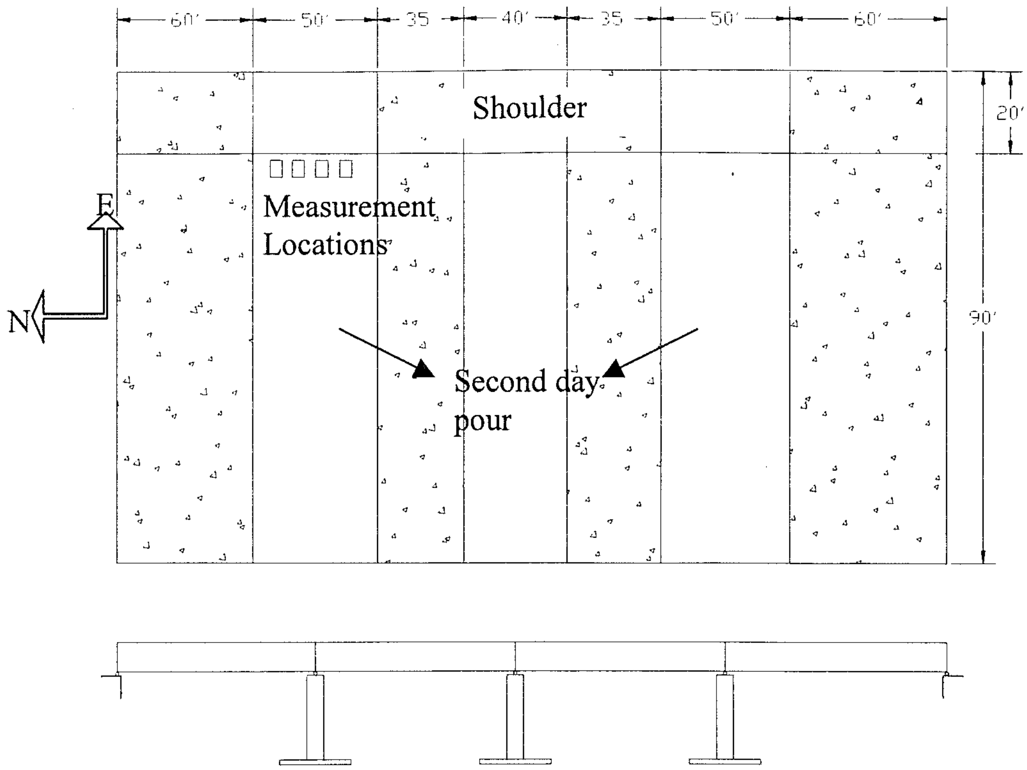


Figure 3. Plan and Cross-Section of Woodward Ave. over I-94 (B2)

The bridge deck concrete was placed in two consecutive nights by staggering the midspans with deck portions over the piers. The standard test specimens were fabricated during the second night at the time of placement at the portions of the deck above the piers. The concrete mix-design is shown in figure 4.

MICHIGAN FOUNDATION CONCRETE

ONE W. JEFFERSON AVENUE
TRENTON, MICHIGAN 48183

MIX ID : ST7002MR(D)[1]

CONCRETE MIX DESIGN
4500 PSI

02/29/00

CONTRACTOR : WALTER TOEBE CONSTRUCTION COMPANY
PROJECT : I-75 & I-94 Interchange.
SOURCE OF CONCRETE : MICHIGAN FOUNDATION CONCRETE
CONSTRUCTION TYPE : For bridge superstructure
PLACEMENT : Conventional and/ or pumpable

WEIGHTS PER CUBIC YARD	(SATURATED, SURFACE-DRY)	YIELD, CU FT
ASTM C-150 Type 1, LB	658	3.35
American Agg, MDOT 2NS, LB	1219	7.37
Presque Isle, MDOT 6AA, LB	1650	10.37
WATER, LB (GAL-US)	272 (32.6)	4.36
TOTAL AIR, %	6.5 +/- 1.5	1.77
	TOTAL	27.22
Euclid Chemical WR-MR, OZ	39.48	
Euclid Chemical AEA-92, OZ	6.6	
WATER/CEMENT RATIO, LBS/LB	0.41	
SLUMP, IN	5.00	
CONCRETE UNIT WEIGHT, PCF	139.6	

Note: Euclid MR will be used at the contractors request to deliver a 4" +/- 1" slump at the job site.

PREPARED BY

Ronald J. Peters

Detroit (313) 921-3410 Trenton (734) 282-9100 Wayne (734) 326-4200

Figure 4. Concrete Mix-Design of Woodward Ave. over I-94 (B2)

3.2.3. Oakman Ave. over Lodge Fwy. (M-10) (B3)

This bridge structure is steel stringers over two continuous spans, shown in photo 5. In addition to the deck replacement, the mid-span pier was also replaced by first shoring the steel stringers on temporary supports.

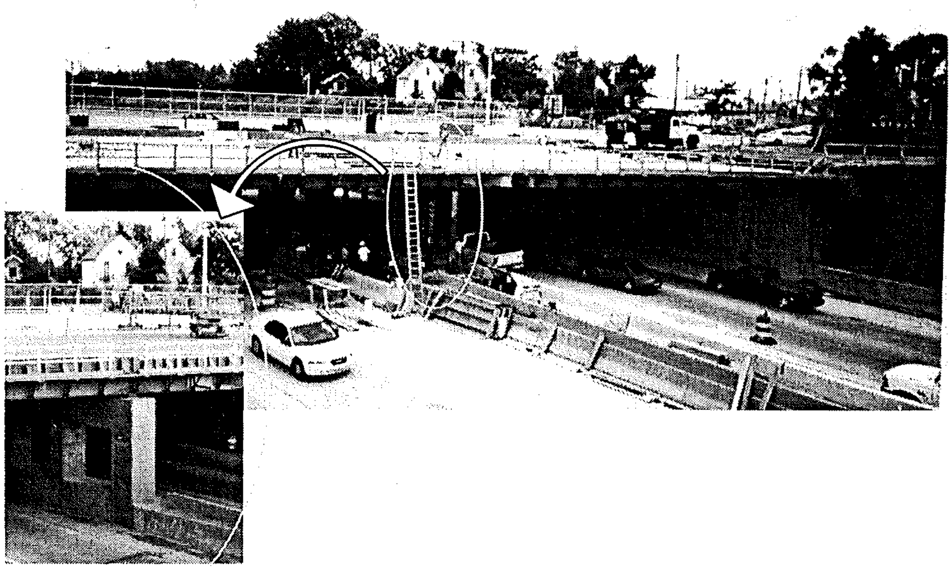


Photo 5. Oakman Ave. over Lodge Fwy. (M-10) (B3)

The plan and the cross-section of the bridge are shown in figure 5. As seen in the figure the bridge is approximately 65' wide and 265' long. The deck consists of two lanes and one sidewalk.

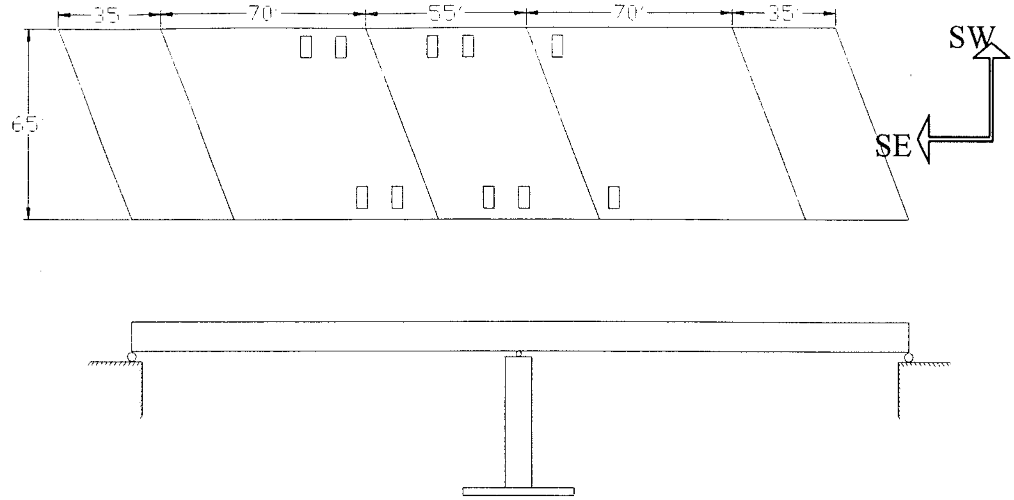


Figure 5. Plan and Cross-section of Oakman Ave over Lodge Fwy. (M-10) (B3)

The bridge deck concrete placement was completed in one evening. The concrete mix-design is shown in figure 6.

. TESTING & RESEARCH Fax : 517-322-1262 Oct 03 '00 13:00 P.03

[illegible] Concrete Company
P.O. Box 788
Novi, Michigan 48376 (800) 549-1668

359344
POSEN CONSTRUCTION

TICKET NO. 53014
0

DATE 08/12/2000

TIME 01:36

SHIP TO: LODGE TO LINWOOD LEFT TO OAKMAN LEFT TO JOB NIGHT CHARGE

QUANTITY	ACC TOTAL	QTY ORDERED	SLUMP
2.50 3.27	217.50 284.48	215.00 281.21	102.00 4.02

PRODUCT DESC. NIGHT CHARGE

PLANT	TRUCK NO.	LOT NO.	RELEASE NO.	P.O. NO.	JOB NO.	PRICE CODE	INITIALS
01	362 B022		0		0		

MATERIAL	DESIGN QTY	REQUIRED	BATCHED	VAR	% VAR	MOISTURE	ACTUAL WATER
JA	271 mL	677 mL	651	-26	-3.84%		
3H	50 kg	1036 kg	1080 +	44	4.25%		
AL	997 kg	4249 kg	4237	-12	-.28%	1.00% M	24.79 L
EM	365 kg	912 kg	987 +	75	8.22%		
A	672 kg	1731 kg	1724	-7	-.40%	3.00% M	50.20 L
OLY	2166 mL	5415 mL	5442	27	0.50%		
ATER	148.3 kg	295.5 kg	288.5 -	-7.0	-2.37%		288.48 L
RA	1006 mL	2514 mL	2514	0	0.00%		

ON-SIMULATED NUM BATCHES: 1
OAD TOTAL: 5679 kg WATER/CEMENT: 0.3217 DESIGN WATER: 370.8 L ACTUAL WATER: 363.5 L TO ADD: 7.3 L
LUMP:102 mm ADJUST WATER: 0.0 L /load TRIM WATER: 0.0 L /m3
NOTE: Manual Feed Occurred.

ARRIVED JOB	START UNLOAD	UNLOAD
1:50	1:50	2:05

0 QTY/UNITS Qty water added by request/authorized by X

TERMS & CONDITIONS ON REVERSE SIDE

Mike

C0700425

10-03-00 11:46 RECEIVED FROM:517 322 1262 P.03

Sep 28 2000 12:07 P.05

Figure 6. Concrete Mix-Design of Oakman Ave. over Lodge Fwy. (M-10) (B3)

3.2.4. NBD I-75 to EBD I-94 Connector (B4 and B5)

The connector consists of 11 spans of simply supported steel stringers, shown in figure 7. The connector is 40' wide and approximately 820' long. The deck surface consists of one lane and one shoulder.

Photo 6. NBD I-75 to EBD I-94 Connector (B4)

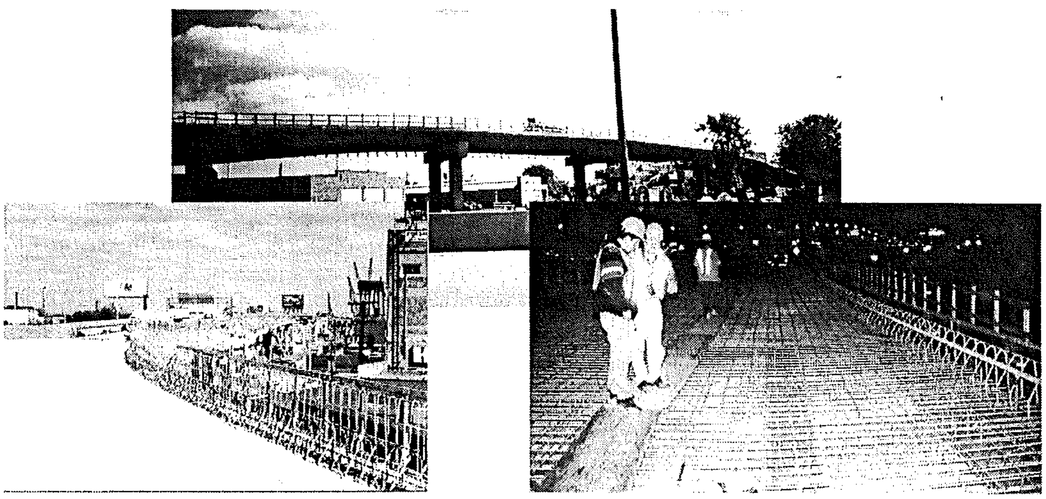


Photo 7. NBD I-75 to EBD I-94 Connector (B5)

The bridge deck concrete was placed in multiple stages over a period of several nights. The standard specimens were prepared during concrete placement on two different portions of the bridge. The concrete mix was the same as shown in figure 4 and delivered by the same supplier.

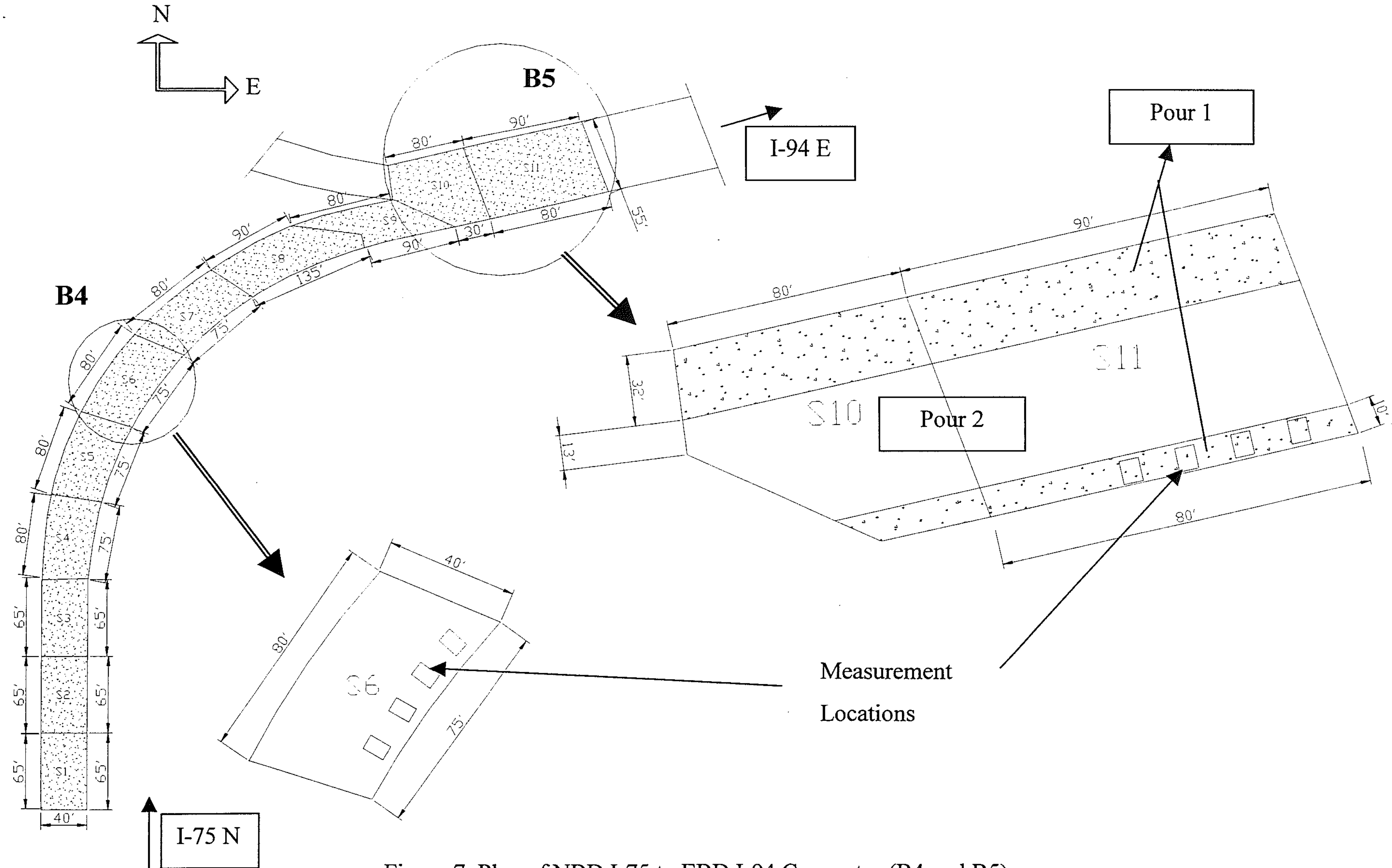


Figure 7. Plan of NBD I-75 to EBD I-94 Connector (B4 and B5)

3.3. Experimental Procedures

3.3.1. Concrete Mechanical Properties

The concrete mechanical properties were determined by the compressive strength test and modulus of elasticity test. Test procedures are described in ASTM C39 and ASTM C469, respectively.

