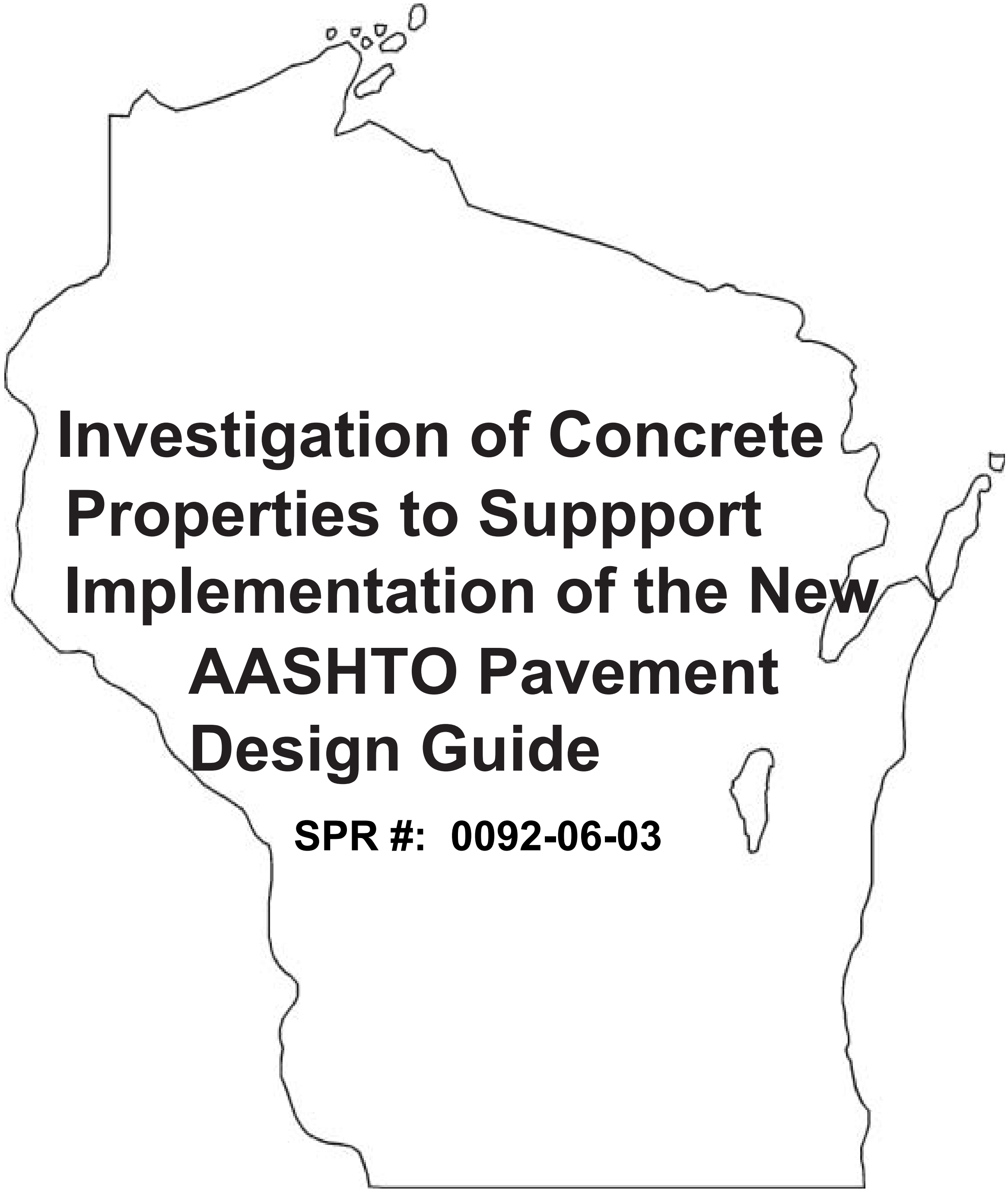
Wisconsin Highway Research Program



Investigation of Concrete Properties to Suppport Implementation of the New AASHTO Pavement Design Guide

SPR #: 0092-06-03

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December 2006

WHRP 06-14

Wisconsin Highway Research Program

Project No. 0092-06-03

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Final Report

by

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Submitted to the Wisconsin Department of Transportation

December 2006

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This research was funded through the Wisconsin Highway Research Program by the Wisconsin Department of Transportation and the Federal Highway Administration under Project # 0092-06-03. The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views of the Wisconsin Department of Transportation or the Federal Highway Administration at the time of publication.

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Acknowledgements

The authors express their deep gratitude to the Wisconsin Department of Transportation (WisDOT) and the Federal Highway Administration (FHWA) for providing funding thorough the Wisconsin Highway Research Program. We are grateful to James Parry of the WisDOT for useful, timely, and constructive comments throughout the planning and execution of this research project.

The authors also wish to thank members of the UWM-CBU laboratory staff and students for their help and cooperation.

The UWM Center for By-Products Utilization was established in 1988 with a generous grant from the Dairyland Power Cooperative, La Crosse, WI; Madison Gas and Electric Company, Madison, WI; National Minerals Corporation, St. Paul, MN; Northern States Power Company, Eau Claire, WI; We Energies, Milwaukee, WI; Wisconsin Power and Light Company, Madison, WI; and, Wisconsin Public Service Corporation, Green Bay, WI. Their financial support and additional grant and support from Manitowoc Public Utilities, Manitowoc, WI, are gratefully acknowledged.

Acronyms and Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
CBU	Center for By-Products Utilization at the University of Wisconsin-Milwaukee
FHWA	Federal Highway Administration
NCHRP	National Cooperative Highway Research Program
UWM	University of Wisconsin-Milwaukee
WHRP	Wisconsin Highway Research Program
WisDOT	Wisconsin Department of Transportation

Cm	Cementitious Materials
FA	Fly Ash
fl oz	fluid ounce
GGBFS	Ground Granulated Blast-Furnace Slag
SSD	Saturated Surface-Dry

Technical Report Documentation Page

1. Report No. WHRP 06-14	2. Government Accession No	3. Recipient's Catalog No
4. Title and Subtitle Investigation of Concrete Properties to Support Implementation of the New AASHTO Pavement Design Guide		5. Report Date December 01, 2006 6. Performing Organization Code
7. Authors Tarun R. Naik, Yoon-moon Chun, and Rudolph N. Kraus		8. Performing Organization Report No. CBU-2006-18
9. Performing Organization Name and Address UWM Center for By-Products Utilization, Department of Civil Engineering and Mechanics University of Wisconsin-Milwaukee P. O. Box 784, Milwaukee, WI 53201		10. Work Unit No. (TRAIS) 11. Contract or Grant No. WisDOT SPR# 0092-06-03
12. Sponsoring Agency Name and Address Wisconsin Department of Transportation 4802 Sheboygan Avenue Madison, WI 73707-7965		13. Type of Report and Period Covered Final Report 10/01/2005 – 12/01/2006 14. Sponsoring Agency Code

15. Supplementary Notes

Research was funded by the Wisconsin DOT and FHWA through the Wisconsin Highway Research Program. Wisconsin DOT contact: Mr. James Parry (608) 246-7939.

16. Abstract

This research was conducted to investigate the splitting tensile strength and coefficient of thermal expansion (CTE) of concrete to support implementation of the AASHTO Mechanistic-Empirical Pavement Design Guide in Wisconsin. WisDOT Grade A-FA Class C fly ash concrete mixtures containing selected types of coarse aggregates from 15 sources were investigated: glacial gravel from six sources, dolomite from five sources, quartzite, granite, diabase, and basalt. In addition, using concrete containing dolomite, effects of cementitious materials were investigated such as the source of cement, the source of fly ash, the use of GGBFS vs. fly ash, and the use of cement alone vs. cement plus fly ash.

The splitting tensile strength test results of the concrete mixtures made with glacial gravel varied when the source of the gravel was changed. The splitting tensile strength of concrete mixtures made with dolomite varied significantly depending on the source. The types and sources of cementitious materials also affected the splitting tensile strength of the concrete made with dolomite. The splitting tensile strength measured by this testing program was about 30% higher, when compared with the values estimated from compressive strength using the mechanistic-empirical design guide for Level 2 design (lower accuracy than Level 1).

Concrete using quartzite had the highest CTE of 12.2×10^{-6}/°C (6.8×10^{-6}/°F). Concrete mixtures using diabase, basalt, and granite had the lowest CTE of 9.3 to 9.5×10^{-6}/°C (5.2 to 5.3×10^{-6}/°F). Concrete mixtures using glacial gravel from the six sources had CTE values of 9.7 to 10.7×10^{-6}/°C (5.4 to 5.9×10^{-6}/°F). Concrete mixtures using dolomite from the five sources had relatively uniform CTE values of 10.4 to 10.8×10^{-6}/°C (5.8 to 6.0×10^{-6}/°F). The types and sources of cementitious materials had a negligible influence, 0.0 to 0.2×10^{-6}/°C (0.0 to 0.1×10^{-6}/°F), on the CTE of concrete made with dolomite.

It is recommended that concrete containing cementitious materials and coarse aggregates other than the ones evaluated in this project be tested for splitting tensile strength. It is also recommended that concrete containing coarse aggregates other than the ones evaluated in this project be tested for CTE. CTE testing of concrete containing other sources of dolomite does not appear to be necessary.

17. Key Words Coefficient of thermal expansion, concrete, mechanistic-empirical design, pavement, splitting tensile strength.	18. Distribution Statement No restriction. This document is available to the public through the National Technical Information Service 5285 Port Royal Road Springfield VA 22161

19. Security Classif. (of this report) Unclassified	19. Security Classif. (of this page) Unclassified	20. No. of Pages	21. Price

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Executive Summary

PROJECT SUMMARY, BACKGROUND, AND PROCESS

This research was conducted to investigate the splitting tensile strength and coefficient of thermal expansion (CTE) of concrete to support implementation of the AASHTO Mechanistic-Empirical Pavement Design Guide in Wisconsin. One of the advantages of such a method is that the pavement behavior is predicted based on actual material properties and response to stresses. The new AASHTO pavement design procedure was developed to estimate the long-term pavement behavior using a more rational method than most of the earlier AASHTO design guides for pavement design.

In order to implement the mechanistic-empirical design procedure and take advantage of the potential cost savings, WisDOT also identified material properties required for the design of rigid pavement (concrete pavement) that had not been previously measured by the WisDOT. The two properties evaluated in this project were the indirect tensile strength as measured by AASHTO T 198, "Splitting Tensile Strength of Cylindrical Concrete Specimens," and the coefficient of thermal expansion (CTE), measured by the AASHTO provisional test standard TP 60, "Coefficient of Thermal Expansion of Hydraulic Cement Concrete." The WisDOT has also reported that the design of the thickness of the pavement, and the predicted performance of the pavement are very sensitive to changes in the splitting tensile strength and the CTE. The focus of this project was to develop input values for the new pavement design procedure for concrete pavement construction in Wisconsin. This project was conducted to document and evaluate the concrete containing specified Wisconsin materials for splitting tensile strength and CTE. Compressive strength of concrete was also determined as additional test information. The sources of cement, GGBFS (ground granulated blast-furnace slag), fly ash, and aggregate were selected in consultation with the WisDOT and the Wisconsin Highway Research Program Project Manager.

WisDOT Grade A-FA (70% cement plus 30% Class C fly ash) concrete mixtures were investigated containing selected types of coarse aggregates from 15 sources: glacial gravel from six sources, dolomite from five sources, quartzite, granite, diabase, and basalt. In addition, the effects of the cementitious materials in concrete mixtures containing dolomite were investigated such as the source of cement, the source of fly ash, the use of GGBFS vs. fly ash, and the use of cement alone vs. cement plus fly ash.

FINDINGS AND CONCLUSIONS

The compressive strength of the concrete was affected significantly by the type and source of the coarse aggregate. The compressive strength of concrete made with glacial gravels from the different sources varied significantly in terms of magnitude and development pattern with time. The compressive strength of concrete made with dolomite also varied significantly depending on the source of the dolomite. The types and sources of cementitious materials influenced the compressive strength of concrete made with dolomite.

The splitting tensile strength test results of the concrete mixtures made with glacial gravel varied when the source of the gravel was changed. The splitting tensile strength of concrete mixtures made with dolomite varied significantly depending on the source. The types and sources of cementitious materials also affected the splitting tensile strength of the concrete made with dolomite.

At a given compressive strength, the corresponding splitting tensile strength varied as much as 1 MPa (about 150 psi), depending on the concrete mixture. In addition, the splitting tensile strength measured by this testing program was on average about 30% higher than the values estimated from compressive strength using the mechanistic-empirical design guide for Level 2 design (lower accuracy than Level 1). Therefore, it is best to establish the splitting tensile strength of concrete by actual testing, rather than estimate it based on compressive strength.

Among the types of coarse aggregates tested, the concrete made with quartzite (Qtz-c1-f1) had the highest CTE, 12.2 microstrain/°C (6.8 microstrain/°F). The concrete mixtures made with diabase, basalt, and granite showed the lowest CTE, ranging from 9.3 to 9.5 microstrain/°C (5.2 to 5.3 microstrain/°F). The CTE of concrete made with glacial gravel from the six sources ranged from 9.7 to 10.7 microstrain/°C (5.4 to 5.9 microstrain/°F). This implies that the sources of glacial gravel selected for this project had different rock and mineral compositions, which affected the CTE. The CTE of concrete mixtures made with dolomite from the five sources was relatively uniform, ranging from 10.4 to 10.8 microstrain/°C (5.8 to 6.0 microstrain/°F). The types and sources of cementitious materials had a negligible influence, 0.0 to 0.2 microstrain /°C (0.0 to 0.1 microstrain/°F), on the CTE of concrete made with dolomite.

RECOMMENDATIONS FOR FURTHER ACTION

It is recommended that test values for splitting tensile strength of concrete mixtures made with the sources of cementitious materials and coarse aggregates not evaluated as part of this project, be determined for use as inputs in the mechanistic-empirical pavement design. CTE testing of concrete made with coarse aggregate from sources not evaluated in this project is also recommended. Based on the relatively uniform CTE values of the concrete mixtures containing the five sources of dolomite, CTE testing of concrete mixtures containing other sources of dolomite does not appear to be necessary.

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Chapter 1. Introduction

1.1 Problem Statement

Wisconsin has over 180,000 km (113,000 miles) of paved state highways and local roads. Construction and repair of existing highway and road pavement is a very significant item included in the budget for the state of Wisconsin. For example, in the 2001-03 biennium, Wisconsin budgeted $2.24 billion for state highway construction, a very significant cost to taxpayers. Cost for road and highway construction has typically increased approximately 6% per year. This budget does not include expenditures by local government or for costs of federal highway construction in Wisconsin. Increased durability of pavements would, in the long-term, significantly reduce the cost of rehabilitation and replacement of portland cement concrete and asphaltic concrete roadway pavements. The National Cooperative Highway Research Program (NCHRP) through a research and development project, Project 1-37A, developed a pavement design procedure that is based on a combination of engineering mechanics and empirical methods [2]. One of the advantages of such a method is that the pavement behavior is predicted based on actual material properties and response to stresses. Most of the earlier AASHTO design guides for pavement design were based on the performance of a pavement section that was subjected to approximately 2 million cycles of axle loads. Currently, many pavement designs require over 100 million load cycles over the design life of the pavement. Clearly an improvement in the reliability of the design was warranted. Therefore, the NCHRP 1-37A pavement design procedure was developed to estimate the long-term pavement behavior using a more rational method. This design procedure is expected to evolve in the future to a design based purely on engineering mechanics. The current state-of-the-art limits the current design guide to a combination of mechanics and empirical methods.

Many departments of transportation (DOTs) in the US have started to review the design procedures outlined in the NCHRP design guide [2] since the design procedure is expected to be officially adopted by AASHTO in the near future. Draft guidelines and a web-based computer program are currently available for evaluation and comment. The present draft of the design guide is expected to be revised based on comments received and then adopted by AASHTO for use after this evaluation period. The Wisconsin Department of Transportation (WisDOT) also has received the "2002 Design Guide, Design of New and Rehabilitated Pavement Structures," and has started the review of the procedure and the effort required to implement the procedure. In order to implement the mechanistic-empirical design procedure and take advantage of the potential cost savings, WisDOT also identified material properties required for the design of rigid pavement (concrete pavement) that had not been previously measured by the WisDOT. The two properties to be evaluated in this project were the indirect tensile strength as measured by AASHTO T 198, "Splitting Tensile Strength of Cylindrical Concrete Specimens," and the coefficient of thermal expansion (CTE), measured by a AASHTO provisional test standard TP 60, "Coefficient of Thermal Expansion of Hydraulic Cement Concrete." The WisDOT has also reported that the design of the thickness of the pavement, and the predicted performance of the pavement are very sensitive to changes in the tensile strength and the CTE. The focus of this project was to develop input values for the new pavement design procedure for concrete pavement construction in Wisconsin. This project was conducted by UWM-CBU to document and evaluate the concrete containing specified Wisconsin materials for splitting tensile strength and CTE. The sources of cement, GGBFS (ground granulated blast-furnace slag), fly ash, and aggregate were selected in consultation with the WisDOT and the Wisconsin Highway Research Program Project Manager.

1.2 Research Objectives

The overall objective of this project was to provide material properties to be used for input into a mechanistic-empirical design procedure for concrete pavements. The use of the mechanistic-empirical design basis for design of concrete pavements is expected to provide increased reliability of pavement structures and to provide a basis for the prediction of service life, and how the pavement design parameters will affect various pavement failure modes including cracking, faulting, and IRI (International Roughness Index). In order to provide the input required for the new mechanistic-empirical design, this project had the following objectives:

(1) Collect existing literature.
(2) Develop a work plan for testing splitting tensile strength and coefficient of thermal expansion (CTE) of concrete.
(3) Evaluate the effect of portland cement, GGBFS, and fly ash sources on splitting tensile strength and CTE of concrete.
(4) Evaluate the effect of source change of glacial gravel on splitting tensile strength and CTE of concrete.
(5) Evaluate the effect of source change of crushed stone on splitting tensile strength and CTE of concrete.
(6) Generate test results for compressive strength in addition to the splitting tensile strength and CTE of concrete.
(7) Submit a final report to WHRP that contains all test results regarding splitting tensile strength, compressive strength, and CTE of concrete and recommendations for future work.

1.3 Work Plan Used

Originally, the WHRP had specified a total of 15 sources of course aggregate for this project. In addition, four sources of cement, two sources of GGBFS, and three sources of fly ash had been specified for consideration for evaluation with the aggregates. If each source of cementitious materials were tested with all of the aggregates specified, the resulting number of mixtures that would be tested would exceed 300 different mixtures. Due to the limited budget designated by the WHRP for this testing work, the effect of all cementitious sources combined with all sources of aggregate could not be done for this project in terms of time or money.

