Lightweight Concrete: Mechanical Properties

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FOREWORD

Broad-based advancements in the field of concrete materials have led to significant enhancements in the performance of lightweight concrete. Although the value of using lightweight concrete within the constructed infrastructure is clear, decades-old performance perceptions continue to raise barriers that hinder wider use of the concrete. Additionally, the lack of modern updates to structural design provisions for lightweight concrete has perpetuated additional barriers to the use of lightweight concrete. In 2007, the Federal Highway Administration (FHWA) embarked on a research program aimed at investigating the structural performance of modern lightweight concretes. This effort both engaged the academic, public sector, and private sector communities to compile the body of knowledge on lightweight concrete while also conducting nearly 100 full-scale structural tests on multiple lightweight concretes.

The American Association of State Highway and Transportation Officials (AASHTO) Subcommittee on Bridges and Structures (SCOBS) Technical Committee 10 (T-10) has expressed interest in updating the AASHTO Load and Resistance Factor Design (LRFD) Bridge Design Specifications to more accurately and consistently reflect the performance of lightweight concrete. FHWA researchers were engaged to compile the overall body of knowledge on this topic then to report back to T-10 with proposals for addressing perceived shortcomings in the current design specifications. This report presents test results and proposed design specification revisions relevant to structural applications of lightweight concrete.

This report corresponds to the TechBrief titled "Lightweight Concrete: Mechanical Properties" (FHWA-HRT-13-062). This report is being distributed through the National Technical Information Service for informational purposes. The content in this report is being distributed "as is" and may contain editorial or grammatical errors.

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16. Abstract

Much of the fundamental basis for the current lightweight concrete provisions in the AASHTO LRFD Bridge Design Specifications is based on research of lightweight concrete (LWC) from the 1960s. The LWC that was part of this research used traditional mixes of coarse aggregate, fine aggregate, portland cement, and water. Broad-based advancement in concrete technology over the past 50 years has given rise to significant advancements in concrete mechanical and durability performance.

This document describes the mechanical property tests that were conducted as part of an overall FHWA research project on LWC. The FHWA test results are included in a sizable LWC database of mechanical properties from tests available in the literature. An analysis of the LWC database was used to develop potential revisions to provisions related to LWC within Chapter 5 of the AASHTO LRFD Specifications. A framework for addressing LWC in the specifications is proposed wherein the definition of LWC, the mechanical properties of LWC, and a modification factor relevant to LWC structural performance is discussed.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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LIST OF ABBREVIATIONS AND NOTATION

ABBREVIATIONS

AASHTO = American Association of State Highway and Transportation Officials

COV = coefficient of variation

ESCSI = Expanded Shale, Clay, and Slate Institute

FHWA = Federal Highway Administration

LRFD = load-and-resistance factor design, the design philosophy used by current AASHTO bridge design specification

LWC = lightweight concrete

NCHRP = National Cooperative Highway Research Program, an applied research program directed by the AASHTO Standing Committee on Research

NWC = normal weight concrete

RC = reinforced concrete

SCOBS = Subcommittee on Bridges and Structures, a part of the overall AASHTO organizational structure

SDC = specified density concrete

TFHRC = Turner-Fairbank Highway Research Center

NOTATION

B = coefficient in the general form of the expression for modulus of elasticity of concrete that represents an offset in the modulus of elasticity

C = coefficient in the general form of the expression for modulus of elasticity of concrete multiplied by the unit weight and compressive strength terms

E_c = modulus of elasticity of concrete

f'_c = concrete compressive strength in reference to material tests values and specified compressive strength in reference to articles of the AASHTO LRFD Specification

f_{ct} = concrete splitting tensile strength

f_{pe} = effective stress in the prestressing steel after losses

f_r = modulus of rupture of concrete

F_{sp} = splitting ratio, splitting tensile strength divided by the square root of compressive strength

$F_{sp,LL}$ = lower limit on splitting ratio used in prediction expressions

$F_{sp,UL}$ = upper limit on splitting ratio used in prediction expressions

K_1 = correction factor for source of aggregate

n_1, n_2 = coefficient in the general form of the expression for modulus of elasticity of concrete that are the exponents for unit weight and compressive strength

V_{ci} = nominal shear resistance provided by concrete when inclined cracking results from combined shear and moment

V_p = component of nominal shear resistance provided by prestressing force

w_c = concrete unit weight, a measure of concrete density

$w_{c,LL}$ = lower limit on unit weight used in prediction expressions

$w_{c,trans}$ = transition unit weight used in prediction

$w_{c,UL}$ = upper limit on unit weight used in prediction expressions

β = factor relating effect of longitudinal strain on the shear capacity of concrete, as indicated by the ability of diagonally cracked concrete to transmit tension

λ = lightweight concrete modification factor

ϕ = resistance factor

CHAPTER 1. INTRODUCTION

INTRODUCTION

Much of the fundamental basis for the current lightweight concrete provisions in the AASHTO LRFD Bridge Design Specifications[1] is based on research of lightweight concrete (LWC) from the 1960s.[2-5] The LWC that was part of this research used traditional mixes of coarse aggregate, fine aggregate, portland cement, and water. Broad-based advancement in concrete technology over the past 50 years has given rise to significant advancements in concrete mechanical and durability performance. Research during the past 30 years including the recent NCHRP studies on different aspects of high-strength concrete has resulted in revisions to the AASHTO LRFD Specifications to capitalize on the benefits of high-strength normal weight concrete (NWC). However, as described by Russell[6], many of the design equations in the AASHTO LRFD Specifications are based on data that do not include tests of LWC specimens, particularly with regard to structural members with compressive strengths in excess of 6 ksi (41 MPa).

The Federal Highway Administration (FHWA) at the Turner-Fairbank Highway Research Center (TFHRC) has executed a research program investigating the performance of LWC with concrete compressive strengths in the range of 6 to 10 ksi (41 to 69 MPa) and equilibrium densities between 0.125 kcf to 0.135 kcf (2000 to 2160 kg/m^3). The research program used LWC with three different lightweight aggregates that are intended to be representative of those available in North America. The program included tests from 27 precast/prestressed LWC girders to investigate topics including transfer length and development length of prestressing strand, the time-dependent prestress losses, and shear strength of LWC. The development and splice length of mild steel reinforcement used in girders and decks made with LWC was also investigated using 40 reinforced concrete (RC) beams. While much of the research program focused on structural behavior, it also included a material characterization component wherein the compressive strength, elastic modulus, and splitting tensile strength of the concrete mixes used in the structural testing program were assessed. One key outcome of the research program is to recommend changes to the AASHTO LRFD Bridge Design Specifications relevant to LWC.

This document describes the results of mechanical property testing that was conducted as part of the prestressed girder and RC beam testing. The mechanical properties of LWC tested in this study are included in a database of mechanical property tests on LWC that was collected from test results available in the literature. This document describes the LWC database and the analysis of mechanical properties in the database. Design expressions in the current edition of the AASHTO LRFD Specifications are compared to the database. Potential revisions to the AASHTO LRFD Specifications relating to LWC are presented.

OBJECTIVE

There are three objectives for this document. The first objective is to describe the results of mechanical property tests on LWC conducted at TFHRC. The second objective is to describe a LWC database including the TFHRC test results and to describe the analysis of the database. The third objective is to develop and present potential revisions to the AASHTO LRFD Specifications relating to the mechanical properties of LWC.

OUTLINE OF DOCUMENT

Introductory material is contained in Chapter 2 and 3 and includes an introduction, a summary of the mechanical properties of LWC, a description of the gap of equilibrium densities that currently exists in AASHTO LRFD, and a summary of LWC modification factors. Chapter 3 describes the LWC mechanical property tests, summarizes the test results, and provides a discussion of the results. A description of the LWC mechanical test database is given in Chapter 4 and includes statistical information about the database. Chapter 5 compares the results of the LWC mechanical tests to design expressions and describes the development of prediction expressions. Potential revisions to the AASHTO LRFD Specifications are included in Chapter 6.

The units for stress and elastic modulus are ksi and the units for unit weight are kcf for all expressions unless stated otherwise. SI units are given in parentheses for values in the text and conversion factors are provided for values in the tables. References to the paper and reports used in the LWC database are included in the last section of this document.

SUMMARY OF PRELIMINARY RECOMMENDATIONS

Four revisions to the AASHTO LRFD Specifications are proposed in this document. The revisions are related to the mechanical properties of LWC and are based on the analysis of a database developed for this research effort. A revised definition of LWC is proposed to include concrete with lightweight aggregates up to a unit weight of 0.135 kcf (2160 kg/m^3), which is considered the lower limit for NWC. Also the terms “sand-lightweight concrete” and “all-lightweight concrete” are removed in the proposed definition to allow other types of LWC mixtures. A revised expression for modulus of elasticity is proposed based on an analysis of several existing design expressions and many potential design expressions. A LWC modification factor is proposed to potentially allow a more unified approach of accounting for the mechanical properties of LWC in the AASHTO LRFD Specifications. A revised expression for the modulus of rupture is proposed and utilizes the proposed lightweight concrete modification factor. The development of the proposed revisions is described in Chapter 5 and are summarized with proposed specification language in Chapter 6.

CHAPTER 2. BACKGROUND

INTRODUCTION

This chapter provides background information relevant to the focus of the research effort. This information includes a description of the mechanical properties of LWC, the gap of equilibrium densities in the AASHTO LRFD Specifications, and the LWC modification factor.

MECHANICAL PROPERTIES OF LWC

The aggregate in LWC can either be manufactured or natural, with a cellular pore system providing for a lower density particle. The density of lightweight aggregate is approximately half of that of normal weight rock. The reduced dead weight of the LWC has many benefits in building and bridge construction such as smaller, lighter members, longer spans, and reduced substructures and foundations requirements.(7)

As compared to NWC, LWC tends to exhibit two specific mechanical property reductions. The modulus of elasticity and the tensile strength of LWC tend to be reduced as compared to a similar compressive strength NWC. These differences are generally attributed to the characteristics of the lightweight aggregate. The reduced modulus of elasticity results in larger deflections, larger prestress losses, and longer transfer lengths. The tensile strength of the lightweight aggregate is typically less than that of normal weight aggregate. The performance of concrete structures is affected by the tensile strength of concrete in several significant ways. The reduced tensile strength of LWC can affect the shear strength, cracking strength at the release of prestress, and bond strength of prestressed and non-prestressed reinforcement.(7)

EQUILIBRIUM DENSITY GAP IN AASHTO LRFD

The definition for LWC in the AASHTO LRFD specifications(1) covers concrete having lightweight aggregate and an air-dry unit weight less than or equal to 0.120 kcf (1920 kg/m^3). Normal weight concrete is defined as having a unit weight from 0.135 to 0.155 kcf (2160 to 2480 kg/m^3). Concretes in the gap of densities between 0.120 and 0.135 kcf (1920 to 2160 kg/m^3) are commonly referred to as “specified density concrete” and are not directly addressed by the AASHTO LRFD Specifications. Specified density concrete (SDC) typically contains a mixture of normal weight and lightweight coarse aggregate.

Modifications to AASHTO LRFD are needed to remove the SDC-related ambiguity, to give the designer the freedom of specifying a slightly lower density than NWC, and to allow for appropriate design with SDC. The inclusion of SDC into AASHTO LRFD could take many forms, but would likely require modifications to both terminology and design expressions.

FACTOR FOR LWC TENSILE STRENGTH

The tendency for LWC to have a reduced tensile strength is not treated consistently in the AASHTO LRFD Specifications. There are many articles where the $\sqrt{f_c'}$ term is used to represent concrete tensile strength. The provisions for shear and tension development length of mild reinforcement currently include a modification for LWC. However, the tensile stress limits in prestressed concrete do not include a modification for LWC. A potential option to provide a more uniform treatment of LWC tensile strength would be to add the definition of a modification factor for LWC, such as λ, to Section 5.4 which could then be referenced in other articles. Then the factor could be added to design expressions where the $\sqrt{f_c'}$ term is used to represent concrete tensile strength.

CHAPTER 3. RESEARCH ON LWC AT TFHRC

INTRODUCTION

This research program focused on LWC with compressive strengths in the range of 6 to 10 ksi (41 to 69 MPa) and equilibrium densities between 0.125 kcf and 0.135 kcf (2000 and 2160 kg/m^3). The research program used LWC with three different lightweight aggregates to produce 27 precast/prestressed LWC girders and 40 reinforced concrete (RC) beams. While the FHWA program focused on structural behavior, it also had a material characterization component that included mechanical property tests on the concrete mixes used in the structural testing program. Mechanical tests included the compressive strength, elastic modulus, and splitting tensile strength. The concrete unit weight was determined using several methods.

This section describes the LWC mix design selection process, summarizes the specimen fabrication at the precaster's facility, and gives details of the specimen testing. The test results are discussed and compared to design expressions.

RESEARCH SIGNIFICANCE

There is a limited amount of test data on the mechanical properties of high-strength specified density concrete. This research project includes a significant number of tests on this type of concrete. The high-strength specified density concrete data from this research is included into a LWC database that covers a range of unit weights in order to determine trends for LWC as a function of unit weight. New design expressions for mechanical properties are proposed for LWC as function of unit weight as opposed to the more common method of using concrete constituent materials.

LWC MIX DESIGNS

The Expanded Shale, Clay, and Slate Institute (ESCSI) assisted FHWA in obtaining specified density mixes that had been used in production. One of the criteria for this research project was to use lightweight aggregate sources that were geographically distributed across the United States. Additional selection criteria included mixes using a large percentage of the coarse aggregate as lightweight coarse aggregate, mixes using natural sand as the fine aggregate, and mixes with a target equilibrium density between 0.125 and 0.135 kcf (2000 and 2160 kg/m^3). In order to make sure that the behavior of the concrete would be controlled by the lightweight aggregate, only mixes with greater than 50% of the coarse aggregate as lightweight aggregate were considered. The concrete density needed to be in the range of densities not currently covered by the AASHTO LRFD Bridge Design Specifications[1] because of the limited amount of test data in this density range. The literature has shown that silica fume can increase LWC compressive strength [8-10] and has also been shown to improve bond of mild steel reinforcement and prestressing strand.[11] As a result, mixes that included silica fume were not selected for this experimental study so that the results would be representative of mechanical properties for specified density concrete without silica fume and most likely conservative for specified density concrete with silica fume.

Three mix designs were selected with a design compressive strength greater than or equal to 6.0 ksi (41.4 MPa) to represent concrete that could be used for bridge girders. Another mix design was selected that had a design compressive strength less than 6.0 ksi (41.4 MPa) to represent concrete that could be used for a bridge deck.

The mix designs selected are shown in Table 1. Each uses partial replacement of the coarse aggregate with lightweight aggregate to achieve their reduced unit weight. The lightweight aggregates in the mixes were Haydite, an expanded shale from Ohio, Stalite, an expanded slate from North Carolina, and Utelite, an expanded shale from Utah. The normal weight coarse aggregate was No. 67 Nova Scotia granite. Natural river sand was used as the fine aggregate. Type III portland cement was used to obtain the high early strengths typically required in high-strength precast girders. Admixtures included a water reducer, an air entrainer, and a high range water reducer.

Table 1. Selected Concrete Mix Designs.

Cast Date	**unit**	**Haydite Girder (HG)**	**Stalite Girder (SG)**	**Utelite Girder (UG)**	**Stalite Deck (SD)**
Design 28-Day Strength	ksi	6.0	10.0	7.0	4.0
Design Release Strength	ksi	3.50	7.5	4.2	-
Target Unit Weight	kcf	0.130	0.126	0.126	0.125
Lightweight Coarse Aggregate	kips	0.80	0.88	0.74	0.51
Normal Weight Coarse	kips	0.52	0.25	0.39	0.73
Normal Weight Sand	kips	1.19	1.22	1.27	1.31
Class F Fly Ash	kips	-	-	0.15	0.12
Type III Portland Cement	kips	0.75	0.80	0.60	0.50 †
Water	kips	0.27	0.25	0.26	0.27
Water Reducer	oz	19	19	19	10
Air Entrainer	oz	2	2	2	4
High Range Water Reducer	oz	34	34	34	15
Water / Cementitious Materials		0.36	0.31	0.34	0.43

† Note that this mix design used Type II Portland Cement

Units: 1.0 ksi = 6.89 MPa, 0.001 kcf = 16.01 kg/m^3, 1.0 kip = 4.45 kN, 1.0 oz = 29.6 mL

SPECIMEN FABRICATION

The girders were fabricated at the Standard Concrete Products (SCP) plant in Mobile, Alabama. Figure 1 is a photograph of the fabrication yard showing two of the beds used to fabricate the girders for FHWA. The quality control building and batch plant is shown in Figure 2. The fabricator was asked to prescriptively produce the concrete mixes, without trying to adjust them for target strengths or unit weight. This was intended to remove batch-to-batch variations as a variable in the study. The lightweight aggregates were stored in three piles at the plant and watered continuously using a sprinkler on each pile as shown in Figure 3.

Figure 1. Photo. Prestress fabrication plant for the LWC girders and splice beams.

Figure 2. Photo. Quality control building (left) and batch plant.

Figure 3. Photo. Lightweight aggregate stockpiles at precaster's facility with continuous sprinklers.

After mixing, the precaster's personnel performed testing of the fresh concrete properties, and made 4 x 8 inch (102 x 203 mm) cylinders for quality control purposes. The percent air, slump, concrete temperature, ambient air temperature, and unit weight measured and recorded by the precaster's personnel are shown in Table 2. Tables of the batch weights automatically recorded by the batch plant for each cast are in Appendix A. The results of the compressive strength tests completed by the precaster's personnel are in Appendix B.

Independently, FHWA personnel made 4 x 8 inch (102 x 203 mm) and 6 x 12 inch (152 x 305 mm) cylinders following ASTM C31(12) for mechanical property testing and density measurements. The cylinders were cast in plastic cylinder molds and after stripping were marked with the mix and casting date in paint marker. The cylinders made by FHWA were stripped the day after casting. Mechanical tests performed for release strength and design strength during girder fabrication utilized the testing equipment in the precaster's quality control building. The remaining cylinders were loaded into wooded crates, packed with sand, and shipped by flatbed truck to TFHRC in McLean, Virginia.

Table 2. Fresh Concrete Properties

Mix Date	Mix Design	% Air	Slump (inch)	Concrete Temperature (°F)	Ambient Temperature (°F)	Unit Weight (kcf)
5/14/2008	HG	2.75	10.5	70	78	134.2
	SG	3.0	10.5	65	78	125.4
	UG	4.0	10.0	67	78	132.3
5/29/2008	HG	--	8.25	88	89	135.9
	SG	4.25	6.0	91	89	128.0
	UG	4.75	10.0	87	90	133.3
5/30/2008	UG	5.0	9.25	88	88	133.7
6/3/2008	HG	3.75	7.5	91	82	131.1
6/9/2008	SG	3.75	7.5	95	89	126.6
	UG	4.25	9.0	90	90	136.3
6/10/2008	HG	4.0	9.0	83	73	138.4
	UG	4.25	9.5	87	73	136.2
6/13/2008	HG	4.25	8.5	85	82	--
	SG	4.0	8.0	85	82	--
	UG	3.75	8.5	80	81	--
6/20/2008	HG	4.25	8.5	82	82	134.4
	SG	4.25	7.25	87	82	125.6
	UG	4.0	9.0	81	82	128.1

Units: 1.0 inch = 25.4 mm, 1 °F = 5(F-32)/9 °C, 0.001 kcf = 16.01 kg/m^3

SPECIMEN TESTING

This section describes the mechanical property testing and density measurements performed on the LWC cylinders. Compression tests were performed to determine the compressive strength and elastic modulus. Splitting tensile tests were performed to determine the indirect tensile strength. Density measurements were made to determine the air-dry density of cylinders used for compression testing, and on separate cylinders for determining the oven-dry density and equilibrium density.

After stripping the plastic molds, the cylinders were air-dried outside under a covered porch that was part of the precaster’s quality control building. The ends of the cylinders that were tested at the precaster’s facility were ground using a concrete grinding wheel attached to a hand-held grinder. Cylinders tested at TFHRC were prepared using a laboratory-grade concrete cylinder grinding machine.

The cylinders tested at the precaster's facility during girder fabrication used a 200-kip (890 kN) Forney testing machine. At TFHRC, cylinders were tested with a 1000-kip (4400 kN) Forney testing machine.

COMPRESSION TESTING

Compression tests were performed on 4 x 8 inch (102 x 203 mm) and 6 x 12 inch (152 x 305 mm) cylinders according to ASTM C39 (13) to determine the compressive strength at release of prestressing, at 28 days, and at girder testing. At both the precaster's facility and TFHRC, neoprene pads were used inside steel caps at each end.

A summary of the results of the compressive strength tests on 4 x 8 inch (102 x 203 mm) cylinders for all three girder mixes is given in Table 3. Detailed results by girder mix, casting date, and specimen age is given in Appendix C. The detailed results of compression tests on 6 x 12 inch (152 x 305 mm) cylinders for all three girder mixes are also given in Appendix C. The air-dry density was calculated using the measured cylinder weight and measured cylinder lengths and diameters to calculate an average volume. The compressive strengths and densities shown are the based on the average of three cylinders.

The elastic modulus was determined following ASTM C469[14] using one of the 4 x 8 inch (102 x 203 mm) cylinders intended for compressive strength testing. Cylinder displacement during loading was measured using a compressometer with a dial gage that was read to the nearest ten-thousandth of an inch (0.003 mm). Displacement readings were taken at loading increments of 5.0 kips (22.2 kN) up 40% of the failure load of a companion compressive strength test. Typically, one cylinder was tested first for compressive strength to determine the proper load level for determining the elastic modulus. A summary of elastic modulus test results are given in Table 3 with detailed results given in Appendix C.