Compressive strength testing was conducted on six 6 in.x12 in cylindrical specimens at 7, 14, 28 and 56-days of specimen age. A total of 120 specimens were tested for strength. Modulus of elasticity testing was conducted on four 6-in.x12 in. cylindrical specimens at 28- and 56-days of specimen age. A total of 60 specimens were tested for modulus of elasticity. The specimens used in both of these tests were wet cured for 28 days and kept in ambient lab conditions until the 56-day tests.

Concrete compressive strength and modulus of elasticity tests were conducted in a uniaxial frame (MTS 550,000 lbs. capacity). During compressive strength testing, load data was acquired while the piston is displaced at a rate of 1.3 mm/min as described in ASTM C 39. A computer program was developed in MATLAB® which reads the data file for each specimen and evaluates the compressive strength. Figure 8 shows the plot of the data output from the MATLAB® analysis which, shows the actuator piston displacement and acquired load against time. The analysis output is shown on the lower plot, which includes the specimen labeling and strength properties.

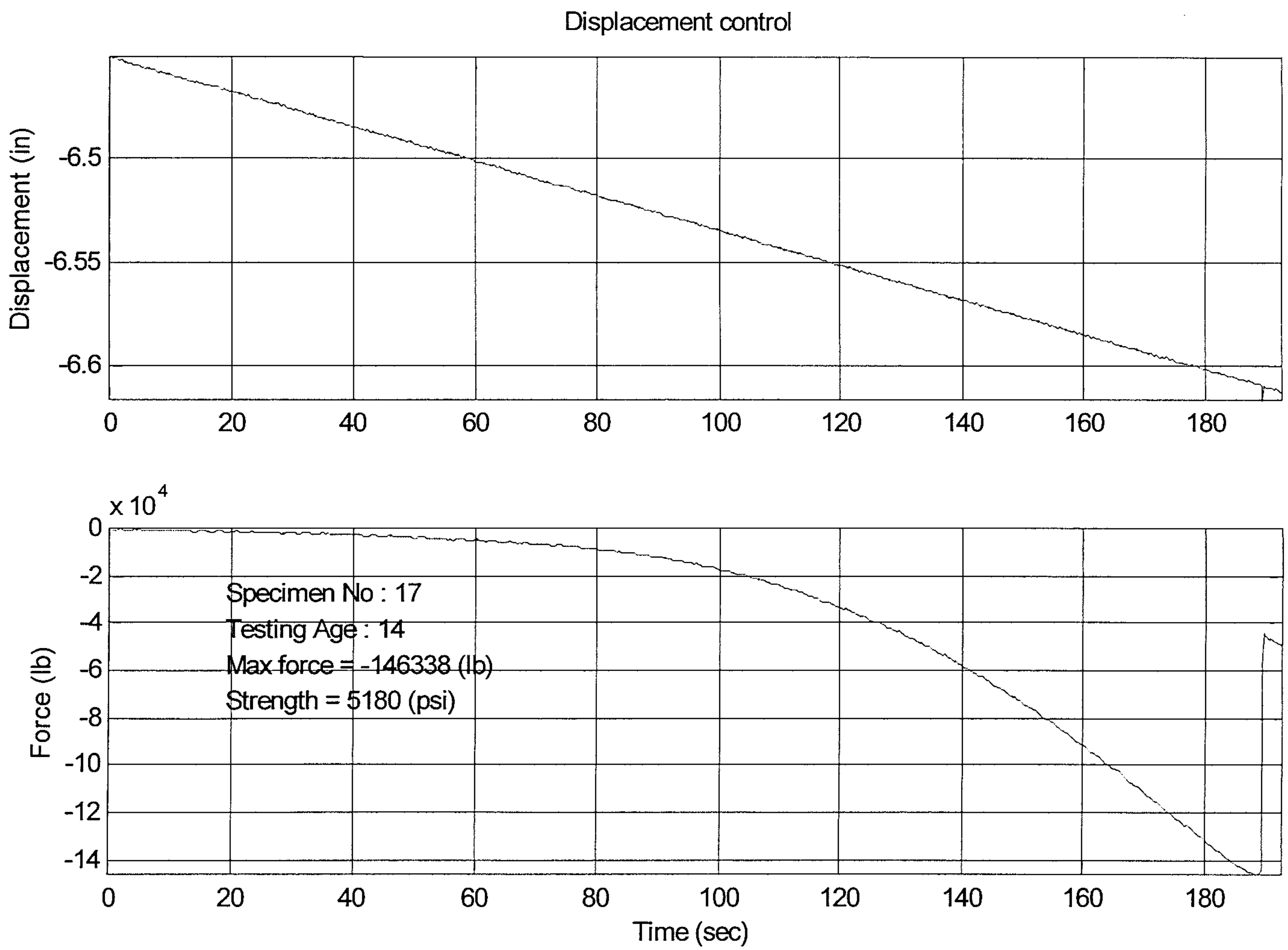


Figure 8. Strength Raw Data and Analysis

Static modulus of elasticity and Poisson's ratio tests were conducted according to ASTM C 469. The axial and radial strains were measured digitally using two DCDT's attached to a fixture working as a combined compressometer -extensometer. Load was applied as specified by ASTM at a constant rate within the range 35±5 psi. Three cycles of load were applied. Load and displacement data were collected using two DCDT's. The data was analyzed using a MATLAB® program.

Figure 9 presents the load, axial and radial strain raw data. Figure 10 shows the analysis results with the top three plots representing the axial stress versus axial strain for each load cycle. The loading slope (El) and unloading slope (Eu) were computed as the modulus of elasticity for that cycle. The loading and unloading elasticity values are given on the plots. Similarly, the lower three plots in Figure 10 report the radial versus axial strain for each load cycle. The ratio of the loading slope (Ml) and unloading (Mu) was computed as Poisson's ratio. The modulus of elasticity and Poisson's ratio is defined as the average obtained from the loading portion of the second and third cycles.

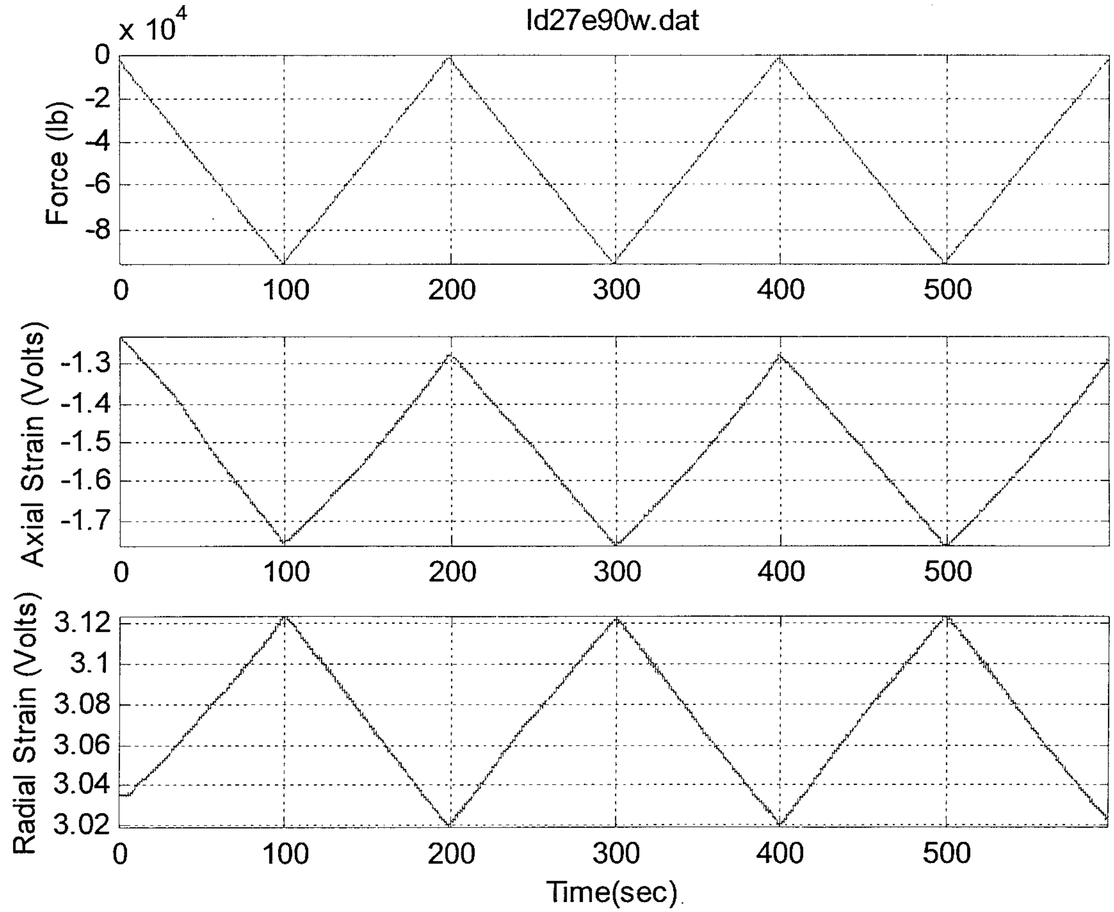


Figure 9. Elasticity Test Raw Data

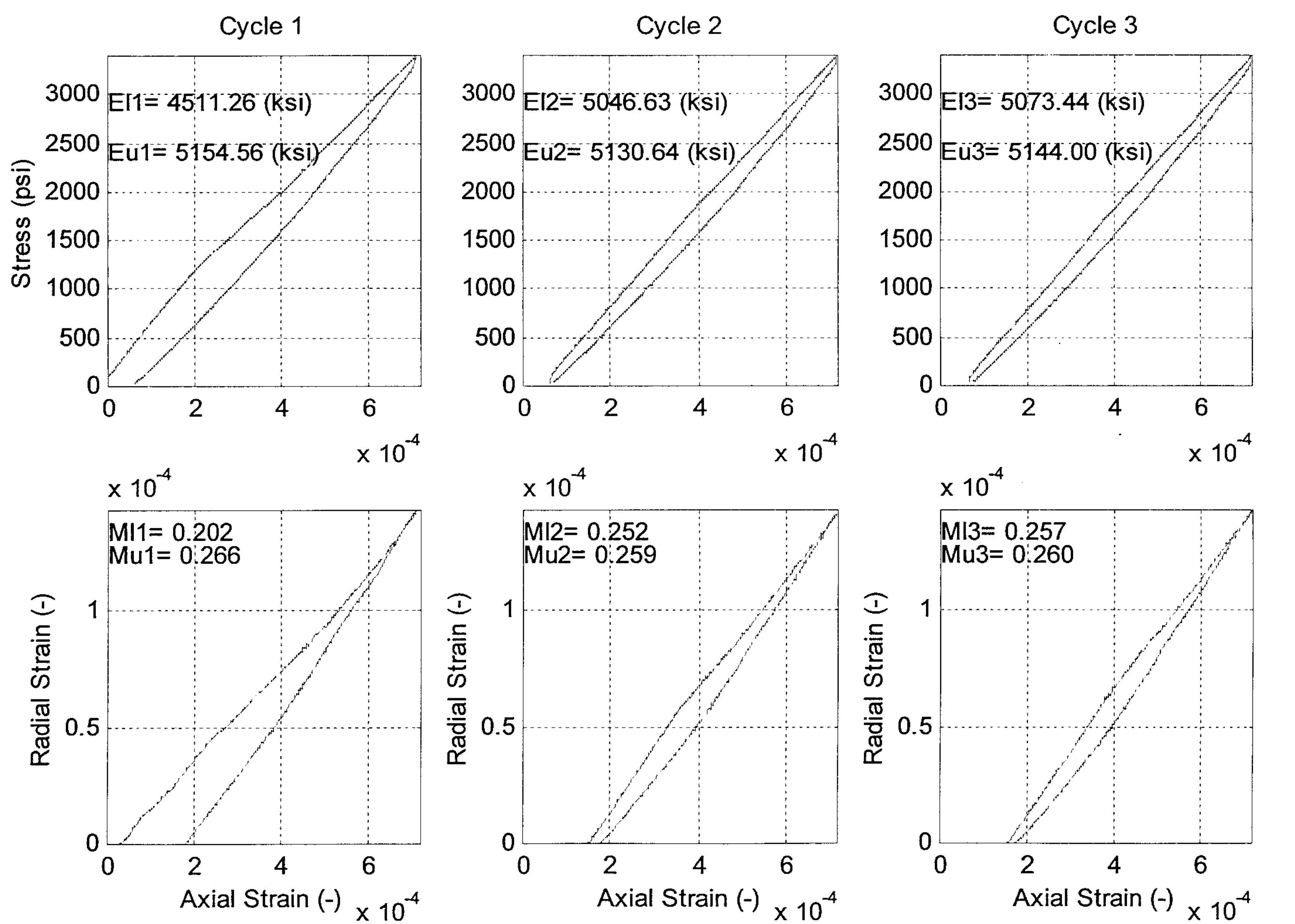


Figure 10. Elasticity Data Analysis

3.3.2. Permeability Tests

Four different lab tests measuring permeability were conducted. The specimens for all the tests were portions of the 4-inch by 8-inch standard cylinder specimens. The lab-permeability tests were RCPT, absorption, gas permeability, and Figg's permeability. Only one field test of concrete permeability was conducted on the bridge decks. The Figg's permeability test was also used in the field. The test procedures are described below.