Based on the initial literature review, the parameter that would have the most effect on the CTE of concrete was the type of aggregate used in the concrete. The glacial gravels were expected to show the most variation, since the materials could be composed of a combination of the materials carried by the glacier and the local bedrock. The material that was expected to show the least variation was the dolomite from various sources. The chemical composition of the dolomite was expected to have little effect on the CTE of concrete.

In order to meet the requirements of the WHRP and determine the effect of the aggregate source on the splitting tensile strength and CTE of concrete, a base mixture with one fixed source of cement and one fixed source of fly ash was selected and the aggregate source was then varied for each mixture. In total, 15 mixtures were evaluated for testing for effects of aggregate sources. Since most concrete pavement mixtures produced in Wisconsin include fly ash, the base mixture that was approved for testing was the WisDOT Grade A-FA (70% cement plus 30% Class C fly ash) mixture. These 15 concrete mixtures were made using cement from Source 1 (Cement 1) and fly ash from Source 1 (Fly ash 1).

The source of the cement, GGBFS, or fly ash was not expected to have a significant effect on the CTE, provided that the volume of each of these components remains similar in the mixture and also, the type of cement remains the same. To evaluate the effects of cementitious materials on the splitting tensile strength and CTE of concrete, four additional concrete mixtures were produced using the following combinations of cementitious materials: (1) Cement 2 plus Fly ash 1; (2) Cement 1 plus GGBFS; (3) Cement 1; and (4) Cement 1 plus Fly ash 2. Each of the four concrete mixtures was produced using a different source of dolomite. Each concrete mixture was compared with its counterpart concrete mixture produced using the same source of dolomite and Cement 1 plus Fly ash 1.

Thus, a total of 19 concrete mixtures were produced for this project. Through concrete production and testing, the splitting tensile strength and CTE of concrete were evaluated for concrete mixtures containing 15 different aggregate sources (using one fixed source of cement combined with one fixed source of fly ash). The effects of four more combinations of cementitious materials were also determined.

Initially, the research team proposed a maximum size of 19 mm (0.75 in.) for all the aggregates selected for the project. This was a result of the requirements of the AASHTO TP 60 test procedure that specifies a 100-mm (4-in.) diameter × 200-mm (8-in.) long cylindrical specimen for determining the CTE of concrete. Previous research on the CTE had shown that using a 100 × 200 mm (4 × 8 in.) cylinder vs. a 150 × 300 mm (6 × 12 in.) cylinder did not affect the CTE [17].

Based on the comments provided by the WisDOT, the concrete mixtures produced for this project used a blend of coarse aggregate sizes, 60% WisDOT No. 1 stone (AASHTO 67, 19 to 5 mm [0.75 to 3/16 in.]) and 40% WisDOT No. 2 stone (AASHTO No. 4, 38 to 19 mm [1.5 to 0.75 in.]). WisDOT indicated that the 100 × 200 mm (4 × 8 in.) cylinders could still be cast using the aggregate blend. The compressive strength, splitting tensile strength, and coefficient of thermal expansion (CTE) of concrete were evaluated using 100 × 200 mm (4 × 8 in.) cylinders.

Chapter 2. Literature Review

2.1 Mechanistic-Empirical Pavement Design Guide

The NCHRP 1-37A pavement design guide [2] was developed to estimate the long-term pavement behavior by using a combination of engineering mechanics and empirical methods. This approach to a mechanistic-empirical design of new and rehabilitated pavement structures considers traffic, climate, subgrade, and existing pavement condition, as well as material properties in order to predict pavement responses to stresses and temperature variations, and to predict pavement failures. Three levels of designs are specified for the method, each with different expected accuracies. Level 1 design produces the highest accuracy and requires that all material properties be established through laboratory and field testing. The splitting tensile strength at the ages of 7, 14, 28, and 90 days are required for Level 1 design. Compressive strength is not required for Level 1 design; but in Level 2 design and Level 3 design, which are design levels of lower accuracy, compressive strength can be used to estimate the modulus of elasticity, flexural strength, and splitting tensile strength of the concrete. Level 2 design provides an intermediate accuracy and would produce results similar to earlier editions of the AASHTO pavement design guides. Level 2 design uses some of the specific material properties through relationships with other known parameters, for example, estimating splitting tensile strength from actual test data of compressive strength. Level 3 design would produce the lowest accuracy. The material properties in Level 3 design would be estimated from historical data, similar estimates, the 28-day flexural strength, and/or the 28-day compressive strength.

In order for the mechanistic-empirical design to produce a rational design, the material properties must be evaluated that are used to predict the material responses to stresses and variations in temperature (climate), and to predict failures.

Other DOTs have also begun activities for implementation of the NCHRP 1-37A pavement design guide. Presentations have been made on the use of the design guide, sensitivity analysis, and design examples [4, 6, 7, 15, 17, 19].

2.2 Splitting Tensile Strength

The splitting tensile strength of concrete has been reported in numerous research publications. For example, the principal investigator for this project, T. Naik, has published reports on over 200 different mixtures of concrete (made with Wisconsin-based aggregates) that contain data for splitting tensile strength and corresponding compressive strength, since the 1970s <http://www.cbu.uwm.edu>. There is no single accepted value for determining the splitting tensile strength as a function of other properties of concrete. According to the ACI Building Code [1], the splitting tensile strength of concrete can be estimated as 6.7 × (compressive strength in psi)$^{0.5}$. The ACI relationship has been accepted for use in building design; however, the ratio of compressive strength to splitting tensile strength has been reported to vary. Grieb and Werner [5] reported that the aggregate type influenced the splitting tensile strength of concrete. The splitting tensile strength of concrete varied between 0.625 × (flexural strength) for a natural river gravel to 0.667 × (flexural strength) for a crushed limestone.

According to Chapter 2 of Part 2 of the mechanistic-empirical design guide [18], at Input Level 1, the splitting tensile strength values of the proposed concrete mixture at 7, 14, 28, and 90 days are required. In addition, the estimated ratio of 20-year to 28-day splitting tensile strength is also required, with 1.20 or less being recommended.

At Input Level 2, inputs for splitting tensile strength are estimated from the 7-day, 14-day, 28-day, and 90-day compressive strength test results, and from the estimated ratio of 20-year to 28-day compressive strength (1.35 or less being recommended). The design guide states that splitting tensile strength can be estimated as 0.67 × flexural strength = 0.67 × [0.79 × (compressive strength in MPa) $^{0.5}$] = 0.53 × (compressive strength in MPa)$^{0.5}$, or 0.67 × [9.5 × (compressive strength in psi)$^{0.5}$] = 6.4 × (compressive strength in psi)$^{0.5}$.

At Input Level 3, the gain in splitting tensile strength is estimated from either the 28-day flexural strength test result or the 28-day compressive strength test result.

2.3 Coefficient of Thermal Expansion (CTE)

The coefficient of thermal expansion (CTE) of concrete has been shown to have a significant impact on the expected pavement durability when used in the mechanistic-empirical pavement design [16]. A sensitivity analysis was conducted on a theoretical pavement design entered into the computer program. Various design parameters were revised including climate, pavement thickness, flexural strength, shoulder design, joint spacing, traffic conditions, lane width, and various concrete material properties. The parameter that had the most effect on cracking, joint faulting, and IRI (International Ride Index) was a change in the aggregate type from limestone with a CTE of 9 × 10^{-6}/°C to a siliceous gravel with a CTE of 12 × 10^{-6}/°C. When the aggregate type was changed from limestone to the siliceous gravel with all other parameters the same, the cracking of the slab increased over five times, the joint faulting increased by 1.5 times, and the IRI increased by 60%. When the flexural strength (Modulus of Rupture (MOR)) of the slab was reduced, the effect on joint faulting and IRI was minimal, while the amount of cracking in a low-MOR concrete increased by approximately four times. This shows that the flexural strength and the CTE are very important factors when using the new pavement design guide.

The CTE of various types of aggregates in concrete have been evaluated since the 1940s [13]. Parsons and Johnson [13] reported on the CTE of concrete using numerous types of aggregates. The CTE of dolomite varied between 6.7 to 8.6 × 10^{-6}/°C, granite 5.9 to 9.2 × 10^{-6}/°C, basalt 4.3 to 7.4 × 10^{-6}/°C, and quartzite 7.0 to 12.2 × 10^{-6}/°C. Parsons and Johnson suggested that the aggregates that had significantly different CTEs than the cement paste (10 to 16 × 10^{-6}/°C), may cause durability problems in concrete. Mindess and Young [9] also reported that the CTE of concrete varies according to the mixture proportions and aggregates used. Only minor variations in the CTE of mortar occurred for the normal ranges of cementitious materials (water to cementitious materials ratio of 0.4 to 0.6); therefore, changes in the mortar composition should not have a significant effect on the CTE of concrete. Mehta also reported that the highest expansion occurred for some natural gravels, sandstone, and quartzite [8].

Naik and Singh [11] reported that mechanical behavior of concrete can be modeled by using available models for composites. Emmanuel and Hulsley [3] have shown that the CTE could be estimated by an empirical relationship between the thermal expansion of each component of concrete (cement paste, coarse aggregate, fine aggregate) and considering the volume fraction of each component in the concrete. Using this relationship, and considering the age of the concrete and the degree of saturation, they estimated the CTE of concrete and compared it with experimental results. The CTE estimated by the empirical relationship was found to be close to actual experimental values. A 1995 study [12] also compared three different methods for obtaining the CTE: a laboratory test, field measurements, and the empirical relationship from Emmanuel and Hulsley [3]. Two concrete bridge structures were evaluated, one containing limestone and the other containing gravel aggregate. CTE results obtained using all three methods were found to be in close agreement.

Ziegeldorf, et al. [20] also tested two types of aggregate in concrete, crushed limestone and river gravel. It was concluded that fine aggregate had a minor effect on CTE of concrete, while the coarse aggregate had a significant effect on CTE. Based on tests conducted in the study, it was concluded that the equation used to predict CTE proposed by Emmanuel and Hulsley [3] did not always result in a reliable CTE. The CTE determined by simply using the product of the volume and CTE of each component did not adequately account for restraint of expansion within the concrete matrix. Another relationship was supported [19], but only when the composition of the aggregates was uniform.

A recent study [10] compared the estimated CTE of concrete and the CTE of concrete measured in accordance with AASHTO TP 60. The estimated CTE values, calculated as weighted averages of the CTEs of aggregates and cement paste, were 10 to 30% higher than the measured CTE values. The study also reported that the CTE of concrete had a significant effect on the predicted percent of slabs cracked.

The moisture condition of the concrete was found to affect the CTE of concrete. For example, the CTE of a concrete containing gravel in an air-dried condition when cooling was 8.1 $\times 10^{-6}$/°C, while the CTE of the concrete in a saturated condition when cooling was 6.1 $\times 10^{-6}$/°C.

The test method used for measurement of the CTE for this project by the WHRP is the AASHTO test procedure TP 60. Several DOTs in the U.S. have already started evaluating concrete pavement using this test procedure. A study was conducted by the University of Texas for the Texas Department of Transportation using the proposed AASHTO TP 60 procedure [17]. This study found that the age of concrete or the rate of heating or cooling did not affect the CTE. Two different sizes of test cylinders were evaluated, 100 × 200 mm (4 × 8 in.) and 150 × 300 mm (6 × 12 in.). The change in the cylinder size also did not have a significant effect on the CTE. The coarse aggregate content was found to have a significant impact on the CTE, approximately a 0.045 $\times 10^{-6}$/°C change for each percent change in the coarse aggregate volume. The aggregate type also had a significant impact on the CTE of concrete. Crushed limestone (11 sources) and gravel (21 sources) were evaluated in many concrete mixtures. Limestone showed minimal variation in CTE between sources, while the CTE for gravel sources varied from 8.1 to 13.0 $\times 10^{-6}$/°C. Using the equipment specified by AASHTO TP 60 to obtain the CTE, problems were reported in repeatability and stability of the readings at 10°C and 50°C [17]. A regression analysis of the CTE of concrete during heating and cooling was recommended as an alternative test method to obtain the CTE while using the AASHTO apparatus.

There were also favorable reports [10, 14] about the equipment and test procedure of the AASHTO TP 60 for measuring the CTE of concrete.

According to the chapter on material characterization in the mechanistic-empirical design guide [18], at Input Level 1, the CTE of concrete is measured using AASHTO TP 60.

At Input Level 2, CTE of concrete is estimated using a weighted average of the CTE values of aggregates and hardened cement paste based on the relative volumes of the constituents. However, the ranges of CTE of aggregates provided in the design guide are quite wide, making it difficult to make a reasonably accurate estimation of the CTE of concrete.

At Input Level 3, CTE of concrete is estimated based on overall historical averages.

Chapter 3. Materials

3.1 Portland Cement

ASTM Type I portland cement obtained from two sources were used in this research. The chemical composition and physical properties of the cements are presented in Table 3-1 and Table 3-2, respectively, along with the requirements of ASTM Standard Specification for Portland Cement (C 150). These data were provided by respective cement producers. The cements used met the chemical and physical requirements of ASTM C 150.

Table 3-1. Chemical Composition of Portland Cement

Item	Lafarge (% by mass)	St Marys (% by mass)	Standard requirement of ASTM C 150 for Type I cement
Silicon dioxide, SiO_2	20.2	19.7	…
Aluminum oxide, Al_2O_3	4.5	5.2	…
Ferric oxide, Fe_2O_3	2.6	2.5	…
Calcium oxide, CaO	64.2	63.2	…
Magnesium oxide, MgO	2.5	3.4	6.0 maximum
Sulfur trioxide, SO_3	2.4	3.6	3.0 maximum, when $C_3A \le 8\%$ 3.5 maximum, when $C_3A > 8\%$
Loss on ignition	1.4	1.5	3.0 maximum
Insoluble residue	0.4	0.1	0.75 maximum
Free lime	1.5	n. a.	…
Tricalcium silicate, C_3S	67	59	…
Dicalcium silicate, C_2S	n. a.	12	
Tricalcium aluminate, C_3A	8	10	…
Tetracalcium aluminoferrite, C_4AF	n. a.	7	
Equivalent alkalies, $Na_2O + 0.658K_2O$	0.53	0.81	…

n. a.: Result not available.

Table 3-2. Physical Properties of Portland Cement

ASTM	Item	Lafarge	St Marys	Standard requirement of ASTM C 150 for Type I cement
C 185	Air content of mortar (volume %)	6	8.2	12 maximum
C 204	Fineness (specific surface) by Blaine air-permeability apparatus (m^2/kg)	364	378	280 minimum
C 151	Autoclave expansion (%)	0.07	0.12	0.80 maximum
C 109	Compressive strength of cement mortars (psi):			
	1 day	2080	n. a.	…
	3 days	3590	3880	1740 minimum
	7 days	4400	4610	2760 minimum
	28 days	5620	5230	…
C 191	Initial time of setting by Vicat needle (minutes)	105	80	Between 45 to 375
C 188	Density (g/cm^3)	3.15	n. a.	…

n. a.: Result not available.

3.2 Fly Ash

ASTM Class C fly ashes obtained from two sources were used in this research. The chemical composition and physical properties of the fly ashes are shown in Table 3-3 and Table 3-4, respectively, along with the requirements of ASTM Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete (C 618). These data were provided by the respective fly ash producers.

Table 3-3. Chemical Composition of Fly Ash

Item	Pleasant Prairie (% by mass)	Weston (% by mass)	Requirement of ASTM C 618 for Class C fly ash
Silicon dioxide, SiO_2	36.2	40.9	…
Aluminum oxide, Al_2O_3	19.0	18.8	…
Ferric oxide, Fe_2O_3	5.6	6.5	…
$SiO_2 + Al_2O_3 + Fe_2O_3$	60.8	66.2	50 minimum
Calcium oxide, CaO	23.4	21.3	…
Magnesium oxide, MgO	3.7	4.5	…
Sulfur trioxide, SO_3	2.1	1.2	5.0 maximum
Sodium oxide, Na_2O	1.0	1.4	…
Potassium oxide, K_2O	1.0	0.8	…

Table 3-4. Physical Properties of Fly Ash

Item	Pleasant Prairie	Weston	Requirement of ASTM C 618 for Class C fly ash
Strength activity index (% of Control) 7 days 28 days	 98 99	 107 Not available	 75 minimum, at either 7 or 28 days
Water requirement (% of Control)	91	94	105 maximum
Autoclave expansion (%)	0.05	0.04	Between -0.80 and +0.80
Density (g/cm^3)	2.53	2.66	…

3.3 GGBFS

ASTM Grade 120 GGBFS (ground granulated blast-furnace slag) obtained from one source was used in this research. The chemical composition and physical properties of the GGBFS are shown in Table 3-5 and Table 3-6, respectively, along with the requirements of ASTM Standard Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars (C 989). These data were provided by the GGBFS producer. The GGBFS met the requirements of ASTM C 989 and AASHTO M-302 for Grade 120 GGBFS.

Table 3-5. Chemical Composition of Grade 120 GGBFS

Item	Lafarge 120	Requirement of ASTM C 989
Sulfide sulfur (S) (%)	1.2	2.5 maximum
Sulfate reported as SO_3 (%)	0.0	4.0 maximum

Table 3-6. Physical Properties of Grade 120 GGBFS

Item	Lafarge 120	Requirement of ASTM C 989
Fineness: Amount retained when wet screened on a 45-µm sieve (%)	1.0	20.0 maximum
Fineness: Specific surface by air permeability (m^2/kg)	557	…
Air content of slag mortar (%)	3.3	12.0 maximum
Slag activity index (%) 7-day index 28-day index	 107 122	 95 minimum 115 minimum
Specific gravity	3.00	…
Reference cement for slag activity tests Total alkalies, $Na_2O + 0.658K_2O$ Compressive strength (MPa)	 0.83 40.4	 0.60 to 0.90 35.0 minimum

3.4 Fine Aggregate (Sand)

Natural sand was used as fine aggregate in this research. The absorption, specific gravity, and bulk density of fine aggregate are shown in Table 3-7. The grading (particle-size distribution) of fine aggregate is presented in Table 3-8, along with the grading requirements of ASTM Standard Specification for Concrete Aggregates (C 33). The sand met the requirements of ASTM C 33.

Table 3-7. Absorption, Specific Gravity, and Bulk Density of Fine Aggregate (Sand)

Absorption (%)	Specific gravity on oven-dry basis	Specific gravity on SSD* basis	Bulk density (kg/m^3)	Bulk density (lb/ft^3)
1.3	2.62	2.66	1800	112

* Saturated surface-dry

Table 3-8. Grading of Fine Aggregate (Sand)

	Fineness modulus	Amounts finer than each sieve (mass %)						
		9.5 mm 3/8 in.	4.75 mm No. 4	2.36 mm No. 8	1.18 mm No. 16	600 µm No. 30	300 µm No. 50	150 µm No. 100
Sand test result	2.7	100	99	87	71	50	18	4
ASTM C 33	2.3~3.1	100	95-100	80-100	50-85	25-60	5-30	0-10

3.5 Coarse Aggregates

In total, coarse aggregates from 15 sources were used in this research project: glacial gravel from six sources, dolomite from five sources, quartzite, granite, diabase, and basalt. Table 3-9 contains a summary of the coarse aggregate sources collected in consultation with WisDOT. Table 3-10 and Table 3-11 show the absorption, specific gravity, and bulk density of the coarse aggregates.