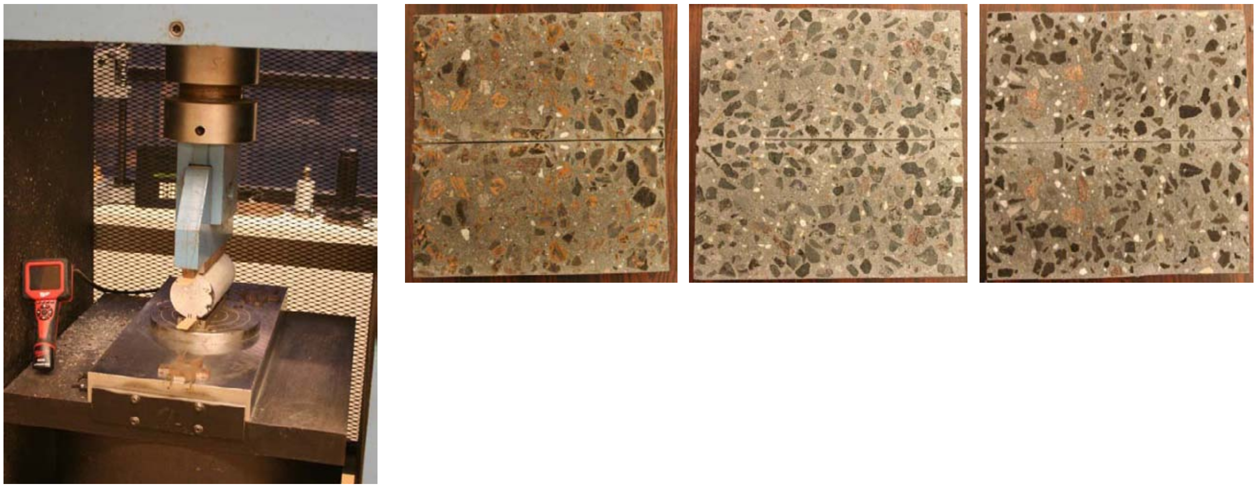
Table 3. Average Concrete Properties from Tests on 4 x 8 inch Cylinders.

Concrete Mix	Specimen Age	Compressive Strength (ksi)	Air-Dry Density (kcf)	Splitting Tensile Strength (ksi)	Elastic Modulus (ksi)
HG	Release	7.07	0.133	0.607	3840
	28 Day	9.50	0.132	0.714	4470
	Test Day	10.45	0.130	0.771	4320
SG	Release	7.32	0.125	0.604	3770
	28 Day	9.66	0.125	0.680	4140
	Test Day	10.56	0.123	0.717	4360
UG	Release	6.04	0.131	0.569	3500
	28 Day	8.68	0.130	0.685	4110
	Test Day	10.10	0.127	0.757	4150
SD	28 Day	5.67	0.138	--	--

Units: 1.0 ksi = 6.89 MPa, 0.001 kcf = 16.01 kg/m^3

SPLITTING TENSILE TESTING

The indirect tensile strength was measured on 4 x 8 inch (102 x 203 mm) cylinders using the splitting tensile test described in ASTM C496[(15)]. A steel apparatus was used to align the cylinder, bearing strips, and supplemental bearing bar. One-eighth inch (3.2 mm) thick luaun plywood cut into 1.0 inch (25.4 mm) wide strips was used for the bearing strips. The length and diameter of the cylinder was measured along the likely failure plane. The cylinders were loaded at the prescribed loading rate until the peak load was achieved. The first load discontinuity, indicating the partial splitting tensile cracking of the specimen, and also the overall peak load, indicating the point when the splitting crack fully traversed the specimen, were both recorded. The peak load was used to calculate the splitting tensile strength per ASTM C496. Figure 4 shows a test in progress. The figure also shows and adjacent faces of typical broken cylinders for the three girder mixes. A summary of the splitting tensile test results are given in Table 3 with detailed results given in Appendix C.



(a) Specimen during test (b) HG mix (c) SG mix (d) UG mix

Figure 4. Photo. Splitting tension test setup and broken specimens.

DENSITY TESTING

Air-dry and oven-dry density was measured on 6 x 12 inch (152 x 305 mm) cylinders. The cylinders were cast with the cylinders for compression testing and split cylinder testing. The procedure in ASTM C567[16] specifies a curing regimen that could not be followed with the equipment available at the precaster’s facility and would have been interrupted by the necessity of shipping all of the specimens back to TFHRC. Once the specimens arrived at TFHRC, they were stored in a lime curing bath at 76 °F (24.4 °C) for 166 days to restore the moisture lost in the field and during shipping. After saturating the cylinders, the weight of the submerged cylinder and the weight of the saturated cylinder in air was measured according to ASTM C567 and then used to calculate the volume. Half of the cylinders were placed in an environmental chamber at 75 °F (23.9 °C) and 50% humidity to determine the air-dry density with time. The other half of the cylinders were placed in an oven at 230 °F (110 °C). The weight of the cylinders was measured periodically and used to calculate the concrete density.

The average air-dry density results for each mix are given in Table 4 and are listed by days of drying. Detailed results for each cast are in Appendix C and were calculated by averaging the values of three cylinders from each cast. Table 5 gives the average oven-dry density for each girder mix and detailed results for each cast are in Appendix C.

In ASTM C567, the term “equilibrium density” is the air-dry unit weight reached when the change in unit weight is less than 0.5% per 28-day period. All air-dry cylinders reached the threshold of changing by less than 0.5% per 28-day period by the first recorded measurement after beginning air drying at 114 days. The equilibrium density is then approximately the density at 114 days. Similarly, the oven-dry density cylinders reached the threshold of changing by less than 0.5% per 1-day period by the first recorded measurement after beginning oven drying at 27 days. The oven-dry density is then approximately the density at 27 days.

Table 4. Average Density of 6 x 12 inch Cylinders by Days of Air Drying.

Girder Mix	Cylinder Density (kcf) by Drying Time (days)				
	0	114	271	404	516
HG	0.134	0.132	0.131	0.131	0.130
SG	0.126	0.125	0.124	0.124	0.124
UG	0.133	0.131	0.131	0.131	0.130

Units: 0.001 kcf = 16.01 kg/m^3

Table 5. Average Density of 6 x 12 inch Cylinders by Days of Oven Drying.

Girder Mix	Cylinder Density (kcf) by Drying Time (days)				
	0	27	33	47	58
HG	0.137	0.129	0.127	0.127	0.126
SG	0.132	0.124	0.124	0.123	0.123
UG	0.138	0.130	0.129	0.128	0.128

Units: 0.001 kcf = 16.01 kg/m^3

DISCUSSION OF RESULTS

This section discusses the importance of the results from the compressive strength, elastic modulus, and splitting tensile strength tests. Then comparisons are made with design expressions from AASHTO LRFD Specifications, NCHRP Project 12-64, and ACI 363-10.

COMPRESSIVE STRENGTH

The development of compressive strength with time for the HG, SG, and UG mixes is shown in Figure 5, Figure 6, and Figure 7, respectively. The compressive strengths shown are from tests on 4 x 8 inch (102 x 203 mm) cylinders and each strength gain “curve” represents tests on concrete from the same casting date. The data used to create the figures is given in Appendix C. The horizontal axis is displayed as logarithmic time in days to emphasize the intervals of time in which cylinders were typically tested. The first group of cylinder tests was at release of prestressing and occurred between 1 and 5 days after casting. The second group of tests was intended to represent the 28 day strengths. These tests actually occurred between 27 and 32 days after casting with 78% occurring between 27 and 29 days after casting. The third group of tests was performed with the prestressed girder tests conducted as part of a broader research program to investigate the development length of prestressing strands and the shear behavior. The tests actually occurred between 651 and 1,090 days after casting. Throughout this section of the report these groups of tests will be referred to as “release”, “28 day”, and “girder test”.

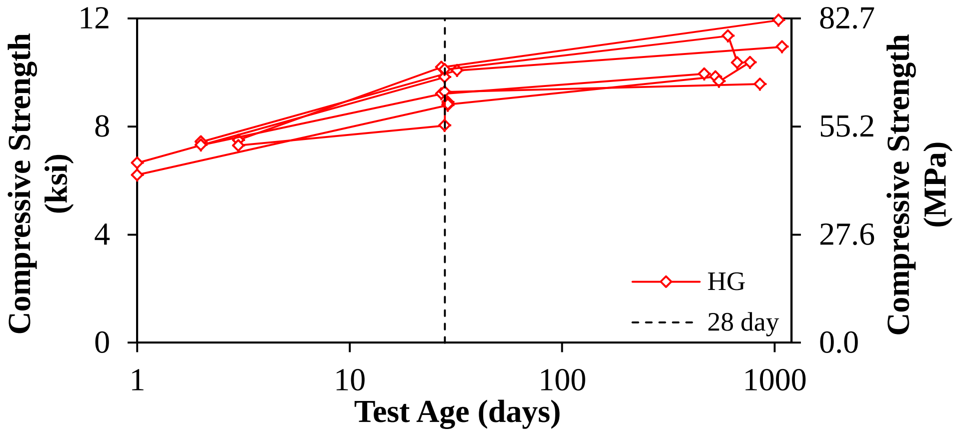


Figure 5. Graph. Compressive Strength with Time for HG Mix.

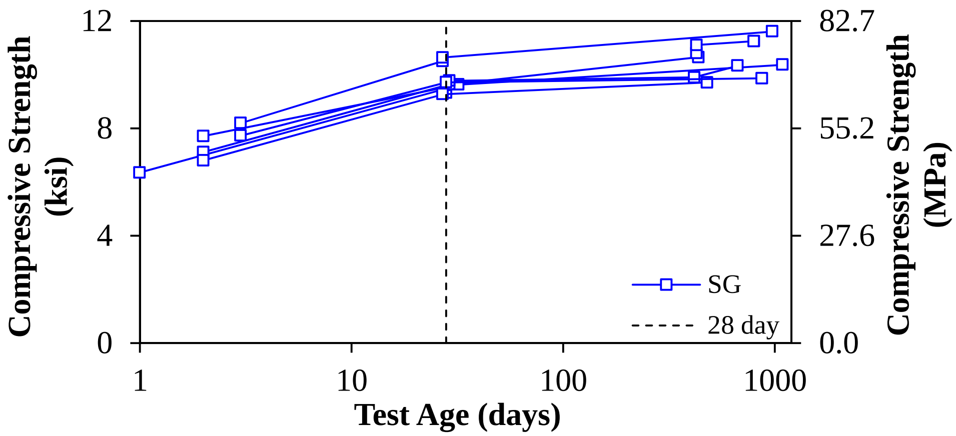


Figure 6. Graph. Compressive Strength with Time for SG Mix.

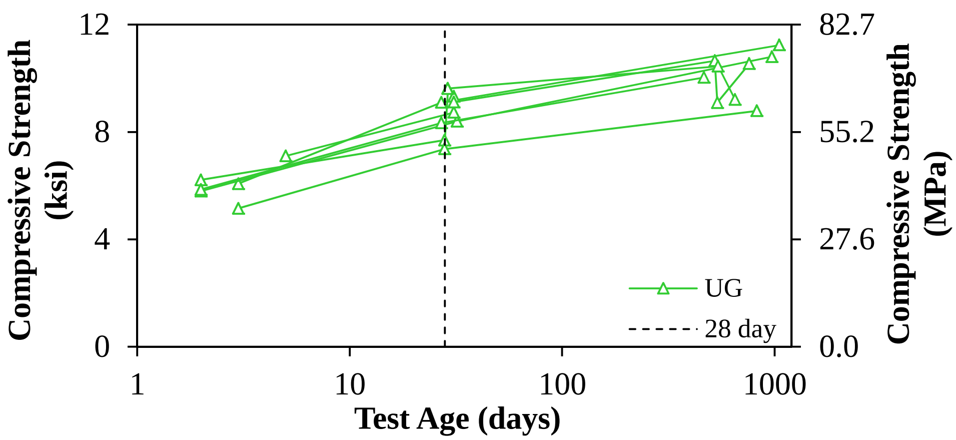


Figure 7. Graph. Compressive Strength with Time for UG Mix.

SPLITTING TENSILE STRENGTH

The splitting tensile strength (f_{ct}) versus compressive strength (f_c') is shown in Figure 8. The horizontal axis is shown as $\sqrt{f_c'}$ because this term is commonly associated with concrete tensile strength. Splitting tensile strength is used in the AASHTO LRFD Specifications[(1)] to define the LWC modification factor for shear (Article 5.8.2.2) and to define a LWC modification factor that increases the development length of mild reinforcement in tension (Article 5.11.2.1.2).

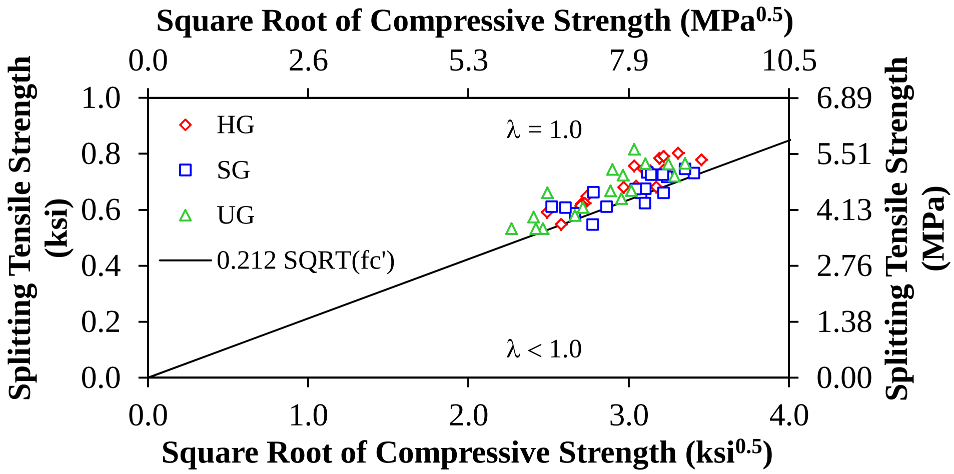


Figure 8. Graph. Splitting Tensile Strength with Square Root of Compressive Strength.

The expression for the LWC modification factor for shear in Article 5.8.2.2 is given by Eq. 1. The ratio of f_{ct} to $\sqrt{f_c'}$ is known as the splitting ratio. Eq. 1 can be rearranged to be expressed as a function of the splitting ratio as shown in Eq. 2. From Article 5.8.2.2, a splitting ratio less than 0.212 indicates the need to modify the $\sqrt{f_c'}$ term in all expressions given in Articles 5.8.2 and 5.8.3 for LWC. A splitting ratio greater than or equal to 0.212 does not require modification of the $\sqrt{f_c'}$ term.

$$4.7f_{ct} = \sqrt{f_c'} \qquad \text{(Eq. 1)}$$

$$\text{Splitting Ratio: } f_{ct}/\sqrt{f_c'} = 1/4.7 = 0.212 \qquad \text{(Eq. 2)}$$

The modification for the development length of mild reinforcement in tension defined in Article 5.11.2.1.2 is given by Eq. 3. Rearranging in terms of the splitting ratio, Eq. 4 shows that the limiting ratio is 0.22, similar to the ratio used for the expressions for shear.

$$0.22\sqrt{f_c'}/f_{ct} \geq 1.0 \qquad \text{(Eq. 3)}$$

$$\text{Splitting Ratio: } f_{ct}/\sqrt{f_c'} = 0.22 \qquad \text{(Eq. 4)}$$

An expression for f_{ct} using the limiting splitting ratio of 0.212 is given by Eq. 5. The expression is also shown in Figure 8 with the LWC test data from this investigation. Nearly all (96%) of the data points in Figure 8 are above the limiting splitting ratio of 0.212 indicating that modifications for these LWC mixes would not be necessary.

The modification factor for LWC is also known as the λ-factor. A splitting ratio greater than or equal to a limiting value indicates no modification is needed and λ is taken as unity. A splitting ratio less than the limiting value indicates modification is needed and λ is taken as less than unity. Eq. 2 is rearranged in the form of a λ-factor and is given by Eq. 6.

$$f_{ct} = 0.212\sqrt{f_c'} \qquad \text{(Eq. 5)}$$

$$\lambda = \frac{f_{ct}}{0.212\sqrt{f_c'}} \qquad \text{(Eq. 6)}$$

DEVELOPMENT OF STRENGTH AND ELASTIC MODULUS WITH TIME

The development of compressive strength (i.e., increase in f_c' with time) is shown in Figure 5, Figure 6, and Figure 7. As the compressive strength develops, the splitting tensile strength and elastic modulus also increase. The ratio of f_c' at release and girder test to the f_c' at 28 days is given in Table 6. The value shown is the mean of the ratios for all three girder mixes. The coefficient of variation (COV) is also shown. Similar mean ratios for f_{ct} and E_c are also given in Table 6. The table shows that the mean ratio of f_c' is lower than the ratio f_{ct} and E_c at release and higher at girder test. Compared to the value at release, f_c' developed more between release and 28-days and between 28-days and girder test than f_{ct} and E_c. The mean ratio for E_c between 28-days and girder test was approximately unity indicating that the elastic modulus was almost fully developed at 28-days, even though the compressive strength and splitting tensile strength continued to develop.

Table 6. Mean Ratio of Compressive Strength, Splitting Tensile Strength, and Elastic Modulus at Release and Girder Test to their Values at 28-days.

	Release		Girder Test	
Ratio	**mean**	**COV**	**mean**	**COV**
$\frac{f_c'}{(f_c')_{28\ day}}$	0.73	7.2%	1.12	8.4%
$\frac{f_{ct}}{(f_{ct})_{28\ day}}$	0.86	6.2%	1.08	6.4%
$\frac{E_c}{(E_c)_{28\ day}}$	0.88	5.7%	1.01	9.3%

Design expressions for E_c and the λ-factor (incorporating f_{ct}) are typically based on specified minimum 28 days test values. Values from normalized design expressions that remain constant during the development of compressive strength will result in predictions of structural performance that also can be expected to remain constant. For example, the splitting factor is an example of f_{ct} normalized by $\sqrt{f_c'}$. If the splitting factor remains constant for data pairs of f_{ct} and f_c' tested at different times, then the resulting λ-factor will be the same and the accuracy of the design expression to predict the cracking behavior can be expected to be similar with respect to time. Figure 9 shows that the splitting factor for the LWC mixes tested in this investigation is relatively constant with time. The horizontal line in Figure 9 represents the limiting splitting ratio of 0.212.

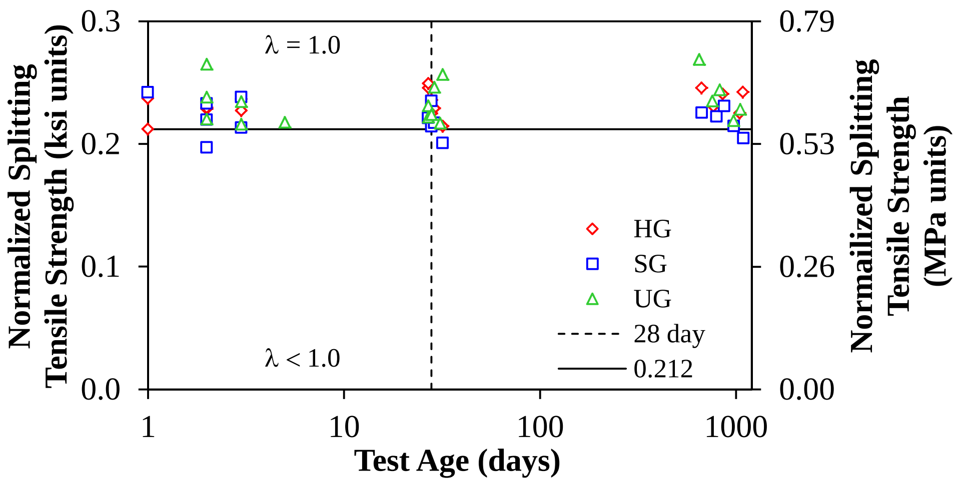


Figure 9. Graph. Splitting Tensile Strength Normalized by $\sqrt{f_c'}$.

The ratio of the splitting factor at release and girder test to the splitting factor at 28 days was calculated for all of the mixes. The ratio mean and COV are shown in Table 7. The mean at both release and girder test were both near unity, indicating that for the LWC mixes tested in this investigation, using $\sqrt{f_c'}$ to normalize f_{ct} results in a design expression whose accuracy changes very little with time.

Table 7. Mean Ratio of Normalized Splitting Tensile Strength at Release and Girder Test to their Values at 28-days.

Normalized Ratio	Release		Girder Test	
	mean	COV	mean	COV
$\frac{[f_{ct}/(f_c')^{0.5}]}{[f_{ct}/(f_c')^{0.5}]_{28\ day}}$	1.00	6.0%	1.02	7.1%

Different normalizing factors were also used to evaluate E_c. Two factors, $\sqrt{f_c'}$ and $f_c'^{\,0.33}$, were selected because of their use in design expressions for E_c in the AASHTO LRFD Specifications and the NCHRP Project 12-64 report. The factors are important because for NWC, f_c' is the only design parameter typically used in the design equation for E_c. Normalized E_c using the two factors is shown in Figure 10 and Figure 11, respectively. The horizontal lines in Figure 10 and Figure 11 at values of 1822 and 2482, respectively, represent the predicted normalized E_c for NWC. The mean ratio of normalized E_c at release and girder test to the normalized E_c at 28 days is given in Table 8. Normalization using $\sqrt{f_c'}$ resulted in means of 1.03 at release and 0.96 at girder test. Both means are near unity, but indicate a slight downward trend for the LWC mixes tested in this investigation. Normalization using $f_c'^{\,0.33}$ resulted in means that were slightly less than unity at both release and girder test.