3.3.2.1. Rapid Chloride Permeability Test (RCPT)

Rapid Chloride Permeability test specimens were saw-cut from 4 x 8 in. standard cylinders. The specimens were approximately 2 inches in thickness. Tests were performed at 28- and 56-days. Eight specimens were tested for each field deck according to ASTM C 1202. The test apparatus included signal conditioners and automatic data acquisition (Photo 9).

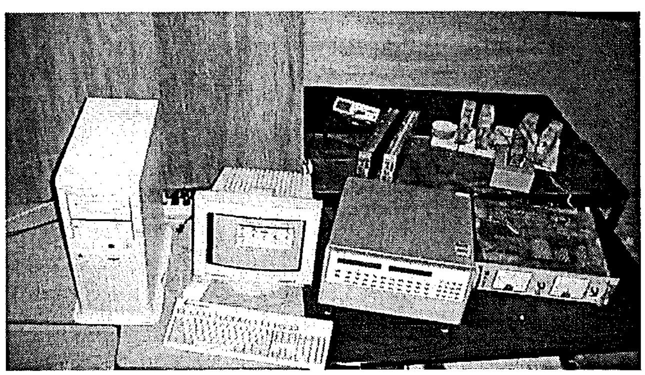


Photo 8. RCPT Cells and Data Acquisition Unit

The specimen pre-conditioning procedure started with coating the sides of the specimen with epoxy paint, which was allowed to cure for one day. Upon curing of the epoxy paint, the specimen was submerged in water in the vacuum saturation unit. The specimens were kept in the vacuum saturation unit for 18 hours. The specimen was then assembled into the voltage cell where a potential difference of 60 volts was maintained between its faces for six hours. The voltage cell was designed such that one surface of the specimen is in contact with 0.3N sodium hydroxide solution, the other surface with 3.0% sodium chloride solution. The charge passing through the specimen was measured and recorded using a data acquisition system (Figure 10) interfaced to a PC. The Voltage measurements were also manually checked intermittently while monitoring the solution temperatures inside the cells. The test was terminated if cell solution temperature exceeds 90 °C, as specified in ASTM C 1202. The RCPT system arrangement in the laboratory contained two cells, allowing two specimens to be tested simultaneously.

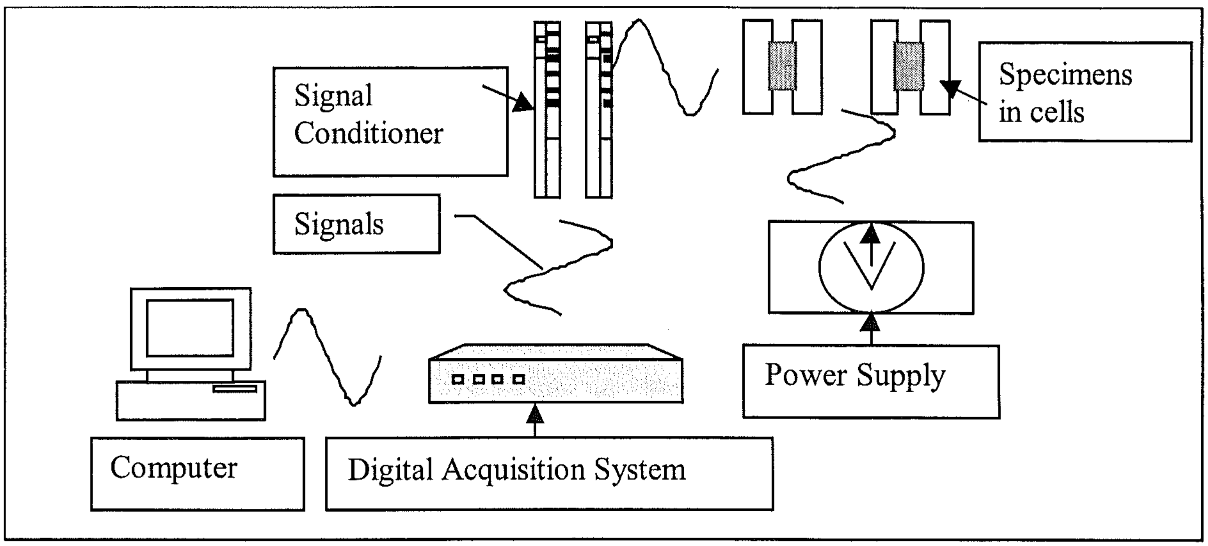


Figure 11. Data Acquisition Unit of RCPT

The experiment setup and the associated computer program were developed during this phase to make digital voltage measurements and allow flow of data to the computer. Amplifiers and conditioners were also utilized for the noise reduction of the output signals.

The computer program processed the data and computed the total-charge-passed through the specimen in a continuous six-hour test period. Total-charge-passed is computed from the integration of the area under the current vs. time curve. The formula below, which is Equation 17, is based on the trapezoidal numerical integration rule as described in ASTM

C1202:

$$Q= 900\ (I_0 + 2(I_{30} + I_{60} + ... + I_{330}) + I_{360}) \tag{17}$$

where 'I_t' is the current at time 't' in minutes and 'Q' is the total charge.

3.3.2.2. Absorption Test

The test was performed according to ASTM C 642 on the 2 in. thick concrete specimens saw-cut from the 4 x 8 in. standard cylinder specimens. Four standard specimens were tested at 28- and 56-days of age for each bridge deck.

The specimens were kept in the drying oven at approximately 50°C and weighed at 24-hour intervals. De-absorption was assumed to be complete when the change in mass of the specimen was less than 0.5% of the mass of the previous mass. The specimens were then immersed in water and weighed every 24 hours to record the mass increases. Absorption was assumed to be complete when the change in mass of the specimen was less than 0.5% of the previous mass interval. Upon saturation, the specimens were kept in boiling water for five hours. After boiling, the specimens were weighed in air then immersed in water and weighed again. The volume of permeable voids (porosity, p) was calculated using the following formula, as given in ASTM C 642:

$$p = (C - A)/(C - D) \times 100 \tag{18}$$

where,

A: Weight of oven-dry sample in air

C: Weight of surface-dry sample in air after immersion and boiling

D: Weight of sample in water after immersion and boiling

3.3.2.3. Gas Permeability Test

This test measures the coefficient of gas permeability of dry concrete. Gas permeability tests were performed at the University of Windsor. The specimens were 2 in. thick saw-cut from 4 x 8 in. standard cylinder specimens. The tests were at 28- and 56-days of age for each bridge deck on a total of eight specimens. At the time of this research ASTM or AASHTO standards were not available for the gas permeability test.

The specimens were oven dried at 50 °C to a constant weight. The specimens were then placed inside a rubber boot confining only the sides of the specimen and sealed. A stream of nitrogen gas was applied to the upstream face of the specimen via a source valve. Upon reaching a steady state flow of gas, both upstream and downstream pressures were recorded. The flow rate through the specimen was determined by measuring the pressure drop across a calibrated orifice located downstream from the sample. Permeability was calculated from the measured flow rate through the specimen using equation 19.

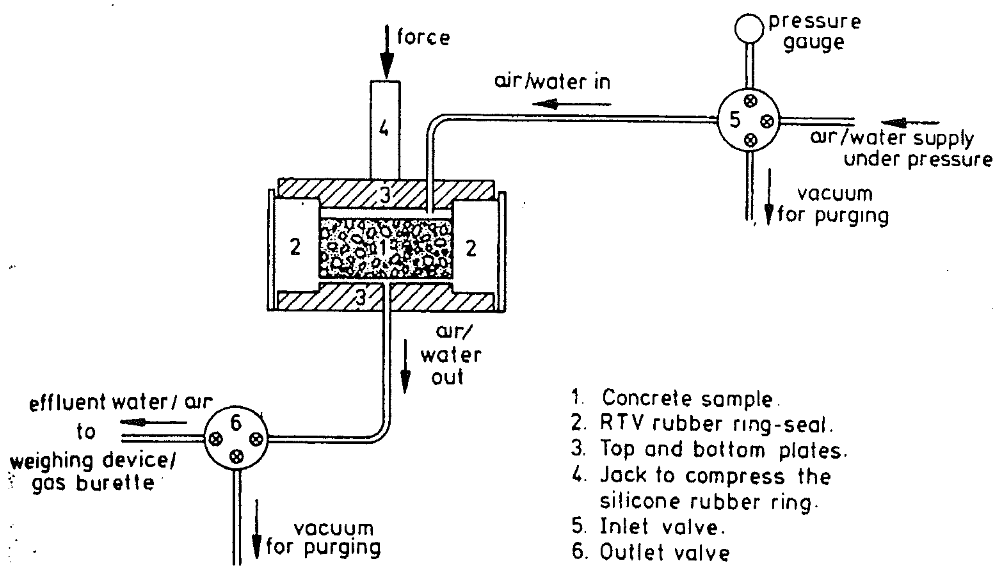


Figure 12. Schematic View of the Permeability Cell

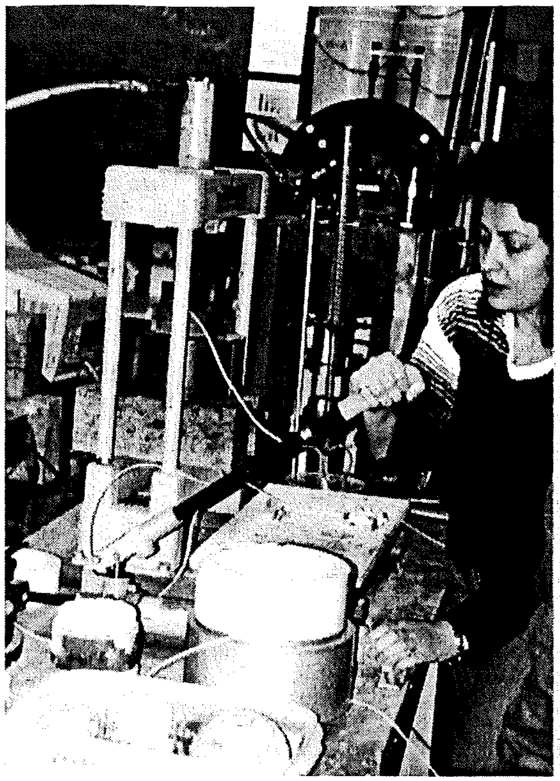


Photo 9. Permeability Test Setup

Pressure induced gas flow through a sample follows Drakes's law, and the porous solid is characterized by its intrinsic permeability coefficient D.

$$\frac{dq}{dt} = D\,A\,\frac{\rho\, g}{\mu}\frac{dh}{dL} \qquad (19)$$

where,

dq/dt	: Rate of flow of gas, permeant (m^3/s)
D	: Intrinsic permeability (m^2)
A	: Cross-sectional area of the sample (m^2)
ρ	: Density of gas, permeant (kg/m^3)
g	: Acceleration due to gravity (m/s^2)
μ	: Viscosity of gas, permeant (kg/m-s)
dh	: Drop in the pressure head through the sample (m)
dL	: Thickness of sample (m)

This equation incorporates Carman's findings (which show inverse relationship between the rate of flow and viscosity of the gas permeant) with Drake's equation. Intrinsic permeability, D, thus depends only on the micro-structural properties of the porous medium and it is independent of the properties of the gas permeant.

The gas permeability tests are rapid and reproducible, but only if the moisture condition is carefully controlled. Moisture content affects intrinsic permeability, because the gas sees the pore water as a solid. The permeable porosity at various moisture levels can be calculated by estimating the wetted surface area and computing the hydraulic mean radius. The moisture level, however, must be assumed constant throughout the specimen.

Rearranging Equation 19, the intrinsic permeability can be determined as

$$D = \frac{dq}{dt}\frac{1}{A}\frac{\mu L}{P_d} \tag{20}$$

where, $P_d = \rho g dh$ is the applied driving pressure in Pa.

3.3.2.4. Figg's Permeability Test

Figg's apparatus was used for conducting field air and water permeability measurements on the bridge-decks and on 6 x 12 in. standard cylindrical specimens. Tests were conducted at 28- and 56-days of concrete age. Permeability measurements were conducted at nine locations on the field-deck specimens and on three locations in the standard specimens.

The experiment was performed using a P-6000 Poroscope apparatus shown in Photo 10. First step of testing is to drill a hole of 3/8 in. diameter and 1 ½ in. deep. The distance between multiple holes and from the specimen edge cannot be less than 1 ¼ in. The cement dust inside the hole was cleaned and vacuumed. A rubber lid was installed as a plug such that the top flange of the plug is seated securely on the concrete surface for an airtight connection. Upon plugging the hole, a hypodermic needle was inserted through the rubber plug (Photo 11).

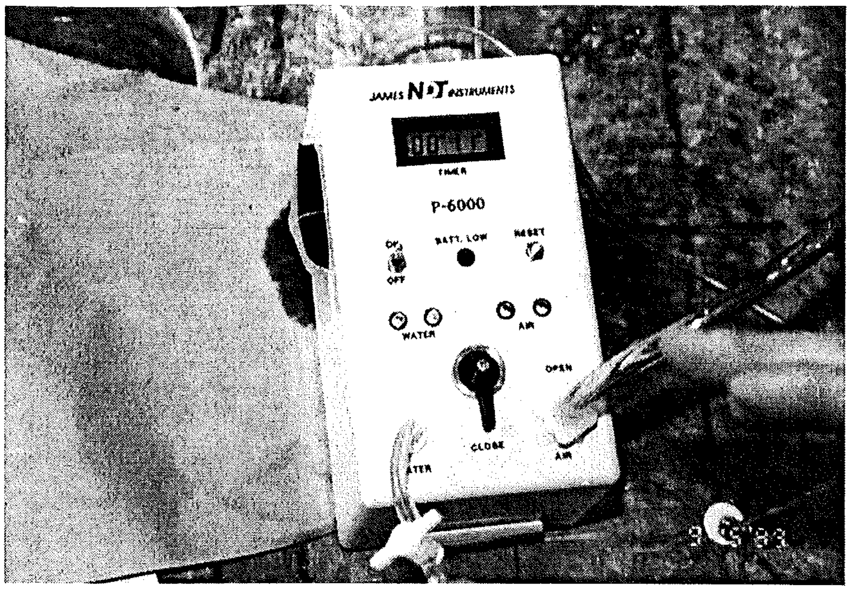


Photo 10. Figg's Test Apparatus (Poroscope P-6000)

Photo 11. Figg's Test Preparation

In conducting the air permeability test, the Figg device was put in the suction mode, until, the pressure inside the hole reached 55 kPa below atmospheric pressure. The time (t) elapsed to reduce the pressure to 50 kPa is measured. The test is repeated four times or until a maximum variability of ±2 % is obtained. However, if time elapsed was below 30 seconds, the test location or plug was assumed defective and the data was discarded. Gas permeability measure, termed the air exclusion rating (AER), was calculated using the following formula:

$$AER=0.247\ t\ (s/ml) \qquad (21)$$

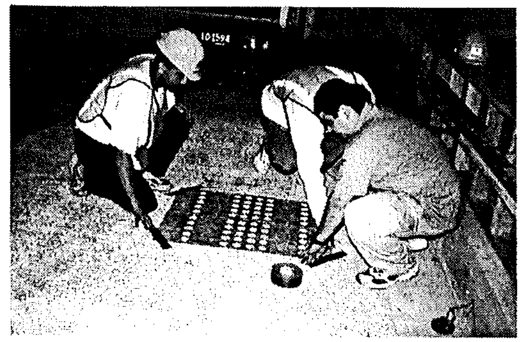
Upon completing the air-permeability tests, water-permeability tests were performed without changing the plug covering the 3/8-inch diameter 1-1/2-inch deep hole. Using the Figg apparatus, distilled water was injected into the hole with slow hand strokes using a syringe attached to the needle until the hole is completely filled. Upon filling the hole with water, a meniscus in the capillary tube connected between the instrument and the hole was positioned by gentle manipulation of the syringe plunger to a position just outside the instrument case. At that time the test starts and the instrument measures the time (t) elapsed until 0.01 ml of water is absorbed. The absorbed water is measured by the changing position of the meniscus in the capillary tube. As a measure of water permeability, the water absorption rate (WAR) is calculated from the following formula:

$$WAR=100\ t\ (s/ml) \qquad (22)$$

3.3.3. UPV Measurements

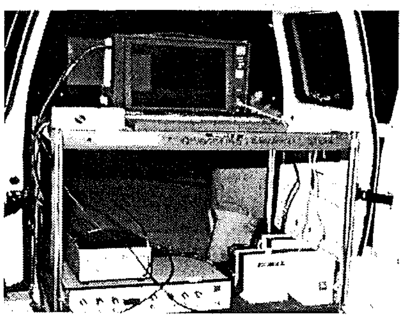
UPV measurements were performed on the deck and on 4 x 8 in. standard cylindrical specimens. The measurements were taken at 14-, 28-, and 56-days of concrete age. Measurements conducted on the bridge decks were indirect UPV where as the direct UPV test is performed on the cylindrical specimens. Four measurement locations were established on each bridge deck. The surface is ground to obtain a smooth finish without fully polishing the surface texturing (tining). In other words, polishing the flat surfaces in between each tining is sufficient for transducer contact. The smooth surface finish is important in order to assure sufficient transducer contact.