Table 3-9. Sources of WisDOT No. 1* and No. 2 Coarse Aggregates Used**

Aggregate designation	Lab No.	Aggregate type†	Source name	County
Gvl1	5	Glacial Gravel – Lake Michigan Lobe	J. W. Peters	Racine
Gvl2	8	Glacial Gravel – Lake Michigan / Green Bay Transition	Evanson Quarry	Manitowoc
Gvl3	4	Glacial Gravel – South End of Green Bay Lobe	Janesville Sand & Gravel	Rock
Gvl4	12	Glacial Gravel – Central Green Bay Lobe	Wimme Pit	Portage
Gvl5	13	Glacial Gravel – Wisconsin Valley Lobe	Crass Road Pit	Lincoln
Gvl6	14	Glacial Gravel – Chippewa River Gravel	Todds Ready-Mix	Barron
Qtz	1	Baraboo Quartzite	Williams Quarry	Columbia
Gnt	10	Granite	Haske Quarry	Wood
Dbs	11	Diabase	RME - Athens	Marathon
Bst	15	Basalt Traprock	Dresser Quarry	Polk
Dlm1	6	Niagara Dolomite	Franklin Quarry - Vulcan	Milwaukee
Dlm2	3	Galena Dolomite	Haverland Quarry	Grant
Dlm3	7	Galena-Platteville Dolomite	Carew Concrete	Outagami
Dlm4	2	Prairie Du Chien Dolomite – SW Wisconsin	Slama Quarry	Crawford
Dlm5	9	Prairie Du Chien Dolomite – NE Wisconsin	Faulk Bros. Quarry	Waupaca

* 19 to 5 mm (0.75 to 3/16 in.)
** 38 to 19 mm (1.5 to 0.75 in.)
† Aggregate types are from WisDOT description of the sources.

Table 3-10. Absorption, Specific Gravity, and Bulk Density of WisDOT No. 1* Coarse Aggregates Used

Aggregate designation	Lab No.	Absorption (%)	Specific gravity on oven-dry basis	Specific gravity on SSD† basis	Bulk density (kg/m^3)	Bulk density (lb/ft^3)
Gvl1-1	5-1	1.7	2.68	2.72	1700	106
Gvl2-1	8-1	0.8	2.78	2.80	1710	107
Gvl3-1	4-1	1.9	2.61	2.66	1660	103
Gvl4-1	12-1	0.9	2.71	2.73	1610	100
Gvl5-1	13-1	1.0	2.72	2.74	1630	102
Gvl6-1	14-1	1.2	2.69	2.72	1660	104
Qtz-1	1-1	0.5	2.63	2.64	1530	95
Gnt-1	10-1	0.6	2.61	2.63	1550	97
Dbs-1	11-1	0.4	2.83	2.85	1640	102
Bst-1	15-1	0.4	2.97	2.98	1610	100
Dlm1-1	6-1	1.9	2.62	2.67	1550	97
Dlm2-1	3-1	2.9	2.59	2.66	1550	97
Dlm3-1	7-1	0.7	2.78	2.80	1650	103
Dlm4-1	2-1	1.9	2.62	2.67	1550	97
Dlm5-1	9-1	1.8	2.68	2.73	1640	102

* 19 to 5 mm (0.75 to 3/16 in.)
† Saturated surface-dry

Table 3-11. Absorption, Specific Gravity, and Bulk Density of WisDOT No. 2* Coarse Aggregates Used

Aggregate designation	Lab No.	Absorption (%)	Specific gravity on oven-dry basis	Specific gravity on SSD† basis	Bulk density (kg/m^3)	Bulk density (lb/ft^3)
Gvl1-2	5-2	1.6	2.67	2.71	1690	105
Gvl2-2	8-2	0.6	2.80	2.81	1710	107
Gvl3-2	4-2	1.5	2.66	2.70	1640	102
Gvl4-2	12-2	0.8	2.55	2.75	1690	106
Gvl5-2	13-2	0.8	2.71	2.73	1670	104
Gvl6-2	14-2	1.1	2.70	2.73	1690	105
Qtz-2	1-2	0.5	2.64	2.66	1530	96
Gnt-2	10-2	0.2	2.64	2.65	1510	94
Dbs-2	11-2	0.3	2.82	2.83	1670	104
Bst-2	15-2	0.2	2.99	3.00	1730	108
Dlm1-2	6-2	1.6	2.62	2.66	1580	98
Dlm2-2	3-2	2.7	2.57	2.64	1500	93
Dlm3-2	7-2	0.5	2.79	2.81	1640	103
Dlm4-2	2-2	2.0	2.59	2.65	1520	95
Dlm5-2	9-2	1.3	2.72	2.76	1550	97

* 38 to 19 mm (1.5 to 0.75 in.)
† Saturated surface-dry

Table 3-12 and Table 3-13 show the sieve analysis results of the coarse aggregates. The grading of as-received samples of some coarse aggregates deviated from the requirements of ASTM C 33. Therefore, coarse aggregates from several sources (Gvl4-1, Gvl3-2, and Bst-2) were sieved and appropriate amounts of sieved portions were combined to improve the grading before using the aggregates to make concrete.

Table 3-12. Grading of WisDOT No. 1* Coarse Aggregates Used

Aggregate designation	Lab No.	Amounts finer than each sieve (mass %)					
		37.5 mm 1.5 in.	25 mm 1 in.	19 mm 3/4 in.	9.5 mm 3/8 in.	4.75 mm No. 4	2.36 mm No. 8
Gvl1-1	5-1	…	100	99	54	11	1
Gvl2-1	8-1	…	100	92	27	2	1
Gvl3-1	4-1	…	100	95	35	2	1
Gvl4-1	12-1	…	100	100	11	1	1
Gvl5-1	13-1	…	100	92	31	2	1
Gvl6-1	14-1	…	100	94	25	3	1
Qtz-1	1-1	…	100	97	32	2	1
Gnt-1	10-1	…	100	100	51	9	4
Dbs-1	11-1	…	100	97	43	6	1
Bst-1	15-1	…	100	98	29	2	1
Dlm1-1	6-1	…	100	93	35	7	1
Dlm2-1	3-1	…	100	98	49	9	3
Dlm3-1	7-1	…	100	81	29	3	2
Dlm4-1	2-1	…	100	94	29	2	1
Dlm5-1	9-1	…	100	98	50	14	7
ASTM C 33	No. 67	…	100	90-100	20-55	0-10	0-5
Gvl4-1†	12-1†	…	100	100	6	1	1

* 19 to 5 mm (0.75 to 3/16 in.)
† As-received aggregate before the treatment (adjustment of grading) for use in concrete.

Table 3-13. Grading of WisDOT No. 2* Coarse Aggregates Used

Aggregate designation	Lab No.	Amounts finer than each sieve (mass %)					
		37.5 mm 1.5 in.	25 mm 1 in.	19 mm 3/4 in.	9.5 mm 3/8 in.	4.75 mm No. 4	2.36 mm No. 8
Gvl1-2	5-2	94	39	4	0	0	0
Gvl2-2	8-2	100	39	2	1	1	1
Gvl3-2	4-2	91	20	2	1	1	1
Gvl4-2	12-2	98	37	5	1	0	0
Gvl5-2	13-2	99	32	5	1	0	0
Gvl6-2	14-2	97	43	7	1	1	1
Qtz-2	1-2	94	42	8	2	2	2
Gnt-2	10-2	100	40	6	1	1	1
Dbs-2	11-2	98	48	18	3	1	1
Bst-2	15-2	92	27	7	1	1	1
Dlm1-2	6-2	96	44	6	2	2	2
Dlm2-2	3-2	99	28	6	2	2	2
Dlm3-2	7-2	99	34	8	2	1	1
Dlm4-2	2-2	99	45	6	2	2	2
Dlm5-2	9-2	96	52	15	2	1	1
ASTM C 33	No. 4	90-100	20-55	0-15	0-5	…	…
Gvl3-2†	4-2†	85	9	1	0	0	0
Bst-2†‡	15-2†‡	71	21	5	1	1	1

* 38 to 19 mm (1.5 to 0.75 in.)
† As-received aggregate before the treatment (adjustment of grading) for use in concrete.
‡ As-received aggregate grading was according to Spec. Product 822.

Table 3-14 shows the grading of the blends of 60% WisDOT No. 1 and 40% WisDOT No. 2 coarse aggregates used in making concrete mixtures in this project.

Table 3-14. Grading of Blends of 60% WisDOT No. 1* and 40% WisDOT No. 2 Coarse Aggregates Used**

Aggregate source	Lab No.	Amounts finer than each sieve (mass %)					
		37.5 mm 1.5 in.	25 mm 1 in.	19 mm 3/4 in.	9.5 mm 3/8 in.	4.75 mm No. 4	2.36 mm No. 8
Gvl1	5	98	76	61	33	7	1
Gvl2	8	100	76	56	16	1	1
Gvl3	4	97	68	58	21	1	1
Gvl4	12	99	75	62	7	1	1
Gvl5	13	99	73	57	19	1	1
Gvl6	14	99	77	59	15	2	1
Qtz	1	98	77	62	20	2	1
Gnt	10	100	76	62	31	6	2
Dbs	11	99	79	65	27	4	1
Bst	15	97	71	61	18	2	1
Dlm1	6	99	78	58	22	5	1
Dlm2	3	100	71	61	30	6	3
Dlm3	7	100	74	52	18	2	1
Dlm4	2	99	78	59	18	2	1
Dlm5	9	98	81	64	31	9	5
ASTM C 33	60% No. 67 + 40% No. 4	96-100	68-82	54-66	12-35	0-6	0-3

* 19 to 5 mm (0.75 to 3/16 in.)
** 38 to 19 mm (1.5 to 0.75 in.)

3.6 Chemical Admixtures

Table 3-15 shows the specific gravity and recommended dosage rates of the water-reducing admixture and air-entraining admixture used in this project.

Table 3-15. Properties of Water-Reducing Admixture and Air-Entraining Admixture

Admixture	Brand name	Specific gravity	Manufacture’s recommended dosage rate
Water-reducing admixture	MasterPave	1.20	260-650 mL/100 kg (4-10 fl oz/100 lb) of cementitious materials
Air-entraining admixture	Micro Air	1.01	8-98 mL/100 kg (0.125-1.5 fl oz/100 lb) of cement

Chapter 4. Specimen Preparation and Test Methods

4.1 Mixing and Specimen Preparation

Test specimens of concrete were prepared and cured in accordance with the ASTM Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory (C 192).

The concrete mixer used in this research was an electrical power driven, revolving drum, tilting mixer.

The cast specimens were removed from their molds 24 ± 4 hours after casting. The demolded specimens were moist cured in a moist room at a temperature of 23 ± 2°C (73 ± 3.5°F) and a relative humidity of not less than 95%.

4.2 Test Methods

Table 4-1 shows the tests methods used to determine the properties of fresh concrete. Table 4-2 shows the test methods, specimens, and ages used for the testing of hardened concrete.

Table 4-1. Test Methods for Fresh Concrete Properties

Property	Test Method
Slump	ASTM C 143
Density	ASTM C 138
Air content by the pressure method	ASTM C 231
Concrete temperature	ASTM C 1064

Table 4-2. Test Methods for Properties of Hardened Concrete

Property	Test method	Specimen	Number of specimens per test age	Test ages (days)
Compressive strength	AASHTO T 22 (ASTM C 39)	100 × 200 mm (4 × 8") cylinder	3	7, 14, 28, and 90
Splitting tensile strength	AASHTO T 198 (ASTM C 496)	100 × 200 mm (4 × 8") cylinder	3	7, 14, 28, and 90
Coefficient of thermal expansion	AASHTO TP 60-00	100 × 200 mm (4 × 8") cylinder	3	28

Photographs of testing, specimens, and test apparatus are shown in Fig. 4-1 to Fig. 4-5.

Fig. 4-1. Compressive strength test of concrete

Fig. 4-2. Splitting tensile strength test of concrete

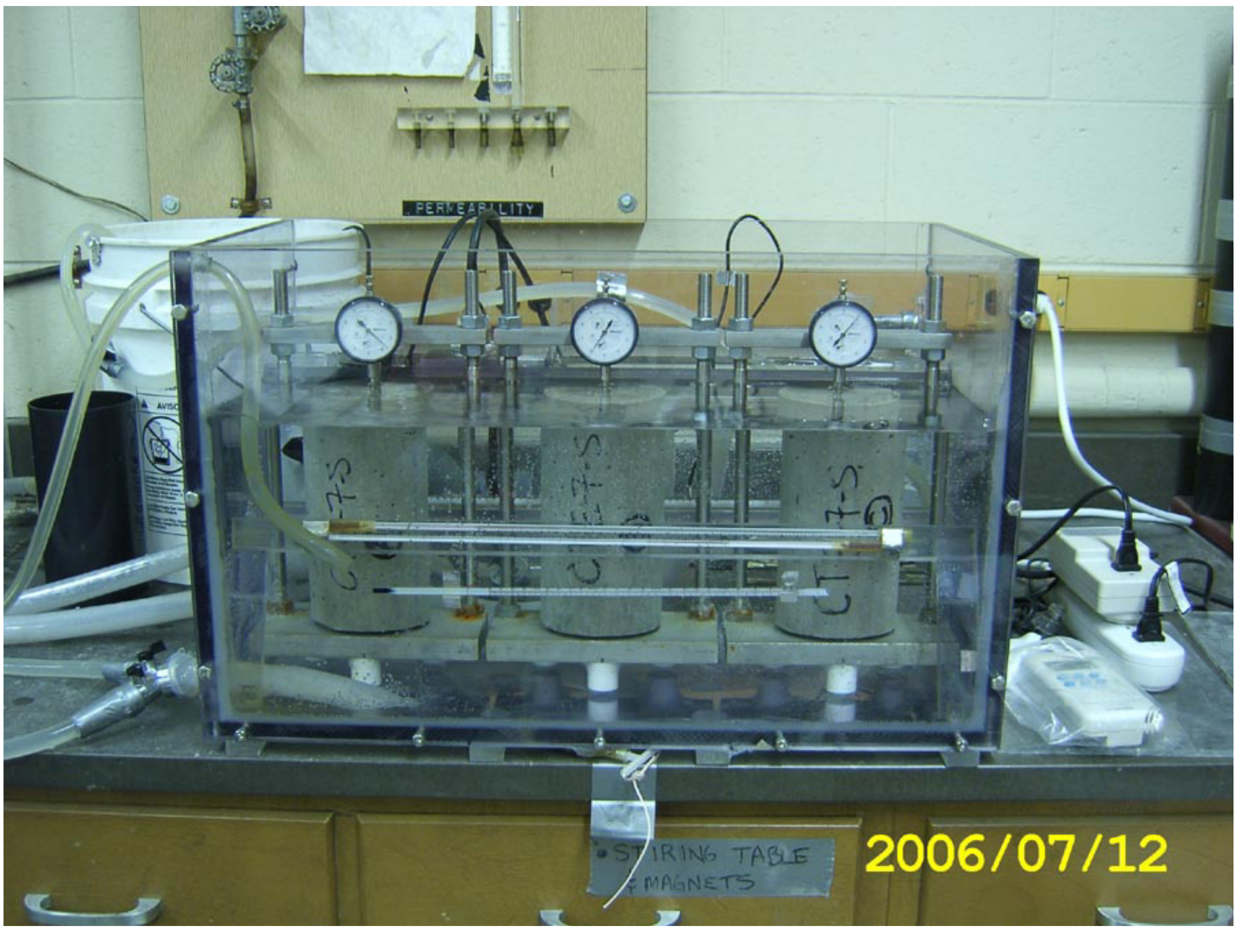

Fig. 4-3. Test apparatus for coefficient of thermal expansion (CTE) of concrete (Front View)

Fig. 4-4. CTE apparatus (Left Side View)

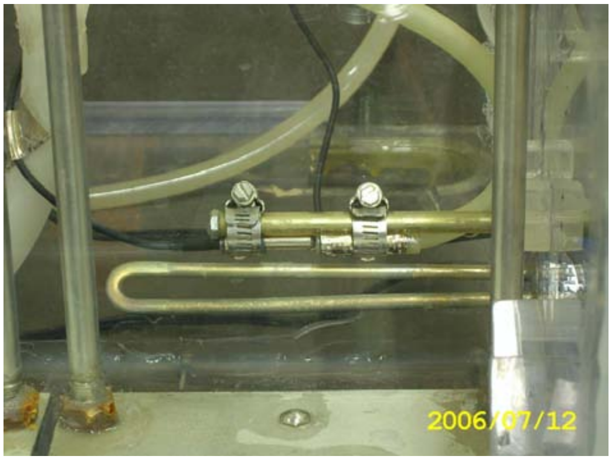

Fig. 4-5. CTE apparatus showing the temperature-controller sensor, cold-water addition tube, and heater element for maintaining either constant 50°C or constant 10°C

Chapter 5. Mixture Proportions and Test Results

5.1 Mixture Proportions

Mixture proportions were based on the proportions for WisDOT concrete Grade A-FA (using 70% cement and 30% Class C fly ash), Grade A (using 100% cement), and Grade A-S (using 70% cement and 30% GGBFS). Fine aggregate constituted 35% of the total aggregate in a concrete mixture. Following the direction from the WisDOT for this project, the coarse aggregate used was a blend of 60% WisDOT No. 1 stone (AASHTO 67, 19 to 5 mm [0.75 to 3/16 in.]) and 40% WisDOT No. 2 stone (AASHTO No. 4, 38 to 19 mm [1.5 to 0.75 in.]).

Fifteen concrete mixtures were evaluated for testing for effects of aggregate sources on the splitting tensile strength and CTE of concrete. Since most concrete pavement mixtures produced in Wisconsin include fly ash, the base mixture that was approved for testing was the WisDOT Grade A-FA mixture. These 15 concrete mixtures were made using cement from Source 1 (Cement 1) and fly ash from Source 1 (Fly ash 1).

To evaluate the effects of cementitious materials on the splitting tensile strength and CTE of concrete, four additional concrete mixtures were produced using the following combinations of cementitious materials: (1) Cement 2 plus Fly ash 1; (2) Cement 1 plus GGBFS; (3) Cement 1; and (4) Cement 1 plus Fly ash 2. Each of the four concrete mixtures was produced using a different source of dolomite. The concrete mixture was compared with its counterpart concrete mixture produced using the same source of dolomite and Cement 1 plus Fly ash 1.