Table 8. Mean Ratio of Normalized Elastic Modulus at Release and Girder Test to their Values at 28-days.

Normalized Ratio	Release		Girder Test	
	mean	COV	mean	COV
$\frac{[E_c/(f_c')^{0.5}]}{[E_c/(f_c')^{0.5}]_{28\ day}}$	1.03	6.8%	0.96	7.5%
$\frac{[E_c/(f_c')^{0.33}]}{[E_c/(f_c')^{0.33}]_{28\ day}}$	0.98	6.2%	0.97	7.9%
$\frac{[E_c/(w_c)^{1.5}(f_c')^{0.5}]}{[E_c/(w_c)^{1.5}(f_c')^{0.5}]_{28\ day}}$	1.03	7.1%	0.99	6.9%
$\frac{[E_c/(w_c)^{2.5}(f_c')^{0.33}]}{[E_c/(w_c)^{2.5}(f_c')^{0.33}]_{28\ day}}$	0.98	6.9%	1.04	7.3%

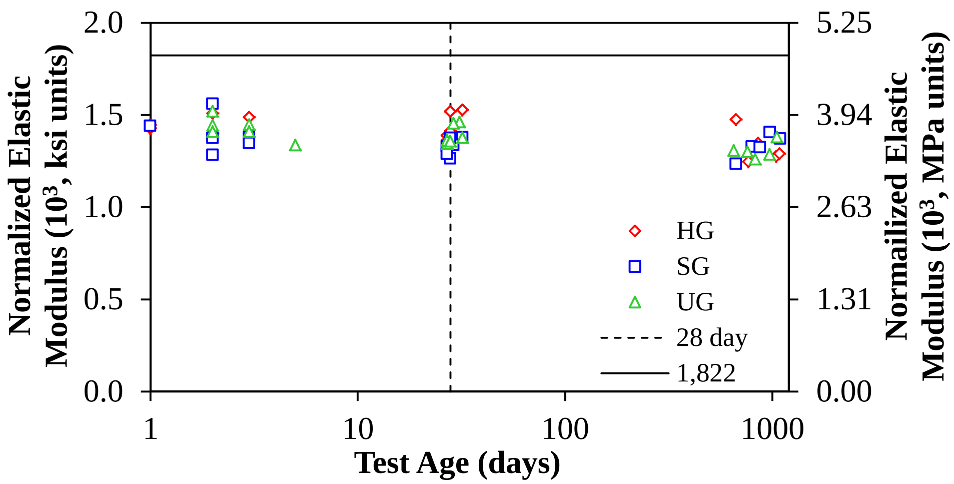


Figure 10. Graph. Elastic Modulus Normalized by $\sqrt{f_c'}$.

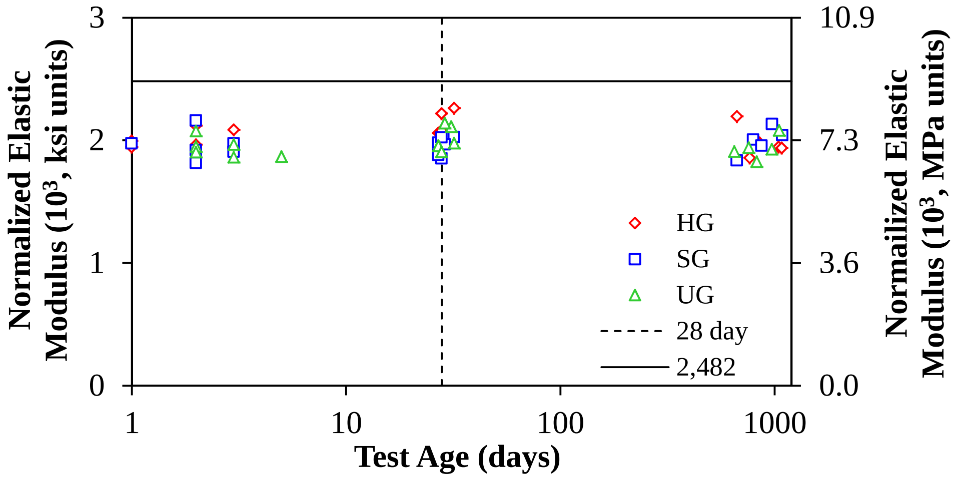


Figure 11. Graph. Elastic Modulus Normalized by $f_c'^{\,0.33}$.

Elastic modulus was also normalized using f_c' with w_c. The factors $w_c^{1.5} f_c'^{\,0.5}$ and $w_c^{2.5} f_c'^{\,0.33}$ were selected because of their use in design expressions for E_c in the AASHTO LRFD Specifications and the NCHRP Project 12-64 report. Normalized E_c for the factors is shown in Figure 12 and Figure 13, where the horizontal lines at 33,000 and 310,000, respectively, represent the predicted normalized E_c for NWC. The mean ratio of normalized E_c at release and girder test was also shown in Table 8 for these factors. The factor $w_c^{1.5} f_c'^{\,0.5}$ gave means that are similar to the means for the factor $\sqrt{f_c'}$, likely due in part to the limited range of unit weights in the data from the LWC mixes tested in this investigation. The factor $w_c^{2.5} f_c'^{\,0.33}$ has a mean at release that is similar to the $f_c'^{\,0.33}$, but the mean at girder test is greater than the mean for $f_c'^{\,0.33}$, indicating a slight upward trend. Figure 13 also shows that nearly all of the data was above the horizontal line for NWC, indicating that the factor $w_c^{2.5} f_c'^{\,0.33}$ predicted an E_c greater than what is expected for NWC.

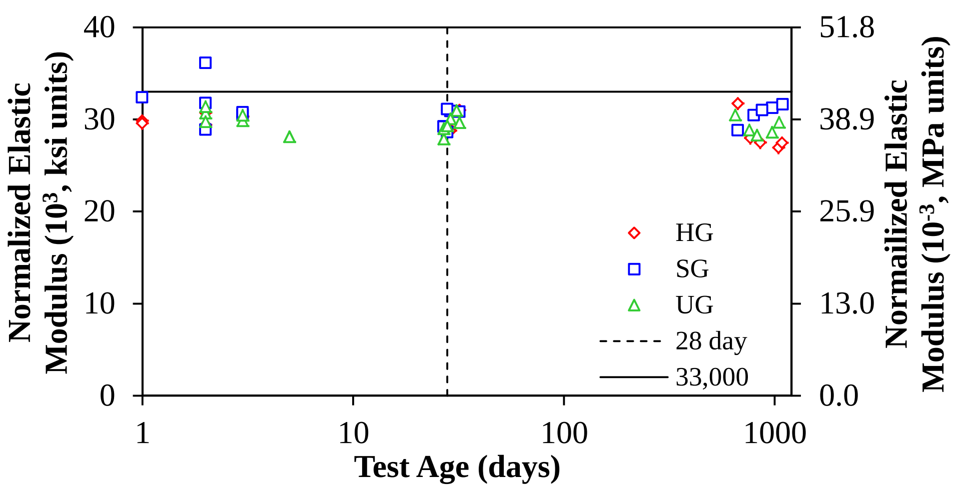


Figure 12. Graph. Elastic Modulus Normalized by $(w_c)^{1.5}(f_c')^{0.5}$.

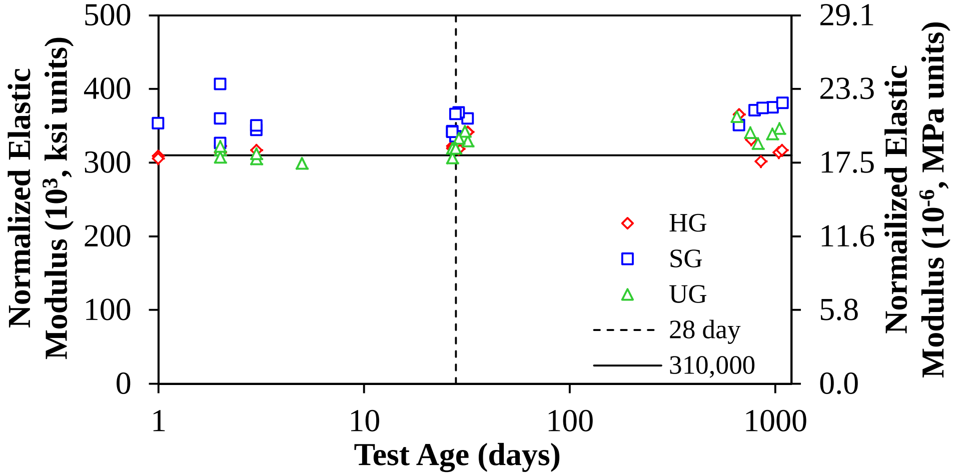


Figure 13. Graph. Elastic Modulus Normalized by $(w_c)^{2.5}(f_c')^{0.33}$.

DESIGN EXPRESSIONS FOR ELASTIC MODULUS

Design expressions for E_c are typically presented in a general form as a function of both f_c' and w_c and then in a simplified form for NWC as a function of only f_c'. The expression for E_c in the AASHTO LRFD Specifications(1) (Article 5.4.2.4) is given by Eq. 7. Article 5.4.2.4 states that the expression is applicable to concrete with unit weight between 0.090 and 0.155 kcf (1440 to 2480 kg/m^3). The simplified expression applicable to NWC found in the commentary (C5.4.2.4) is given by Eq. 8. A design expression for E_c evaluated in the NCHRP Project 12-64 Report(17) is given by Eq. 9. This expression was developed for concrete strengths up to 18 ksi (124 MPa) using over 4400 data points. ACI Committee 363, High-Strength Concrete, gives an expression for E_c in its document, "Report on High-Strength Concrete".(18) The ACI 363 expression is given by Eq. 10.

$$E_c = 33{,}000 K_1 w_c^{1.5}\sqrt{f_c'} \qquad \text{(Eq. 7)}$$

$$E_c = 1{,}820\sqrt{f_c'} \qquad \text{(Eq. 8)}$$

$$E_c = 310{,}000 K_1 w_c^{2.5} f_c'^{\,0.33} \qquad \text{(Eq. 9)}$$

$$E_c = 22.9 w_c^{1.5}\sqrt{f_c'} + 1{,}000{,}000(w_c/145)^{1.5} \qquad \text{(Eq. 10)}$$

(where E_c and f_c' are in psi and w_c is in pcf)

The design expressions for E_c given by Eq. 7 (AASHTO LRFD), Eq. 9 (NCHRP 12-64), and Eq. 10 (ACI 363) were calculated for the LWC data tested in this investigation. The mean test-to-prediction ratio of E_c for the HG, SG, and UG mixes using the three design expressions is given in Table 9. Graphs of the predicted E_c versus the measured E_c are given in Figure 14,

Figure 15, and Figure 16. The mean test-to-prediction ratios in Table 9 and the graphs show that E_c was over-estimated by AASHTO LRFD expression (mean ratio of 0.91), and under-estimated by the NCHRP expression (mean ratio of 1.08) and the ACI 363 expression (mean ratio of 1.03).

The test-to-prediction ratios for the three expressions for E_c given by Eq. 7, Eq. 9, and Eq. 10 are shown graphically in Figure 17, Figure 18, and Figure 19. These three figures show the test-to-prediction ratios versus both compressive strength and unit weight. As shown in Figure 17 and Figure 19, the AASHTO LRFD expression and ACI 363 expression give uniform predictions with compressive strength and unit weight. The NCHRP expression exhibits increased scatter when compared to compressive strength and a decreasing trend in the test-to-prediction ratio with unit weight as shown in Figure 18.

Table 9. Mean Ratio of Measured-to-Predicted Elastic Modulus.

	All		HG		SG		UG	
Prediction Equation	**mean**	**COV**	**mean**	**COV**	**mean**	**COV**	**mean**	**COV**
AASHTO LRFD (Eq. 7)	0.906	5.2%	0.888	4.9%	0.933	5.8%	0.896	3.5%
NCHRP 12-64 (Eq. 9)	1.083	7.2%	1.040	6.1%	1.158	5.4%	1.048	5.3%
ACI 363 (Eq. 10)	1.027	5.0%	1.010	4.7%	1.062	5.0%	1.007	3.4%

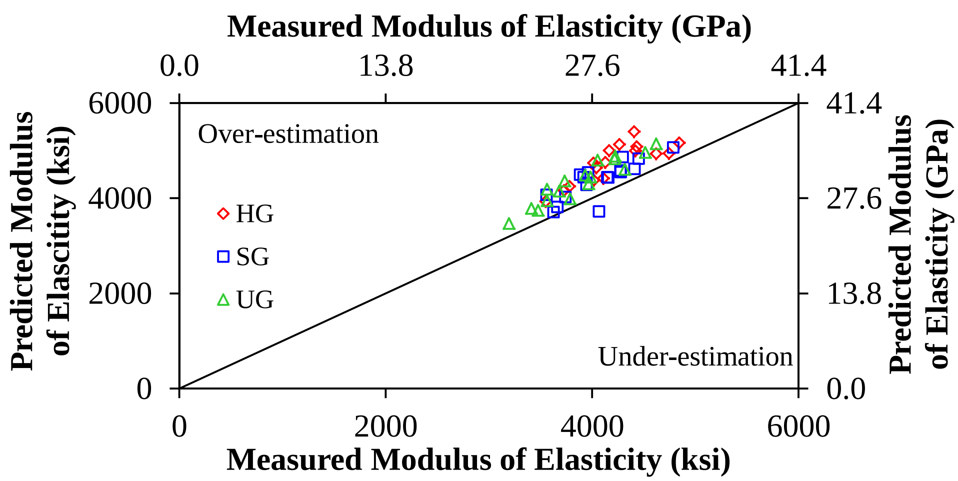


Figure 14. Graph. Comparison of Measured Modulus of Elasticity to Prediction by AASHTO LRFD Equation (Eq. 7).

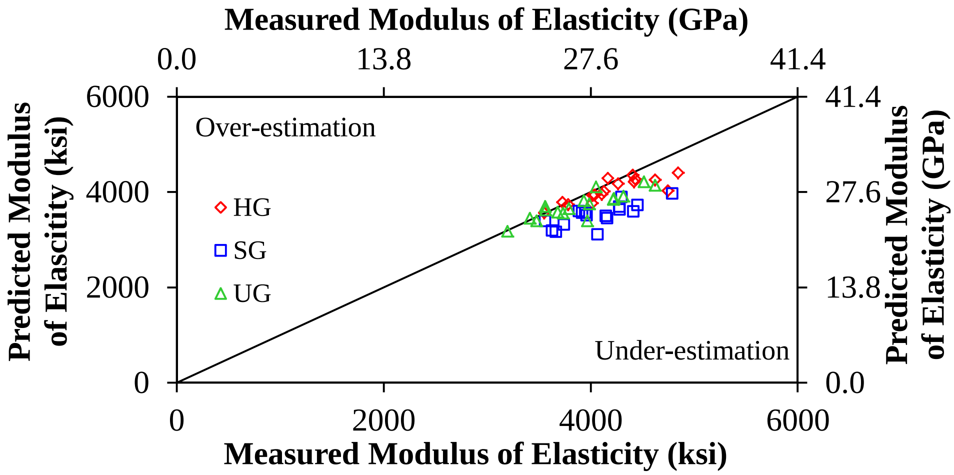


Figure 15. Graph. Comparison of Measured Modulus of Elasticity to Prediction by NCHRP Project 12-64 Equation (Eq. 9).

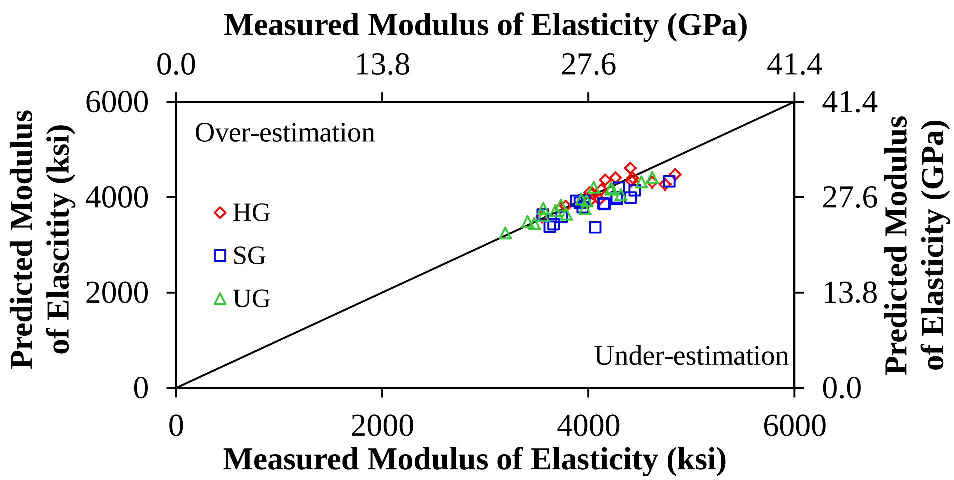


Figure 16. Graph. Comparison of Measured Modulus of Elasticity to Prediction by ACI 363-10 Equation (Eq. 10).

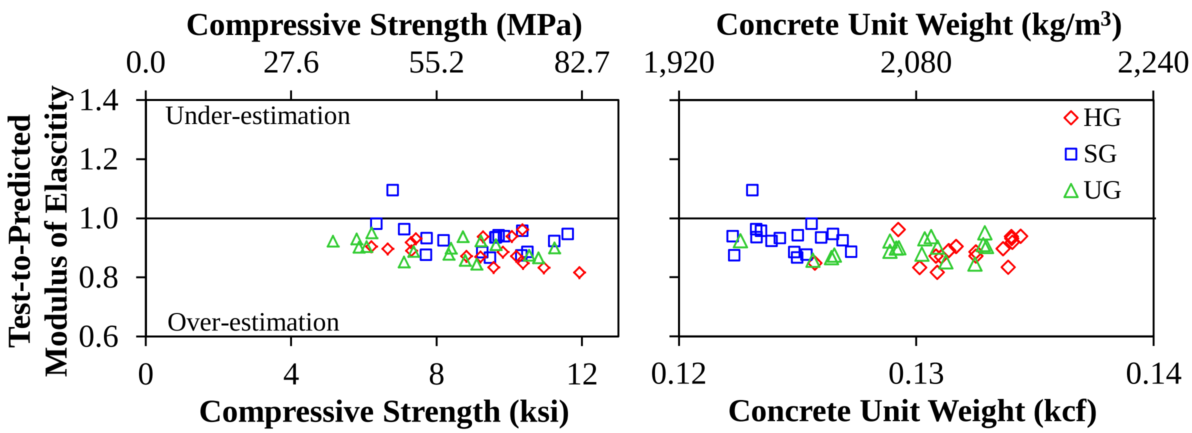


Figure 17. Graph. Modulus of Elasticity Test-Prediction Ratio Compared to Compressive Strength and Unit Weight for AASHTO LRFD Equation (Eq. 7).

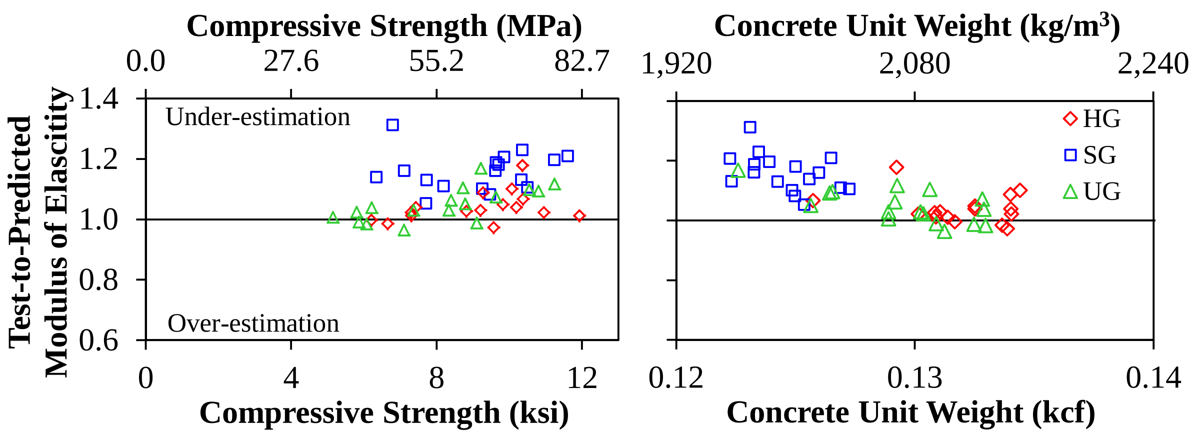


Figure 18. Graph. Modulus of Elasticity Test-Prediction Ratio Compared to Compressive Strength and Unit Weight for NCHRP Project 12-64 Equation (Eq. 9).

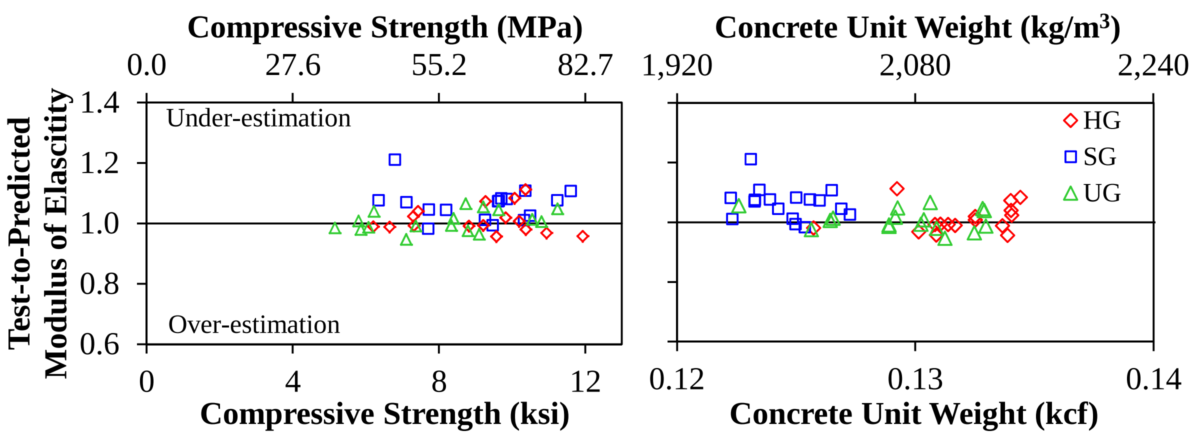


Figure 19. Graph. Modulus of Elasticity Test-Prediction Ratio Compared to Compressive Strength and Unit Weight for ACI 363-10 Equation (Eq. 10).