(a) Grinding



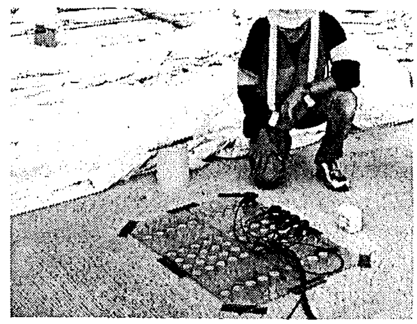
(b) Placing the UPV Template

Photo 12. Preparation for UPV Testing



(a) The Apparatus

(b) The Van



(c) Testing

Photo 13. Field UPV Setup

Pulse transit time for preset path lengths were measured. Pulse transit time is defined as the time elapsed between the time of pulse application and arrival at the location of the receiving transducer. By clocking the time of pulse application and the time of wave arrival, the pulse transit time was measured. The acquisition system was synchronized to the pulser so that data collection starts at the precise time of pulse application. The arrival times differ due to the presence of noise superposed with the wave signal. Filtering and wave averaging algorithms are used to reduce the errors in detecting the arrival time. The arrival time of a wave was evaluated using a computer-implemented algorithm with an automated arrival time detection program that is coded in MATLAB®. The arrival time detection is illustrated in Figure 12.

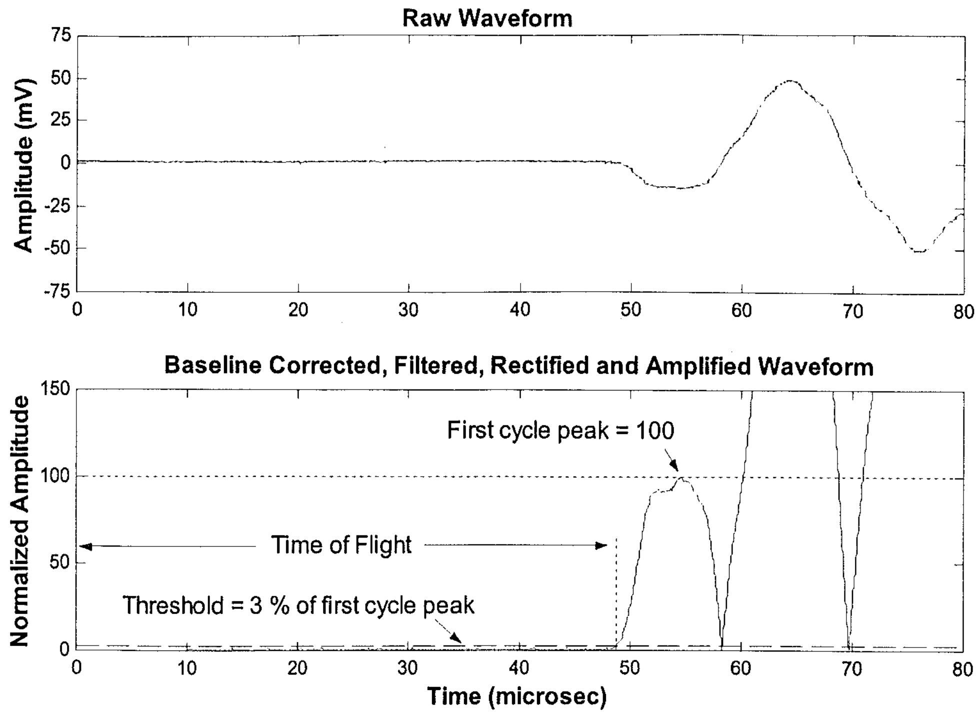


Figure 13. Arrival Time (Time of Flight) Determination Procedure

Indirect UPV measurements on the bridge decks were made using a plexiglass template that was designed to locate the pulsing and receiving transducers at preset locations (Photo 13c). The indirect UPV was computed using four measurements along an axis with transducers placed at 8 in. to 15 in. separations. Upon evaluating the transit time of four measurements, the indirect UPV was determined from the slope of the transit-time transducer separation plot. The detailed indirect UPV measurement procedure is described in Yaman et al. (2000).

3.4. Experimental Data

3.4.1. Plastic Concrete Properties

Plastic concrete test results consisting of slump, entrapped and entrained air content, and unit weight measurements are presented in Table 4. These tests were conducted at the construction site prior to concrete placement.

Table 4. Plastic Concrete Test Results

WSU Bridge ID	**Test Date**	**Slump (in)**	**Entrained Air (%)**	**Unit Weight (lb/ft^3)**
B1	**17-Jul-00**	4.5	6.4	141
B2	**4-Aug-00**	4.5	7.4	141
B3	**11-Aug-00**	5.0	6.7	142
B4	**8-Sep-00**	5.5	6.6	143
B5	**14-Sep-00**	4.0	6.5	144

3.4.2. Concrete Mechanical Properties

Mechanical properties of concrete consist of specific gravity, compressive strength, and modulus of elasticity measurements. The dry bulk and saturated bulk (surface saturated dry, SSD) specific gravities of the standard cylinder specimens were determined using the ASTM C642 and presented in Tables 5(a) & (b). The 7-, 14-, 28-, and 56-day compression strength test results are presented in Table 6. It should be noted that specimens are kept saturated for 28 days and kept in ambient lab conditions until the 56-day tests. The modulus of elasticity and Poisson's ratio measurements are presented in Table 7(a) & (b). Table 8 presents a summary of the mechanical property test results, which are bulk specific gravity, compressive strength, and the modulus of elasticity, for the subject bridge decks. Results presented are the means of the aforementioned tests at 28 and 56 days of concrete age.

Table 5a. Dry Bulk Specific Gravity Test Results

Bridge ID	Test Age (days)	Bulk Specific Gravity (dry)					
		#1	#2	#3	#4	Mean	COV (%)
B1	28	2.13	2.12	2.15	2.22	**2.15**	**2.2**
	56	2.29	2.23	2.24	2.20	**2.24**	**1.6**
B2	28	2.23	2.22	2.20	2.24	**2.22**	**0.8**
	56	2.20	2.21	2.20	2.22	**2.21**	**0.4**
B3	28	2.22	2.19	2.27	2.32	**2.25**	**2.6**
	56	2.30	2.31	2.30	2.18	**2.27**	**2.8**
B4	28	2.23	2.23	2.24	2.24	**2.23**	**0.4**
	56	2.25	2.23	2.25	2.22	**2.24**	**0.6**
B5	28	2.27	2.27	2.25	2.28	**2.27**	**0.6**
	56	2.14	2.25	2.38	2.26	**2.26**	**4.3**

Table 5b. Saturated Bulk Specific Gravity Test Results

Bridge ID	Test Age (days)	Bulk Specific Gravity (SSD)					
		#1	#2	#3	#4	Mean	COV (%)
B1	28	2.18	2.17	2.20	2.28	**2.21**	**2.2**
	56	2.34	2.30	2.30	2.27	**2.30**	**1.3**
B2	28	2.27	2.26	2.25	2.29	**2.27**	**0.8**
	56	2.22	2.23	2.23	2.24	**2.23**	**0.4**
B3	28	2.25	2.23	2.31	2.36	**2.29**	**2.5**
	56	2.32	2.33	2.32	2.21	**2.30**	**2.6**
B4	28	2.28	2.28	2.30	2.29	**2.29**	**0.4**
	56	2.28	2.27	2.29	2.27	**2.28**	**0.5**
B5	28	2.31	2.31	2.28	2.31	**2.30**	**0.5**
	56	2.18	2.29	2.43	2.31	**2.30**	**4.4**

Table 6. Compressive Strength Test Results

Bridge ID	Test Age (days)	Compressive Strength (psi)							
		#1	#2	#3	#4	#5	#6	Mean	COV (%)
B1	7	5800	6120	5460	5650	5910	5190	**5688**	5.8
	14	6290	6410	6490	6210	6470	6380	**6375**	1.7
	28	7210	6750	7050	6630	6510	6490	**6773**	4.4
	56	7470	7510	7750	7280	7340	7210	**7427**	2.6
B2	7	4840	4790	4780	4690	4520	5040	**4777**	3.6
	14	5100	5000	4730	5300	5270	5050	**5075**	4.1
	28	5450	5120	5350	5470	5410	5650	**5408**	3.2
	56	6040	6620	6050	6180	5760	6390	**6173**	4.9
B3	7	3910	3710	3780	3650	3930	3520	**3750**	4.2
	14	4130	4270	4020	4200	4100	4180	**4150**	2.1
	28	4480	4710	4900	4580	4590	4680	**4657**	3.1
	56	5010	5300	5070	4930	5100	5110	**5087**	2.4
B4	7	4470	4360	4370	4430	4580	4340	**4425**	2.0
	14	5210	4860	4820	4910	4750	4840	**4898**	3.3
	28	5480	5120	5370	5420	5250	5360	**5333**	2.4
	56	6470	6380	6260	6410	6180	6090	**6298**	2.3
B5	7	4740	4990	5290	4920	4750	5240	**4988**	4.7
	14	5160	5570	5310	5690	5160	5330	**5370**	4.0
	28	5900	5700	6140	5970	5840	5960	**5918**	2.5
	56	7000	7370	6900	7510	7100	6730	**7102**	4.1

Table 7a. Modulus of Elasticity Test Results

Bridge ID	Test Age (days)	Specimen Condition	Modulus of Elasticity (ksi)						Mean	COV (%)
			#1	#2	#3	#4	#5	#6		
B1	28	Wet	4946	4974	5123	5211	5000	4982	**5039**	**2.1**
		Dry	4513	4491	4665	4494	4646	4567	**4563**	**1.7**
	56	Air Dry	4976	5004	4990	5106	4853	4952	**4980**	**1.6**
B2	28	Wet	4683	4734	4589	4919	5105	4819	**4808**	**3.8**
		Dry	4183	4200	4172	4245	4230	4368	**4233**	**1.7**
	56	Air Dry	4708	5151	4610	5011	4790	4802	**4845**	**4.1**
B3	28	Wet	4651	4654	4729	4584	4752	4817	**4698**	**1.8**
		Dry	3579	3834	3736	3754	3768	3612	**3714**	**2.6**
	56	Air Dry	4244	4631	4057	4189	3724	4142	**4165**	**7.0**
B4	28	Wet	4743	4851	5007	4851	4676	4866	**4832**	**2.4**
		Dry	4717	4774	4883	4778	4663	4766	**4763**	**1.5**
	56	Air Dry	5157	4843	4769	4795	4989	4709	**4877**	**3.4**
B5	28	Wet	5000	5282	5016	4928	4942	4984	**5025**	**2.6**
		Dry	4827	5029	4928	4830	4892	4975	**4913**	**1.6**
	56	Air Dry	5055	5015	5118	5080	5063	5073	**5067**	**0.7**

Table 7b. Poisson's Ratio Test Results

Bridge ID	Test Age (days)	Specimen Condition	Poisson's Ratio #1	#2	#3	#4	#5	#6	Mean	COV (%)
B1	28	Wet	0.27	0.26	0.26	0.27	0.26	0.26	**0.26**	**2.24**
		Dry	0.26	0.26	0.26	0.26	0.26	0.25	**0.26**	**1.51**
	56	Air Dry	0.24	0.24	0.25	0.25	0.25	0.25	**0.25**	**1.91**
B2	28	Wet	0.24	0.23	0.24	0.23	0.24	0.24	**0.24**	**2.81**
		Dry	0.21	0.21	0.21	0.18	0.21	0.22	**0.21**	**6.37**
	56	Dry	0.24	0.26	0.26	0.23	0.25	0.25	**0.25**	**4.95**
B3	28	Wet	0.25	0.23	0.22	0.23	0.24	0.25	**0.24**	**4.01**
		Dry	0.18	0.21	0.20	0.19	0.20	0.19	**0.19**	**5.10**
	56	Dry	0.25	0.25	0.21	0.25	0.21	0.25	**0.24**	**7.92**
B4	28	Wet	0.24	0.24	0.26	0.24	0.25	0.25	**0.25**	**3.43**
		Dry	0.23	0.24	0.24	0.24	0.24	0.23	**0.24**	**1.97**
	56	Dry	0.24	0.25	0.24	0.24	0.25	0.24	**0.24**	**2.90**
B5	28	Wet	0.24	0.25	0.24	0.25	0.24	0.24	**0.25**	**1.18**
		Dry	0.24	0.25	0.23	0.25	0.24	0.24	**0.24**	**3.01**
	56	Dry	0.26	0.26	0.25	0.25	0.24	0.25	**0.25**	**3.62**

Table 8. Mechanical Property Test Results

Bridge ID	Bulk Specific Gravity		Compressive Stregth (psi)		Modulus of Elasticity (ksi)	
	Test Age (days)					
	28	56	28	56	28	56
B1	2.21	2.30	6773	7427	5039	4980
B2	2.27	2.23	5408	6173	4808	4845
B3	2.29	2.30	4657	5087	4698	4165
B4	2.29	2.28	5333	6298	4832	4877
B5	2.30	2.30	5918	7102	5025	5067

3.4.3. UPV Measurements

Direct UPV measurements on standard specimens are summarized in Table 9, inclusive of the specimen age, condition, and variability. As indicated the UPV measurements on standard cylinder specimens are performed using direct arrangement of the pulser and receiver transducers.