Table 5-1 provides an overview of the 19 concrete mixtures produced in this project.

Table 5-1. An Overview of Concrete Mixtures Produced

15 mixtures for evaluating effects of aggregate source	Four mixtures for evaluating effects of cementitious materials
Gvl1-c1-f1	
Gvl2-c1-f1	
Gvl3-c1-f1	
Gvl4-c1-f1	
Gvl5-c1-f1	
Gvl6-c1-f1	
Qtz-c1-f1	
Gnt-c1-f1	
Dbs-c1-f1	
Bst-c1-f1	
Dlm1-c1-f1	
Dlm2-c1-f1	Dlm2-c2-f1
Dlm3-c1-f1	Dlm3-c1-s
Dlm4-c1-f1	Dlm4-c1
Dlm5-c1-f1	Dlm5-c1-f2

c1: Cement 1. c2: Cement 2. f1: Fly Ash 1. f2: Fly Ash 2. s: GGBFS

The mixture proportions and fresh properties of concrete mixtures are given in Table 5-2 and Table 5-3 in SI (metric) units, and in Table 5-4 and Table 5-5 in US customary units.

In most of the cases, the water-cementitious ratio (W/Cm) was 0.40, which was the design W/Cm. The W/Cm of several concrete mixtures varied by 0.01 or 0.02 (ranged from 0.38 to 0.41). The slump of concrete mixtures ranged from 25 to 105 mm (1 to 4 in.). The air content ranged from 4.8 to 7.9%.

Table 5-2. Mixture Proportions and Fresh Properties of Concrete Made With Gravel, Quartzite, Granite, Diabase, or Basalt (SI [Metric] Units)

Mixture Designation	Gvl1-c1-f1	Gvl2-c1-f1	Gvl3-c1-f1	Gvl4-c1-f1	Gvl5-c1-f1	Gvl6-c1-f1	Qtz-c1-f1	Gnt-c1-f1	Dbs-c1-f1	Bst-c1-f1
Laboratory mixture designation	5	8	4	12	13	14	1	10	11	15
Cement, Lafarge I (kg/m^3)	236	241	232	241	239	238	233	229	248	244
Class C fly ash, Pleasant Prairie (kg/m^3)	102	104	100	104	103	103	101	99	107	105
Grade 120 GGBFS, Lafarge (kg/m^3)	0	0	0	0	0	0	0	0	0	0
Water (kg/m^3)	135	138	133	138	137	136	130	134	143	140
Fine aggregate, SSD (kg/m^3)	652	664	641	664	661	657	644	633	685	673
No. 1 coarse aggregate, 19 to 5 mm, SSD (kg/m^3)	729	737	719	738	735	732	712	701	756	743
No. 2 coarse aggregate, 38 to 19 mm, SSD (kg/m^3)	486	491	477	491	489	487	475	465	504	494
Water-reducing admixture (L/m^3)	0.18	0.17	0.05	0.05	0.08	0.07	0.32	0.77	0.15	0.05
Air-entraining admixture (L/m^3)	0.93	1.41	0.96	1.49	1.07	0.98	1.93	1.66	1.14	2.35
Water-cementitious ratio, W/Cm	0.40	0.40	0.40	0.40	0.40	0.40	0.39	0.41	0.40	0.40
Slump (mm)	80	80	70	75	75	105	50	75	30	55
Air content (%)	5.9	6.4	6.1	5.4	5.8	5.2	6.1	7.9	4.8	6.4
Air temperature (°C)	22	22	23	22	22	22	22	22	21	21
Concrete temperature (°C)	21	20	21	22	22	22	21	21	21	21
Density (kg/m^3)	2340	2370	2300	2380	2360	2350	2300	2260	2440	2400

Table 5-3. Mixture Proportions and Fresh Properties of Concrete Made With Dolomite and Different Cementitious Materials (SI [Metric] Units)

Mixture Designation	Dlm1-c1-f1	Dlm2-c1-f1	Dlm2-c2-f1	Dlm3-c1-f1	Dlm3-c1-s	Dlm4-c1-f1	Dlm4-c1	Dlm5-c1-f1	Dlm5-c1-f2
Laboratory mixture designation	6	3	3-c2	7	7-s	2	2-c1	9	9-f2
Cement, Lafarge I (kg/m^3)	232	226	231*	241	238	229	323	239	234
Class C fly ash, Pleasant Prairie (kg/m^3)	100	97	99	104	0	99	0	103	101†
Grade 120 GGBFS, Lafarge (kg/m^3)	0	0	0	0	102	0	0	0	0
Water (kg/m^3)	133	123	124	138	137	132	127	138	135
Fine aggregate, SSD (kg/m^3)	641	624	636	664	661	635	634	661	647
No. 1 coarse aggregate, 19 to 5 mm, SSD (kg/m^3)	719	707	721	736	731	711	711	740	724
No. 2 coarse aggregate, 38 to 19 mm, SSD (kg/m^3)	478	470	479	490	486	475	478	491	480
Water-reducing admixture (L/m^3)	1.31	0.73	0.16	0.17	0.67	0.32	0.94	0.16	0.16
Air-entraining admixture (L/m^3)	0.58	0.89	0.87	1.49	1.56	0.80	1.17	2.14	1.64
Water-cementitious ratio, W/Cm	0.40	0.38	0.38	0.40	0.40	0.40	0.39	0.40	0.40
Slump (mm)	65	75	65	65	30	105	55	25	100
Air content (%)	7.0	7.3	6.0	6.2	5.6	6.0	6.1	5.6	6.8
Air temperature (°C)	21	22	22	22	22	21	22	22	22
Concrete temperature (°C)	21	22	22	19	22	21	22	22	21
Density (kg/m^3)	2300	2250	2290	2370	2360	2280	2270	2370	2320

* St. Marys cement.
† Weston fly ash.

Table 5-4. Mixture Proportions and Fresh Properties of Concrete Made With Gravel, Quartzite, Granite, Diabase, or Basalt (U.S. Customary Units)

Mixture Designation	Gvl1-c1-f1	Gvl2-c1-f1	Gvl3-c1-f1	Gvl4-c1-f1	Gvl5-c1-f1	Gvl6-c1-f1	Qtz-c1-f1	Gnt-c1-f1	Dbs-c1-f1	Bst-c1-f1
Laboratory mixture designation	5	8	4	12	13	14	1	10	11	15
Cement, Lafarge I (lb/yd^3)	398	405	391	405	403	401	393	386	418	410
Class C fly ash, Pleasant Prairie (lb/yd^3)	172	175	169	175	174	173	169	167	180	177
Grade 120 GGBFS, Lafarge (lb/yd^3)	0	0	0	0	0	0	0	0	0	0
Water (lb/yd^3)	227	233	224	232	231	230	219	225	240	236
Fine aggregate, SSD (lb/yd^3)	1100	1120	1080	1120	1110	1110	1090	1070	1150	1130
No. 1 coarse aggregate, 0.75 to 3/16 ", SSD (lb/yd^3)	1230	1240	1210	1240	1240	1230	1200	1180	1270	1250
No. 2 coarse aggregate, 1.5 to 0.75", SSD (lb/yd^3)	818	826	804	828	823	821	799	783	848	832
Water-reducing admixture (fl oz/yd^3)	4.6	4.3	1.2	1.3	2.1	1.7	8.3	19.8	4.0	1.3
Air-entraining admixture (fl oz/yd^3)	23.9	36.4	24.8	38.5	27.7	25.4	49.8	42.9	29.5	60.6
Water-cementitious ratio, W/Cm	0.40	0.40	0.40	0.40	0.40	0.40	0.39	0.41	0.40	0.40
Slump (in.)	3-1/4	3-1/4	2-3/4	3	3	4-1/4	2	3	1-1/4	2-1/4
Air content (%)	5.9	6.4	6.1	5.4	5.8	5.2	6.1	7.9	4.8	6.4
Air temperature (°F)	71	71	73	71	71	71	71	71	70	70
Concrete temperature (°F)	70	68	69	71	71	71	70	70	70	69
Density (lb/ft^3)	146	148	144	148	147	147	143	141	152	150

Table 5-5. Mixture Proportions and Fresh Properties of Concrete Made With Dolomite and Different Cementitious Materials (U.S. Customary Units)

Mixture Designation	Dlm1-c1-f1	Dlm2-c1-f1	Dlm2-c2-f1	Dlm3-c1-f1	Dlm3-c1-s	Dlm4-c1-f1	Dlm4-c1	Dlm5-c1-f1	Dlm5-c1-f2
Laboratory mixture designation	6	3	3-c2	7	7-s	2	2-c1	9	9-f2
Cement, Lafarge I (lb/yd^3)	391	381	388*	405	400	386	545	403	394
Class C fly ash, Pleasant Prairie (lb/yd3)	168	164	167	175	0	167	0	174	170†
Grade 120 GGBFS, Lafarge (lb/yd^3)	0	0	0	0	173	0	0	0	0
Water (lb/yd^3)	225	207	209	233	231	223	213	232	227
Fine aggregate, SSD (lb/yd^3)	1080	1050	1070	1120	1110	1070	1070	1110	1090
No. 1 coarse aggregate, 0.75 to 3/16 ", SSD (lb/yd^3)	1210	1190	1210	1240	1230	1200	1200	1250	1220
No. 2 coarse aggregate, 1.5 to 0.75", SSD (lb/yd^3)	805	791	807	825	819	800	804	827	809
Water-reducing admixture (fl oz/yd^3)	33.8	18.9	4.1	4.3	17.2	8.3	24.2	4.3	4.2
Air-entraining admixture (fl oz/yd^3)	14.9	22.9	22.5	38.5	40.4	20.5	30.2	55.3	42.5
Water-cementitious ratio, W/Cm	0.40	0.38	0.38	0.40	0.40	0.40	0.39	0.40	0.40
Slump (in.)	2-3/4	3	2-1/2	2-3/4	1-1/4	4-1/4	2-1/4	1	4
Air content (%)	7.0	7.3	6.0	6.2	5.6	6.0	6.1	5.6	6.8
Air temperature (°F)	70	72	71	71	72	70	71	71	71
Concrete temperature (°F)	70	72	71	66	72	70	71	71	70
Density (lb/ft^3)	144	140	143	148	147	142	142	148	145

* St. Marys cement.
† Weston fly ash.

5.2 Compressive Strength

The test results for compressive strength of concrete are given in Table 5-6 and Table 5-7 in MPa, and in Table 5-8 and Table 5-9 in psi. The results are also presented in Fig. 5-1 and Fig. 5-2. Test results for individual specimens are given in Appendix A.

The compressive strength of the concrete was affected significantly by the type and source of the coarse aggregate. The compressive strength of concrete made with glacial gravels from the different sources varied significantly in terms of magnitude and development pattern with time (Table 5-6, Fig. 5-1, and Table 5-8). The compressive strength of concrete made with dolomite also varied significantly depending on the source of dolomite (Table 5-7, Fig. 5-2, and Table 5-9).

The types and sources of cementitious materials affected the compressive strength of the concrete made with dolomite (Table 5-7, Fig. 5-2, and Table 5-9). The source of cement (Dlm2-c1-f1 vs. Dlm2-c2-f1) and the source of Class C fly ash (Dlm5-c1-f1 vs. Dlm5-c1-f2) affected the compressive strength significantly. Using a blend of cement and Grade 120 GGBFS (Dlm3-c1-s), instead of the blend of cement and Class C fly ash from Source 1 (Dlm3-c1-f1), increased the 7-day, 14-day, and 28-day compressive strength values slightly. Use of cement alone (Dlm4-c1) increased the compressive strength, when compared with the use of cement and Class C fly ash from Source 1 (Dlm4-c1-f1).

Table 5-6. Compressive Strength of Concrete Made With Gravel, Quartzite, Granite, Diabase, or Basalt (MPa)

Mixture	7-day	14-day	28-day	90-day
Gvl1-c1-f1	24.5	26.3	33.6	41.2
Gvl2-c1-f1	19.0	20.5	26.1	31.8
Gvl3-c1-f1	20.3	24.0	28.0	34.3
Gvl4-c1-f1	23.3	27.4	30.5	35.0
Gvl5-c1-f1	19.8	22.4	24.5	30.7
Gvl6-c1-f1	19.9	25.0	28.9	37.9
Qtz-c1-f1	22.5	25.2	30.1	34.7
Gnt-c1-f1	23.9	26.4	27.0	34.6
Dbs-c1-f1	26.2	31.4	38.3	40.8
Bst-c1-f1	19.1	20.8	26.9	29.5

Table 5-7. Compressive Strength of Concrete Made With Dolomite and Different Cementitious Materials (MPa)

Mixture	7-day	14-day	28-day	90-day
Dlm1-c1-f1	28.3	32.9	36.4	41.4
Dlm2-c1-f1	21.7	24.9	29.9	35.0
Dlm2-c2-f1	19.6	34.1	36.4	46.1
Dlm3-c1-f1	25.0	30.1	35.3	40.7
Dlm3-c1-s	27.9	33.8	37.0	40.7
Dlm4-c1-f1	20.0	23.5	27.2	31.9
Dlm4-c1	24.1	29.6	32.8	33.9
Dlm5-c1-f1	25.5	32.4	36.1	40.3
Dlm5-c1-f2	19.0	22.0	24.6	31.2

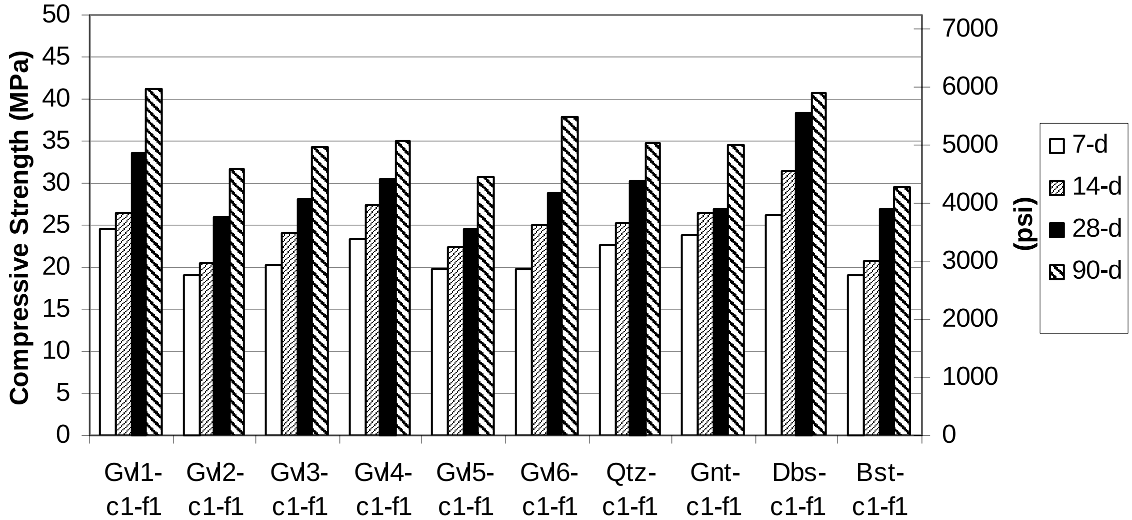

Fig. 5-1. Compressive strength of concrete made with gravel, quartzite, granite, diabase, or basalt

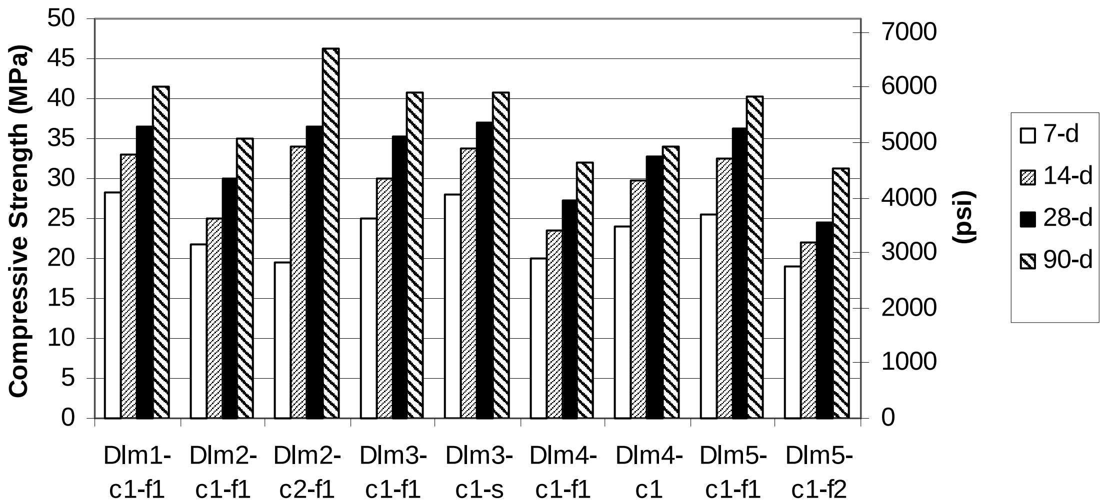

Fig. 5-2. Compressive strength of concrete made with dolomite and different cementitious materials

Table 5-8. Compressive Strength of Concrete Made With Gravel, Quartzite, Granite, Diabase, or Basalt (psi)

Mixture	7-day	14-day	28-day	90-day
Gvl1-c1-f1	3550	3820	4870	5970
Gvl2-c1-f1	2760	2980	3780	4610
Gvl3-c1-f1	2950	3480	4060	4970
Gvl4-c1-f1	3380	3970	4430	5070
Gvl5-c1-f1	2870	3250	3550	4450
Gvl6-c1-f1	2880	3620	4190	5490
Qtz-c1-f1	3270	3660	4370	5040
Gnt-c1-f1	3470	3830	3910	5020
Dbs-c1-f1	3800	4560	5560	5920
Bst-c1-f1	2770	3020	3900	4280

Table 5-9. Compressive Strength of Concrete Made With Dolomite and Different Cementitious Materials (psi)

Mixture	7-day	14-day	28-day	90-day
Dlm1-c1-f1	4110	4770	5280	6010
Dlm2-c1-f1	3150	3610	4340	5070
Dlm2-c2-f1	2840	4940	5280	6690
Dlm3-c1-f1	3620	4360	5120	5900
Dlm3-c1-s	4050	4900	5370	5910
Dlm4-c1-f1	2900	3410	3940	4630
Dlm4-c1	3490	4300	4750	4920
Dlm5-c1-f1	3700	4700	5240	5840
Dlm5-c1-f2	2750	3190	3570	4520

5.3 Splitting Tensile Strength

The test results for splitting tensile strength of concrete in MPa are given in Table 5-10 and Table 5-11, and splitting tensile strength in psi in Table 5-12 and Table 5-13. The results are also presented in Fig. 5-3 and Fig. 5-4.