SUMMARY

The performance of four LWC mix designs were investigated in this research program. The mix designs included two expanded shales and one expanded slate. For the three mix designs applicable to precast girder production, the design compressive strength ranged from 6 to 10 ksi (41 to 69 MPa) and the target unit weight ranged from 0.126 to 0.130 kcf (2020 to 2080 kg/m^3). These mixes were prescriptively produced at the precaster's facility for use in LWC prestressed girders and reinforced concrete beams. The resulting concrete had a range in 28-day compressive strength of only 8.7 to 9.7 ksi (60.0 to 66.9 MPa) and an air-dry density range of 0.125 to 0.132 kcf (2000 to 2110 kg/m^3). The one mix design applicable to field-cast bridge decks used an expanded slate and was used in the production of LWC reinforced concrete beams. The design compressive strength was 4 ksi (18 MPa) and the target unit weight was 0.125 kcf (2000 kg/m^3). The resulting concrete had a 28-day compressive strength of 5.7 ksi (39.3 MPa) and an air-dry density of 0.138 kcf (2210 kg/m^3).

On average, the compressive strength increased with time at a higher rate than the splitting tensile strength or the modulus of elasticity. However, the ratio of splitting tensile strength to $\sqrt{f_c'}$ (known as the splitting ratio), did not vary significantly with time. The ratio of the modulus of elasticity to $w_c^n f_c'^n$, where n were various exponents commonly used in design expressions, also did not vary significantly with time.

The LWC tests results were compared to design expressions for a lightweight modification factor and for modulus of elasticity. Nearly all splitting tensile tests on all three mixes gave splitting ratios that were greater than the splitting ratio requiring modification of LWC for shear and development length of mild steel in tension. The modulus of elasticity was over-estimated by the AASHTO LRFD expression, and under-estimated by the NCHRP 12-64 expression and ACI 363-10 expression.

CHAPTER 4. TFHRC LIGHTWEIGHT CONCRETE DATABASE

INTRODUCTION

This chapter describes the information available in the overall TFHRC LWC Database and subset databases for modulus of elasticity and splitting tensile strength. The type of information included in each line of the database is described as well as the protocol for deciding which reviewed data was collected and added to the database. The chapter describes the method for choosing lines of data in the database to be used as subset databases for the evaluation of design expressions in the AASHTO LRFD Specifications. The chapter also includes statistical information on the mechanical properties of data in the TFHRC LWC subset databases.

TFHRC LWC DATABASE

A thorough literature review was performed to find published journal papers, conference papers, technical reports, and university dissertations that included tests, analysis, or discussions of LWC. Over 500 references were found in the literature that mentioned LWC. These references were reviewed for LWC data consisting of a compressive strength value and data from at least one other mechanical test. A data line consisted of concrete mix information, the results from at least two mechanical tests, and information about the mechanical tests. A data line represented mechanical tests performed at the same concrete specimen age. The recorded mechanical tests included compressive strength, modulus of elasticity, splitting tensile test, modulus of rupture, and Poisson's Ratio. Up to two measures of concrete density were also recorded. Concrete mix information was recorded including the type of coarse and fine aggregate, the use of chemical admixtures, and the use of supplementary cementitious materials. Information about the mechanical tests was recorded including the specimen size, duration and type of curing, and specimen age.

Several criteria were used to determine whether test data was included in the overall database. A reference was used if it contained at least two data lines. Test result data was only recorded if it was presented in a table, in the text, or as text on a figure. The magnitude of test results was not interpreted from points on a graph. Unpublished test data and NWC test data was not included in the database. Data lines with a compressive strength less than 2.0 ksi (13.8 MPa) were avoided during database collection and were not used for evaluation. Article 5.4.2.1 in the AASHTO LRFD Specifications states that concrete with a compressive strength less than 2.4 ksi (16.5 MPa) should not be used in structural applications. The 2.0 ksi (13.8 MPa) limit for the database was selected so as to include some data below the 2.4 ksi (16.5 MPa) limit for structural concrete without allowing low strength LWC that is commonly used for insulating purposes to bias the analysis of mechanical properties. A limited number of tests on concrete that included lightweight aggregate had a unit weight greater than 0.135 kcf (2160 kg/m^3). This test data was included in the overall database but was not used in any analyses that are described in this document.

The TFHRC LWC Database consists of 3835 data lines. This data was collected from a total of 128 references. The mean number of data lines per reference is 30, while the maximum number of data lines from one reference is 416. There were 69 references that contributed ten or fewer data lines and 18 references that contributed 50 or more data lines. A full list of references for the TFHRC LWC Database is included in Chapter 8.

Table 10 summarizes the types of concrete mixtures in the TFHRC LWC Database. The definitions of different types of lightweight concrete mixtures have been traditionally based on the use of lightweight or normal weight constituent materials. The types of concrete mixtures used in the database included all-lightweight, sand-lightweight, specified density, and inverted mix. All-lightweight was defined as concrete with lightweight fine and coarse aggregate. Sand-lightweight was defined as concrete with lightweight coarse aggregate and either sand or a mixture of sand and lightweight fine aggregate. Specified density was defined as concrete with a mixture of normal weight and lightweight coarse aggregate and either sand or lightweight fine aggregate. An inverted mix was defined as concrete with normal weight coarse aggregate and lightweight fine aggregate or a mixture of lightweight fine aggregate and sand.

Table 10. Summary of the Types of Concrete Mixtures in the TFHRC LWC Database.

Mixture Variable Type	Variable	No. of Data Lines
Concrete type	All-lightweight	1771
	Sand-lightweight	1904
	Specified density	114
	Inverted mix	46
Lightweight aggregate	Manufactured	3300
	Natural	47
	Unspecified	488
Admixtures	None	2681
	Only 1	774
	2 or more	380
Supplementary cementitious	None	2745
	Only 1	946
	2 or more	144

The most common types of lightweight aggregate were expanded shale, clay, or slate. Pelletized fly ash was frequently described in European references. Forty-seven data lines were from natural lightweight aggregate, with the most common being pumice. Many more lines of test data on natural lightweight aggregate were available in the literature but were not collected because the reported compressive strength was less than 2.0 ksi (13.8 MPa).

TFHRC SUBSET DATABASES

Data lines were selected for evaluating material properties based on the presence of available data and on being within a range of material property values. For each material property, data lines were selected if there was a measured compressive strength, a measured unit weight, and a measured value for the material property being evaluated. For example, data lines selected for the evaluation of modulus of elasticity had measured values for compressive strength, modulus of elasticity, and unit weight. The data lines in the subset databases were also limited to those with a compressive strength greater than or equal to 2.0 ksi (13.8 MPa) and a unit weight that is less than or equal to 0.135 kcf (2160 kg/m^3). The 2.0 ksi (13.8 MPa) limit on compressive strength was discussed previously. The 0.135 kcf (2160 kg/m^3) limit on unit weight was chosen because the AASHTO LRFD Specifications (AASHTO 2012) define NWC as having a unit weight as low as 0.135 kcf (2160 kg/m^3). Table 11 gives the total number of data lines for material property tests and the number of data lines in each subset database used for the evaluation of modulus of elasticity, splitting tensile strength, modulus of rupture, and Poisson's Ratio. The number of data lines is grouped in ranges of material property values.

For over 1600 data lines, the concrete density was determined and reported from more than one method of measurement. Equilibrium density is a type of air-dry density defined by ASTM C567.[16] A demolded density is measured on cylinders immediately following demolding. A saturated density is measured on cylinders that have been submerged in water. The type of measurement was specified in the reference. The equilibrium density was preferred over the other types of density measurements and was selected as the "unit weight" if there were two or more measurements for unit weight. The preference order for the other methods of measuring concrete density is given in Table 12. The term "unit weight" is used in the AASHTO LRFD Specifications to describe concrete density and will be used in this document to describe the value obtained by the more preferred method of measuring concrete density. If the oven dry measurement was used as the preferred method, then an additional 0.003 kcf (48 kg/m^3) was added to the measurement to obtain a calculated equilibrium density as specified by ASTM C567.

A series of tables and figures were created to give statistical information by ranges of mechanical property data and show the distribution of the mechanical property data. The distribution of compressive strength, modulus of elasticity, and unit weight for specified ranges of E_c is given in Table 13. The variation of compressive strength and unit weight with E_c is shown in Figure 20 and Figure 21, respectively. The distribution of compressive strength, splitting tensile strength, and unit weight for specified ranges of f_{ct} is given in Table 14. The variation of compressive strength and unit weight with f_{ct} is shown in Figure 22 and Figure 23, respectively. The distribution of compressive strength, modulus of rupture, and unit weight for specified ranges of f_r is given in Table 15. The variation of compressive strength and unit weight with f_r is shown in Figure 24 and Figure 25, respectively. The distribution of compressive strength, Poisson's Ratio, and unit weight for Poisson's Ratio is given in Table 16. The variation of compressive strength and unit weight with Poisson's Ratio is shown in Figure 26 and Figure 27, respectively.

Table 11. Mechanical Property and Unit weight Distribution in TFHRC LWC Database and Subset Databases.

		No. of Data Lines				
Property	**Range**	**TFHRC LWC Database**	**E_c Database**	**f_{ct} Database**	**f_r Database**	**Poisson's Ratio Database**
Compressive strength	2.0 to 4.0 ksi	792	552	184	197	106
	4.0 to 6.0 ksi	1321	887	383	399	119
	6.0 to 8.0 ksi	910	697	412	293	43
	8.0 to 10.0 ksi	436	305	274	84	52
	> 10.0 ksi	158	115	79	37	38
Modulus of elasticity	< 1000 ksi	18	8			
	1000 to 2000 ksi	623	443			
	2000 to 3000 ksi	1357	1278			
	3000 to 4000 ksi	642	584			
	> 4000 ksi	291	243			
Splitting tensile strength	< 0.2 ksi	20		1		
	0.2 to 0.4 ksi	451		317		
	0.4 to 0.6 ksi	710		552		
	0.6 to 0.8 ksi	444		426		
	> 0.8 ksi	41		36		
Modulus of rupture	< 0.2 ksi	6			4	
	0.2 to 0.4 ksi	179			140	
	0.4 to 0.6 ksi	420			346	
	0.6 to 0.8 ksi	434			381	
	> 0.8 ksi	146			139	
Unit weight	< 0.090 kcf	116	69	17	40	2
	0.090 to 0.100 kcf	846	524	156	312	46
	0.100 to 0.110 kcf	603	456	143	149	85
	0.110 to 0.120 kcf	932	798	421	291	136
	0.120 to 0.135 kcf	940	709	595	218	89
	> 0.135 kcf	76	0	0	0	0

Units: 1.0 ksi = 6.89 MPa, 0.001 kcf = 16.01 kg/m^3

Table 12. Order of Preference for Concrete Density Measurement Method.

Concrete Density Measurement Method	Order of Preference	Comment
Equilibrium density	1	--
air dry	2	--
moist room	3	--
demolding	4	--
oven dry	5	Add 0.003 kcf
plastic (fresh)	6	--
saturated	7	--
not specified	8	--

Units: 0.001 kcf = 16.01 kg/m^3

Table 13. Distribution of Mechanical Properties in Subset Database for Modulus of Elasticity.

Range (ksi)	Property	No. of Data Lines	Mean	COV	Max.	Min.
$E_c \leq 1000$	f'_c (ksi)	8	2.50	18.3%	3.27	2.04
	E_c (ksi)	8	774	25.8%	970	420
	w_c (kcf)	8	0.078	13.2%	0.091	0.062
$1000 < E_c \leq 2000$	f'_c (ksi)	443	3.85	33.9%	9.04	2.01
	E_c (ksi)	443	1758	10.8%	1996	1050
	w_c (kcf)	443	0.099	9.7%	0.134	0.079
$2000 < E_c \leq 3000$	f'_c (ksi)	1278	5.28	28.5%	9.73	2.01
	E_c (ksi)	1278	2425	11.0%	2990	2000
	w_c (kcf)	1278	0.109	8.3%	0.134	0.088
$3000 < E_c \leq 4000$	f'_c (ksi)	584	7.34	25.7%	14.85	2.54
	E_c (ksi)	584	3458	8.3%	3990	3000
	w_c (kcf)	584	0.120	4.2%	0.134	0.100
$4000 < E_c$	f'_c (ksi)	243	8.94	16.7%	14.17	3.92
	E_c (ksi)	243	4341	5.7%	5180	4000
	w_c (kcf)	243	0.124	2.7%	0.134	0.114

Units: 1.0 ksi = 6.89 MPa, 0.001 kcf = 16.01 kg/m^3

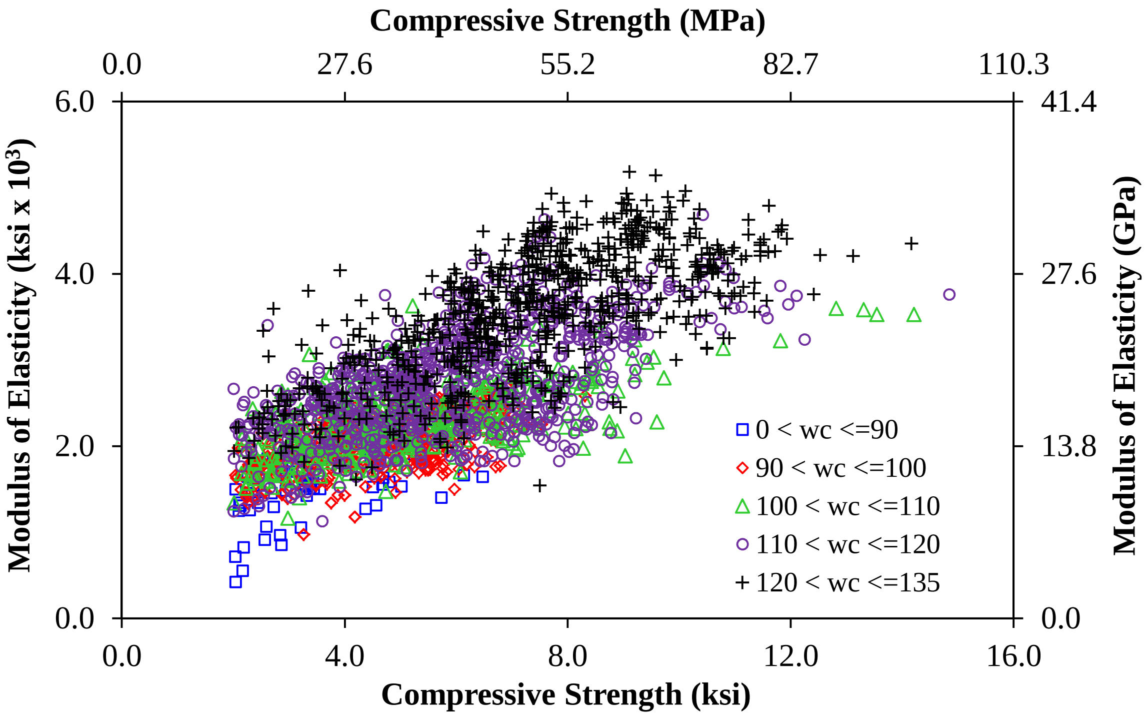


Figure 20. Graph. Modulus of Elasticity versus Compressive Strength in TFHRC LWC Database – E_c Subset Showing Variation by Unit Weight.

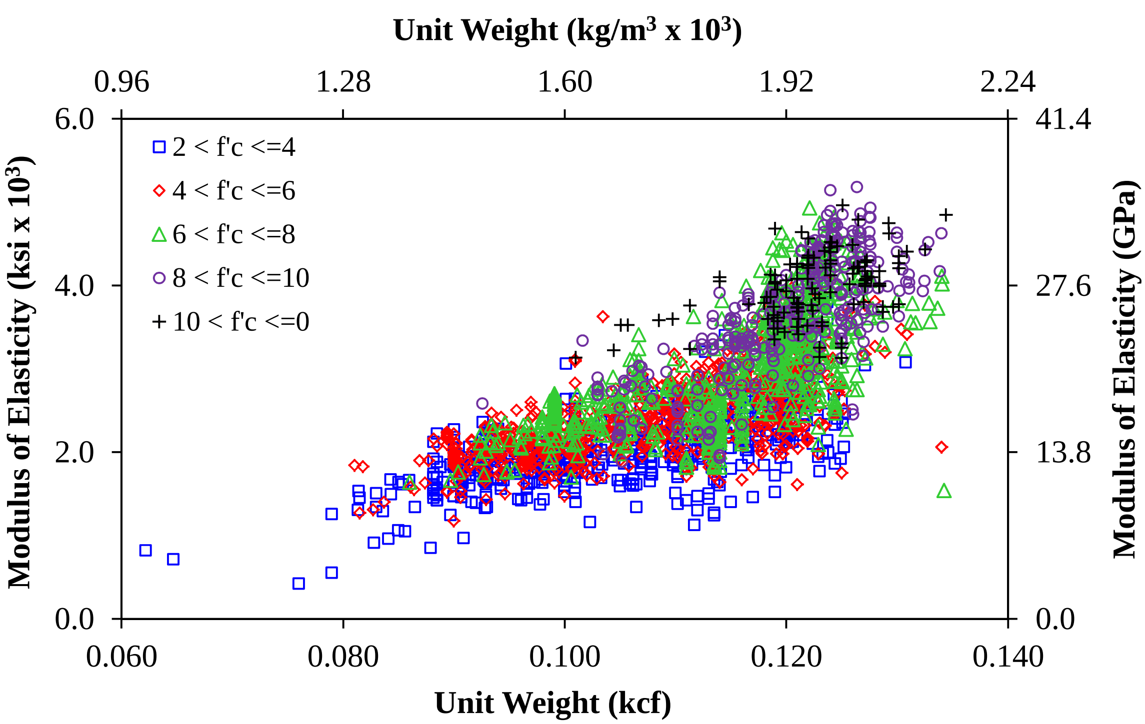


Figure 21. Graph. Modulus of Elasticity versus Unit Weight in TFHRC LWC Database – E_c Subset Showing Variation by Compressive Strength.

Table 14. Distribution of Mechanical Properties in Subset Database for Splitting Tensile Strength.

Range (ksi)	Property	No. of Data Lines	Mean	COV	Max.	Min.
$f_{ct} \leq 0.2$	f'_c (ksi)	1	2.19	--	--	--
	f_{ct} (ksi)	1	0.151	--	--	--
	w_c (kcf)	1	0.062	--	--	--
$0.2 < f_{ct} \leq 0.4$	f'_c (ksi)	317	4.31	34.4%	10.12	2.02
	f_{ct} (ksi)	317	0.337	13.1%	0.399	0.203
	w_c (kcf)	317	0.105	10.0%	0.131	0.065
$0.4 < f_{ct} \leq 0.6$	f'_c (ksi)	552	6.48	28.9%	14.21	3.20
	f_{ct} (ksi)	552	0.513	11.3%	0.598	0.400
	w_c (kcf)	552	0.117	6.7%	0.134	0.089
$0.6 < f_{ct} \leq 0.8$	f'_c (ksi)	426	7.96	18.8%	13.55	3.60
	f_{ct} (ksi)	426	0.679	7.7%	0.798	0.600
	w_c (kcf)	426	0.123	3.3%	0.134	0.101
$0.8 < f_{ct}$	f'_c (ksi)	36	9.69	13.0%	14.85	7.67
	f_{ct} (ksi)	36	0.855	8.8%	1.200	0.802
	w_c (kcf)	36	0.125	3.0%	0.132	0.111

Units: 1.0 ksi = 6.89 MPa, 0.001 kcf = 16.01 kg/m^3

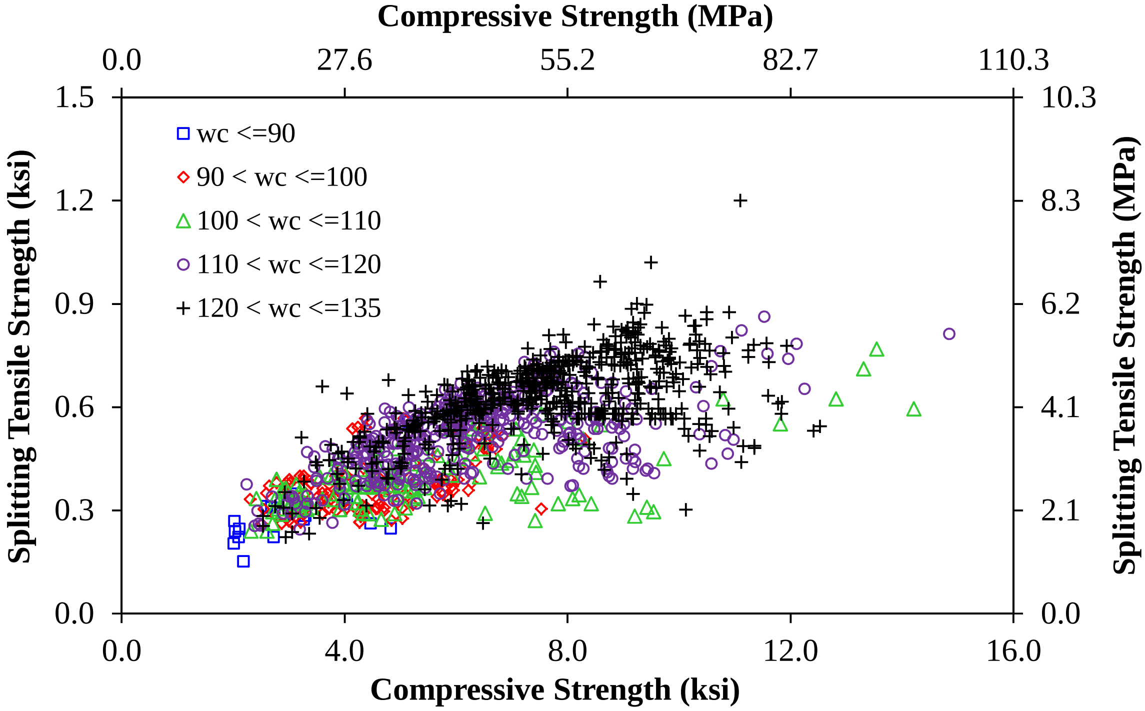


Figure 22. Graph. Splitting Tensile Strength versus Compressive Strength in TFHRC LWC Database – f_{ct} Subset Showing Variation by Unit Weight.