Table 9. Direct UPV Results

Bridge ID	Test Age (days)	Specimen Condition	UPV (ft/s)	
			Mean	COV (%)
B1	14	Wet	15,512	1.23
	28	Wet	16,290	1.07
	56	Air Dry	16,071	1.16
B2	14	Wet	15,561	1.21
	28	Wet	15,824	1.26
	56	Air Dry	15,872	1.36
B3	14	Wet	15,737	1.20
	28	Wet	15,701	1.18
	56	Air Dry	15,648	0.62
B4	14	Wet	15,567	0.77
	28	Wet	15,875	0.90
	56	Air Dry	15,648	0.62
B5	14	Wet	16,104	1.18
	28	Wet	16,056	1.46
	56	Air Dry	16,054	1.27

The field UPV measurements are summarized in Table 10. The measurements represent the average of 160 measurements taken at four locations on each bridge deck with the indirect transducer arrangement using the procedure described in section 3.3.3 of this report. UPV measurements were discontinued on Bridge 2, after the 14th day measurements.

Table 10. Field UPV Results

Bridge ID	Location	Indirect UPV (ft/s)					
		Test Age (days)					
		14		28		56	
		Mean	COV (%)	Mean	COV (%)	Mean	COV (%)
B1	#1	14,142	2.1	14,173	4.6	14,423	2.5
	#2	14,222	2.2	14,280	5.4	14,639	2.6
	#3	13,684	1.0	14,123	4.5	14,020	2.4
	#4	14,345	1.6	14,336	1.8	14,428	1.9
B2	#1	13,688	2.1	N/A	N/A	N/A	N/A
	#2	13,492	1.5	N/A	N/A	N/A	N/A
	#3	13,575	2.9	N/A	N/A	N/A	N/A
	#4	14,019	2.6	N/A	N/A	N/A	N/A
B3	#1	13,822	1.9	12,857	2.0	13,293	3.1
	#2	13,096	1.9	13,270	2.3	13,730	3.1
	#3	13,540	3.2	13,512	4.0	13,857	3.5
	#4	13,102	1.9	13,680	5.6	13,779	2.2
B4	#1	13,748	2.8	13,511	3.6	13,940	1.9
	#2	14,220	4.9	14,022	1.4	14,365	3.2
	#3	13,877	2.1	13,916	1.8	14,247	2.6
	#4	14,245	3.0	14,403	2.8	14,621	2.1
B5	#1	14,776	3.2	13,913	2.0	14,511	1.7
	#2	14,387	3.6	13,838	2.1	14,750	2.3
	#3	14,603	2.6	13,834	3.1	14,852	1.1
	#4	14,277	2.2	13,707	2.3	14,631	1.3

N/A Data not available

3.4.3. Permeability Tests

3.4.3.1. RCPT

RCPT results are presented in Table 11. Four specimens are tested at 28- and 56-days of concrete age, and the mean and variability in RCPT measurements are presented in the last two columns of Table 11.

Table 11. RCPT Results

Bridge ID	Test Age (days)	RCPT (Coulombs Passed)					
		#1	#2	#3	#4	Mean	COV (%)
B1	**28**	8590	7542	7631	8970	**8183**	**8.6**
	56	5983	6097	-	-	**6040**	**1.3**
B2	**28**	6374	7375	-	7940	**7230**	**11.0**
	56	5453	5833	6480	6217	**5996**	**7.5**
B3	**28**	6367	7805	7029	8647	**7462**	**13.2**
	56	3666	5322	4425	-	**4471**	**18.5**
B4	**28**	4256	3857	-	5426	**4513**	**18.1**
	56	5668	-	4574	4499	**4914**	**13.3**
B5	**28**	-	5202	5094	5010	**5102**	**1.9**
	56	4463	4732	3952	3791	**4234**	**10.4**

- Data not reliable and discarded

3.4.3.2. Concrete Porosity Tests Results

The summary of concrete porosity (volume of permeable voids) measurements is presented in Table 12. Concrete porosities are measured using ASTM C642. Four specimens were tested at each age; the mean and variability of the four tests are presented at the last two columns of Table 12.

Table 12. Porosity Test Results

Bridge ID	Test Age (days)	Porosity (%)					
		#1	#2	#3	#4	Mean	COV (%)
B1	**>90**	8.31	9.33	9.02	8.60	**8.82**	**5.1**
B2	**>90**	8.50	8.50	8.05	7.73	**8.20**	**4.6**
B3	**>90**	8.59	9.33	8.93	8.72	**8.89**	**3.6**
B4	**>90**	7.69	7.12	7.47	7.08	**7.34**	**4.0**
B5	**>90**	6.93	7.63	6.99	7.53	**7.27**	**5.0**

3.4.3.3. Gas Permeability Measurements

Gas permeability tests were performed by the project consultant at the University of Windsor, Canada. The results are summarized in Table 13.

Table 13. Gas Permeability Measurements

Bridge ID	Test Age (days)	Intrinsic Permeability of Gas ($m^2 \times 10^{-15}$)					
		#1	#2	#3	#4	Mean	COV (%)
B1	28	4.85	4.79	5.25	4.52	4.85	6.2
	56	0.95	1.00	1.16	1.01	1.03	8.8
B2	28	2.15	2.00	2.32	2.11	2.15	6.1
	56	0.55	0.63	0.60	0.72	0.63	11.6
B3	28	1.36	1.39	1.58	1.66	1.50	9.7
	56	1.92	1.51	1.77	1.58	1.70	11.0
B4	28	0.34	0.31	0.40	0.31	0.34	12.4
	56	0.30	0.30	0.19	0.23	0.26	21.9
B5	28	0.22	0.26	0.25	0.24	0.24	6.8
	56	0.17	0.18	0.17	0.17	0.17	3.3

3.4.3.4. Figg's Air Permeability Measurements

Figg's air permeability tests were conducted by project consultant. Figg's tests were performed on the standard cylinder specimens and also in the field within the proximity of the UPV measurement locations.

Figg's air permeability test results performed on the standard cylinder specimens at 28 and 56 days of concrete age are presented in Tables 13(a) & (b). A total of nine measurements were made on three 6 inches by 12 inch cylinders. In Table 13(a) & (b) the first group of rows presents the time elapsed for the reduction of vacuum pressure from -55 kPa to -50 kPa. The second group of rows presents the index of permeability called the air extrusion rate (AER) as defined in Figg's apparatus users manual. Finally, the last group of rows presents the associated rating obtained from AER, also described in the users manual (CSTR 1987). The rating is a five point ordinal scale between 0 to 4 with 0 corresponding to a concrete permeability of worst quality, and 4 corresponding to best quality.

Table 13a. Figg's Air-Permeability Measurements for Standard Specimens, 28-Day

Bridge ID	28 days										
	Time (sec)										
	#1	#2	#3	#4	#5	#6	#7	#8	#9	Mean	COV (%)
B1	1000	-	-	1000	237	190	32	33	-	**415**	**111**
B2	1000	1000	1000	1000	1000	1000	1000	842	1000	**982**	**5**
B3	306	324	122	1000	197	680	129	495	-	**407**	**75**
B4	1000	1000	1000	-	1000	-	1000	-	1000	**1000**	**0**
B5	-	1000	1000	1000	1000	800	1000	1000	811	**951**	**9**
	AER (s/ml)										
B1	247	-	-	247	59	47	8	8	-	**103**	**111**
B2	247	247	247	247	247	247	247	208	247	**243**	**5**
B3	75	80	30	247	49	168	32	122	-	**100**	**75**
B4	247	247	247	-	247	-	247	-	247	**247**	**0**
B5	-	247	247	247	247	198	247	247	200	**235**	**9**
	Rating										
B1	4	-	-	4	3	3	1	1	-	**3**	**51**
B2	4	4	4	4	4	4	4	4	4	**4**	**0**
B3	3	3	3	4	3	4	3	4	-	**3**	**15**
B4	4	4	4	-	4	-	4	-	4	**4**	**0**
B5	-	4	4	4	4	4	4	4	4	**4**	**0**

- Data not reliable

Table 13b. Figg's Air-Permeability Measurements for Standard Specimens, 56-Day

Bridge ID	56 days										
	Time (sec)										
	#1	#2	#3	#4	#5	#6	#7	#8	#9	Mean	COV (%)
B1	649	-	-	1000	1000	1000	1000	650	-	**883**	**20**
B2	1000	1000	1000	154	1000	242	1000	1000	1000	**822**	**43**
B3	32	32	39	229	138	166	56	55	-	**93**	**80**
B4	706	1000	1000	-	1000	-	1000	-	1000	**951**	**13**
B5	-	1000	1000	1000	1000	1000	1000	1000	1000	**1000**	**0**
	AER (s/ml)										
B1	160	-	-	247	247	247	247	161	-	**218**	**20**
B2	247	247	247	38	247	60	247	247	247	**203**	**43**
B3	8	8	10	56	34	41	14	14	-	**23**	**80**
B4	174	247	247	-	247	-	247	-	247	**235**	**13**
B5	-	247	247	247	247	247	247	247	247	**247**	**0**
	Rating										
B1	4	-	-	4	4	4	4	4	-	**4**	**0**
B2	4	4	4	3	4	3	4	4	4	**4**	**12**
B3	1	1	1	3	3	3	2	2	-	**2**	**46**
B4	4	4	4	-	4	-	4	-	4	**4**	**0**
B5	-	4	4	4	4	4	4	4	4	**4**	**0**

- Data not reliable

Figg's air permeability measurements made on the bridge decks at 28 and 56 days of concrete age are presented in Tables 14(a) & (b).

Table 14a. Figg's Field Air-Permeability Measurements at Field, 28-Day

Bridge ID	**28 days**									
	Time (sec)									
	#1	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**	**#8**	**Mean**	**COV (%)**
B1	180	1000	451	16	383	1000	364	909	**538**	**71**
B2	---	---	---	---	---	---	---	---	---	---
B3	71	-	38	453	34	263	202	335	**199**	**81**
B4	1000	1000	-	1000	1000	1000	1000	1000	**1000**	**0**
B5	1000	1000	1000	643	863	1000	863	1000	**921**	**14**
	AER (s/ml)									
B1	44	247	111	4	95	247	90	225	**133**	**71**
B2	---	---	---	---	---	---	---	---	---	---
B3	18	-	9	112	8	65	50	83	**49**	**81**
B4	247	247	-	247	247	247	247	247	**247**	**0**
B5	247	247	247	159	213	247	213	247	**228**	**14**
	Rating									
B1	3	4	4	1	3	4	3	4	**3**	**32**
B2	---	---	---	---	---	---	---	---	---	---
B3	2	-	1	4	1	3	3	3	**2**	**47**
B4	4	4	-	4	4	4	4	4	**4**	**0**
B5	4	4	4	4	4	4	4	4	**4**	**0**

- Data not reliable

--- Tests are not performed for B2 at 28- and 56-days

Table 14b. Figg's Field Air-Permeability Measurements at Field, 56-Day

Bridge ID	56 days									
	Time (sec)									
	#1	#2	#3	#4	#5	#6	#7	#8	Mean	COV (%)
B1	1000	688	19	1000	1000	600	940	-	**750**	**48**
B2	---	---	---	---	---	---	---	---	---	---
B3	1000	-	1000	-	-	-	-	-	**1000**	**0**
B4	1000	1000	1000	1000	928	1000	1000	1000	**991**	**3**
B5	1000	1000	1000	1000	1000	1000	747	479	**903**	**21**
	AER (s/ml)									
B1	247	170	5	247	247	148	232	-	**185**	**48**
B2	---	---	---	---	---	---	---	---	---	---
B3	247	-	247	-	-	-	-	-	**247**	**0**
B4	247	247	247	247	229	247	247	247	**245**	**3**
B5	247	247	247	247	247	247	185	118	**223**	**21**
	Rating									
B1	4	4	1	4	4	4	4	-	**4**	**32**
B2	---	---	---	---	---	---	---	---	---	---
B3	4	-	4	-	-	-	-	-	**4**	**0**
B4	4	4	4	4	4	4	4	4	**4**	**0**
B5	4	4	4	4	4	4	4	4	**4**	**0**

- Data not reliable

--- Tests are not performed for B2 at 28- and 56-days

3.4.3.5. Figg's Water Permeability Measurements

Figg's water permeability tests were conducted by project consultant. Figg's tests were conducted on standard cylinder specimens and within the proximity of the UPV measurement locations.

Tables 15(a) & (b) presents the Figg's water permeability measurements on standard specimens at 28- and 56-day. In Tables 15(a) & (b), the first group of rows is the elapsed time for concrete to absorb 0.01 ml of water. The second group of rows is the index of permeability, the water absorption rate (WAR), and the last group of rows presents the associated concrete quality rating given in the Figg's apparatus users manual of the. The concrete quality ratings are the same as the gas permeability ratings with five ordinal scales between 0 to 4, with 0 corresponding to concrete permeability rated "worst", and 4 rated "best".

Table 15a. Figg's Water-Permeability Test Results for Standard Specimens, 28-Day

Bridge ID	**28 days**										
	Time (sec)										
	#1	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**	**#8**	**#9**	**Mean**	**COV (%)**
B1	860	-	-	282	524	286	670	637	-	**543**	**42**
B2	1000	1000	1000	340	1000	1000	100	840	797	**786**	**43**
B3	41	98	18	216	128	232	19	270	-	**128**	**79**
B4	521	571	717	-	991	-	374	-	768	**657**	**33**
B5	-	931	1000	1000	974	1000	916	1000	949	**971**	**4**
	WAR (s/ml)										
B1	86	-	-	28	52	29	67	64	-	**54**	**42**
B2	100	100	100	34	100	100	10	84	80	**79**	**43**
B3	4	10	2	22	13	23	2	27	-	**13**	**79**
B4	52	57	72	-	99	-	37	-	-	**63**	**37**
B5	-	93	100	100	97	100	92	100	95	**97**	**4**
	Rating										
B1	3	-	-	2	3	2	3	3	-	**3**	**19**
B2	3	3	3	3	3	3	2	3	3	**3**	**12**
B3	1	1	0	2	2	2	0	2	-	**1**	**71**
B4	3	3	3	-	3	-	3	-	-	**3**	**0**
B5	-	3	3	3	3	3	3	3	3	**3**	**0**

- Data not reliable

Table 15b. Figg's Water-Permeability Test Results for Standard Specimens, 56-Day

Bridge ID	56 days										
	Time (sec)										
	#1	#2	#3	#4	#5	#6	#7	#8	#9	Mean	COV (%)
B1	232	-	-	218	178	178	468	217	-	**249**	**44**
B2	18	-	-	44	43	43	50	30	-	**38**	**31**
B3	177	95	39	1000	1000	-	82	33	69	**312**	**137**
B4	1000	772	75	1000	1000	-	1000	116	1000	**745**	**55**
B5	1000	1000	428	1000	1000	-	-	1000	-	**905**	**26**
	WAR (s/ml)										
B1	23	-	-	22	18	18	47	22	-	**25**	**44**
B2	2	-	-	4	4	4	5	3	-	**4**	**31**
B3	18	10	4	100	100	-	8	3	7	**31**	**137**
B4	100	77	8	100	100	-	100	12	100	**75**	**55**
B5	100	100	43	100	100	-	-	100	-	**90**	**26**
	Rating										
B1	2	-	-	2	2	2	3	2	-	**2**	**19**
B2	0	-	-	1	1	1	1	0	-	**1**	**77**
B3	2	1	1	3	3	-	1	1	1	**2**	**56**
B4	3	3	1	3	3	-	3	2	3	**3**	**28**
B5	3	3	3	3	3	-	-	3	-	**3**	**0**

- Data not reliable

Figg's water-permeability measurements performed on each bridge deck at 28- and 56-days of concrete age are presented in Tables 16(a) & (b). Tables 16(a) & (b) are similar to all the previous Figg permeability measurement tables: 13(a) & (b), 14(a) & (b), and 15(a) & (b). The concrete permeability rating was previously described.