The splitting tensile strength test results of the concrete mixtures made with glacial gravel varied when the source of the gravel was changed (Table 5-10, Fig. 5-3, and Table 5-12). The splitting tensile strength of concrete mixtures made with dolomite varied significantly depending on the source of dolomite (Table 5-11, Fig. 5-4, and Table 5-13).

The types and sources of cementitious materials also affected the splitting tensile strength of the concrete made with dolomite (Table 5-11, Fig. 5-4, and Table 5-13). This is based on the testing of very limited number of concrete mixtures for this project. Changing the source of cement (Dlm2-c1-f1 vs. Dlm2-c2-f1) had some influence on splitting tensile strength. Splitting tensile strength of the concrete mixture using cement from Source 2 (Dlm2-c2-f1) had a higher splitting tensile strength at test ages of 7, 14, and 28 days, but nearly identical strength at 90 days, when compared to the concrete mixture using cement from Source 1 (Dlm2-c1-f1). The use of Grade 120 GGBFS (Dlm3-c1-s) improved the splitting tensile strength at 7, 14, and 28 days but lowered the 90-day splitting tensile strength, when compared with the use of Class C fly ash from Source 1 (Dlm3-c1-f1). The use of cement alone (Dlm4-c1) slightly increased the 7-day, 14-day, and 28-day splitting tensile strength, and slightly lowered the 90-day splitting tensile strength, when compared with the use of cement plus Class C fly ash from Source 1 (Dlm4-c1-f1). The change in the source of Class C fly ash (Dlm5-c1-f1 vs. Dlm5-c1-f2) influenced the splitting tensile strength significantly.

Table 5-10. Splitting Tensile Strength of Concrete Made With Gravel, Quartzite, Granite, Diabase, or Basalt (MPa)

Mixture	7-day	14-day	28-day	90-day
Gvl1-c1-f1	2.90	3.31	3.79	4.34
Gvl2-c1-f1	3.03	2.96	3.45	4.62
Gvl3-c1-f1	3.31	3.65	4.00	4.69
Gvl4-c1-f1	2.83	3.45	3.79	4.55
Gvl5-c1-f1	2.76	3.17	3.38	4.14
Gvl6-c1-f1	2.76	3.45	3.72	4.48
Qtz-c1-f1	3.38	3.45	4.07	4.62
Gnt-c1-f1	3.03	3.65	3.72	4.21
Dbs-c1-f1	3.65	3.72	4.48	5.03
Bst-c1-f1	3.24	3.45	4.00	4.76

Table 5-11. Splitting Tensile Strength of Concrete Made With Dolomite and Different Cementitious Materials (MPa)

Mixture	7-day	14-day	28-day	90-day
Dlm1-c1-f1	3.72	4.14	4.62	5.52
Dlm2-c1-f1	2.76	2.83	3.45	4.27
Dlm2-c2-f1	2.83	3.72	3.86	4.21
Dlm3-c1-f1	2.76	3.59	3.59	5.45
Dlm3-c1-s	3.86	4.21	4.21	5.03
Dlm4-c1-f1	3.24	3.45	3.72	4.48
Dlm4-c1	3.45	3.72	4.07	4.34
Dlm5-c1-f1	3.45	3.45	3.86	4.69
Dlm5-c1-f2	2.62	2.90	3.72	3.72

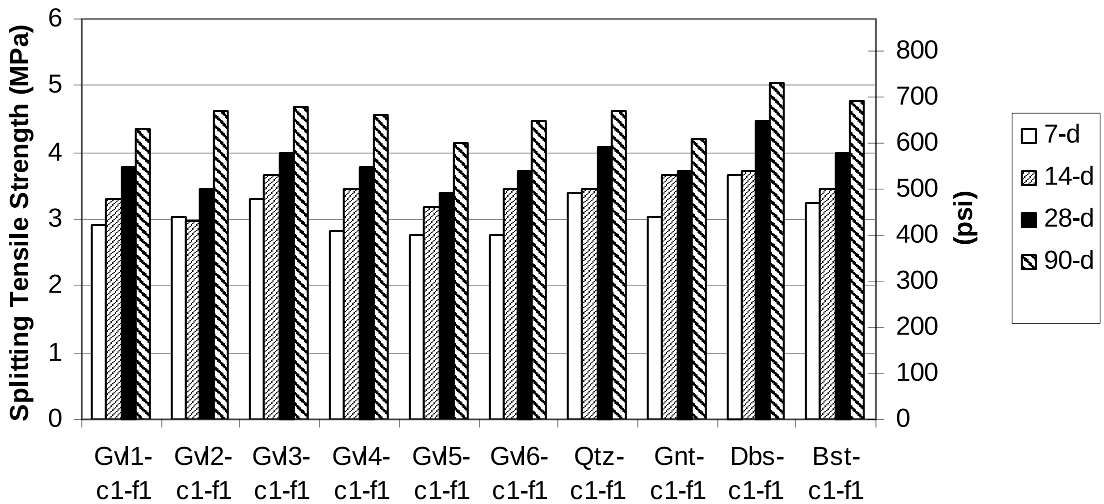

Fig. 5-3. Splitting tensile strength of concrete made with gravel, quartzite, granite, diabase, or basalt

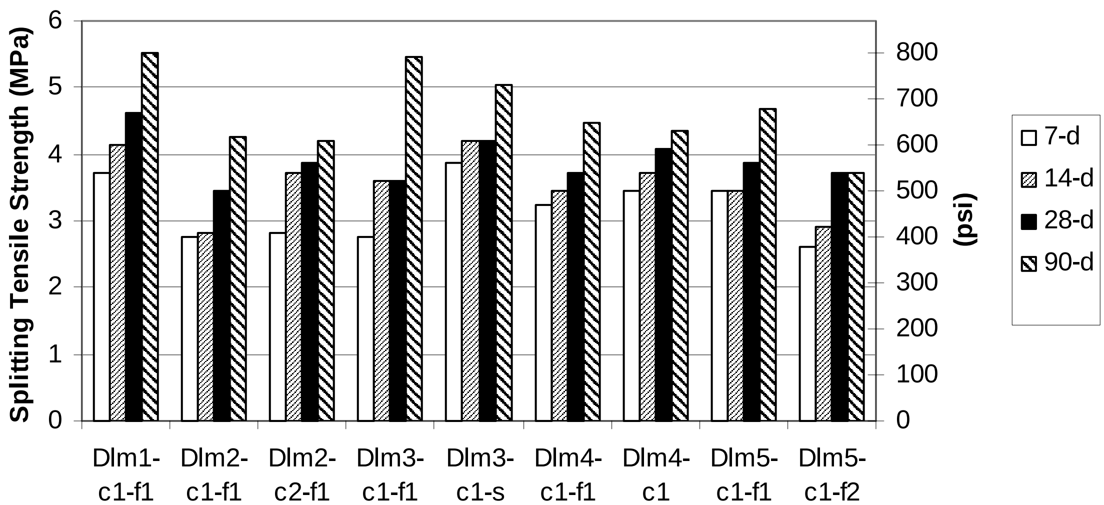

Fig. 5-4. Splitting tensile strength of concrete made with dolomite and different cementitious materials

Table 5-12. Splitting Tensile Strength of Concrete Made With Gravel, Quartzite, Granite, Diabase, or Basalt (psi)

Mixture	7-day	14-day	28-day	90-day
Gvl1-c1-f1	420	480	550	630
Gvl2-c1-f1	440	430	500	670
Gvl3-c1-f1	480	530	580	680
Gvl4-c1-f1	410	500	550	660
Gvl5-c1-f1	400	460	490	600
Gvl6-c1-f1	400	500	540	650
Qtz-c1-f1	490	500	590	670
Gnt-c1-f1	440	530	540	610
Dbs-c1-f1	530	540	650	730
Bst-c1-f1	470	500	580	690

Table 5-13. Splitting Tensile Strength of Concrete Made With Dolomite and Different Cementitious Materials (psi)

Mixture	7-day	14-day	28-day	90-day
Dlm1-c1-f1	540	600	670	800
Dlm2-c1-f1	400	410	500	620
Dlm2-c2-f1	410	540	560	610
Dlm3-c1-f1	400	520	520	790
Dlm3-c1-s	560	610	610	730
Dlm4-c1-f1	470	500	540	650
Dlm4-c1	500	540	590	630
Dlm5-c1-f1	500	500	560	680
Dlm5-c1-f2	380	420	540	540

5.4 Relationship Between Compressive Strength and Splitting Tensile Strength

The relationship between the 28-day compressive strength and the 28-day splitting tensile strength is shown in Fig. 5-5 and Fig. 5-6. At a given compressive strength, the corresponding splitting tensile strength varied as much as 1 MPa (about 150 psi), depending on the concrete mixture. In addition, the splitting tensile strength was higher by an average of approximately 30% than the values estimated from compressive strength using the mechanistic-empirical design guide for Level 2 design (lower accuracy than Level 1). Therefore, these observations show that it is best to establish the splitting tensile strength of concrete by actual testing, rather than estimate it based on compressive strength.

Overall, the compressive strength and splitting tensile strength of the concrete mixtures made with crushed stone (quartzite, granite, diabase, basalt, and dolomite) were higher than those of the concrete mixtures made with glacial gravel (Fig. 5-5 and Fig. 5-6).

Additional graphs showing the relationship between compressive strength and splitting tensile strength are provided in Appendix B.1 (7, 14, 28, and 90-day ages).

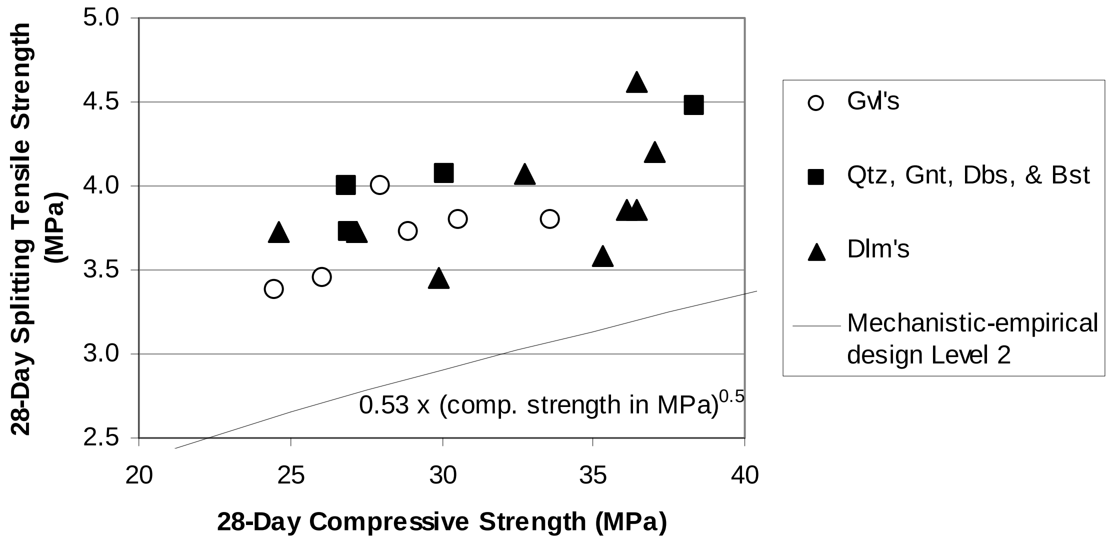

Fig. 5-5. Relationship between the 28-day compressive strength in MPa and the 28-day splitting tensile strength in MPa

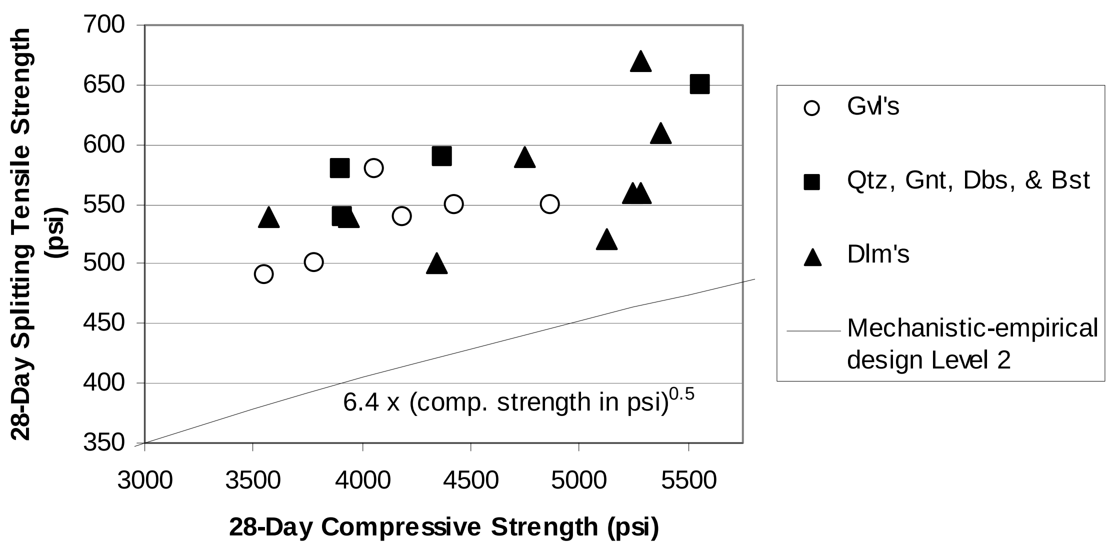

Fig. 5-6. Relationship between the 28-day compressive strength in psi and the 28-day splitting tensile strength in psi

Fig. 5-7 shows a regression model of the splitting tensile strength data in MPa collected at 7, 14, 28, and 90 days. Dotted lines show a 95% confidence interval for the estimate of the mean value of splitting tensile strength. Fig. 5-8 shows a regression model of splitting tensile strength in psi.

The regression model y = 0.70 × (compressive strength in MPa)$^{0.5}$ [or 8.5 × (compressive strength in psi)$^{0.5}$] estimates the mean value of splitting tensile strength about 30% higher than the equation y = 0.53 × (compressive strength in MPa)$^{0.5}$ [or 6.4 × (compressive strength in psi)$^{0.5}$] given in mechanistic-empirical design guide.

Additional regression models of splitting tensile strength are provided in Appendix B.2, one model for each of 7, 14, 28, and 90 days.

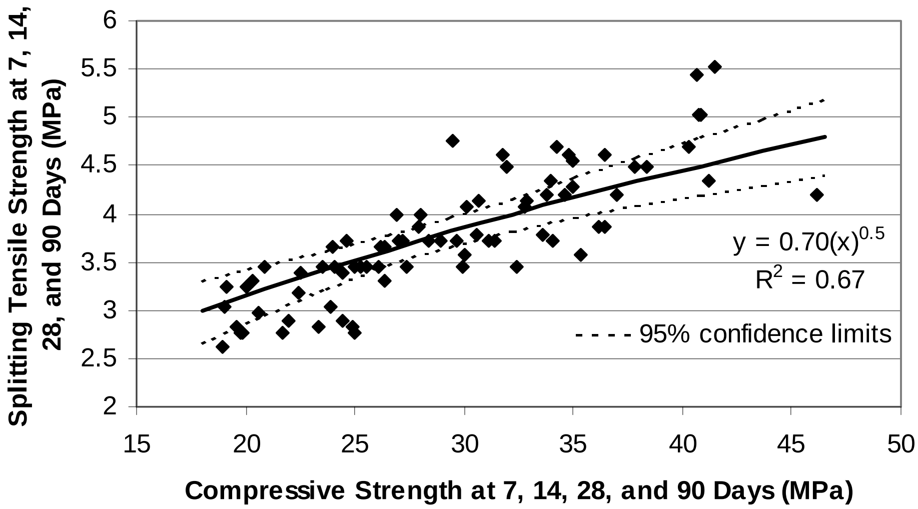

Fig. 5-7. Regression model of splitting tensile strength data in MPa collected at 7, 14, 28, and 90 days

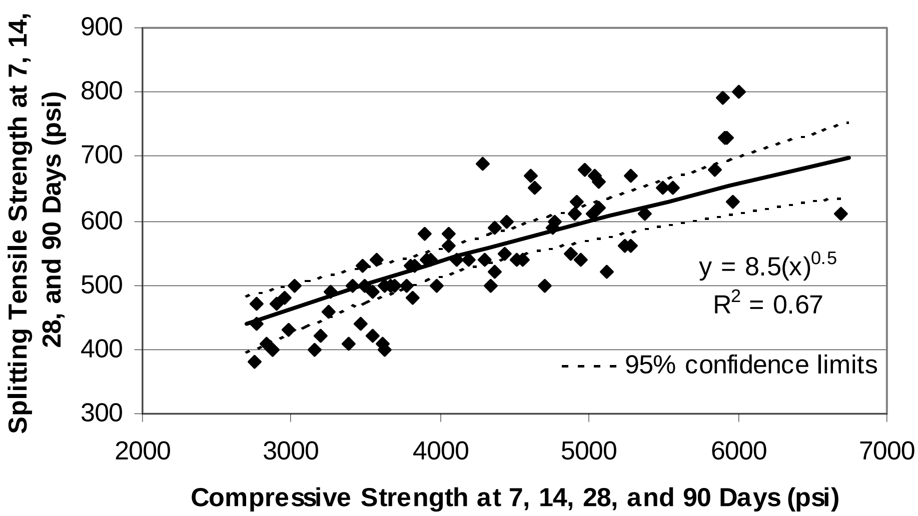

Fig. 5-8. Regression model of splitting tensile strength data in psi collected at 7, 14, 28, and 90 days

5.5 Coefficient of Thermal Expansion

The test results for coefficient of thermal expansion (CTE) of concrete are given in Table 5-14 and Table 5-15 in units of microstrain/°C (10^{-6}/°C), and in Table 5-16 and Table 5-17 in units of microstrain/°F (10^{-6}/°F). The results are also presented Fig. 5-9 and Fig. 5-10.

Among the types of coarse aggregate tested, the concrete made with quartzite (Qtz-c1-f1) had the highest CTE, 12.2 microstrain/°C (6.8 microstrain/°F) (Table 5-14, Table 5-16, and Fig. 5-9). The concrete mixtures made with diabase, basalt, and granite showed the lowest CTE, ranging from 9.3 to 9.5 microstrain/°C (5.2 to 5.3 microstrain/°F). The CTE of concrete made with glacial gravel from the six sources ranged from 9.7 to 10.7 microstrain/°C (5.4 to 5.9 microstrain/°F). This implies that the sources of glacial gravel selected for this project had different rock and mineral compositions, which affected the CTE. The CTE of concrete mixtures made with dolomite from the five sources was relatively uniform, ranging from 10.4 to 10.8 microstrain/°C (5.8 to 6.0 microstrain/°F) (Table 5-15, Table 5-17, and Fig. 5-10).