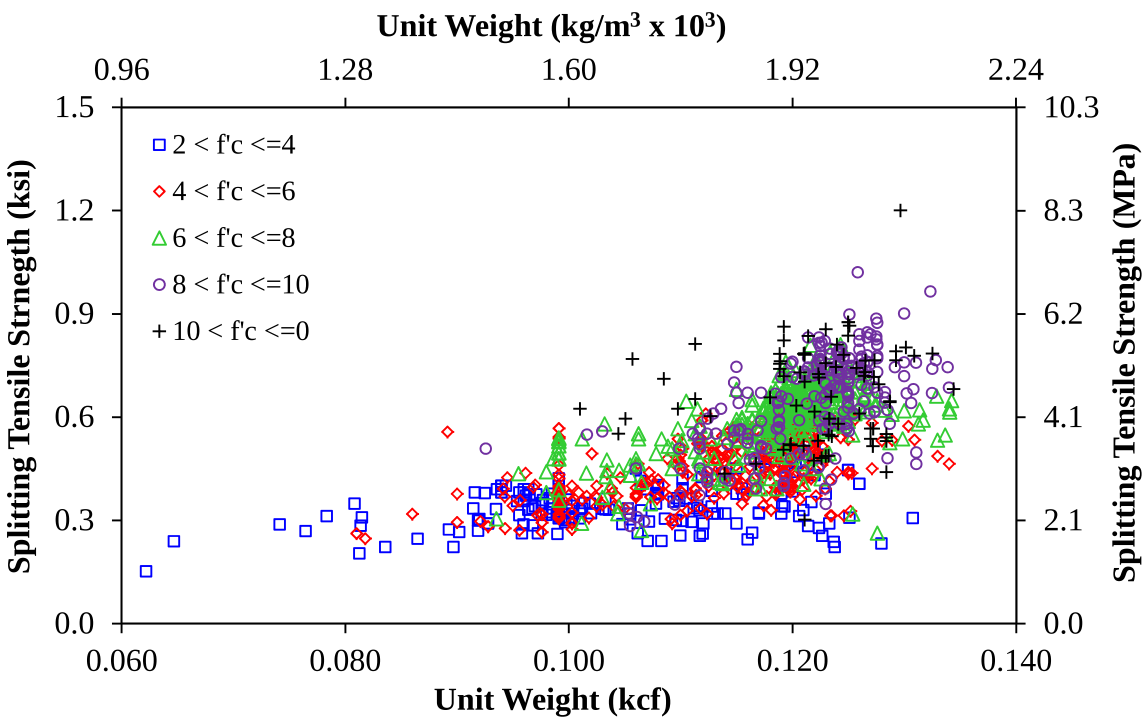


Figure 23. Graph. Splitting Tensile Strength versus Unit Weight in TFHRC LWC Database – f_{ct} Subset Showing Variation by Compressive Strength.

Table 15. Distribution of Mechanical Properties in Subset Database for Modulus of Rupture.

Range (ksi)	Property	No. of Data Lines	Mean	COV	Max.	Min.
$f_r \leq 0.2$	f'_c (ksi)	4	2.71	42.4%	4.43	2.05
	f_r (ksi)	4	0.142	41.5%	0.190	0.068
	w_c (kcf)	4	0.079	18.2%	0.097	0.062
$0.2 < f_r \leq 0.4$	f'_c (ksi)	140	5.10	37.5%	10.59	2.02
	f_r (ksi)	140	0.330	14.1%	0.398	0.210
	w_c (kcf)	140	0.101	9.9%	0.128	0.065
$0.4 < f_r \leq 0.6$	f'_c (ksi)	346	4.61	33.4%	10.09	2.01
	f_r (ksi)	346	0.504	11.3%	0.599	0.400
	w_c (kcf)	346	0.106	11.2%	0.133	0.082
$0.6 < f_r \leq 0.8$	f'_c (ksi)	381	5.96	23.3%	10.87	2.34
	f_r (ksi)	381	0.681	8.1%	0.798	0.600
	w_c (kcf)	381	0.111	11.3%	0.133	0.088
$0.8 < f_r$	f'_c (ksi)	139	8.41	24.5%	14.85	3.89
	f_r (ksi)	139	0.924	11.9%	1.283	0.800
	w_c (kcf)	139	0.119	6.2%	0.132	0.099

Units: 1.0 ksi = 6.89 MPa, 0.001 kcf = 16.01 kg/m^3

Table 16. Distribution of Mechanical Properties in Subset Database for Poisson's Ratio.

Property	No. of Data Lines	Mean	COV	Max.	Min.
f'_c (ksi)	358	5.80	44.8%	11.72	2.02
Poisson's Ratio	358	0.191	14.0%	0.326	0.083
w_c (kcf)	358	0.112	8.8%	0.129	0.085

Units: 1.0 ksi = 6.89 MPa, 0.001 kcf = 16.01 kg/m^3

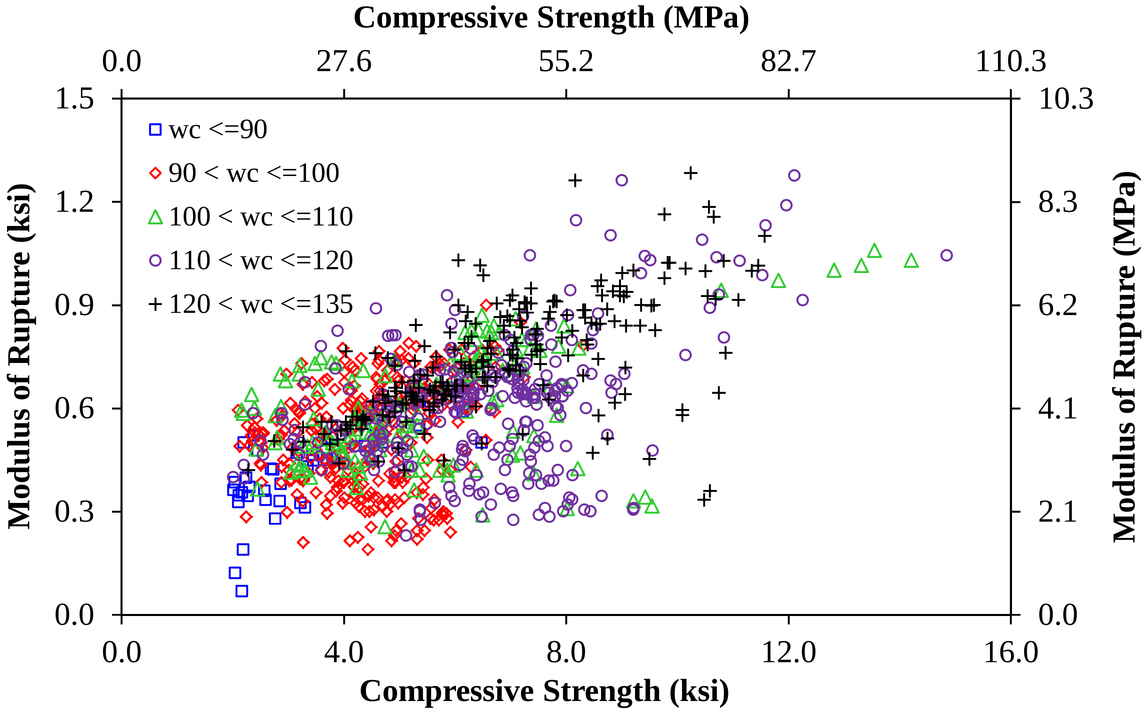


Figure 24. Graph. Modulus of Rupture versus Compressive Strength in TFHRC LWC Database – f_r Subset Showing Variation by Unit Weight.

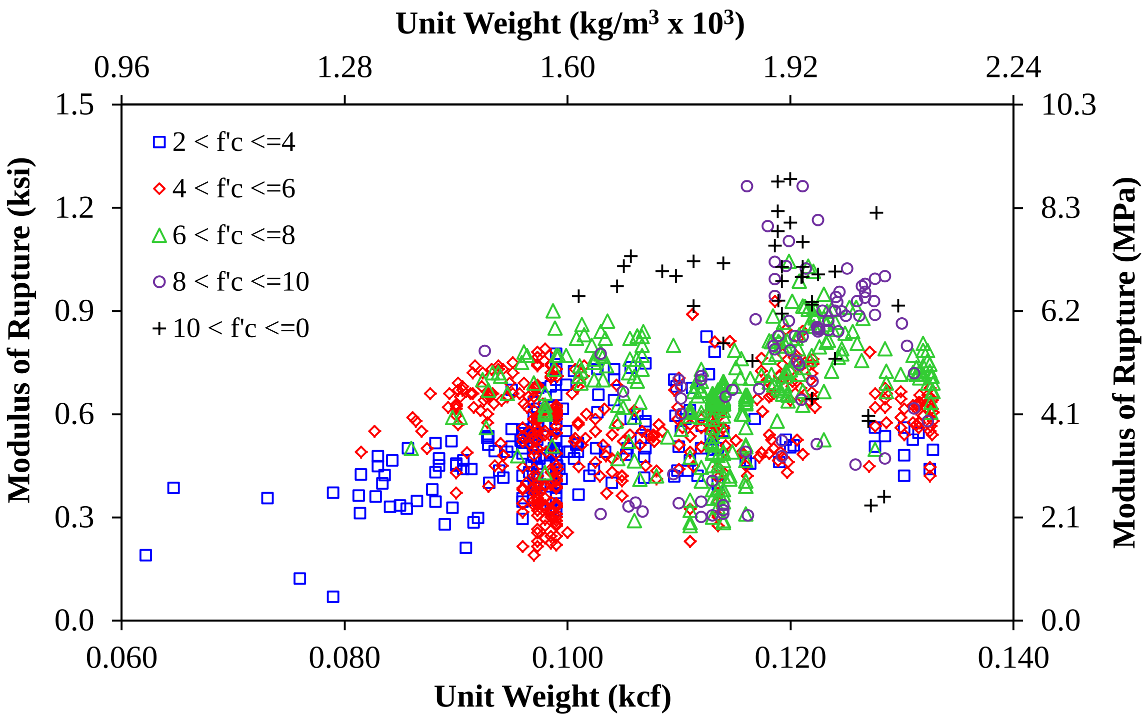


Figure 25. Graph. Modulus of Rupture versus Unit Weight in TFHRC LWC Database – f_r Subset Showing Variation by Compressive Strength.

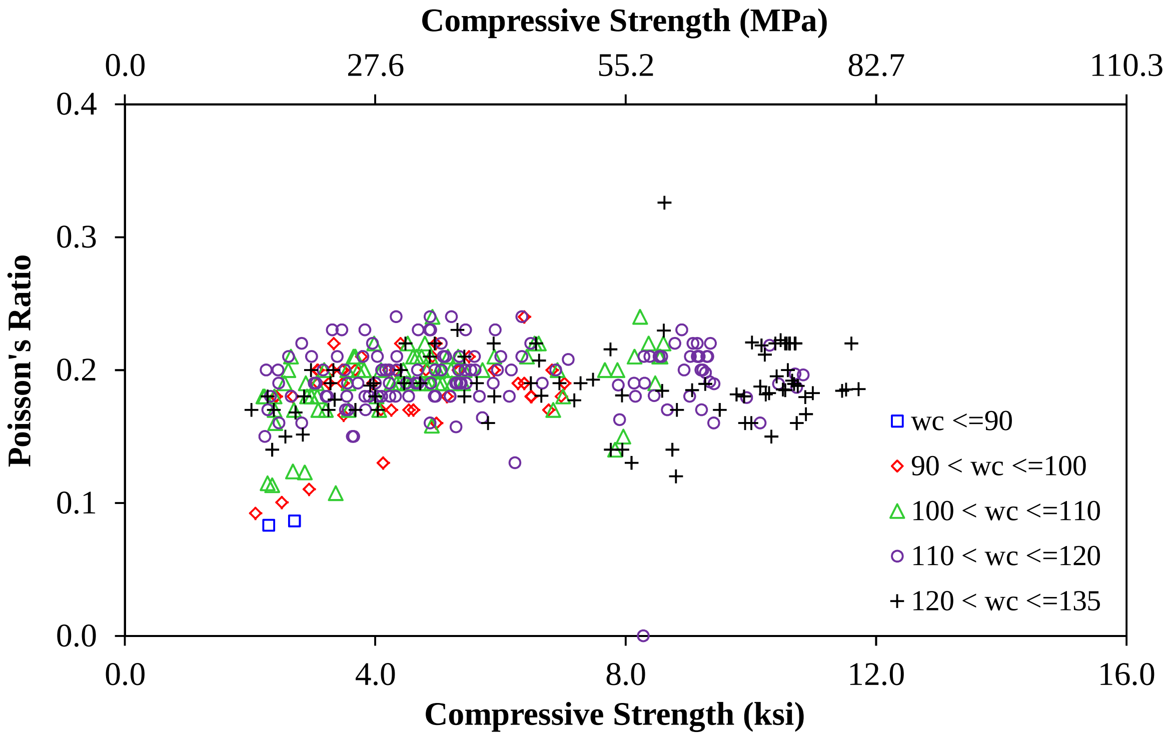


Figure 26. Graph. Poisson's Ratio versus Compressive Strength in TFHRC LWC Database – Poisson's Ratio Subset Showing Variation by Unit Weight.

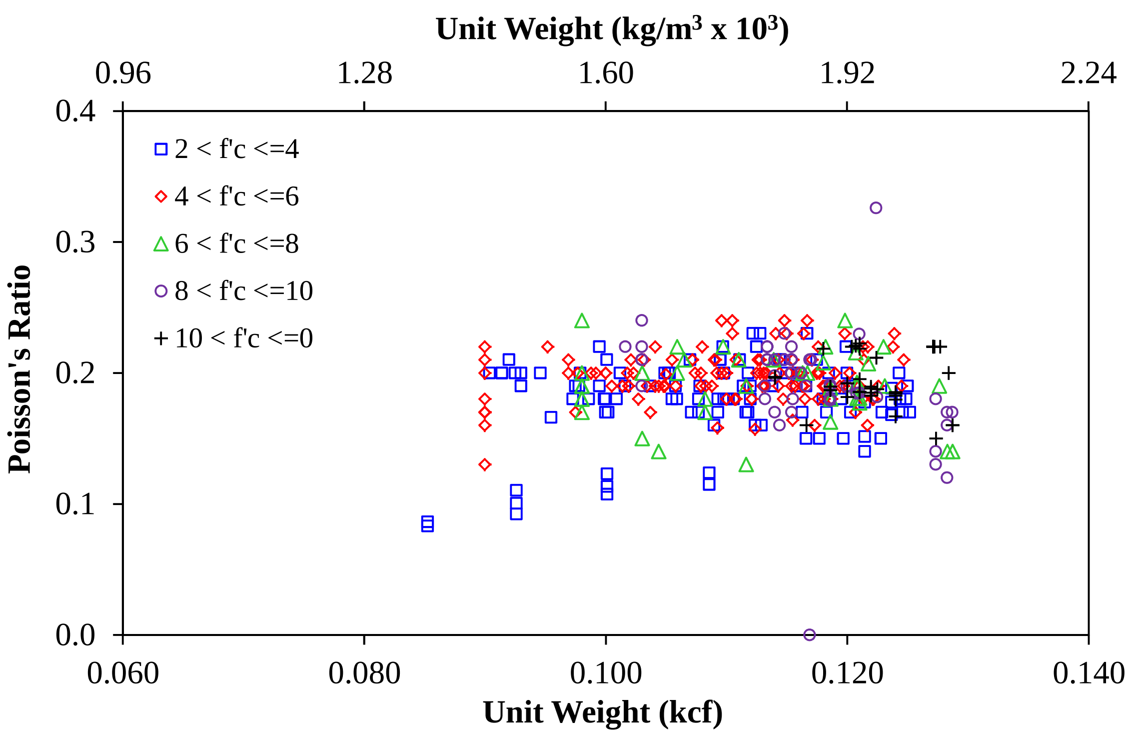


Figure 27. Graph. Poisson's Ratio versus Unit Weight in TFHRC LWC Database – Poisson's Ratio Subset Showing Variation by Compressive Strength.

CHAPTER 5. MECHANICAL PROPERTY ANALYSIS OF TFHRC LWC DATABASE

INTRODUCTION

This chapter compares the TFHRC LWC subset databases for modulus of elasticity, splitting tensile strength, and modulus of rupture to prediction expressions. For modulus of elasticity, the subset database is compared to three design expressions. Then the effect of varying the exponents in the expression for E_c in the AASHTO LRFD Specifications is analyzed and four potential expressions are developed. For splitting tensile strength, the subset database is compared to two piecewise continuous expressions and two expressions with abrupt transitions. A piecewise continuous expression for a LWC modification factor is developed and compared to the subset database. For modulus of rupture, a special subset database of moist-cured specimens was compared to the expression for f_r in the AASHTO LRFD Specifications. A new expression for f_r that is applicable to NWC and LWC and includes the LWC modification factor is presented.

The term potential expression in this document refers to a prediction expression that was created for the purposes of evaluating the effect of the variables in the expression and for evaluating the effect of the expression on its ability to predict a measured value in the database. The quality of the prediction is given by its test-to-prediction ratio and the coefficient of variation (COV) describing the distribution of the ratios. A test-to-prediction ratio that is greater than unity indicates that the expression has under-estimated the measured value, while a ratio that is less than unity indicates an over-estimated value. The COV indicates the amount of scatter in the test-to-prediction ratio and a small COV is preferred.

The term proposed expression in the document refers to a prediction expression that is being proposed to AASHTO Subcommittee on Bridges and Structures (SCOBS) T-10 for consideration as a design expression in the AASHTO LRFD Specifications. Proposed expressions will also be included in the chapter of this document titled "Preliminary Recommendations for AASHTO LRFD Specifications".

IMPORTANCE OF THE PREDICTED MODULUS OF ELASTICITY

The accuracy of the predicted modulus of elasticity is very important for many types of concrete structures. In the AASHTO LRFD Specifications (1), the modulus of elasticity is used directly to calculate deflections (Articles 5.7.3.6.2 and 4.5.2.2) and in the estimation of prestress losses. The calculations for prestress losses use E_c in the expression for elastic losses (Article 5.9.5.2.3), and if the refined estimate of losses is used (Article 5.9.5.4), E_c also affects shrinkage, creep, and possibly relaxation. For steel structures, E_c is used to calculate fiber stresses in composite sections (Article 6.10.1.1.1b).

Through the calculation of prestress losses (and as a result the effective prestress, f_{pe}), the accuracy of the expression for E_c affects many significant aspects in the design of prestressed members. Several important aspects include the calculation of concrete fiber stresses, the nominal shear resistance (through β and V_p, Article 5.8.3.3), the average stress in unbonded strands used to calculate the nominal moment capacity (through f_{pe}, Article 5.7.3.1.2), and the development length of prestressing strand (Article 5.11.4.2).

DESIGN EXPRESSIONS FOR MODULUS OF ELASTICITY

A total of 2556 data lines are in the TFHRC subset database for modulus of elasticity. The distribution of data lines for this data is given by Table 11 and Table 13. As discussed previously, the data lines were limited to those with a unit weight less than 0.135 kcf (2160 kg/m^3). In order to compare design expressions for modulus of elasticity to both NWC and LWC data, the E_c database from NCHRP Project 12-64 (17) was utilized. The data in NCHRP Project 12-64 contains lines of compressive strength, modulus of elasticity, and unit weight for both NWC and LWC. The database as published by NCHRP does not include any information about the sources of specific lines of data, or the constituents of the mix design. For this evaluation, the NCHRP 12-64 data was divided into two groups based on the unit weight: the group of data consisting of 629 data lines with a unit weight less than 0.135 kcf (2160 kg/m^3) is termed the "NCHRP LWC data" in this document, and the rest of data for a total of 3795 data lines is termed the "NCHRP NWC data". A unit weight of 0.135 kcf (2160 kg/m^3) was selected to divide the database because it is the lower limit used to define NWC in the AASHTO LRFD Specifications. The 0.135 kcf (2160 kg/m^3) limit was also selected because the LWC data in the TFHRC database uses a unit weight of 0.135 kcf (2160 kg/m^3) as its upper limit.