Table 16a. Figg's Water-Permeability Test Results at Field, 28-Day

Bridge ID	**28 days**									
	Time (sec)									
	#1	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**	**#8**	**Mean**	**COV (%)**
B1	13	27	24	24	304	54	33	637	**139**	**160**
B2	---	---	---	---	---	---	---	---	---	---
B3	228	-	168	46	126	533	51	20	**167**	**106**
B4	1000	527	-	360	272	157	136	130	**369**	**85**
B5	92	79	134	31	53	55	53	325	**103**	**93**
	WAR (s/ml)									
B1	1	3	2	2	30	5	3	64	**14**	**160**
B2	---	---	---	---	---	---	---	---	---	---
B3	23	-	17	5	13	53	5	2	**17**	**106**
B4	100	53	-	36	27	16	14	13	**37**	**85**
B5	9	8	13	3	5	6	5	32	**10**	**93**
	Rating									
B1	0	0	0	0	3	1	1	3	**1**	**131**
B2	---	---	---	---	---	---	---	---	---	---
B3	2	-	2	1	2	3	1	0	**2**	**62**
B4	3	3	-	3	2	2	2	2	**2**	**22**
B5	1	1	2	1	1	1	1	3	**1**	**54**

- Data not reliable

--- Tests are not performed for B2 at 28- and 56-days

Table 16b. Figg's Water-Permeability Test Results at Field, 56-Day

Bridge ID	56 days									
	Time (sec)									
	#1	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**	**#8**	**Mean**	**COV (%)**
B1	1000	266	69	1000	923	707	875	-	**691**	**54**
B2	---	---	---	---	---	---	---	---	---	---
B3	748	-	151	-	-	-	-	-	**450**	**94**
B4	1000	231	335	1000	84	974	734	385	**593**	**64**
B5	1000	-	1000	1000	659	701	924	889	**882**	**16**
	WAR (s/ml)									
B1	100	27	7	100	92	71	88	-	**69**	**54**
B2	---	---	---	---	---	---	---	---	---	---
B3	75	-	15	-	-	-	-	-	**45**	**94**
B4	100	23	34	100	8	97	73	39	**59**	**64**
M **B5**	100	-	100	100	66	70	92	89	**88**	**16**
B5										
	3	2	1	3	3	**Rating** 3	3	-	**3**	**31**
B1	---	---	---	---	---	---	---	---	---	---
B2	3	-	2	-	-	-	-	-	**3**	**28**
B3	3	2	3	3	1	3	3	3	**3**	**28**
B4	3	-	3	3	3	3	3	3	**3**	**0**
B5										

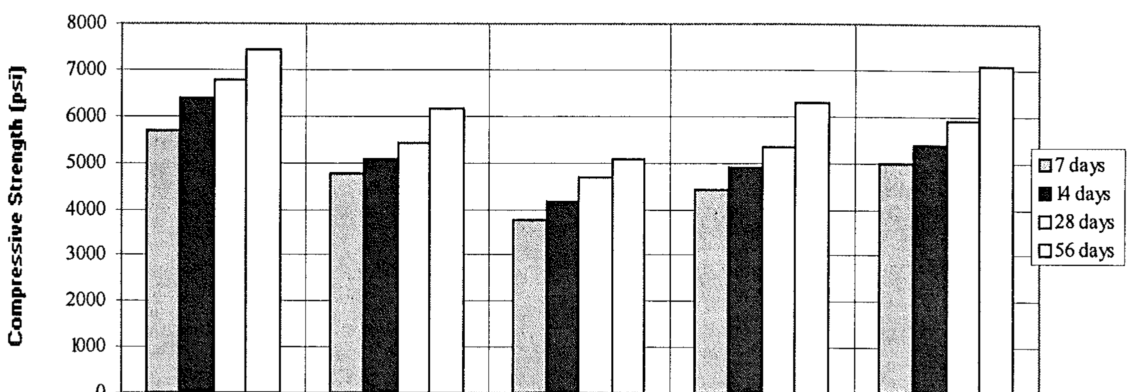
- Data not reliable

--- Tests are not performed for B2 at 28- and 56-days

4.0. DISCUSSION OF RESULTS

4.1. Concrete Mechanical Properties

Compressive strength tests results performed at 7-, 14-, 28-, and 56-days of concrete age are summarized in Figure 14. The 56-day test specimens were kept in the ambient lab air following 28 days of moist curing. Beyond 28-day moisture loss from the specimens are expected. It is documented that the compressive strength of mature concrete increases with the loss of moisture. Thus, a more rapid strength gain is expected between the 28- and 56-day of concrete maturity. In figure 14 as expected, concrete strength increased with age, and in some cases (B2, B4, B5) more rapidly beyond 28 days. The lowest average compressive strengths were reported for B3, located at Oakman Avenue over Lodge Freeway (M-10).



	B1	B2	B3	B4	B5
7 days	5688	4777	3750	4425	4988
14 days	6375	5075	4150	4898	5370
28 days	6773	5408	4657	5333	5918
56 days	7427	6173	5087	6298	7102

Bridge ID

Figure 14. Results of Compressive Strength Tests

The modulus of elasticity test results are presented in Figure 15. The 56-day concrete test specimens were moist cured for 28 days then they were air-dried until test day. Whereas 28-day measurements were performed on wet specimens moist cured until the day of testing. Unlike the effect of moisture loss on compressive strength, there is a loss of concrete modulus of elasticity from saturated to dry state. In most cases the loss is compensated by the gain in the modulus of elasticity with maturity. For that reason, no significant change in the modulus of elasticity was observed between the 28- and 56-day measurements for all bridges, except B3, Oakman Avenue over Lodge Freeway (M-10).

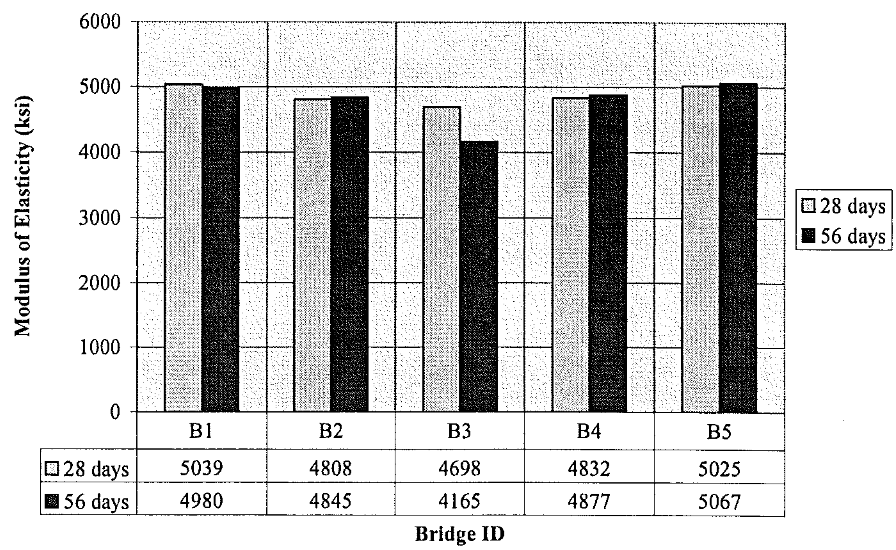


Figure 15. Results of Modulus of Elasticity Tests

4.2. Concrete Permeability Measurement Results

Four different permeability tests were conducted on the standard cylinder specimens. One field permeability test was conducted on the in-situ bridge-decks.

As reported in Figure 16, the RCPT measurements show a visible decrease of the measured parameter (coulombs passed) from 28 days to 56 days with increasing concrete age. The lowest coulombs passed were measured on standard specimens of concrete mixture used in B4 and B5, I-75 NBD to I-94 EBD connector.

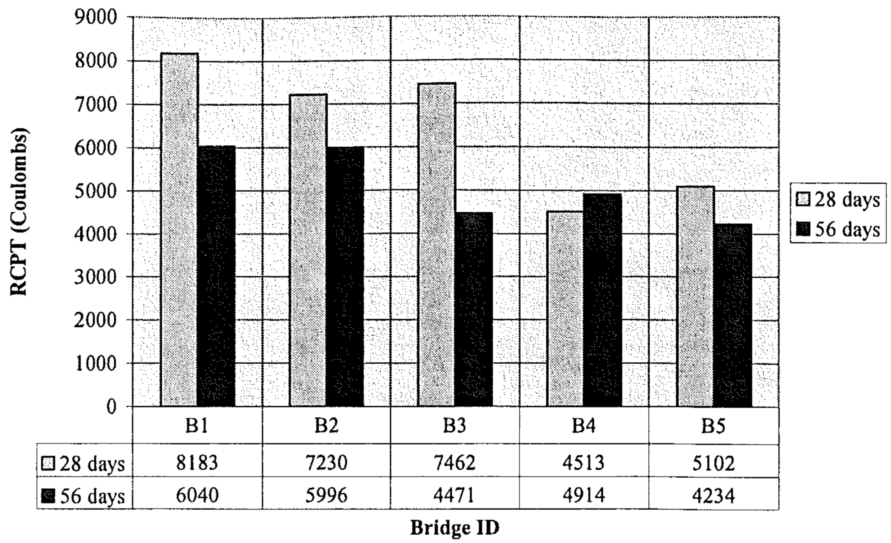


Figure 16. Results of RCPT Test

Figure 17 presents the 90-day porosity measurements. Using only the 90-day results will make the comparisons useful.

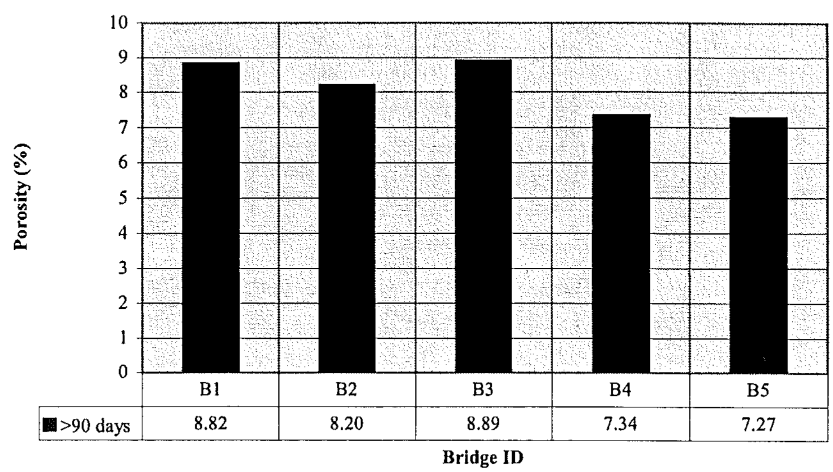


Figure 17. Results of Porosity Test

Figure 18 presents the gas permeability test results. The highest measured gas permeability was observed on B1, Scotten Street over Michigan Avenue. However, due to a significant decrease from 28- to 56-day measurements for that bridge the 28-day data maybe unreliable. For most of the bridge decks, the gas permeability coefficient decreased between the 28 to 56 days measurements.

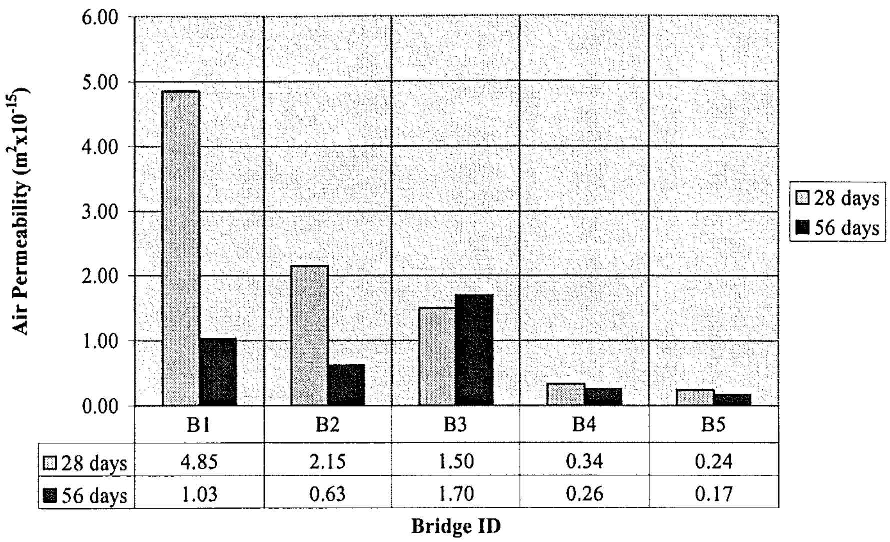
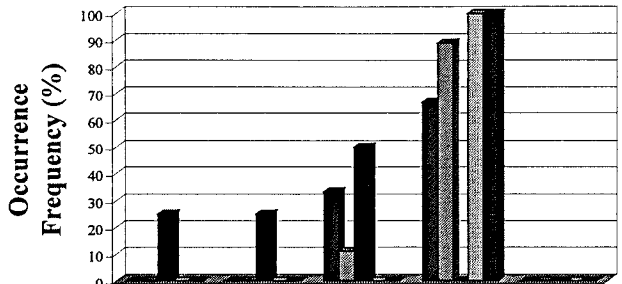


Figure 18. Results of Gas permeability Test

Figg's air and water permeability tests cannot provide a quantitative evaluation of concrete permeability. The data is used to qualitatively evaluate the permeability of the standard specimens and field measurements on the bridge decks. In the qualitative assessment, the occurrence frequency of the concrete rating obtained from Figg's test measurements for the standard specimens are plotted against the rating in Figure 19 and for the bridge decks in Figure 20.