The types and sources of cementitious materials had a negligible influence on the CTE of the concrete made with dolomite (Table 5-15, Table 5-17, and Fig. 5-10). CTE was influenced very little (0.0 to 0.2 microstrain/°C [0.0 to 0.1 microstrain/°F]) by: (1) the source of cement (Dlm2-c1-f1 vs. Dlm2-c2-f1); (2) the source of Class C fly ash (Dlm5-c1-f1 vs. Dlm5-c1-f2); (3) the use of Class C fly ash from Source 1 vs. Grade 120 GGBFS (Dlm3-c1-f1 vs. Dlm3-c1-s); and (4) the use of cement plus Class C fly ash from Source 1 vs. cement alone (Dlm4-c1-f1 vs. Dlm4-c1).

The mechanistic-empirical design guide provides ranges of CTE values of aggregates for use in estimating CTE of concrete for Level 2 design [18]. However, these ranges are quite wide, for example CTE of 7.0 to 9.9 × 10^{-6}/°C (3.9 to 5.5 × 10^{-6}/°F) for dolomite aggregate. For the most accurate design, the CTE of concrete should be determined by actual testing.

Table 5-14. Coefficient of Thermal Expansion (CTE) of Concrete Made With Gravel, Quartzite, Granite, Diabase, or Basalt (microstrain/°C)

Mixture	28-day CTE (microstrain/°C)
Gvl1-c1-f1	10.4
Gvl2-c1-f1	10.5
Gvl3-c1-f1	10.7
Gvl4-c1-f1	9.9
Gvl5-c1-f1	9.7
Gvl6-c1-f1	10.1
Qtz-c1-f1	12.2
Gnt-c1-f1	9.5
Dbs-c1-f1	9.3
Bst-c1-f1	9.3

Table 5-15. Coefficient of Thermal Expansion (CTE) of Concrete Made With Dolomite and Different Cementitious Materials (microstrain/°C)

Mixture	28-day CTE (microstrain/°C)
Dlm1-c1-f1	10.6
Dlm2-c1-f1	10.5
Dlm2-c2-f1	10.5
Dlm3-c1-f1	10.4
Dlm3-c1-s	10.5
Dlm4-c1-f1	10.6
Dlm4-c1	10.7
Dlm5-c1-f1	10.8
Dlm5-c1-f2	10.6

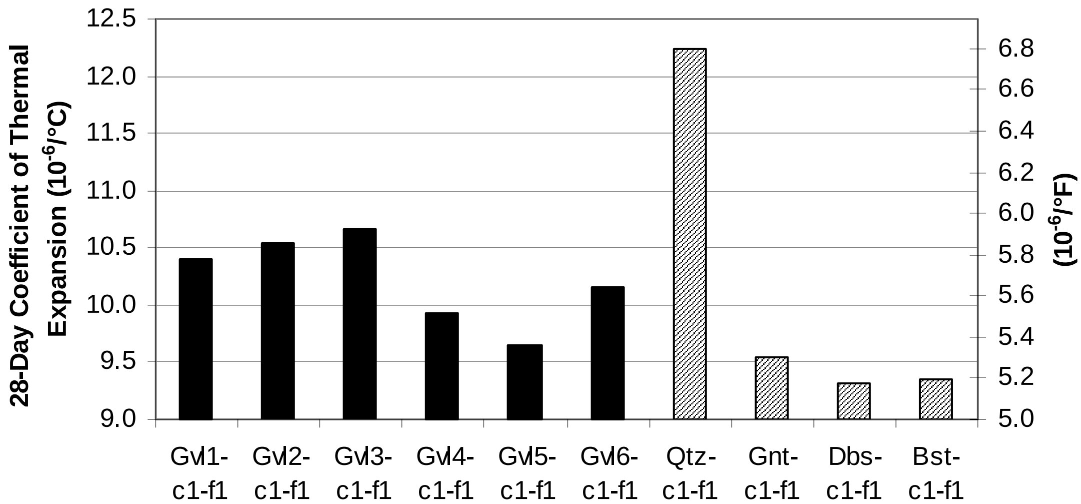

Fig. 5-9. Coefficient of thermal expansion of concrete made with gravel, quartzite, granite, diabase, or basalt

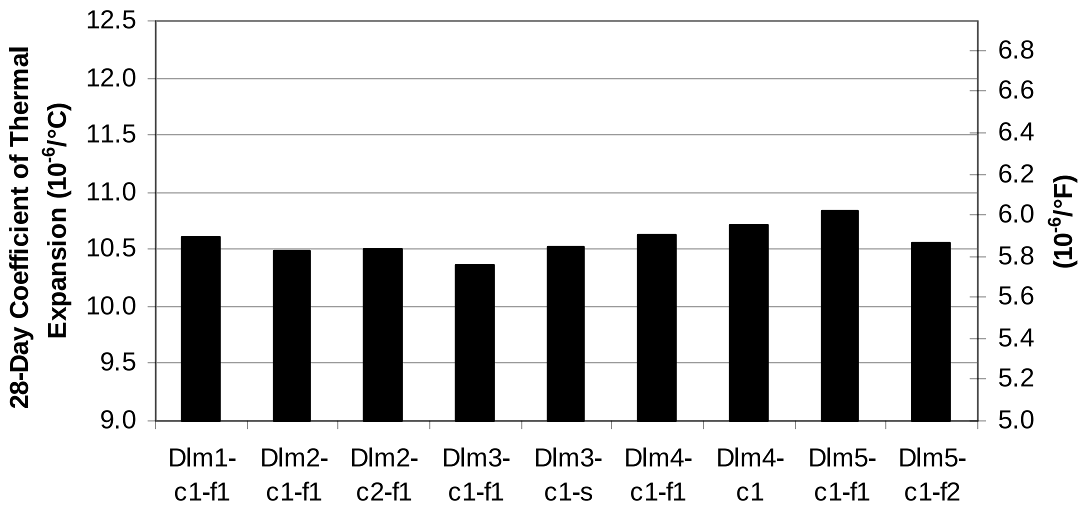

Fig. 5-10. Coefficient of thermal expansion of concrete made with dolomite and different cementitious materials

Table 5-16. Coefficient of Thermal Expansion (CTE) of Concrete Made With Gravel, Quartzite, Granite, Diabase, or Basalt (microstrain/°F)

Mixture	28-day CTE (microstrain/°F)
Gvl1-c1-f1	5.8
Gvl2-c1-f1	5.9
Gvl3-c1-f1	5.9
Gvl4-c1-f1	5.5
Gvl5-c1-f1	5.4
Gvl6-c1-f1	5.6
Qtz-c1-f1	6.8
Gnt-c1-f1	5.3
Dbs-c1-f1	5.2
Bst-c1-f1	5.2

Table 5-17. Coefficient of Thermal Expansion (CTE) of Concrete Made With Dolomite and Different Cementitious Materials (microstrain/°F)

Mixture	28-day CTE (microstrain/°F)
Dlm1-c1-f1	5.9
Dlm2-c1-f1	5.8
Dlm2-c2-f1	5.8
Dlm3-c1-f1	5.8
Dlm3-c1-s	5.8
Dlm4-c1-f1	5.9
Dlm4-c1	6.0
Dlm5-c1-f1	6.0
Dlm5-c1-f2	5.9

Chapter 6. Summary and Recommendations for Future Work

6.1 Summary

This research was conducted to investigate the splitting tensile strength and coefficient of thermal expansion (CTE) of concrete to support implementation of the AASHTO Mechanistic-Empirical Pavement Design Guide in Wisconsin. Compressive strength of concrete was also determined as additional test information.

WisDOT Grade A-FA (70% cement plus 30% Class C fly ash) concrete mixtures were investigated containing selected types of coarse aggregates from 15 sources: glacial gravel from six sources, dolomite from five sources, quartzite, granite, diabase, and basalt. In addition, the effects of the cementitious materials in concrete mixtures were investigated such as the source of cement, the source of fly ash, the use of GGBFS vs. fly ash, and the use of cement alone vs. cement plus fly ash.

The compressive strength of the concrete was affected significantly by the type and source of the coarse aggregate. The types and sources of cementitious materials influenced the compressive strength of concrete made with dolomite.

The splitting tensile strength test results of the concrete mixtures made with glacial gravel varied when the source of the gravel was changed. The splitting tensile strength of concrete mixtures made with dolomite varied significantly depending on the source. The types and sources of cementitious materials also affected the splitting tensile strength of the concrete made with dolomite. The splitting tensile strength estimated from compressive strength (using the relationship specified in the mechanistic-empirical design guide for Level 2 design) was considerably lower than the splitting tensile strength determined by actual testing.

Among the types of coarse aggregates tested, the concrete made with quartzite (Qtz-c1-f1) had the highest CTE, 12.2 microstrain/°C (6.8 microstrain/°F). The concrete mixtures made with diabase, basalt, and granite showed the lowest CTE, ranging from 9.3 to 9.5 microstrain/°C (5.2 to 5.3 microstrain/°F). The CTE of concrete made with glacial gravel from the six sources ranged from 9.7 to 10.7 microstrain/°C (5.4 to 5.9 microstrain/°F). The CTE of concrete mixtures made with dolomite from the five sources was relatively uniform, ranging from 10.4 to 10.8 microstrain/°C (5.8 to 6.0 microstrain/°F). The types and sources of cementitious materials had a negligible influence on the CTE of concrete made with dolomite.

6.2 Recommendations

It is recommended that concrete mixtures made with cementitious materials and coarse aggregates from other sources also be tested for splitting tensile strength for use as inputs in the mechanistic-empirical pavement design. CTE testing of concrete made with any other sources of coarse aggregate in Wisconsin not evaluated in this project is also recommended. CTE testing of concrete mixtures containing dolomite from any other sources does not appear to be necessary since the CTE of concrete containing the five sources of dolomite for this project was approximately the same.

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Appendix A. Test Data for Individual Specimens

A.1 Compressive Strength

Table A-1. Compressive Strength of Concrete Made With Gravel (MPa)

Age (days)	Gvl1-c1-f1		Gvl2-c1-f1		Gvl3-c1-f1		Gvl4-c1-f1		Gvl5-c1-f1		Gvl6-c1-f1	
	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.
7	25.1 24.5 23.9	24.5	20.3 15.8 21.0	19.0	21.2 18.4 21.4	20.3	23.9 23.8 22.3	23.3	21.2 20.1 18.1	19.8	20.1 19.2 20.3	19.9
14	26.1 26.3 26.6	26.3	19.8 21.4 20.3	20.5	24.1 25.4 22.5	24.0	28.9 24.3 29.0	27.4	21.9 23.4 21.9	22.4	24.1 25.6 25.2	25.0
28	32.9 35.3 32.6	33.6	27.5 24.7 26.1	26.1	28.6 28.1 27.3	28.0	30.0 28.4 33.2	30.5	25.6 21.9 25.9	24.5	28.8 27.0 30.9	28.9
90	40.0 42.0 41.5	41.2	31.6 31.2 32.5	31.8	36.7 32.8 33.3	34.3	35.1 32.5 37.2	35.0	32.8 30.6 28.6	30.7	39.7 38.3 35.6	37.9

Table A-2. Compressive Strength of Concrete Made With Quartzite, Granite, Diabase, or Basalt (MPa)

Age (days)	Qtz-c1-f1		Gnt-c1-f1		Dbs-c1-f1		Bst-c1-f1	
	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.
7	23.2 23.7 20.6	22.5	23.5 24.1 24.2	23.9	25.3 26.3 27.0	26.2	17.9 19.7 19.7	19.1
14	25.9 26.2 23.5	25.2	28.0 24.2 27.0	26.4	* 31.1 31.7	31.4	20.7 22.9 19.0	20.8
28	28.9 31.9 29.6	30.1	24.3 27.4 29.2	27.0	38.2 38.5 38.3	38.3	26.5 27.8 26.4	26.9
90	34.5 33.6 36.1	34.7	33.6 37.5 32.8	34.6	41.4 36.5 44.5	40.8	27.0 32.8 28.7	29.5

* Test result eliminated (≥ 15% from average).

Table A-3. Compressive Strength of Concrete Made With Dolomite and Different Cementitious Materials (MPa)

Age (days)	Dlm1-c1-f1		Dlm2-c1-f1		Dlm2-c2-f1		Dlm3-c1-f1		Dlm3-c1-s		Dlm4-c1-f1		Dlm4-c1		Dlm5-c1-f1		Dlm5-c1-f2	
	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.
7	27.0 31.6 26.5	28.3	18.4 23.9 22.9	21.7	20.3 16.6 21.9	19.6	26.2 24.5 24.1	25.0	28.8 27.6 27.2	27.9	18.9 22.1 19.1	20.0	24.1 23.6 24.6	24.1	28.8 23.2 24.5	25.5	19.0 19.7 18.1	19.0
14	30.6 35.1 32.9	32.9	22.9 23.2 28.6	24.9	33.5 33.4 35.2	34.1	29.4 29.4 31.3	30.1	33.7 33.9 n. a.	33.8	24.1 23.6 23.0	23.5	28.8 30.8 29.4	29.6	29.9 31.7 35.6	32.4	20.1 22.1 23.7	22.0
28	37.6 34.4 37.1	36.4	27.6 30.5 31.6	29.9	38.5 33.5 37.2	36.4	35.1 35.6 35.3	35.3	38.1 35.9 n. a.	37.0	27.2 26.3 28.1	27.2	32.5 33.3 32.4	32.8	36.1 38.4 33.9	36.1	24.3 25.1 24.5	24.6
90	40.2 43.0 41.2	41.4	34.9 35.4 34.5	35.0	43.9 44.2 50.3	46.1	41.2 40.2 40.7	40.7	42.5 39.0 n. a.	40.7	31.7 33.5 30.5	31.9	36.1 32.8 32.9	33.9	43.2 41.9 35.6	40.3	34.5 29.2 29.7	31.2

n. a.: Result not available.

Table A-4. Compressive Strength of Concrete Made With Gravel (psi)

Age (days)	Gvl1-c1-f1		Gvl2-c1-f1		Gvl3-c1-f1		Gvl4-c1-f1		Gvl5-c1-f1		Gvl6-c1-f1	
	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.
7	3640 3560 3460	3550	2950 2290 3040	2760	3070 2670 3100	2950	3460 3450 3240	3380	3070 2920 2630	2870	2920 2790 2940	2880
14	3780 3810 3860	3820	2870 3110 2950	2980	3500 3680 3270	3480	4190 3530 4200	3970	3170 3400 3170	3250	3490 3720 3650	3620
28	4770 5120 4730	4870	3990 3580 3780	3780	4150 4070 3960	4060	4350 4120 4810	4430	3720 3180 3760	3550	4170 3920 4480	4190
90	5800 6090 6020	5970	4580 4530 4720	4610	5330 4750 4830	4970	5090 4720 5400	5070	4760 4440 4150	4450	5760 5550 5160	5490

Table A-5. Compressive Strength of Concrete Made With Quartzite, Granite, Diabase, or Basalt (psi)

Age (days)	Qtz-c1-f1		Gnt-c1-f1		Dbs-c1-f1		Bst-c1-f1	
	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.
7	3370 3440 2990	3270	3410 3490 3510	3470	3670 3820 3920	3800	2600 2850 2860	2770
14	3760 3800 3410	3660	4060 3510 3920	3830	* 4510 4600	4560	3000 3320 2750	3020
28	4190 4620 4300	4370	3530 3970 4240	3910	5540 5590 5560	5560	3840 4030 3830	3900
90	5010 4880 5230	5040	4870 5440 4760	5020	6000 5300 6450	5920	3920 4750 4160	4280

* Test result eliminated (≥ 15% from average).

Table A-6. Compressive Strength of Concrete Made With Dolomite and Different Cementitious Materials (psi)

Age (days)	Dlm1-c1-f1		Dlm2-c1-f1		Dlm2-c2-f1		Dlm3-c1-f1		Dlm3-c1-s		Dlm4-c1-f1		Dlm4-c1		Dlm5-c1-f1		Dlm5-c1-f2	
	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.
7	3920 4580 3840	4110	2670 3470 3320	3150	2940 2410 3170	2840	3800 3550 3500	3620	4180 4010 3950	4050	2740 3200 2770	2900	3490 3420 3570	3490	4170 3360 3560	3700	2760 2850 2630	2750
14	4440 5090 4770	4770	3320 3370 4150	3610	4860 4850 5110	4940	4270 4270 4540	4360	4890 4910 n. a.	4900	3490 3420 3330	3410	4170 4460 4270	4300	4340 4600 5160	4700	2920 3200 3440	3190
28	5460 4990 5380	5280	4010 4420 4580	4340	5590 4860 5400	5280	5090 5160 5120	5120	5520 5210 n. a.	5370	3940 3820 4070	3940	4710 4830 4700	4750	5240 5570 4910	5240	3530 3640 3550	3570
90	5830 6240 5970	6010	5060 5140 5000	5070	6370 6410 7290	6690	5980 5830 5900	5900	6170 5650 n. a.	5910	4600 4860 4420	4630	5230 4750 4770	4920	6270 6070 5170	5840	5010 4230 4310	4520

n. a.: Result not available.

A.2 Splitting Tensile Strength

Table A-7. Splitting Tensile Strength of Concrete Made With Gravel (MPa)

Age (days)	Gvl1-c1-f1		Gvl2-c1-f1		Gvl3-c1-f1		Gvl4-c1-f1		Gvl5-c1-f1		Gvl6-c1-f1	
	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.
7	3.03 3.17 2.55	2.90	2.83 3.17 3.10	3.03	3.24 3.52 3.17	3.31	2.96 2.90 2.69	2.83	2.62 2.76 2.96	2.76	2.55 3.03 2.76	2.76
14	3.24 3.38 3.31	3.31	2.96 2.96 3.03	2.96	3.59 3.86 3.52	3.65	3.65 3.31 3.45	3.45	3.10 3.10 3.38	3.17	3.45 3.59 3.38	3.45
28	3.93 3.79 3.72	3.79	3.03 3.52 3.72	3.45	4.07 4.07 3.93	4.00	3.65 3.93 3.72	3.79	3.52 3.45 3.10	3.38	3.65 3.79 3.79	3.72
90	4.34 4.27 4.34	4.34	4.69 4.62 4.62	4.62	5.03 4.41 4.55	4.69	4.83 4.41 4.34	4.55	4.14 4.14 4.14	4.14	4.07 4.96 4.41	4.48

Table A-8. Splitting Tensile Strength of Concrete Made With Quartzite, Granite, Diabase, or Basalt (MPa)

Age (days)	Qtz-c1-f1		Gnt-c1-f1		Dbs-c1-f1		Bst-c1-f1	
	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.
7	3.38 3.45 3.38	3.38	2.90 2.83 3.31	3.03	3.79 3.65 3.52	3.65	3.31 3.17 3.24	3.24
14	3.52 3.52 3.31	3.45	3.86 3.52 3.59	3.65	3.52 4.14 3.45	3.72	* 3.52 3.31	3.45
28	4.34 4.07 3.72	4.07	3.52 4.21 3.52	3.72	4.34 4.34 4.69	4.48	3.79 4.00 4.14	4.00
90	4.76 4.83 4.34	4.62	3.93 4.48 n. a.	4.21	5.17 4.83 5.10	5.03	5.03 4.07 5.17	4.76

* Test result eliminated (≥ 15% from average).
n. a.: Result not available.