The modulus of elasticity data was compared to three designs expressions. The design expression for E_c in the AASHTO LRFD Specifications is given by Eq. 7.[(1)] NCHRP Project 12-64 proposed the expression given by Eq. 9 [(17)] and was developed for concrete strengths up to 18 ksi (124 MPa) using over 4400 data points. ACI Committee 363, High-Strength Concrete, gives Eq. 10 [(18)] as a design expression for E_c in its document, "Report on High-Strength Concrete". The ratio of the tested E_c to the E_c predicted by the three design expressions is given in Table 17. The table shows statistical information for the data in the NCHRP 12-64 database as a whole, for the NCHRP LWC data, and for the NCHRP NWC data. A test-to-prediction ratio greater than unity indicates an under-estimation of E_c, while a ratio less than unity indicates an over-estimation of E_c.

Table 17. Test-to-Prediction Ratio of Elastic Modulus for 3795 NWC Data Points and 629 LWC Data Points in the NCHRP 12-64 Database.

Data Source	Statistical Measure	AASHTO LRFD (Eq. 7)	NCHRP 12-64 (Eq. 9)	ACI 363 (Eq. 10)
NCHRP NWC and LWC	mean	0.968	1.039	1.083
	COV	17.5%	16.3%	15.2%
	maximum	1.765	2.455	2.020
	minimum	0.540	0.554	0.618
	Percent ≥ 1.0	37.4%	52.9%	60.2%
	Percent < 1.0	54.0%	38.5%	31.2%
	Percent ≥ 1.2	18.5%	29.7%	42.0%
	Percent < 0.8	34.2%	20.2%	11.3%
NCHRP LWC	mean	0.935	1.182	0.996
	COV	17.4%	17.8%	13.7%
	maximum	1.707	2.455	1.767
	minimum	0.595	0.755	0.618
	Percent ≥ 1.0	32.6%	79.0%	49.1%
	Percent < 1.0	67.4%	21.0%	50.9%
	Percent ≥ 1.2	5.7%	44.0%	5.9%
	Percent < 0.8	21.8%	0.3%	7.5%
NCHRP NWC	mean	0.972	1.007	1.094
	COV	17.3%	14.5%	14.9%
	maximum	1.765	1.778	2.020
	minimum	0.484	0.394	0.453
	Percent ≥ 1.0	41.9%	52.9%	68.5%
	Percent < 1.0	58.1%	47.1%	31.5%
	Percent ≥ 1.2	9.5%	9.1%	24.6%
	Percent < 0.8	17.9%	6.5%	2.0%

NOTE: The E_c data from NCHRP 12-64 was defined as NWC if for $w_c \geq 0.135$ kcf and defined as LWC for $w_c < 135$ kcf.

Table 18 gives a comparison of the three E_c design equations to the LWC data in the TFHRC database. The mean test-to-prediction ratio for the TFHRC LWC data in Table 18 is very close to the mean test-to-prediction ratio for NCHRP LWC data in Table 17 for all three design expressions. Also, the three expressions show the same trends for both the TFHRC LWC data and the NCHRP LWC data in that the AASHTO LRFD expression over-estimates and the NCHRP 12-64 under-estimates the prediction of E_c., and the ACI 363-10 closely predicted E_c.

Table 18. Test-to-Prediction Ratio of Elastic Modulus for 2556 LWC Data Points in the TFHRC Database and 3795 additional NWC Data Points in the NCHRP 12-64 Database.

Data Source	Statistical Measure	AASHTO LRFD (Eq. 7)	NCHRP 12-64 (Eq. 9)	ACI 363 (Eq. 10)
TFHRC LWC and NCHRP NWC	mean	0.957	1.087	1.056
	COV	17.0%	18.8%	15.5%
	maximum	1.765	2.119	2.020
	minimum	0.346	0.386	0.387
	Percent ≥ 1.0	38.2%	65.0%	62.1%
	Percent < 1.0	61.8%	35.0%	37.9%
	Percent ≥ 1.2	7.2%	25.9%	18.0%
	Percent < 0.8	18.2%	4.9%	5.2%
TFHRC LWC	mean	0.936	1.206	1.001
	COV	16.3%	18.3%	14.9%
	maximum	1.643	2.119	1.606
	minimum	0.346	0.386	0.387
	Percent ≥ 1.0	32.6%	82.9%	52.7%
	Percent < 1.0	67.4%	17.1%	47.3%
	Percent ≥ 1.2	3.9%	50.9%	8.4%
	Percent < 0.8	18.6%	2.6%	10.0%

NOTE: The E_c data from NCHRP 12-64 was defined as NWC if for $w_c \geq 0.135$ kcf and defined as LWC for $w_c < 135$ kcf.

The test-to-prediction ratios for the three E_c expressions are represented graphically in Figure 28 through Figure 33. The test-to-prediction ratios using the AASHTO LRFD expression is compared to compressive strength in Figure 28. This figure shows that the E_c for most of the NWC data with compressive strengths greater than 15.0 ksi (103.4 MPa) is over-estimated by the AASHTO LRFD expression. Figure 29 shows the test-to-prediction ratios using the AASHTO LRFD expression compared to unit weight.

Similar graphs for the NCHRP 12-64 expression comparing the test-to-prediction ratios to compressive strength and unit weight are shown in Figure 30 and Figure 31, respectively. Figure 30 shows that a large number of LWC data points with a compressive strength less than 5.0 ksi (34.5 MPa) are under-estimated by more than 50% (ratio > 1.5). Figure 31 shows that most of the LWC data with a unit weight less than 0.110 kcf (1760 kg/m^3) is under-estimated.

Graphs for the ACI 363-10 expression comparing the test-to-prediction ratios to compressive strength and unit weight are shown in Figure 32 and Figure 33. These figures show that E_c is closely predicted for most of the LWC data. This trend is also given in Table 18.

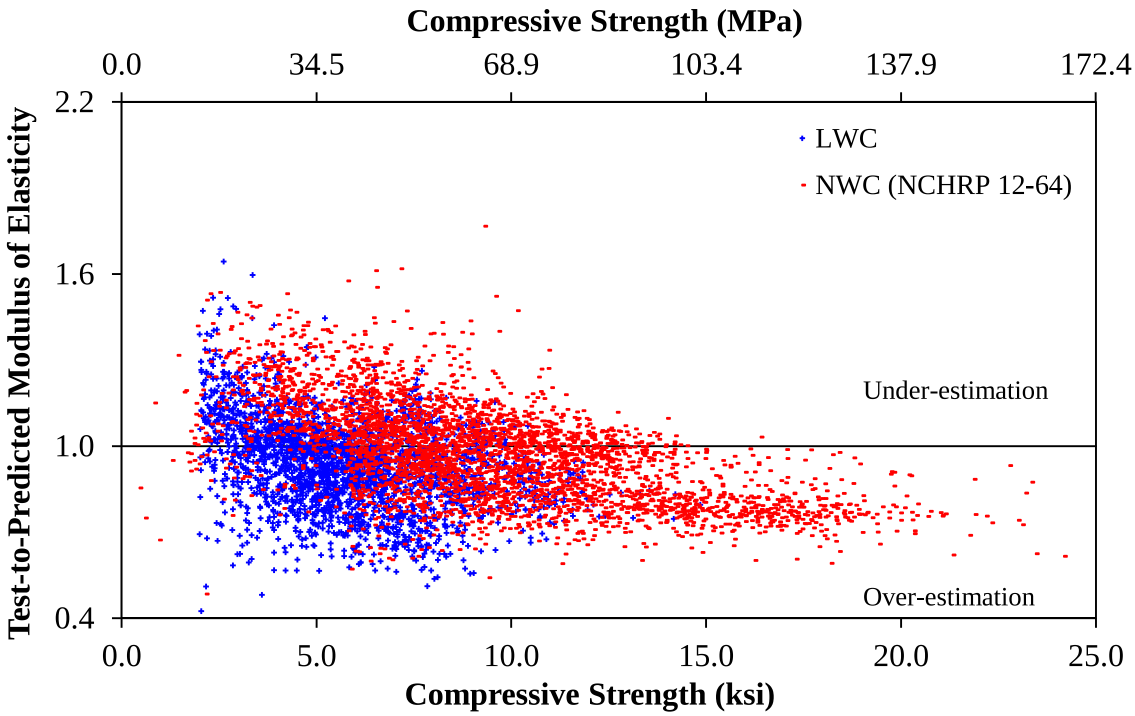


Figure 28. Graph. Modulus of Elasticity Test-to-Prediction Ratio Compared to Compressive Strength for AASHTO LRFD Equation (Eq. 7).

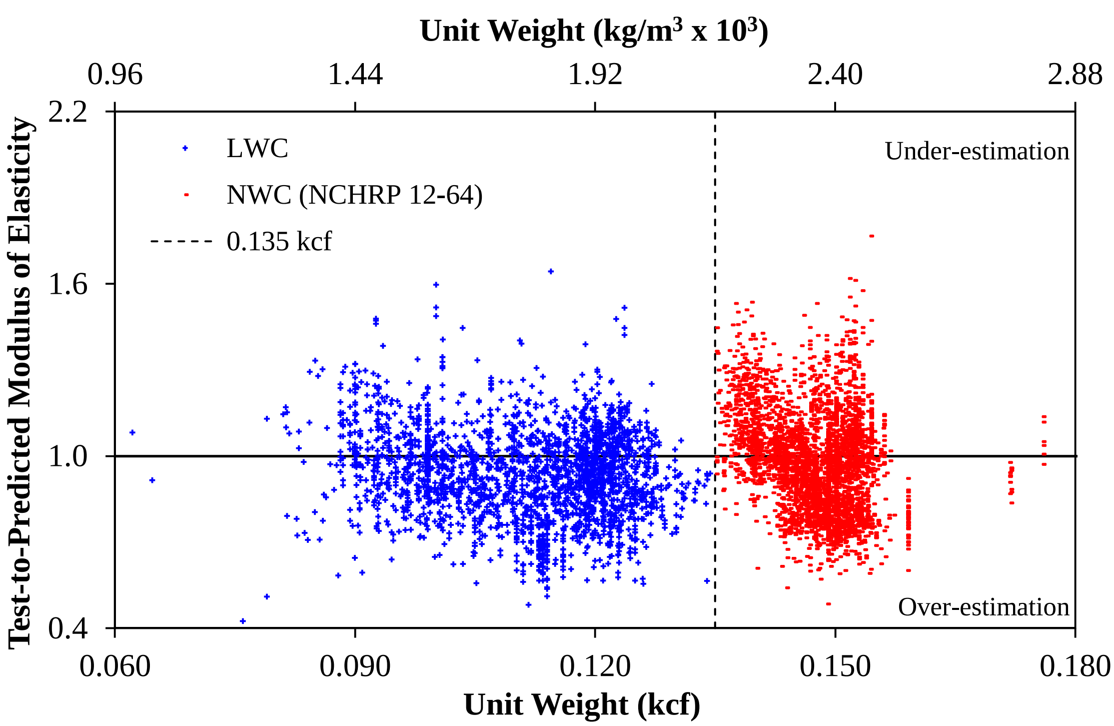


Figure 29. Graph. Modulus of Elasticity Test-to-Prediction Ratio Compared to Unit Weight for AASHTO LRFD Equation (Eq. 7).

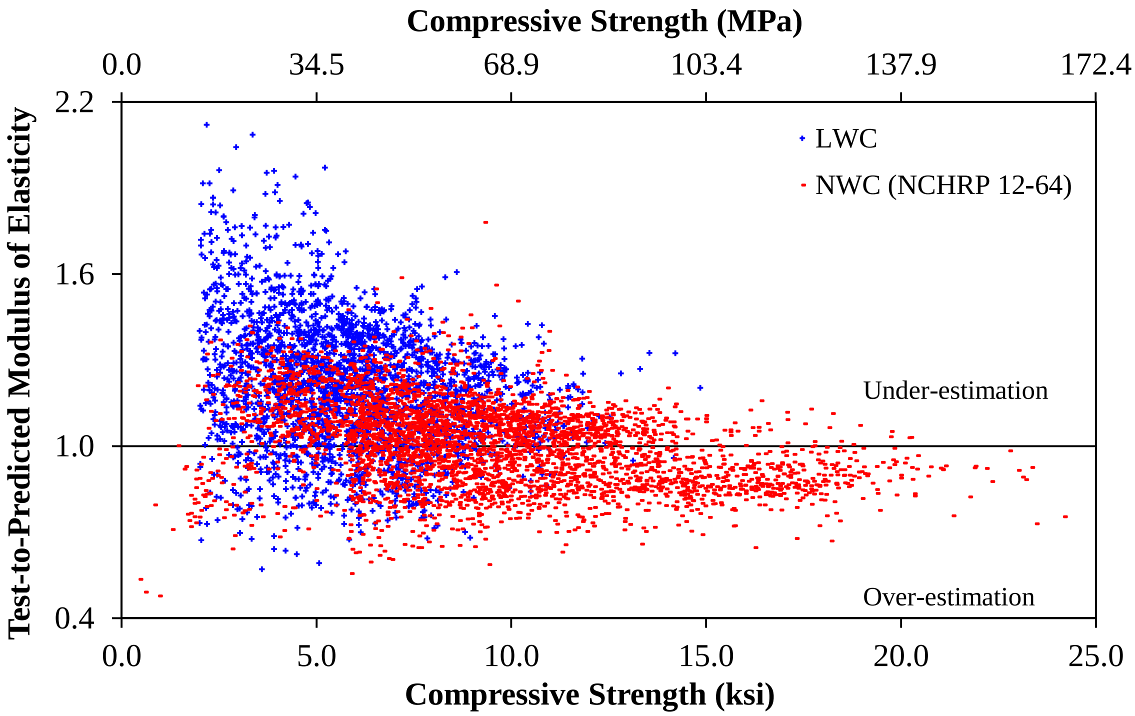


Figure 30. Graph. Modulus of Elasticity Test-to-Prediction Ratio Compared to Compressive Strength for NCHRP Project 12-64 Equation (Eq. 9).

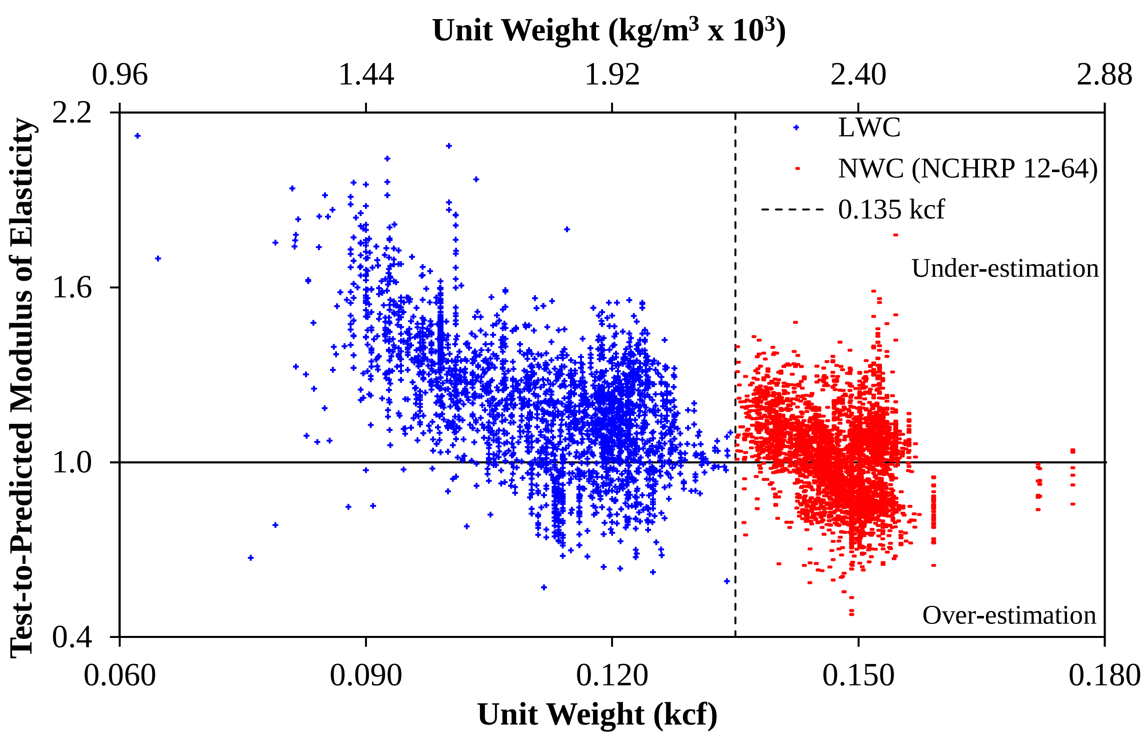


Figure 31. Graph. Modulus of Elasticity Test-to-Prediction Ratio Compared to Unit for NCHRP Project 12-64 Equation (Eq. 9).

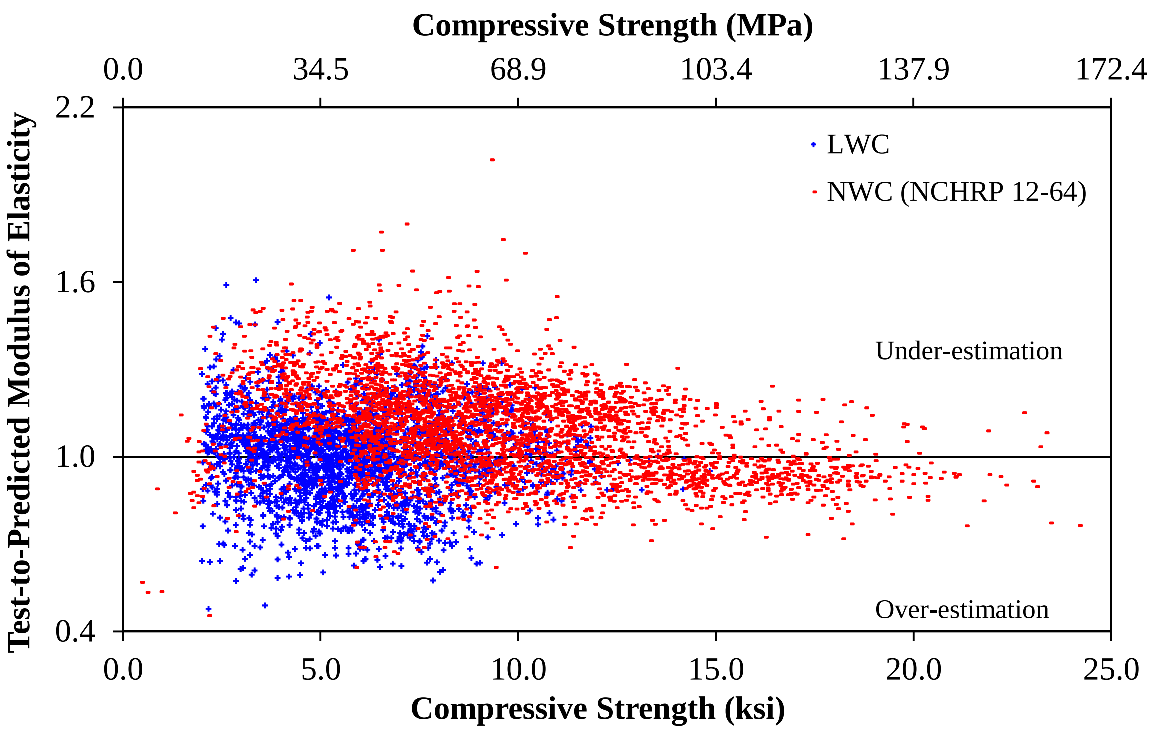


Figure 32. Graph. Modulus of Elasticity Test-to-Prediction Ratio Compared to Compressive Strength for ACI 363-10 Equation (Eq. 10).

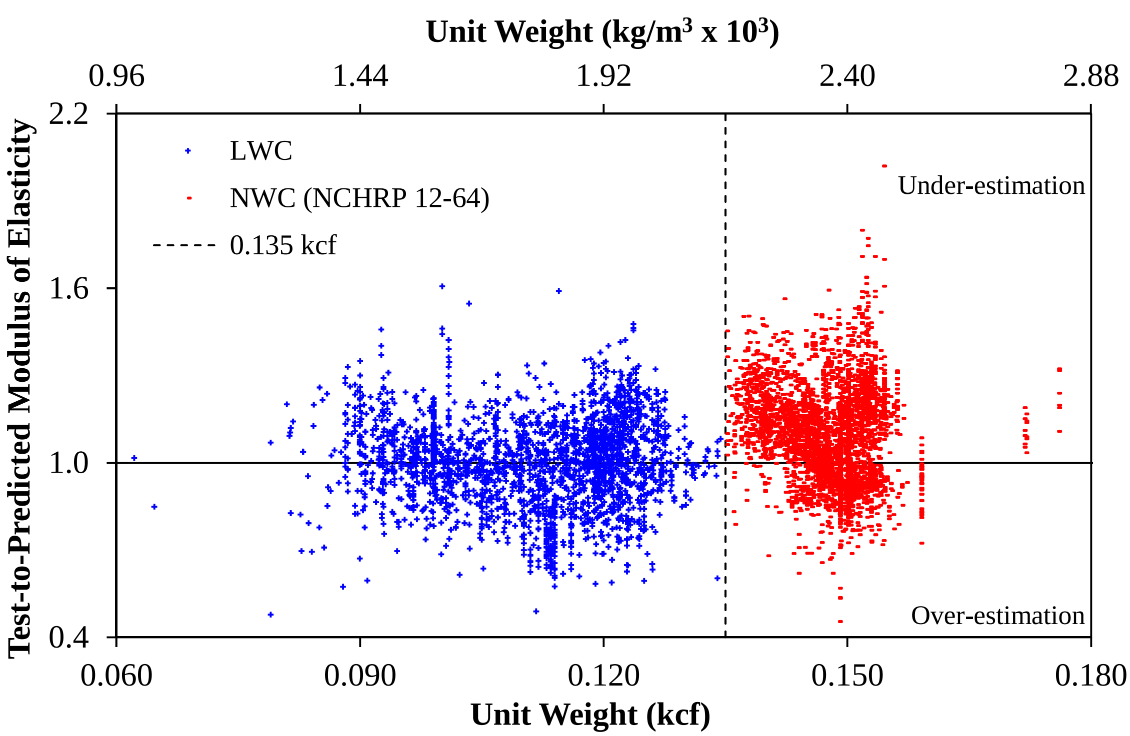


Figure 33. Graph. Modulus of Elasticity Test-to-Prediction Ratio Compared to Unit Weight for ACI 363-10 Equation (Eq. 10).