	0, Poor	1, Not Good	2, Fair	3, Good	4, Excellent
B1	0	0	33	67	0
B2	0	0	11	89	0
B3	25	25	50	0	0
B4	0	0	0	100	0
B5	0	0	0	100	0

Rating

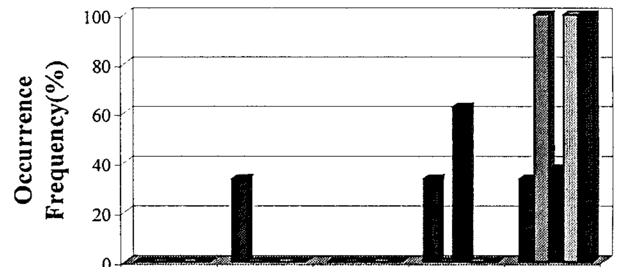
(28 days)

	0, Poor	1, Not Good	2, Fair	3, Good	4, Excellent
B1	0	0	83	17	0
B2	33	67	0	0	0
B3	0	63	13	25	0
B4	0	0	0	100	0
B5	0	0	0	100	0

Rating

(56 days)

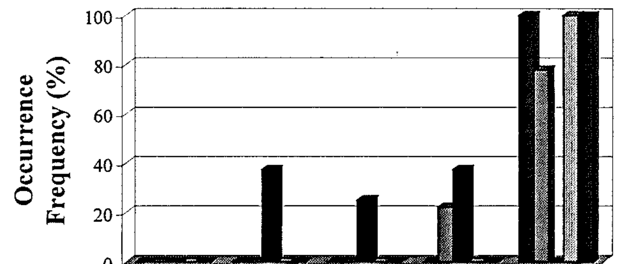
Figg's Water Permeability Test



	0, Poor	1, Not Good	2, Fair	3, Good	4, Excellent
B1	0	33	0	33	33
B2	0	0	0	0	100
B3	0	0	0	63	38
B4	0	0	0	0	100
B5	0	0	0	0	100

Rating

(28 days)



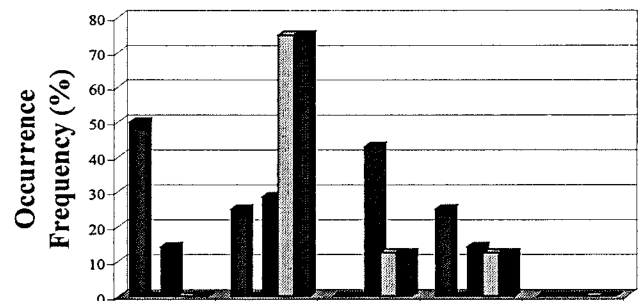
	0, Poor	1, Not Good	2, Fair	3, Good	4, Excellent
B1	0	0	0	0	100
B2	0	0	0	22	78
B3	0	38	25	38	0
B4	0	0	0	0	100
B5	0	0	0	0	100

Rating

(56 days)

Figg's Gas permeability Test

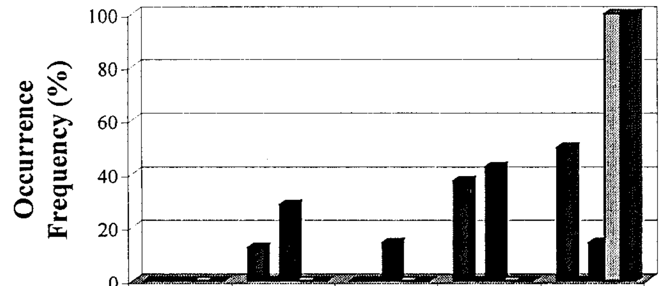
Figure 19. Results of Figg's Water and Gas permeability Tests for Standard Specimens



	0, Poor	1, Not Good	2, Fair	3, Good	4, Excellent
B1	50	25	0	25	0
B2	---	---	---	---	---
B3	14	29	43	14	0
B4	0	75	13	13	0
B5	0	75	13	13	0

Rating

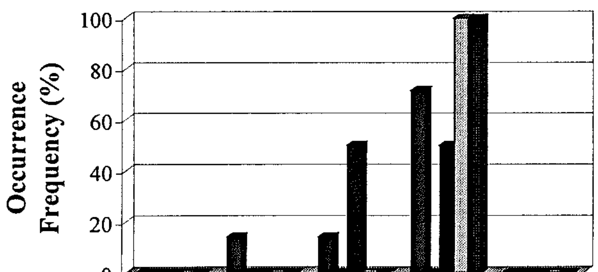
(28 days)



	0, Poor	1, Not Good	2, Fair	3, Good	4, Excellent
B1	0	13	0	38	50
B2	---	---	---	---	---
B3	0	29	14	43	14
B4	0	0	0	0	100
B5	0	0	0	0	100

Rating

(28 days)

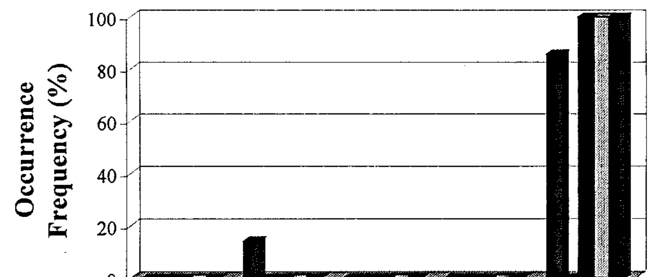


	0, Poor	1, Not Good	2, Fair	3, Good	4, Excellent
B1	0	14	14	71	0
B2	0	0	0	0	0
B3	0	0	50	50	0
B4	0	0	0	100	0
B5	0	0	0	100	0

Rating

(56 days)

Figg's Water Permeability Test



	0, Poor	1, Not Good	2, Fair	3, Good	4, Excellent
B1	0	14	0	0	86
B2	---	---	---	---	---
B3	0	0	0	0	100
B4	0	0	0	0	100
B5	0	0	0	0	100

Rating

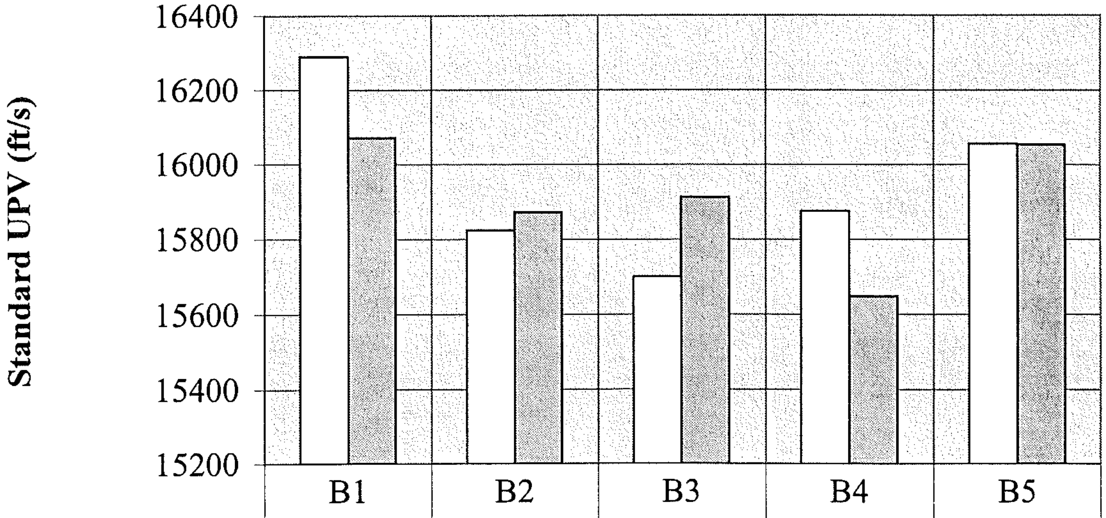
(56 days)

Figg's Gas permeability Test

Figure 20. Results of Figg's Water and Gas permeability Tests on Bridge Decks

4.3. UPV Measurement Results

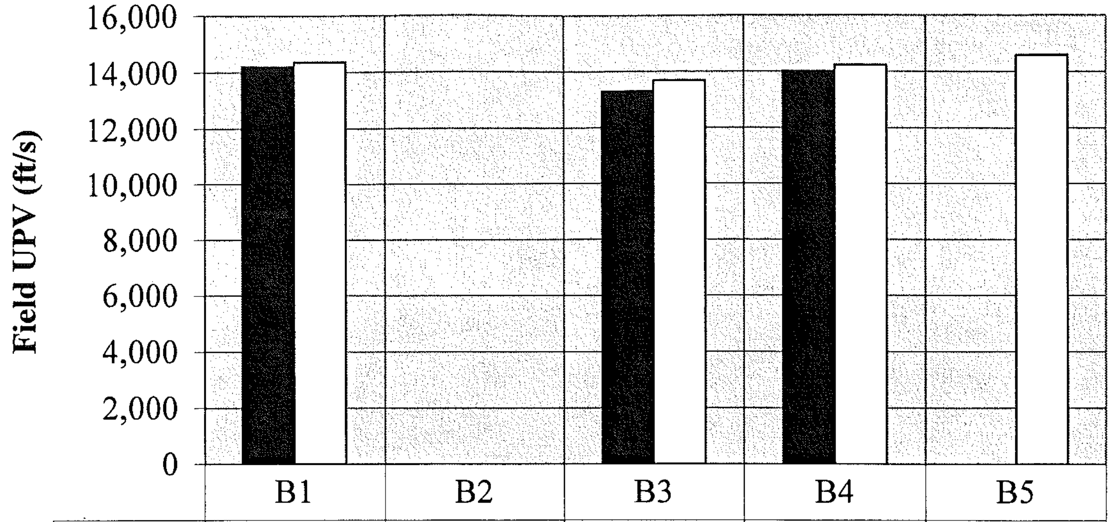
The UPV measurement results started from standard cylinder specimens at 28- and 56-days of age are presented in Figure 21. The lowest UPV was measured for B3, Oakman Avenue over Lodge Freeway (M-10).



	B1	B2	B3	B4	B5
□ 28 days, wet	16290	15824	15701	15875	16056
▨ 56 days, air	16071	15872	15912	15648	16054

Figure 21. Results of UPV Measurements on the Standard Cylinders

Figure 22 presents the UPV measurements obtained on the bridge decks at 28- and 56-days of age. The UPV measured on the bridge decks can change with the type of coarse aggregate in the concrete mix. In the cases where coarse aggregate remains the same, the decrease in UPV is indicative of other mix parameters (water cement ratio and entrained air) and curing regimes. In this study, we will not be making comparative evaluations of UPV measurements on various bridge decks. The UPV comparisons will be made for each deck between the measurements made on the standard specimens and field measurements, which will be described in the next section.



	B1	B2	B3	B4	B5
■ 28 days	14,201	N/A	13,293	14,018	T.B.D.
□ 56 days	14,355	N/A	13,689	14,243	14,597

Bridge ID

Figure 22. Results of UPV Measurements on the Field Bridge Decks

4.4. Paste Quality Loss (PQL) Evaluation

The paste efficiency relationship for concrete permeability provided the impetus for the development of the ultrasonic pulse velocity measurement procedure for the assessment of bridge deck permeability. The paste efficiency principle is implemented, during the casting of five bridge decks as follows:

- Standard specimens were prepared and cured in the laboratory
- UPV measurements were obtained on the bridge deck and on the standard specimens at 28- and 56-day.
- The decrease in bridge deck UPV from the UPV of standard specimens at 28- and 56-day is proportional to the increased in permeability of the deck concrete.
- The change in UPV and its variability is quantified by a parameter described as the "Paste Quality Loss (PQL)".

The field permeability of concrete in relation to standard specimens is defined in the following relation as in Figure 23. In Figure 23, the two bell curves describe the UPV measurements obtained from standard specimens and bridge decks and their probabilities. The PQL is calculated from the means of these two measurements and their variability.

The variability of the UPV measurements on the standard specimens is the inherent variability, which is due to changing coarse aggregate arrangement, changing air content between the specimens, and differences in compaction. The variability of the UPV measurements on the bridge decks beyond the inherent variability is due to defects that adversely affect concrete permeability.

$$PQL = \alpha \frac{\overline{V}_s - \overline{V}_F}{\overline{V}_s}$$

$$\alpha = \frac{0.954}{P_F}$$

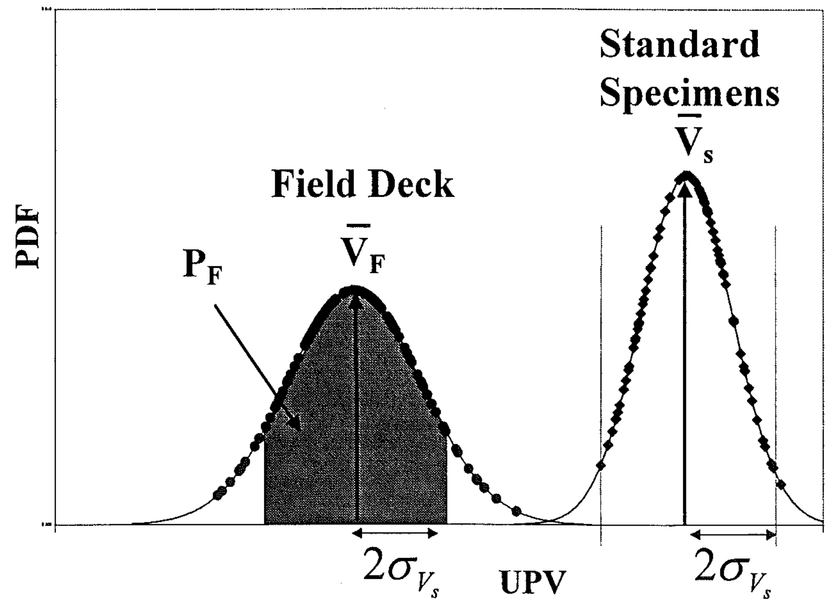


Figure 23. PQL Definition

Paste efficiency principle procedure assumes that the concrete is proportioned according to specifications and the measured loss of paste quality is due to field effects. The coefficient "α" shown in the equation is a statistical parameter for normalizing the variability of concrete mixture parameters such as entrained air with field variability. The PQL gives the change in intrinsic permeability between the standard and field concrete.

The results are presented in Table 17, which shows the 14-, 28- and 56-day UPV measurements obtained from the five bridge decks and the standard specimens associated with the decks and the evaluated PQL. PQL is shown separately for the individual measurement locations, and the second value combines all the measurement locations to yield a global PQL value. As observed from the table B3, Oakman Avenue over Lodge Freeway (M-10), the highest PQL of 31% at 56 days of concrete age.

Table 17. PQL for Bridge Decks

Bridge ID	Location	PQL (%)			Location	PQL (%)		
		14	28	56		14	28	56
B1	#1	11	30	14	all	12	23	15
	#2	10	34	13				
	#3	11	30	17				
	#4	8	14	12				
B2	#1	14	---	---	all	16	---	---
	#2	13	---	---				
	#3	19	---	---				
	#4	14	---	---				
B3	#1	14	20	40	all	22	23	31
	#2	18	19	34				
	#3	21	26	35				
	#4	18	33	24				
B4	#1	24	32	20	all	20	21	23
	#2	31	13	24				
	#3	17	16	21				
	#4	19	17	13				
B5	#1	14	14	10	all	15	T.B.D.	9
	#2	19	15	10				
	#3	13	18	7				
	#4	14	16	9				

--- Tests are not performed for B2 at 28- and 56- day

5.0. SUMMARY AND CONCLUSIONS

5.1. Summary

This phase of the research dealt with the field implementation procedure for the assessment of concrete permeability using ultrasonic pulse velocity measurements. The methods and procedures developed in the previous phases of this research project are applied to actual bridge decks for concrete bridge deck durability assessment at early ages.

In order to calibrate the implementation procedure of the paste efficiency method, four bridge deck replacement projects were selected. The field implementation consisted of execution of the paste efficiency principle on the bridge decks. UPV measurements were conducted on the test decks at 14, 28 and 56 days following concrete placement. Figg's air and water permeability tests were also conducted on the test decks at 28 and 56 day. Standard 4 in. and 6 in. diameter cylindrical specimens were prepared during concrete placement and tested to document the concrete properties.

The final outcome of the implementation procedure was to establish the PQL parameter. The PQL is a quantitative measure comparing the permeability of the STD concrete specimens exposed to ideal curing condition against the field permeability of the respective in-situ concrete. The PQL measures the aggregate of all factors adversely affecting concrete permeability between the time concrete delivered to site and until 56 day of age of the bridge deck.