Table A-9. Splitting Tensile Strength of Concrete Made With Dolomite and Different Cementitious Materials (MPa)

Age (days)	Dlm1-c1-f1		Dlm2-c1-f1		Dlm2-c2-f1		Dlm3-c1-f1		Dlm3-c1-s		Dlm4-c1-f1		Dlm4-c1		Dlm5-c1-f1		Dlm5-c1-f2	
	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.
7	4.07 3.31 3.86	3.72	2.69 2.83 2.83	2.76	3.03 2.48 3.03	2.83	2.41 3.31 2.55	2.76	3.72 4.00 3.79	3.86	2.90 3.38 3.38	3.24	3.45 3.59 3.38	3.45	3.38 3.59 3.31	3.45	2.55 2.69 2.69	2.62
14	4.14 4.34 3.86	4.14	2.96 2.83 2.69	2.83	4.00 3.52 3.59	3.72	3.38 3.93 3.52	3.59	4.41 4.27 3.93	4.21	3.52 3.52 3.24	3.45	3.52 3.72 3.86	3.72	3.52 3.38 3.52	3.45	3.17 2.83 2.69	2.90
28	4.90 4.69 4.21	4.62	3.59 3.38 3.38	3.45	4.00 3.59 3.93	3.86	3.72 3.52 3.45	3.59	4.69 3.93 3.93	4.21	4.00 3.65 3.52	3.72	4.07 4.14 4.07	4.07	3.72 3.93 3.86	3.86	3.79 3.38 3.93	3.72
90	5.65 5.38 5.52	5.52	4.14 3.93 4.76	4.27	4.34 4.34 4.00	4.21	5.45 5.58 5.24	5.45	5.58 4.69 4.83	5.03	4.90 4.00 4.48	4.48	4.41 4.07 4.48	4.34	4.90 4.41 4.83	4.69	3.86 3.86 3.52	3.72

Table A-10. Splitting Tensile Strength of Concrete Made With Gravel (psi)

Age (days)	Gvl1-c1-f1		Gvl2-c1-f1		Gvl3-c1-f1		Gvl4-c1-f1		Gvl5-c1-f1		Gvl6-c1-f1	
	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.
7	440 460 370	420	410 460 450	440	470 510 460	480	430 420 390	410	380 400 430	400	370 440 400	400
14	470 490 480	480	430 430 440	430	520 560 510	530	530 480 500	500	450 450 490	460	500 520 490	500
28	570 550 540	550	440 510 540	500	590 590 570	580	530 570 540	550	510 500 450	490	530 550 550	540
90	630 620 630	630	680 670 670	670	730 640 660	680	700 640 630	660	600 600 600	600	590 720 640	650

Table A-11. Splitting Tensile Strength of Concrete Made With Quartzite, Granite, Diabase, or Basalt (psi)

Age	Qtz-c1-f1		Gnt-c1-f1		Dbs-c1-f1		Bst-c1-f1	
(days)	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.
7	490 500 490	490	420 410 480	440	550 530 510	530	480 460 470	470
14	510 510 480	500	560 510 520	530	510 600 500	540	* 510 480	500
28	630 590 540	590	510 610 510	540	630 630 680	650	550 580 600	580
90	690 700 630	670	570 650 n. a.	610	750 700 740	730	730 590 750	690

* Test result eliminated (≥ 15% from average).
n. a.: Result not available.

Table A-12. Splitting Tensile Strength of Concrete Made With Dolomite and Different Cementitious Materials (psi)

Age	Dlm1-c1-f1		Dlm2-c1-f1		Dlm2-c2-f1		Dlm3-c1-f1		Dlm3-c1-s		Dlm4-c1-f1		Dlm4-c1		Dlm5-c1-f1		Dlm5-c1-f2	
(days)	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.	Ind.	Avg.
7	590 480 560	540	390 410 410	400	440 360 440	410	350 480 370	400	540 580 550	560	420 490 490	470	500 520 490	500	490 520 480	500	370 390 390	380
14	600 630 560	600	430 410 390	410	580 510 520	540	490 570 510	520	640 620 570	610	510 510 470	500	510 540 560	540	510 490 510	500	460 410 390	420
28	710 680 610	670	520 490 490	500	580 520 570	560	540 510 500	520	680 570 570	610	580 530 510	540	590 600 590	590	540 570 560	560	550 490 570	540
90	820 780 800	800	600 570 690	620	630 630 580	610	790 810 760	790	810 680 700	730	710 580 650	650	640 590 650	630	710 640 700	680	560 560 510	540

A.3 Coefficient of Thermal Expansion (CTE)

Table A-13. 28-Day CTE of Concrete (10^{-6}/°C)

Mixture	Specimen A	Specimen B	Specimen C	28-day Average
Gvl1-c1-f1	10.4	10.8	10.0	10.4
Gvl2-c1-f1	10.4	10.7	10.5	10.5
Gvl3-c1-f1	10.6	10.8	10.6	10.7
Gvl4-c1-f1	9.8	10.1	9.9	9.9
Gvl5-c1-f1	9.5	9.7	9.7	9.7
Gvl6-c1-f1	9.9	10.4	10.1	10.1
Qtz-c1-f1	12.1	12.4	12.2	12.2
Gnt-c1-f1	9.6	9.5	9.5	9.5
Dbs-c1-f1	9.4	n. a.	9.2	9.3
Bst-c1-f1	9.1	9.5	9.4	9.3
Dlm1-c1-f1	10.6	10.9	10.4	10.6
Dlm2-c1-f1	10.3	10.7	10.4	10.5
Dlm2-c2-f1	10.5	10.4	10.5	10.5
Dlm3-c1-f1	10.4	10.5	10.2	10.4
Dlm3-c1-s	10.4	10.8	10.4	10.5
Dlm4-c1-f1	10.4	11.0	10.4	10.6
Dlm4-c1	10.7	10.7	10.8	10.7
Dlm5-c1-f1	10.8	11.1	10.7	10.8
Dlm5-c1-f2	10.4	10.9	10.3	10.6

n. a.: Result not available.

Table A-14. 28-Day CTE of Concrete (10^{-6}/°F)

Mixture	Specimen A	Specimen B	Specimen C	28-day Average
Gvl1-c1-f1	5.8	6.0	5.6	5.8
Gvl2-c1-f1	5.8	6.0	5.8	5.9
Gvl3-c1-f1	5.9	6.0	5.9	5.9
Gvl4-c1-f1	5.4	5.6	5.5	5.5
Gvl5-c1-f1	5.3	5.4	5.4	5.4
Gvl6-c1-f1	5.5	5.8	5.6	5.6
Qtz-c1-f1	6.7	6.9	6.8	6.8
Gnt-c1-f1	5.3	5.3	5.3	5.3
Dbs-c1-f1	5.2	n. a.	5.1	5.2
Bst-c1-f1	5.1	5.3	5.2	5.2
Dlm1-c1-f1	5.9	6.0	5.8	5.9
Dlm2-c1-f1	5.7	5.9	5.8	5.8
Dlm2-c2-f1	5.9	5.8	5.9	5.8
Dlm3-c1-f1	5.8	5.8	5.7	5.8
Dlm3-c1-s	5.8	6.0	5.8	5.8
Dlm4-c1-f1	5.8	6.1	5.8	5.9
Dlm4-c1	5.9	5.9	6.0	6.0
Dlm5-c1-f1	6.0	6.1	5.9	6.0
Dlm5-c1-f2	5.8	6.1	5.7	5.9

n. a.: Result not available.

Appendix B. More Graphs of Relationship Between Compressive Strength and Splitting Tensile Strength

B.1 Graphs Showing Aggregate Type

Fig. B-1 to Fig. B-4 show the relationship between compressive strength and splitting tensile strength in MPa at 7, 14, 28, and 90 days, respectively. Fig. B-5 to Fig. B-8 show the relationship in psi.

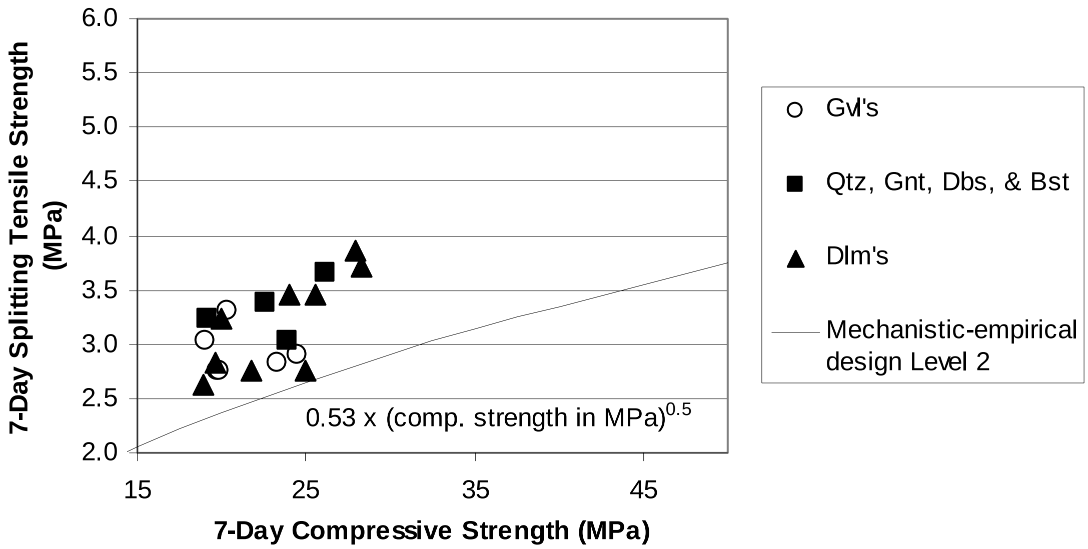

Fig. B-1. Relationship between compressive strength and splitting tensile strength of concrete at 7 days, both in MPa

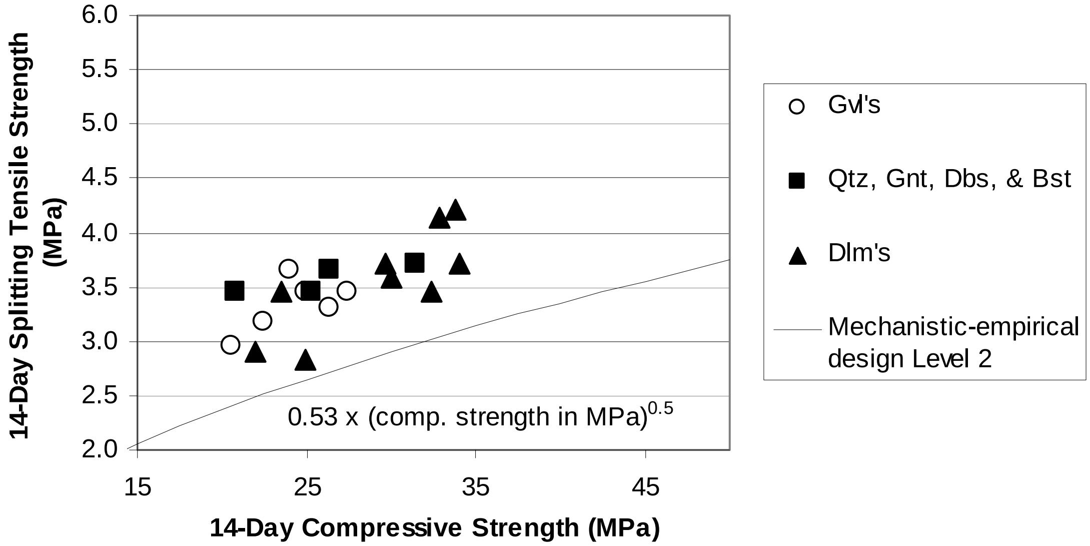

Fig. B-2. Relationship between compressive strength and splitting tensile strength of concrete at 14 days, both in MPa

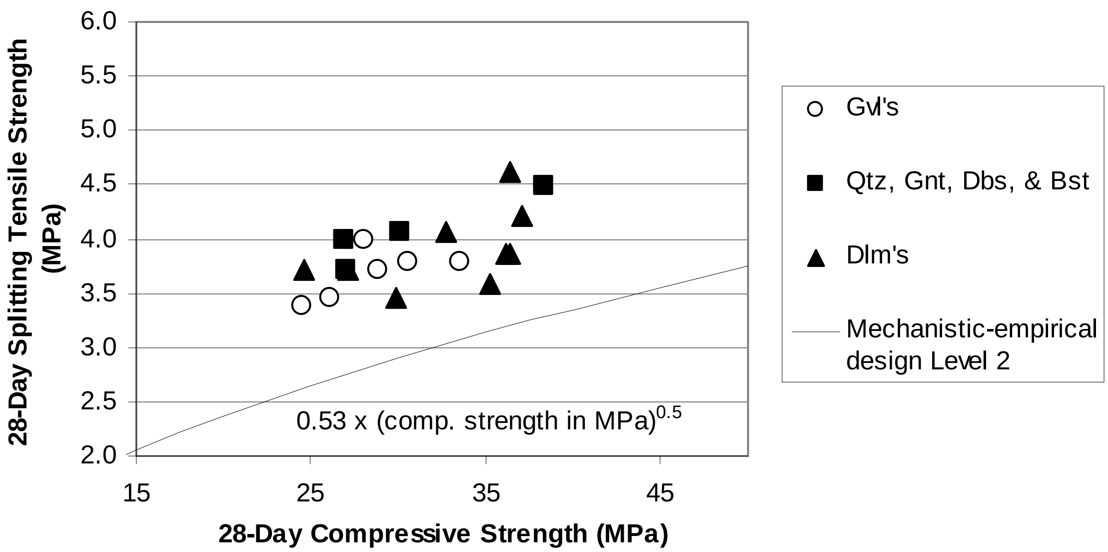

Fig. B-3. Relationship between compressive strength and splitting tensile strength of concrete at 28 days, both in MPa

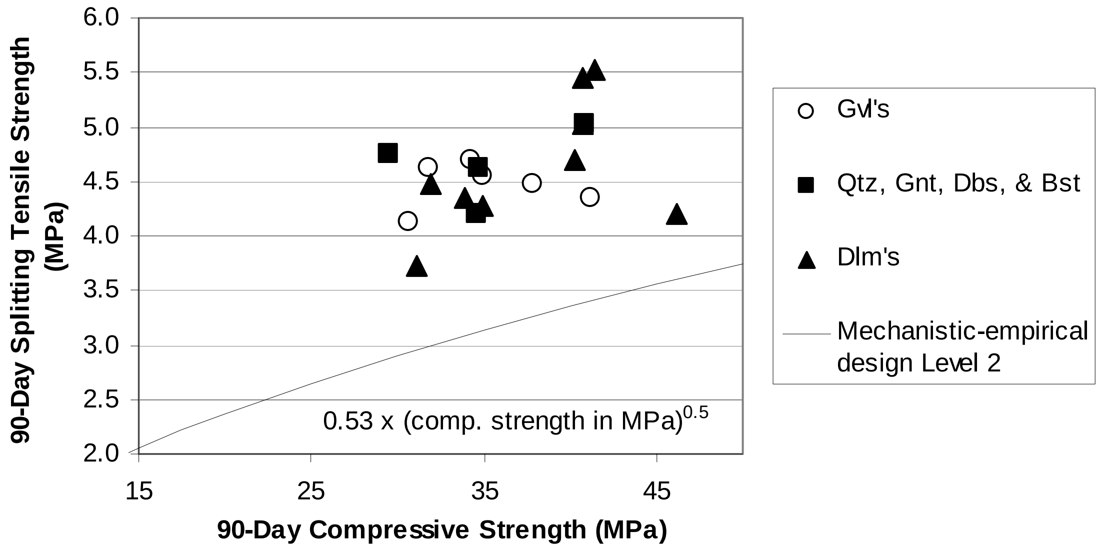

Fig. B-4. Relationship between compressive strength and splitting tensile strength of concrete at 90 days, both in MPa

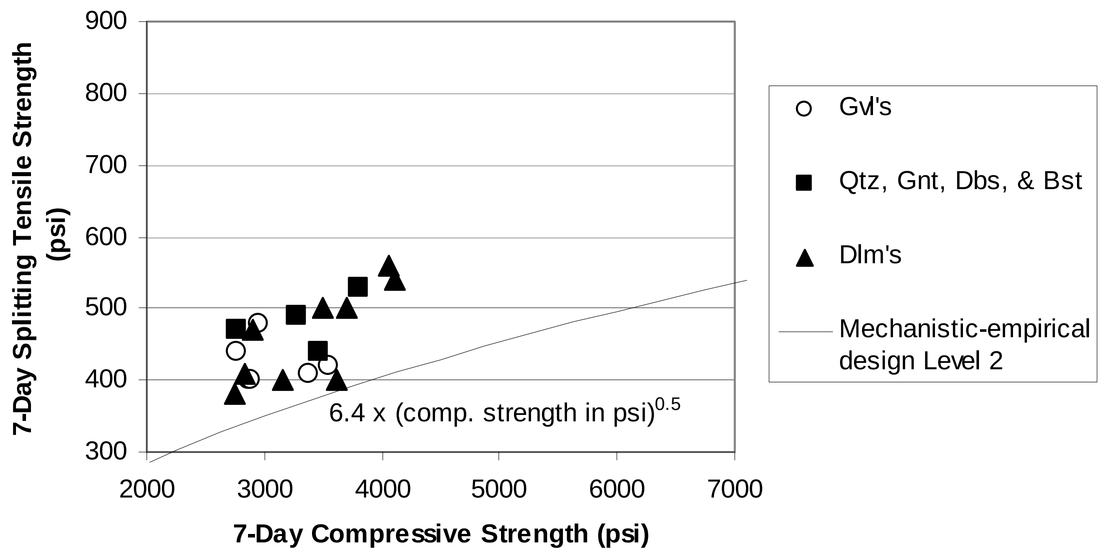

Fig. B-5. Relationship between compressive strength and splitting tensile strength of concrete at 7 days, both in psi