OPTIMIZATION OF MODULUS OF ELASTICITY EQUATION VARIABLES

An analysis was performed to evaluate the effect of different exponents on the basic form of the expression for E_c given by Eq. 11. The analysis was performed on a database consisting of the TFHRC LWC subset database combined with the NCHRP 12-64 NWC database. The analysis was divided into in three parts. In the first part of the analysis, the exponent applied to the unit weight term was varied (n_1 in Eq. 11). In the second part, the exponent applied to the compressive strength term was varied (n_2 in Eq. 11). The third part of the analysis was to vary the exponents applied to both unit weight and compressive strength, based upon the results of the first two analyses.

$$E_c = C(w_c)^{n_1}(f_c')^{n_2} + B \qquad \text{(Eq. 11)}$$

In all of the analyses, after the exponent was varied, the factor "C" in Eq. 11 was adjusted until the mean test-to-prediction ratio for E_c was equal to 1.000 for the combined LWC and NWC database. In order to have a direct comparison between the AASHTO LRFD expression and the expressions with varying exponents, an "optimized factor" was determined for an expression with the same exponents as the AASHTO LRFD expression. The Optimized Factor AASHTO LRFD expression is given by Eq. 12. A comparison between the actual AASHTO LRFD expression and the Optimized Factor expression is given in Table 19. Changing the factor 33,000 in the existing AASHTO LRFD expression to 31,580 in the optimized expression did not change the distribution of the test-to-prediction ratios as indicated by COV remaining the same, but it did change the mean ratios for the combined LWC and NWC data and the LWC and NWC data individually.

$$E_c = 31{,}580 w_c^{1.5} f_c'^{\,0.50} \qquad \text{(Eq. 12)}$$

A 1000 ksi (6.9 GPa) E_c offset multiplied by normalized unit weight (factor "B" Eq. 11) was added to the expression for E_c to observe the effect of a similar offset used in the ACI 363-10 expression. The factor "C" was adjusted and the resulting expression is given by Eq. 13. The results of this comparison are given in Table 19 and show that the resulting expression over-estimates E_c for LWC and under-estimates E_c for NWC. A similar result was shown for the ACI 363-10 expression for E_c in Table 17 and Table 18.

$$E_c = 24{,}590 w_c^{1.5} f_c'^{\,0.50} + 1000(w_c/0.145)^{1.5} \qquad \text{(Eq. 13)}$$

In the first and second parts of the analysis, the exponent used in the AASHTO LRFD expression was used as a starting point. The exponent was then increased and decreased to observe the effect on the mean test-to-prediction ratios and coefficient of variation (COV). Depending upon whether an increase or decrease in the exponent caused a reduction in the COV, the exponent was then increased or decreased one more step to determine whether there would be another decrease in COV.

Table 19. Test-to-Prediction Ratios for Modulus of Elasticity Expressions Showing Effect of Optimized Factor and E_c Offset.

Data Source[1]	Statistical Measure	AASHTO LRFD (Eq. 7)	Optimize Factor (Eq. 12)	E_c Offset (Eq. 13)
LWC and NWC	mean	0.957	1.000	1.000
	COV	17.0%	17.0%	15.5%
	COV change[2]	--	0.0%	-1.5%
	maximum	1.765	1.844	1.908
	minimum	0.346	0.361	0.366
	Percent ≥ 1.0	38.2%	49.6%	49.2%
	Percent < 1.0	61.8%	50.4%	50.8%
	Percent ≥ 1.2	7.2%	11.5%	9.4%
	Percent < 0.8	18.2%	11.6%	8.7%
LWC	mean	0.936	0.977	0.949
	COV	16.3%	16.3%	14.9%
	COV change[2]	--	0.0%	-1.4%
	maximum	1.643	1.716	1.528
	minimum	0.346	0.361	0.366
	Percent ≥ 1.0	32.6%	45.1%	36.6%
	Percent < 1.0	67.4%	54.9%	63.4%
	Percent ≥ 1.2	3.9%	7.3%	3.0%
	Percent < 0.8	18.6%	13.8%	15.2%
NWC	mean	0.972	1.015	1.034
	COV	17.3%	17.3%	15.0%
	COV change[2]	--	0.0%	-2.3%
	maximum	1.765	1.844	1.908
	minimum	0.484	0.505	0.433
	Percent ≥ 1.0	41.9%	52.6%	57.7%
	Percent < 1.0	58.1%	47.4%	42.3%
	Percent ≥ 1.2	9.5%	14.3%	13.8%
	Percent < 0.8	17.9%	10.1%	4.3%

Notes: (1) LWC refers to 2556 data points in the TFHRC database, NWC refers to 3795 data points in the NHCRP 12-64 database with $w_c \geq 0.135$ kcf; (2) Difference between the COV of the Optimized Factor and E_c Offset expressions and the COV of the AASHTO LRFD expression

Table 20 shows the result of varying the exponent applied to unit weight. An exponent of 1.5 is used in the AASHTO LRFD expression. The exponent was decreased to 0.5 and increased to 2.0. Table 20 shows that the decrease in exponent caused a considerable increase in COV, while an increase in exponent caused a slight increase in COV. The increase in exponent to 2.0 also caused the mean test-to-prediction ratio to be greater than unity for LWC indicating a slight under-estimation. The exponent was increased again to 2.5 to match the exponent of the NCHRP 12-64 expression. The result was a large increase in COV when compared to the optimized equation (Eq. 12). The three new expressions evaluated in this part of the analysis are given by Eq. 14, Eq. 15, and Eq. 16.

$$E_c = 4{,}200 w_c^{0.5} f_c'^{\,0.50} \quad \text{(Eq. 14)}$$

$$E_c = 87{,}400 w_c^{2.0} f_c'^{\,0.50} \quad \text{(Eq. 15)}$$

$$E_c = 243{,}700 w_c^{2.5} f_c'^{\,0.50} \quad \text{(Eq. 16)}$$

The result of varying the exponent applied to compressive strength is given in Table 21. An exponent of 0.5 is used in the AASHTO LRFD expression. A decrease in exponent to 0.33 caused a slight reduction in COV while an increase in the exponent to 0.75 caused a considerable increase in COV. The exponent was reduced again to 0.25 and resulted in slight increase in COV when compared with the COV using an exponent of 0.33. The reduction in exponent caused a reduction in the mean test-to-prediction ratio for LWC indicating an over-estimation of E_c. The three new expressions evaluated in this part of the analysis are given by Eq. 17, Eq. 18, and Eq. 19.

$$E_c = 51{,}600 w_c^{1.5} f_c'^{\,0.25} \quad \text{(Eq. 17)}$$

$$E_c = 44{,}040 w_c^{1.5} f_c'^{\,0.33} \quad \text{(Eq. 18)}$$

$$E_c = 19{,}620 w_c^{1.5} f_c'^{\,0.75} \quad \text{(Eq. 19)}$$

Table 20. Test-to-Prediction Ratios for Modulus of Elasticity Expressions Showing Effect of Varying the Exponent on Unit Weight.

Data Source[(1)]	Statistical Measure	Decrease w_c Exponent ($w_c^{0.5}$) (Eq. 14)	Optimize Factor ($w_c^{1.5}$) (Eq. 12)	Increase w_c Exponent ($w_c^{2.0}$) (Eq. 15)	Increase w_c Exponent ($w_c^{2.5}$) (Eq. 16)
LWC and NWC	mean	1.000	1.000	1.000	1.000
	COV	23.0%	17.0%	18.8%	24.1%
	COV change[(2)]	6.0%	0.0%	1.8%	7.1%
	maximum	2.141	1.844	1.903	2.356
	minimum	0.254	0.361	0.357	0.349
	Percent ≥ 1.0	46.8%	49.5%	48.0%	43.8%
	Percent < 1.0	53.2%	50.5%	52.0%	56.2%
	Percent ≥ 1.2	19.6%	11.4%	14.1%	18.7%
	Percent < 0.8	20.4%	11.7%	16.2%	21.0%
LWC	mean	0.814	0.977	1.066	1.157
	COV	17.8%	16.3%	18.2%	21.6%
	COV change[(2)]	1.5%	0.0%	1.9%	5.3%
	maximum	1.478	1.715	1.903	2.356
	minimum	0.254	0.361	0.357	0.349
	Percent ≥ 1.0	11.0%	45.0%	62.7%	73.1%
	Percent < 1.0	89.0%	55.0%	37.3%	26.9%
	Percent ≥ 1.2	0.6%	7.3%	21.5%	38.9%
	Percent < 0.8	48.3%	13.8%	8.2%	4.9%
NWC	mean	1.125	1.015	0.956	0.894
	COV	16.7%	17.3%	17.8%	18.6%
	COV change[(2)]	-0.6%	0.0%	0.6%	1.3%
	maximum	2.141	1.844	1.696	1.548
	minimum	0.566	0.505	0.473	0.440
	Percent ≥ 1.0	71.0%	52.6%	38.1%	24.1%
	Percent < 1.0	29.0%	47.4%	61.9%	75.9%
	Percent ≥ 1.2	32.4%	14.2%	9.1%	5.1%
	Percent < 0.8	1.5%	10.2%	21.6%	31.9%

Notes: (1) LWC refers to 2556 data points in the TFHRC database, NWC refers to 3795 data points in the NHCRP 12-64 database with $w_c \geq 0.135$ kcf; (2) Difference between the COV of the expression being evaluated and the COV of the AASHTO LRFD expression

Table 21. Test-to-Prediction Ratios for Modulus of Elasticity Expressions Showing Effect of Varying the Exponent on Compressive Strength.

Data Source[1]	Statistical Measure	Decrease f'_c Exponent ($f'_c{}^{0.25}$) (Eq. 17)	Decrease f'_c Exponent ($f'_c{}^{0.33}$) (Eq. 18)	Optimize Factor ($f'_c{}^{0.50}$) (Eq. 12)	Increase f'_c Exponent ($f'_c{}^{0.75}$) (Eq. 19)
LWC and NWC	mean	1.000	1.000	1.000	1.000
	COV	16.0%	15.3%	17.0%	25.1%
	COV change[2]	-1.0%	-1.7%	0.0%	8.1%
	maximum	1.972	1.933	1.844	2.173
	minimum	0.325	0.360	0.361	0.352
	Percent ≥ 1.0	48.8%	47.7%	49.5%	44.2%
	Percent < 1.0	51.2%	52.3%	50.5%	55.8%
	Percent ≥ 1.2	10.6%	9.1%	11.4%	19.1%
	Percent < 0.8	10.3%	9.1%	11.7%	22.1%
LWC	mean	0.912	0.933	0.977	1.043
	COV	15.3%	14.9%	16.3%	22.8%
	COV change[2]	-1.0%	-1.4%	0.0%	6.5%
	maximum	1.397	1.469	1.715	2.173
	minimum	0.325	0.360	0.361	0.352
	Percent ≥ 1.0	24.6%	30.8%	45.0%	52.7%
	Percent < 1.0	75.4%	69.2%	55.0%	47.3%
	Percent ≥ 1.2	2.1%	2.2%	7.3%	21.7%
	Percent < 0.8	20.5%	17.5%	13.8%	14.1%
NWC	mean	1.060	1.045	1.015	0.971
	COV	13.6%	14.0%	17.3%	26.3%
	COV change[2]	-3.6%	-3.3%	0.0%	9.1%
	maximum	1.972	1.933	1.844	2.099
	minimum	0.375	0.413	0.505	0.466
	Percent ≥ 1.0	65.1%	59.1%	52.6%	38.5%
	Percent < 1.0	34.9%	40.9%	47.4%	61.5%
	Percent ≥ 1.2	16.3%	13.7%	14.2%	17.3%
	Percent < 0.8	3.4%	3.3%	10.2%	27.5%

Notes: (1) LWC refers to 2556 data points in the TFHRC database, NWC refers to 3795 data points in the NHCRP 12-64 database with $w_c \geq 0.135$ kcf; (2) Difference between the COV of the expression being evaluated and the COV of the AASHTO LRFD expression

The first analysis showed that an exponent of 1.5 or 2.0 applied to unit weight resulted in the lowest COV and a test-to-prediction ratio near unity for the LWC data. The second analysis showed that the exponent applied to compressive strength should be 0.33 or 0.5 for a low COV without considerable over-estimation of E_c for LWC data. Table 22 shows a comparison of the test-to-prediction ratios for four E_c expressions with the unit weight exponent of either 1.5 or 2.0 and a compressive strength exponent of either 0.33 or 0.50. Potential Expressions 1, 2, and 3 in Table 22 were previously evaluated in Table 19, Table 20, and Table 21. Potential Expression 1 has the same exponents as the expression in AASHTO LRFD and was previously referred to as the Optimized Factor expression. The test-to-prediction ratios are represented graphically in Figure 34 through Figure 39 for Potential Expressions 1 through 3. In Figure 34 and Figure 35 the test-to-prediction ratios for Potential Expression 1 are compared to compressive strength and unit weight, respectively. The test-to-prediction ratios for Potential Expression 2 are shown in Figure 36 and Figure 37. Figure 38 and Figure 39 shows the test-to-prediction ratios for Potential Expression 3.

A new expression, Potential Expression 4, has an exponent of 2.0 for unit weight and 0.33 for compressive strength and is given by Eq. 20. A comparison of the results given by the four potential expressions is given in Table 22. The results of the analysis on test-to-prediction ratios for E_c show that Potential Expression 4 has the lowest COV of the four potential expressions. The mean test-to-prediction ratios for Potential Expression 4 is 1.02 for the LWC data indicating that the expression slightly under-estimates the prediction of E_c, while the mean for the NWC data is 0.99. The test-to-prediction ratios for Potential Expression 4 are compared to compressive strength and unit weight in Figure 40 and Figure 41, respectively.

$$E_c = 121{,}400 w_c^{2.0} f_c'^{\,0.33} \quad \text{(Eq. 20)}$$

Table 22. Test-to-Prediction Ratios for Modulus of Elasticity Expressions Showing Effect of Varying the Exponent on Unit Weight and Compressive Strength.

Data Source[1]	Statistical Measure	Potential Expression 1 ($w_c^{1.5}\ f'_c{}^{0.50}$) (Eq. 12)	Potential Expression 2 ($w_c^{2.0}\ f'_c{}^{0.50}$) (Eq. 15)	Potential Expression 3 ($w_c^{1.5}\ f'_c{}^{0.33}$) (Eq. 18)	Potential Expression 4 ($w_c^{2.0}\ f'_c{}^{0.33}$) (Eq. 20)
LWC and NWC	mean	1.000	1.000	1.000	1.000
	COV	17.0%	18.8%	15.3%	14.8%
	COV change[2]	0.0%	1.8%	-1.7%	-2.2%
	maximum	1.844	1.903	1.933	1.784
	minimum	0.361	0.357	0.360	0.362
	Percent ≥ 1.0	49.5%	48.0%	47.7%	51.8%
	Percent < 1.0	50.5%	52.0%	52.3%	48.2%
	Percent ≥ 1.2	11.4%	14.1%	9.1%	7.9%
	Percent < 0.8	11.7%	16.2%	9.1%	8.6%
LWC	mean	0.977	1.066	0.933	1.019
	COV	16.3%	18.2%	14.9%	15.6%
	COV change[2]	0.0%	1.9%	-1.4%	-0.7%
	maximum	1.715	1.903	1.469	1.684
	minimum	0.361	0.357	0.360	0.362
	Percent ≥ 1.0	45.0%	62.7%	30.8%	57.7%
	Percent < 1.0	55.0%	37.3%	69.2%	42.3%
	Percent ≥ 1.2	7.3%	21.5%	2.2%	11.0%
	Percent < 0.8	13.8%	8.2%	17.5%	9.4%
NWC	mean	1.015	0.956	1.045	0.987
	COV	17.3%	17.8%	14.0%	14.1%
	COV change[2]	0.0%	0.6%	-3.3%	-3.2%
	maximum	1.844	1.696	1.933	1.784
	minimum	0.505	0.473	0.413	0.388
	Percent ≥ 1.0	52.6%	38.1%	59.1%	47.9%
	Percent < 1.0	47.4%	61.9%	40.9%	52.1%
	Percent ≥ 1.2	14.2%	9.1%	13.7%	5.8%
	Percent < 0.8	10.2%	21.6%	3.3%	8.0%

Notes: (1) LWC refers to 2556 data points in the TFHRC database, NWC refers to 3795 data points in the NHCRP 12-64 database with $w_c \geq 0.135$ kcf; (2) Difference between the COV of the expression being evaluated and the COV of the AASHTO LRFD expression

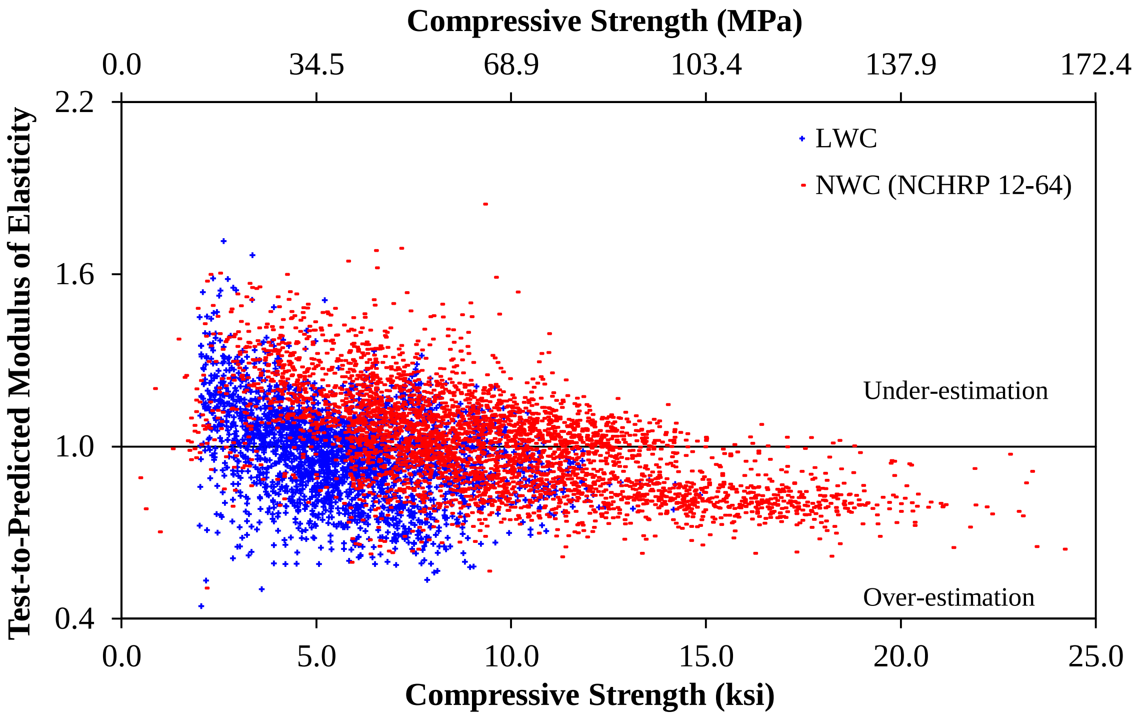


Figure 34. Graph. Modulus of Elasticity Test-to-Prediction Ratio Compared to Compressive Strength for Potential Expression 1 (Eq. 12).

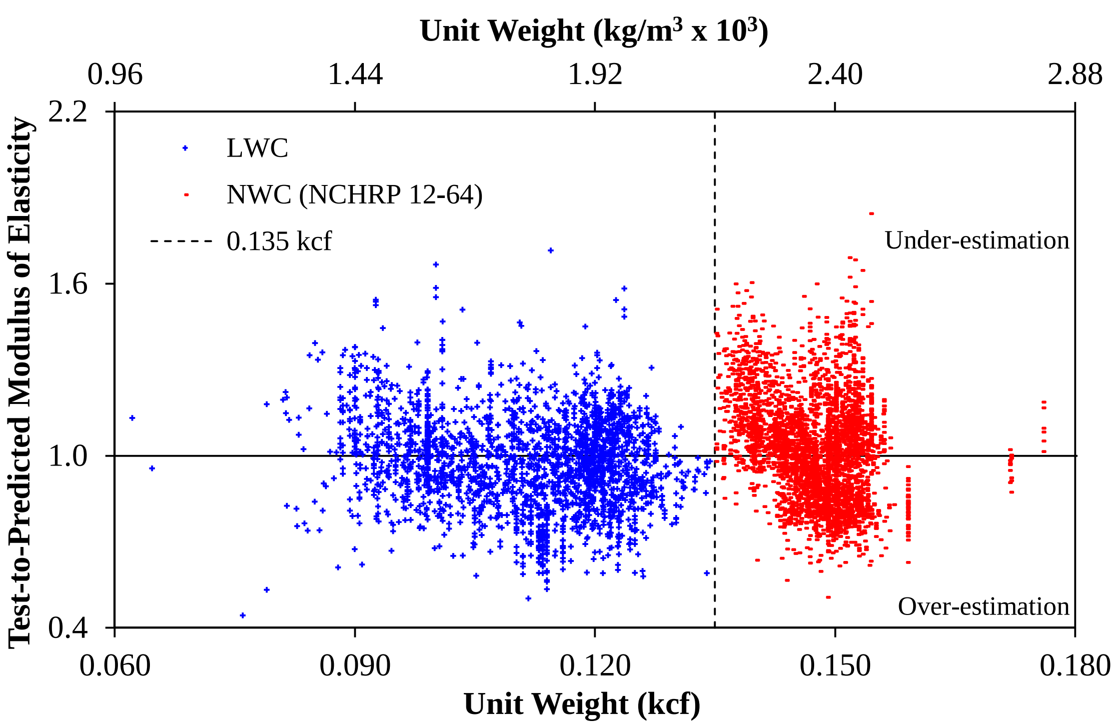


Figure 35. Graph. Modulus of Elasticity Test-to-Prediction Ratio Compared to Unit Weight for Potential Expression 1 (Eq. 12).