5.2. Conclusions

The research objective was the development and verification of a non-destructive method for early age assessment of concrete bridge deck permeability using UPV measurements. An implementations study compared UPV measurements on deck specimens subjected to different curing procedures. Higher UPV was measured in moist cured deck specimens when compared to decks cured only with the application of a curing compound. Additionally, variability of UPV measurements was significantly lower for moist cured decks. Based on these findings, a parameter called "Paste Quality Loss" (PQL) is defined. In accomplishing the research objective, a theoretical relationship is developed between concrete permeability and UPV. The theoretical relationship relates permeability to the change in UPV.
The empirical study showed the feasibility of developing a permeability measurement procedure using UPV measurements. In the empirical study permeability measured using RCPT showed an increase of 1000 coulombs changes UPV by 215 ft/s. A second empirical study with air entrained concrete showed that a 1% increase of permeable voids reduces UPV by 90 ft/s.

The PQL parameter defines the increase in permeability of concrete in the field from the lowest attainable permeability for that mixture. The UPV measurement for the PQL evaluation can be made between 14 and 56 days.

A field implementation study on four deck replacement projects showed PQL values between 9% to 31%. Knowing that concrete permeability is a credible index of durability, PQL should provide a relative measure of durability.

5.3. Suggestions for Future Research

The research resulted in the development of a tool (PQL) that can quantify the theoretical permeability changes to field concrete permeability that affects its long-term durability. The PQL measure developed here incorporates the aggregate effects of field casting, curing, and finishing practices, structural system and its mechanical properties, and design and detailing of the structural system. The PQL measure developed in this research will be a very useful feedback tool for evaluating the impact of an isolated parameter on durability. For example, the measure could be used to evaluate the effect of different bridge deck curing regimes. Other potential use of the durability measure may be for health monitoring of bridge decks for the timing of preventive maintenance procedures. In this implementation the bridge deck UPV will be measured intermittently. Changes will be documented with the rate of change in UPV, which can be correlated to the deck deterioration rate. A clear model between the UPV changes and deck deterioration can be developed by testing of multiple decks at different levels of deterioration.

6.0. REFERENCES

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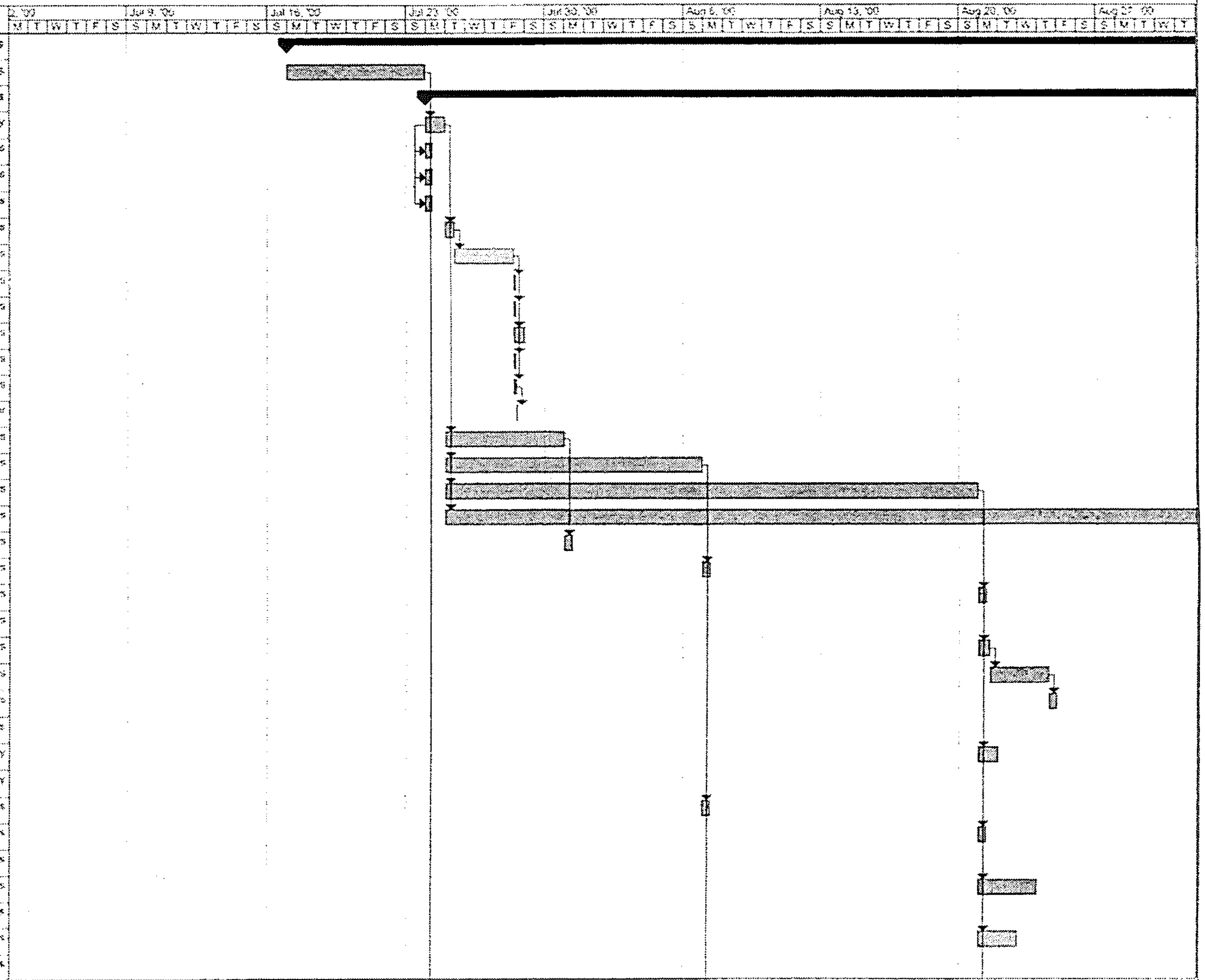
APPENDIX

Test Schedule for the Bridge Decks

Field UPV Measurements of Bridge Decks for Paste Efficiency Implementation

Table 1. Testing Schedule for the Bridges

ID	Task Name	Duration
1	**Testing of Bridges**	**118 days**
2	B01 Uncertainity Time	7 days
3	**Bridge 1**	**59 days**
4	B01_Casting of concr	1 day
5	B01_Unit weight test	2 mins
6	B01_Slump test	2 mins
7	B01_Air content test	2 mins
8	B01_Removal from th	3 hrs
9	B01_Wait for cuts	3 days
10	B01_Cutting the ends	2 hrs
11	B01_Cutting the ends	2 hrs
12	B01_Cutting the ends	6 hrs
13	B01_Cutting the ends	2 hrs
14	B01_Slicing the 4 by (	3 hrs
15	B01_Labeling of the s	1 hr
16	B01_Curing for 7 days	6 days
17	B01_Curing for 14 day	13 days
18	B01_Curing for 28 day	27 days
19	B01_Curing for 56 day	55 days
20	B01_7 day strength	2 hrs
21	B01_14 day strength	2 hrs
22	B01_28 day strength	2 hrs
23	B01_56 day strength	2 hrs
24	B01_28 day saturated	6 hrs
25	B01_dry 28 day elastic	3 days
26	B01_28 day dry elastic	6 hrs
27	B01_56 day elasticity	6 hrs
28	B01_28 day Figg test	1 day
29	B01_56 day Figg test	1 day
30	B01_UPV Specimens	2 hrs
31	B01_UPV Specimens	2 hrs
32	B01_UPV Specimens	2 hrs
33	B01_Porosity 28 day	3 days
34	B01_Porosity 56 day	3 days
35	B01_RCPT 28 day	2 days
36	B01_RCPT 56 day	2 days



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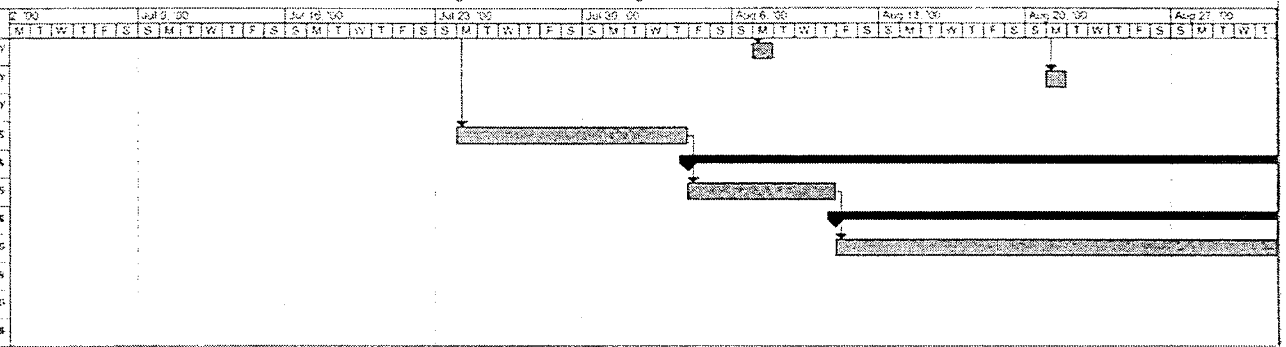
Field UPV Measurements of Bridge Decks for Paste Efficiency Implementation

Table 1. Testing Schedule for the Bridges

ID	Task Name	Duration
37	B01_UPV Field 14 da	1 day
38	B01_UPV Field 28 da	1 day
39	B01_UPV Field 56 da	1 day
40	B02 Uncertainity Time	11 days
41	**Bridge 2**	**59 days**
78	B03 Uncertainity Time	7 days
79	**Bridge 3**	**59 days**
116	B04 Uncertainity Time	28 days
117	**Bridge 4**	**59 days**
154	B05 Uncertainity Time	6 days
155	**Bridge 5**	**59 days**



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Field UPV Measurements of Bridge Decks for Paste Efficiency Implementation

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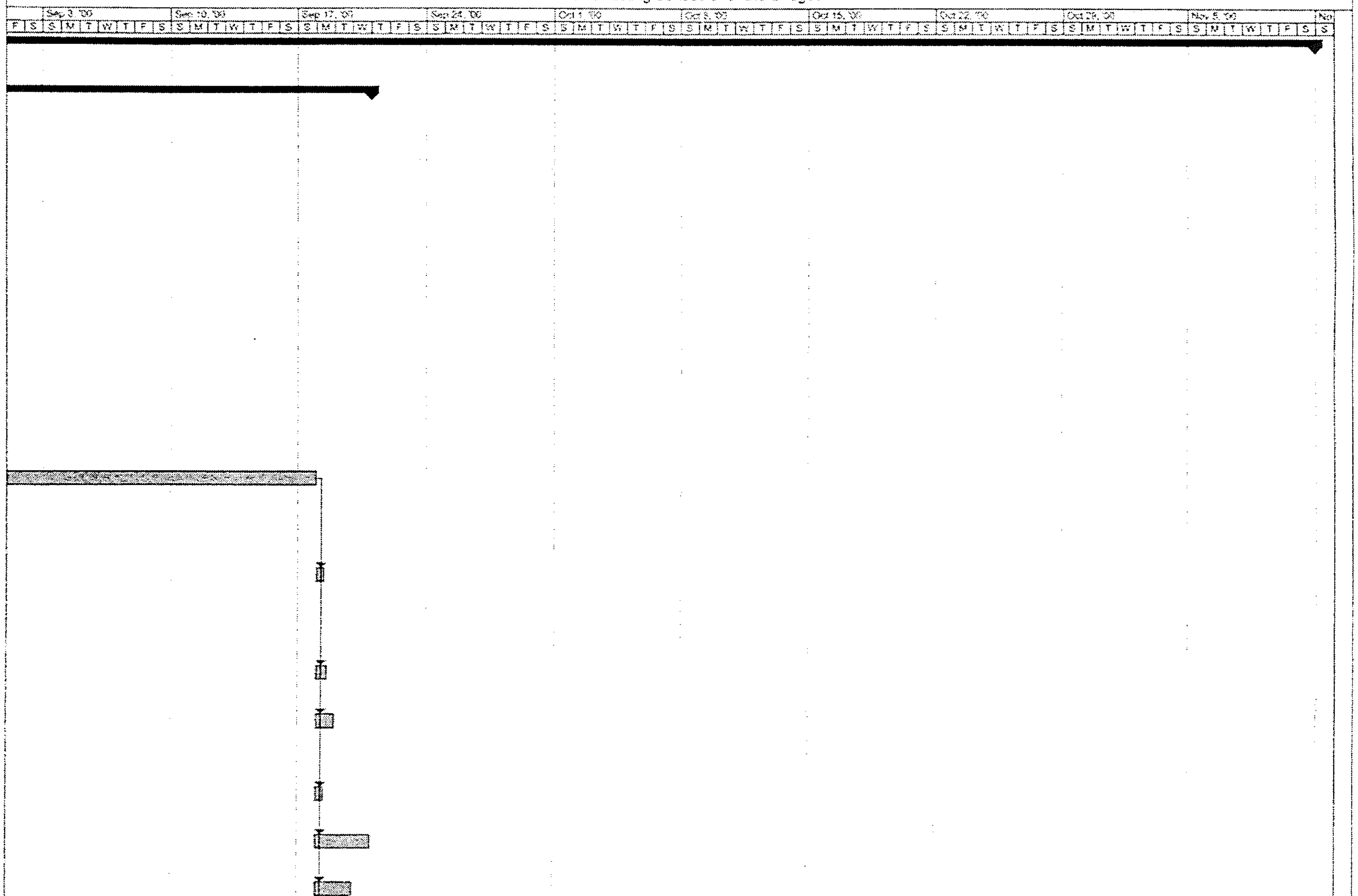

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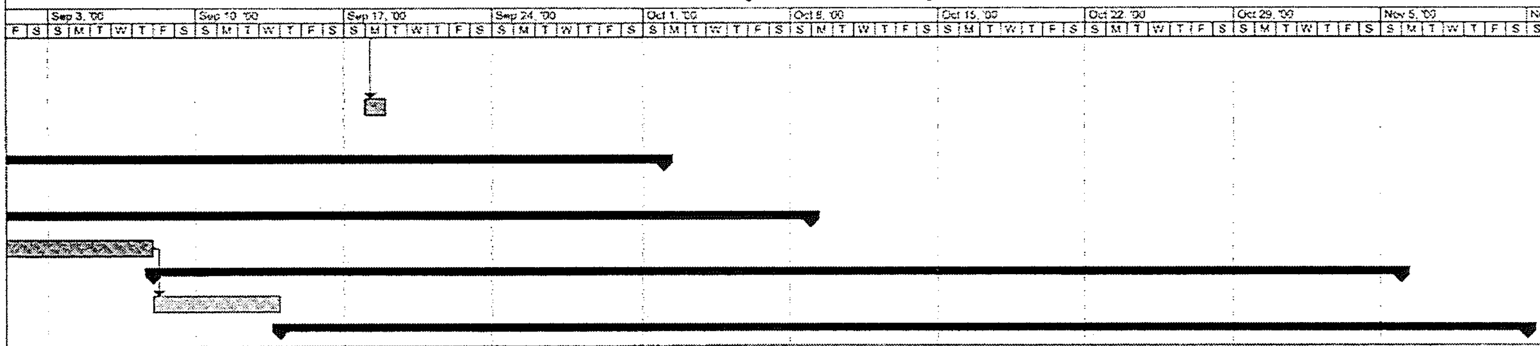
Field UPV Measurements of Bridge Decks for Paste Efficiency Implementation

Table 1. Testing Schedule for the Bridges



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