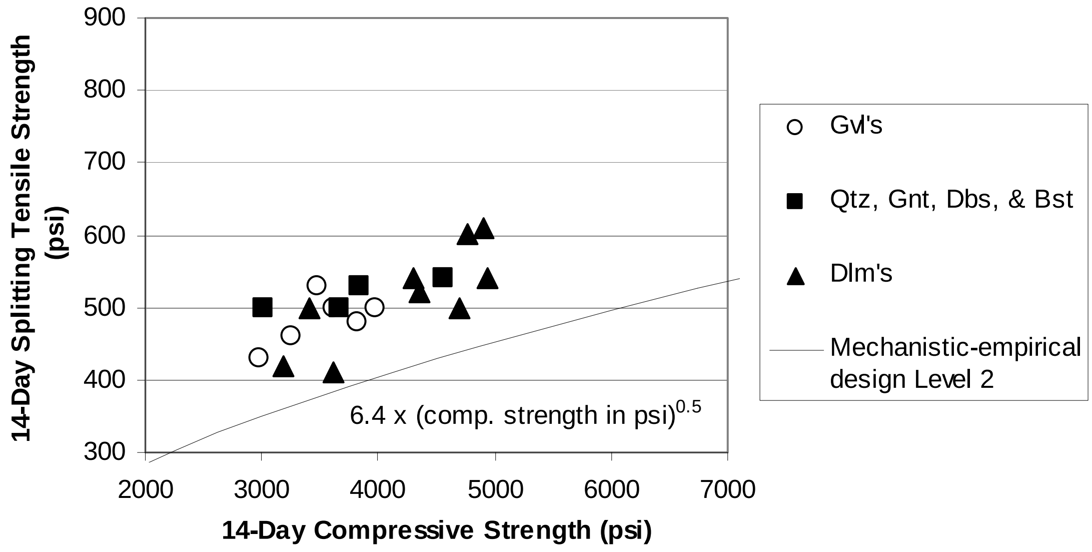

Fig. B-6. Relationship between compressive strength and splitting tensile strength of concrete at 14 days, both in psi

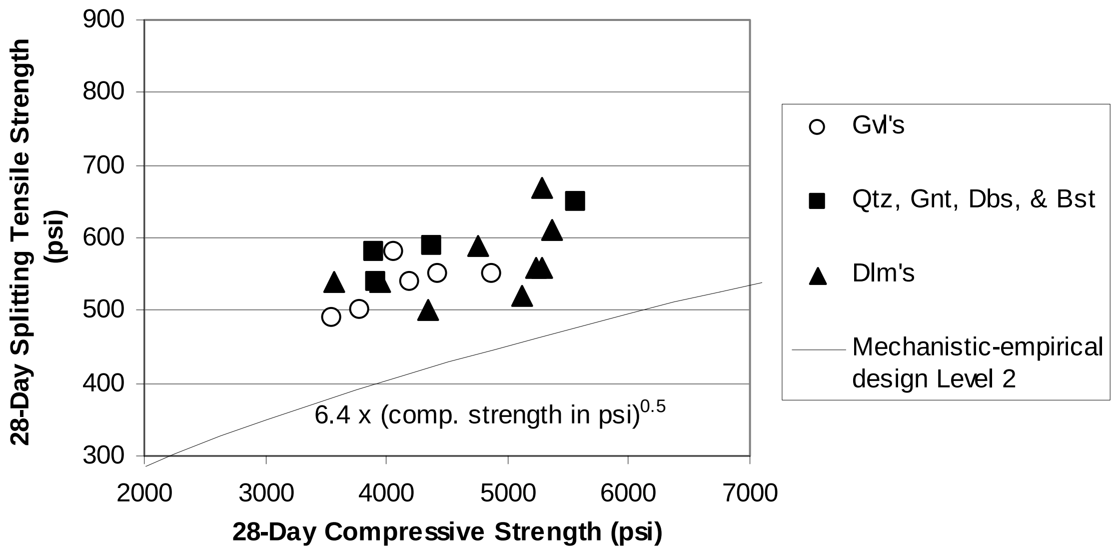

Fig. B-7. Relationship between compressive strength and splitting tensile strength of concrete at 28 days, both in psi

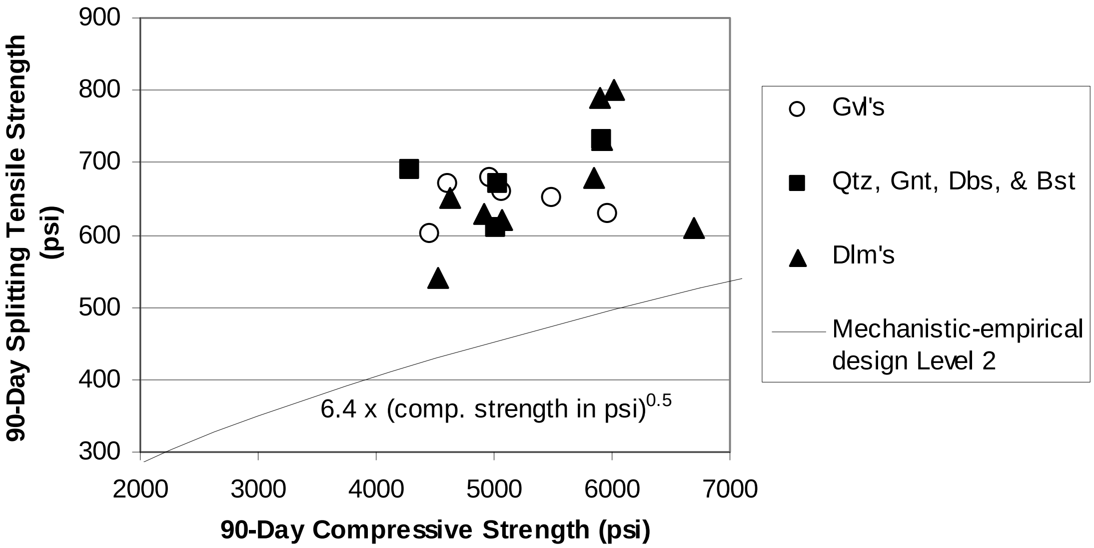

Fig. B-8. Relationship between compressive strength and splitting tensile strength of concrete at 90 days, both in psi

B.2 Regression Models of Splitting Tensile Strength

Fig. B-9 to Fig. B-12 show regression models of splitting tensile strength data in MPa at 7, 14, 28, and 90 days, respectively. In each figure, dotted lines show a 95% confidence interval for the estimate of the mean value of splitting tensile strength. Fig. B-13 to Fig. B-16 show regression models of splitting tensile strength data in psi.

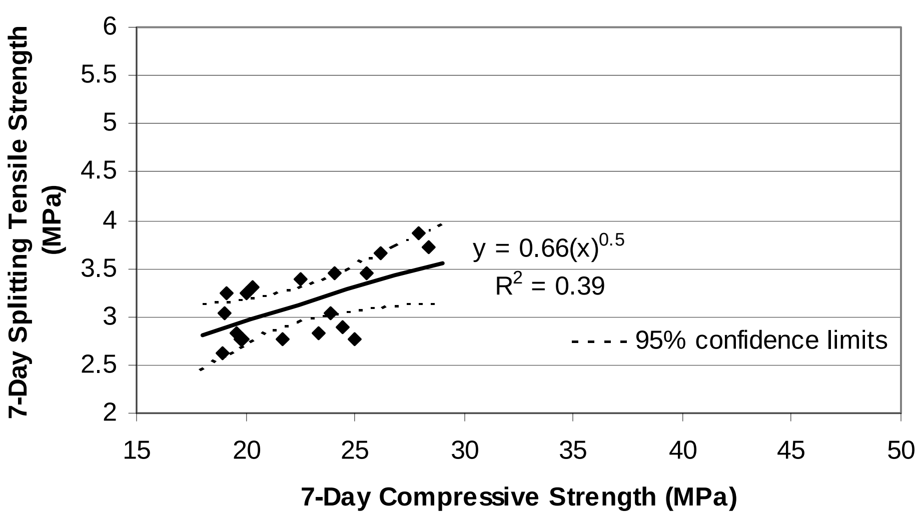

Fig. B-9. Regression model of splitting tensile strength data in MPa at 7 days

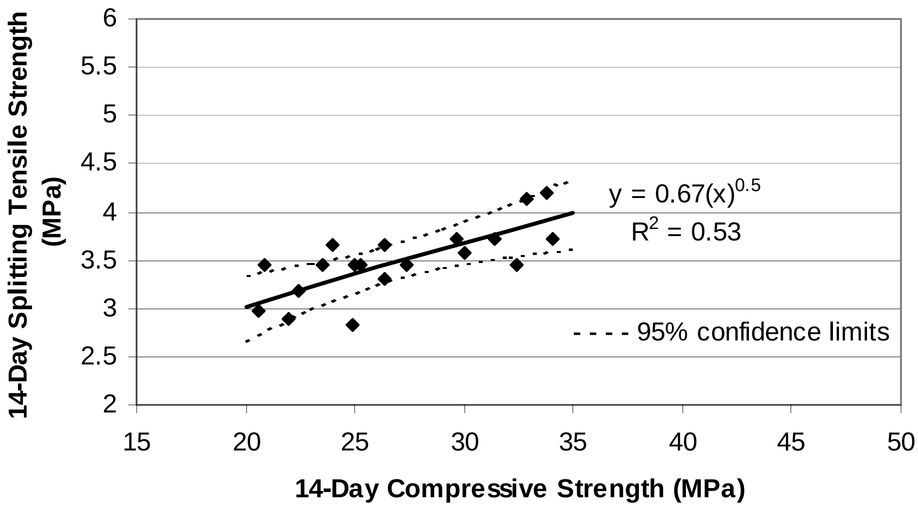

Fig. B-10. Regression model of splitting tensile strength data in MPa at 14 days

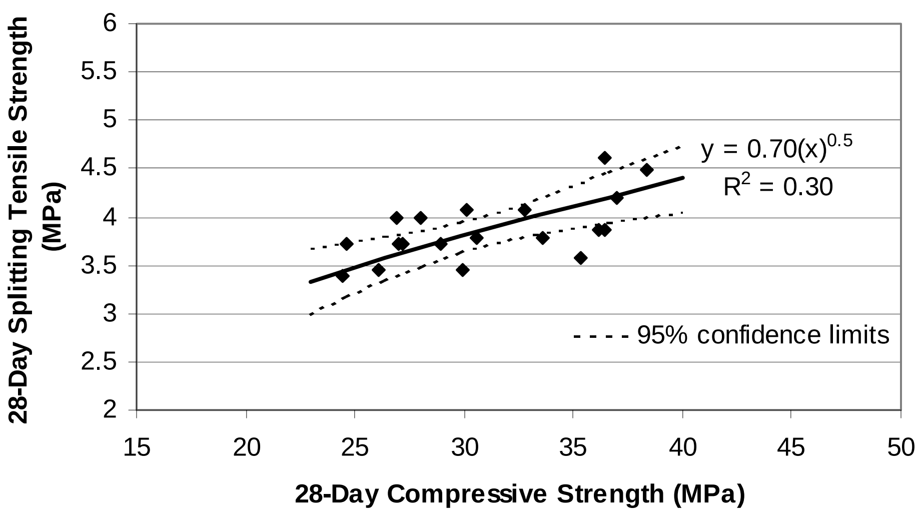

Fig. B-11. Regression model of splitting tensile strength data in MPa at 28 days

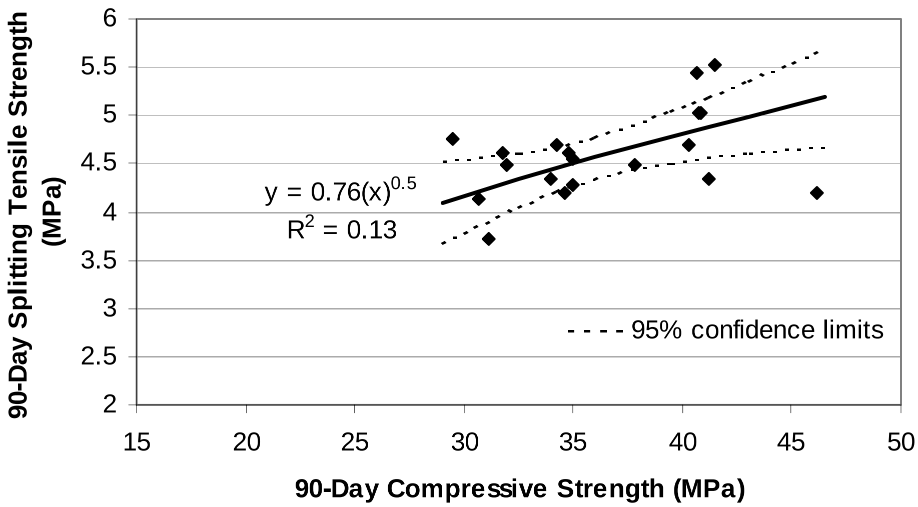

Fig. B-12. Regression model of splitting tensile strength data in MPa at 90 days

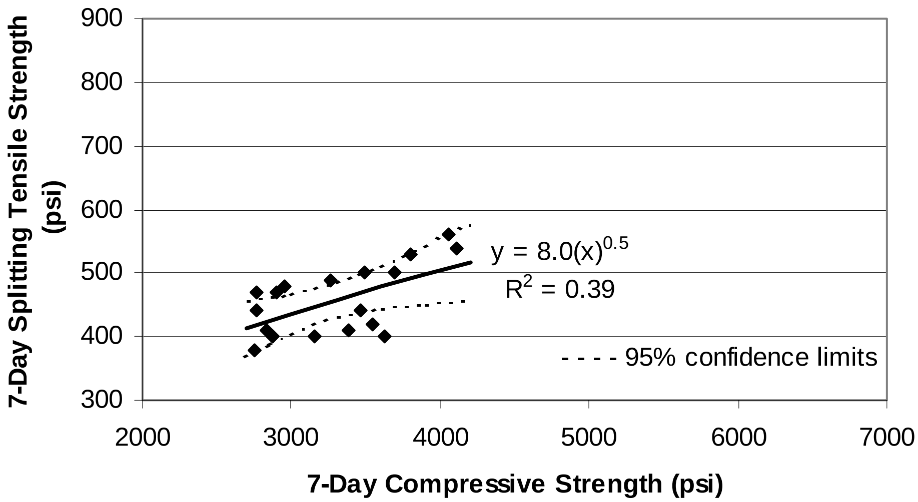

Fig. B-13. Regression model of splitting tensile strength data in psi at 7 days

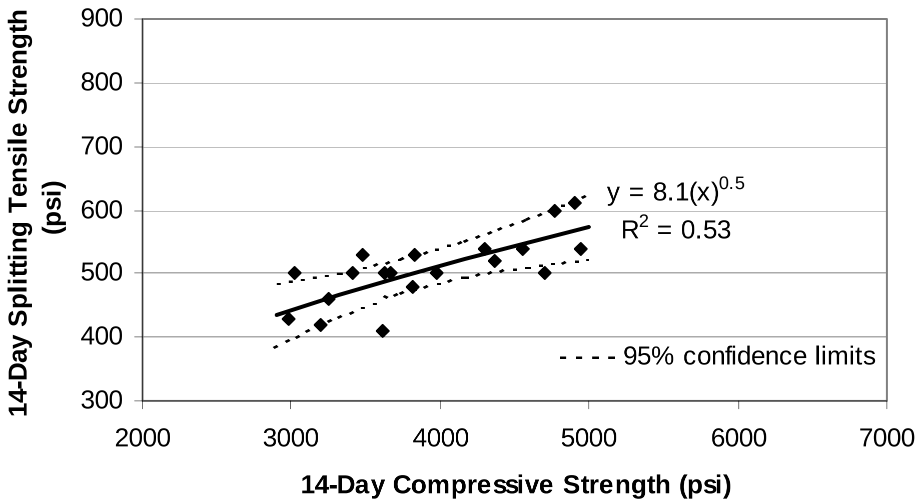

Fig. B-14. Regression model of splitting tensile strength data in psi at 14 days

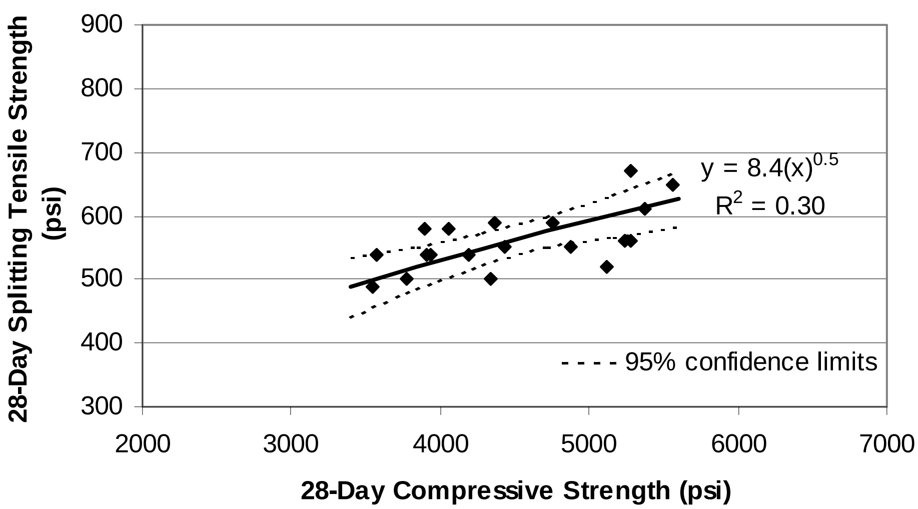

Fig. B-15. Regression model of splitting tensile strength data in psi at 28 days

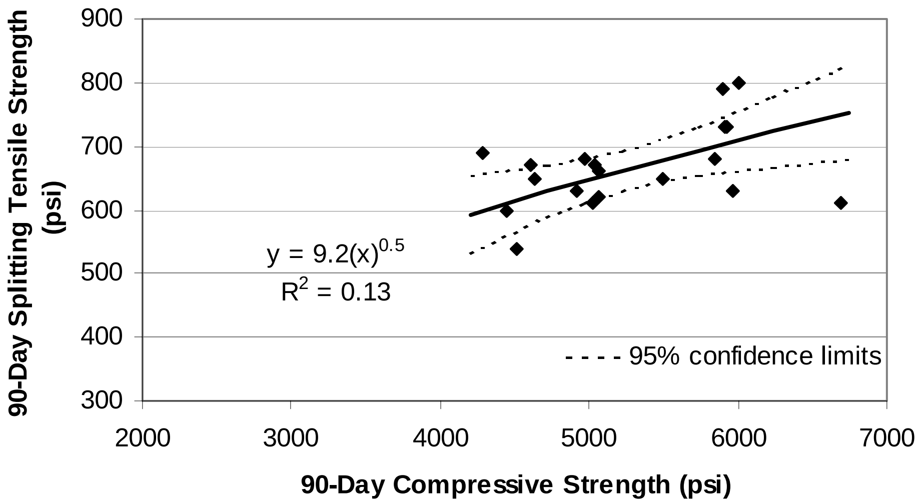

Fig. B-16. Regression model of splitting tensile strength data in psi at 90 days

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