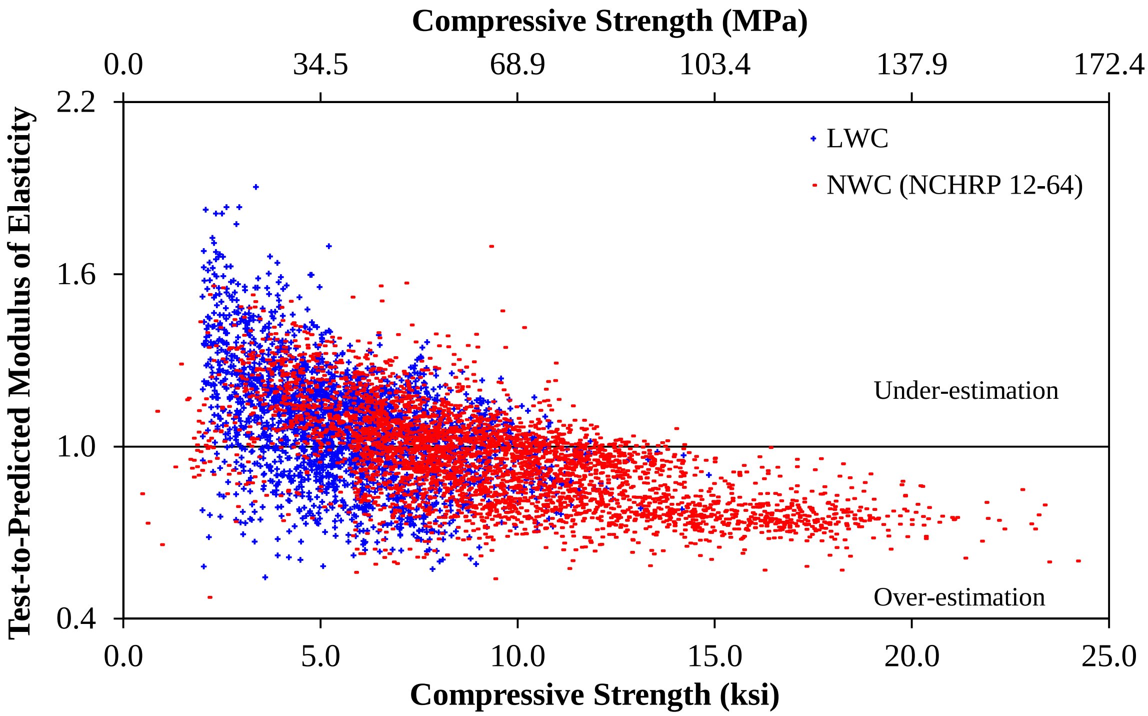


Figure 36. Graph. Modulus of Elasticity Test-to-Prediction Ratio Compared to Compressive Strength for Potential Expression 2 (Eq. 15).

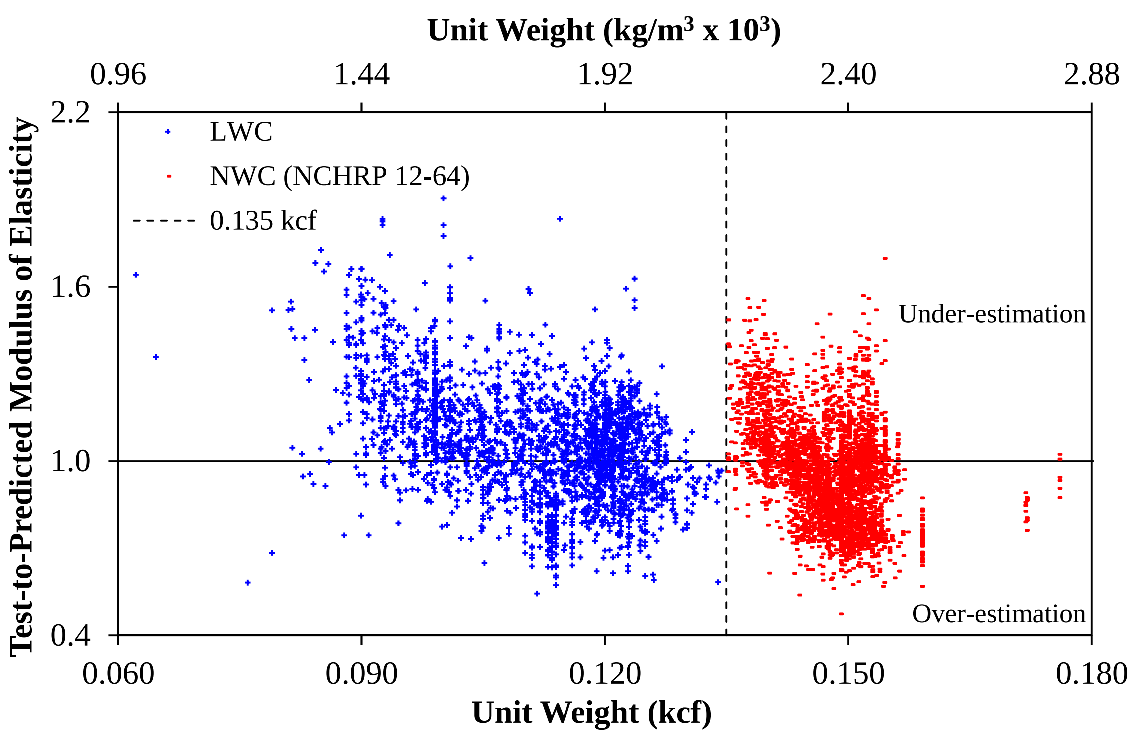


Figure 37. Graph. Modulus of Elasticity Test-to-Prediction Ratio Compared to Unit Weight for Potential Expression 2 (Eq. 15).

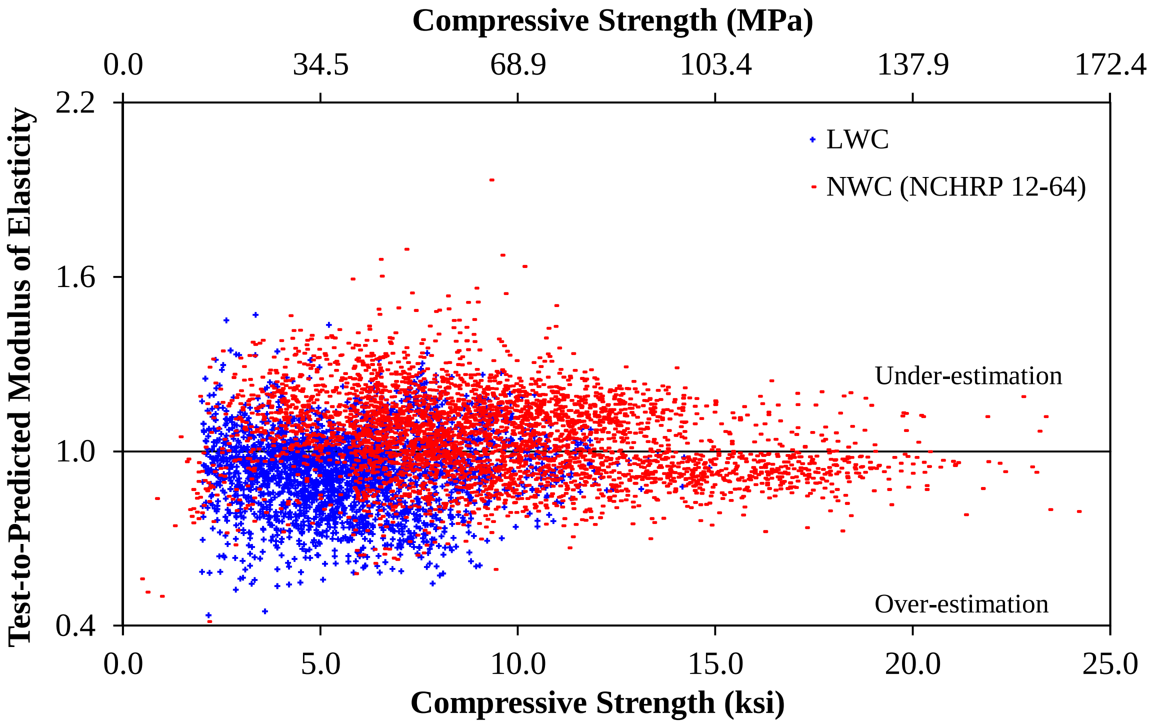


Figure 38. Graph. Modulus of Elasticity Test-to-Prediction Ratio Compared to Compressive Strength for Potential Expression 3 (Eq. 18).

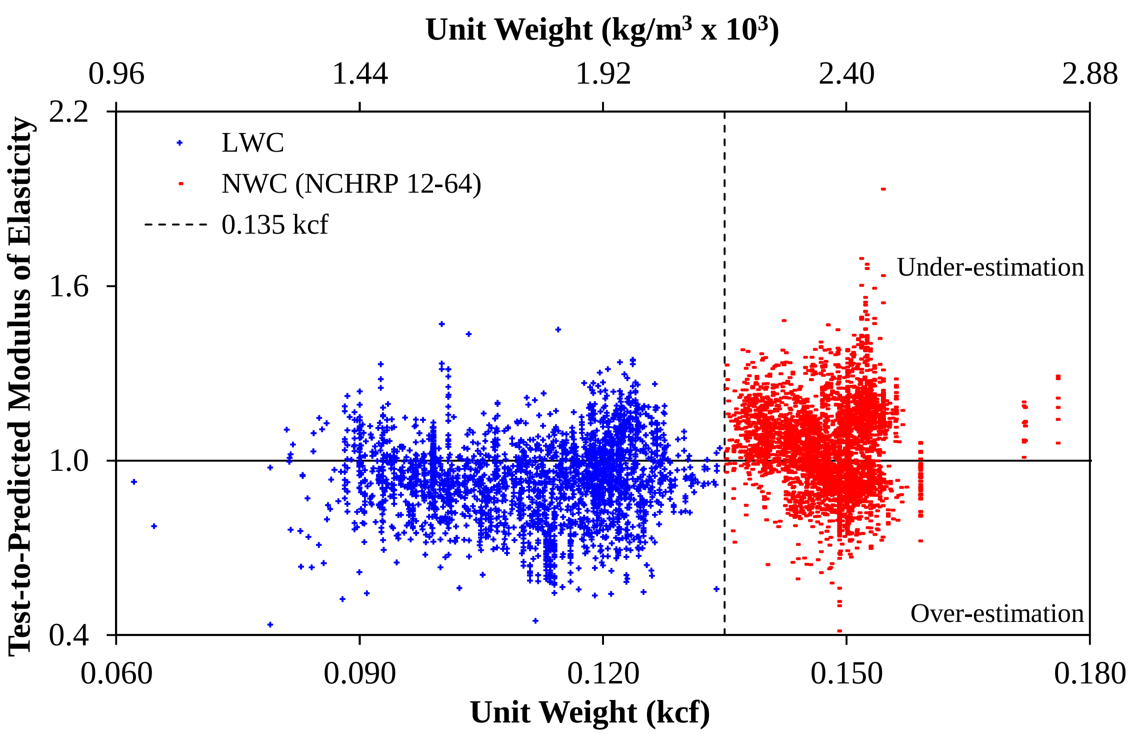


Figure 39. Graph. Modulus of Elasticity Test-to-Prediction Ratio Compared to Unit Weight for Potential Expression 3 (Eq. 18).

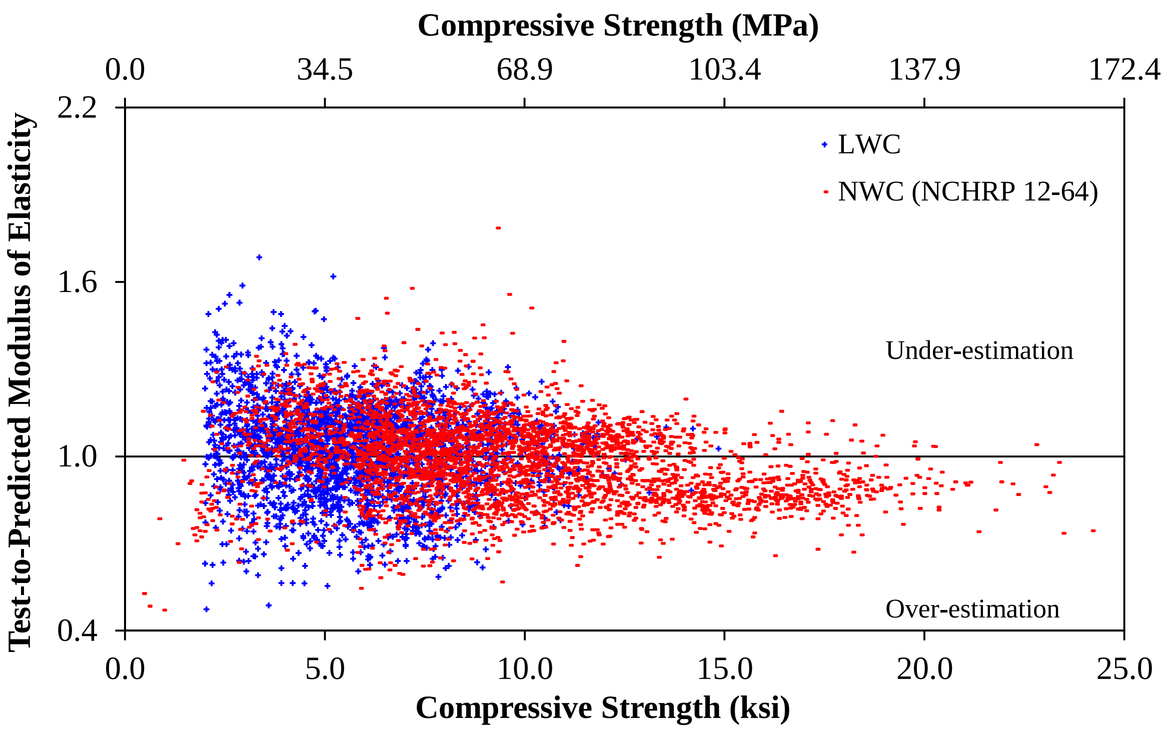


Figure 40. Graph. Modulus of Elasticity Test-to-Prediction Ratio Compared to Compressive Strength for Potential Expression 4 (Eq. 20).

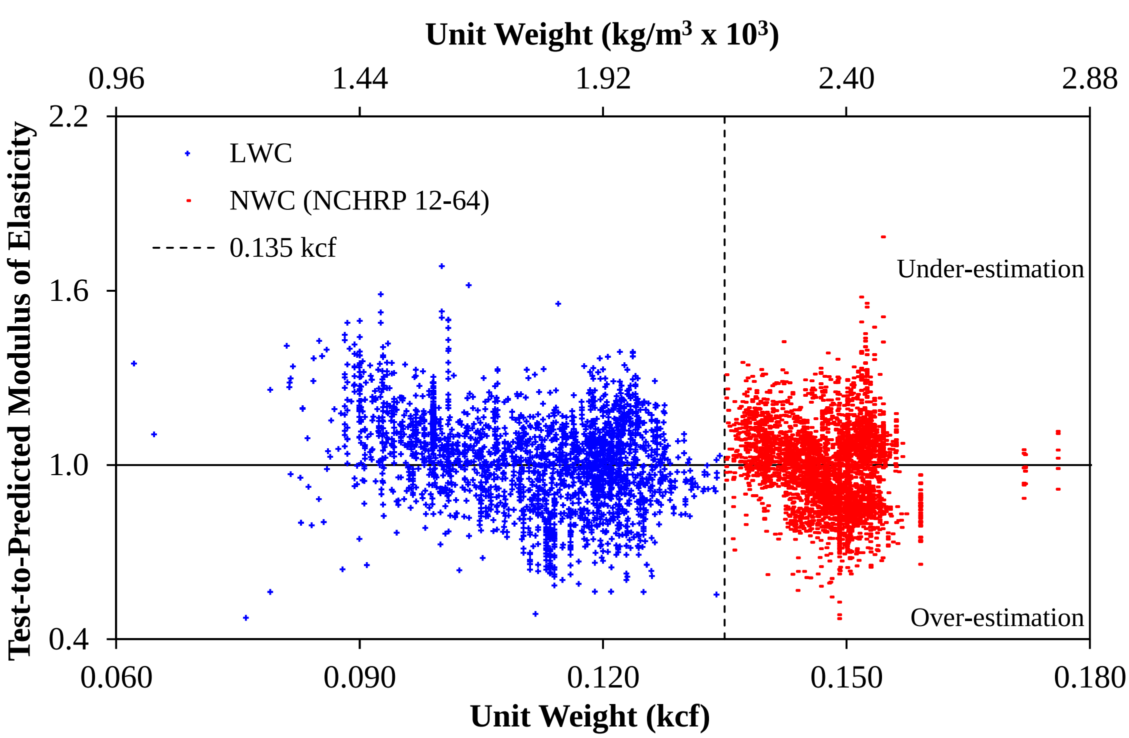


Figure 41. Graph. Modulus of Elasticity Test-to-Prediction Ratio Compared to Unit Weight for Potential Expression 4 (Eq. 20).

LIGHTWEIGHT CONCRETE MODIFICATION FACTOR

The AASHTO LRFD Specifications (1) account for the reduced tensile strength of LWC in a variety of ways. Article 5.8.2.2 gives a modification for LWC that is applicable to the articles of the specifications involving sectional analysis of nominal shear resistance. In this article, a 0.75 factor is used for all-lightweight concrete and a 0.85 factor is used for sand-lightweight concrete. The article allows interpolation between the two factors for partial sand replacement. Article 5.11.2.1.2 describing the development length of mild reinforcement in tension also includes modification factors all-lightweight concrete and sand-lightweight concrete and allows for interpolation to be used with partial sand replacement. Unfortunately, the amount of sand replacement may is rarely known during the design phase of a project. Also, a definition based on the proportions of constituent materials becomes more cumbersome if partial replacement of normal weight coarse aggregate with lightweight coarse aggregate is also considered.

A lightweight concrete modification factor based on a specified mix property, such as concrete density, would be easier for a designer to use. This section describes the development of a LWC modification factor based on unit weight, a mix property typically specified for LWC. This approach was originally proposed by Meyer (19). The subset database for splitting tensile strength is described in terms of the splitting ratio and two expressions are given for predicting the splitting ratio. The expressions for splitting ratio are then converted to expressions for LWC modification factors and a simplified expression for design is given.

PREDICTION OF THE SPLITTING RATIO IN AASHTO LRFD

The ratio of the splitting tensile strength to the square root of the compressive strength is known as the splitting ratio. Early reference to the splitting ratio in the literature was made by Hanson (3) and ACI Committee 318 (20). The term splitting ratio is no longer used in the AASHTO LRFD Specifications but the definition is still part of the modification factor for LWC in Article 5.8.2.2 and Article 5.11.2.1.2 where splitting tensile strength is related to compressive strength. The modification factor for shear in Article 5.8.2.2 can be rearranged in terms of the splitting ratio, F_{sp}, as shown in Eq. 2. Concrete with a splitting ratio greater than 0.212 does not require modification of the expressions in Articles 5.8.2 and 5.8.3 for LWC.

The splitting ratios implied by the AASHTO LRFD Specifications for sand-lightweight concrete and all-lightweight concrete are given by Eq. 22 and are based on the 0.85 and 0.75 modification factors described in Article 5.8.2.2.

$$\text{Splitting Ratio for Sand-Lightweight: } 0.85\frac{f_{ct}}{\sqrt{f_c'}} = 0.85 \times 0.212 = 0.180 \qquad \text{(Eq. 22a)}$$

$$\text{Splitting Ratio for All-Lightweight: } 0.75\frac{f_{ct}}{\sqrt{f_c'}} = 0.75 \times 0.212 = 0.159 \qquad \text{(Eq. 22b)}$$

The splitting tensile strength subset of the TFHRC LWC database was used to evaluate the expression for the splitting ratio implied by the AASHTO LRFD Specifications. The database has a total of 1332 data lines and includes 954 lines of sand-lightweight concrete and 311 lines of all-lightweight concrete. The splitting tensile strength of sand-lightweight data is shown in Figure 42 and Figure 43 and compared to compressive strength and unit weight, respectively. Figure 44 and Figure 45 show the splitting tensile strength of the all-lightweight concrete data compared to compressive strength and unit weight. The expression for predicting splitting tensile strength implied by AASHTO LRFD is shown in Figure 42 for sand-lightweight concrete and in Figure 44 for all-lightweight concrete. The test-to-prediction ratios for the AASHTO LRFD expression for F_{sp} are given in Table 23 for sand-lightweight concrete and in Table 24 for all-lightweight concrete.

In Figure 45, some of the data points are arranged along a vertical line near a unit weight of 0.100 kcf (1600 kg/m^3). The reason for the linear arrangement is that these points are from the same study and the unit weight was based on the fresh concrete unit weight, while the compressive strength and splitting tensile strengths were tested at a range of ages. The vertical arrangement of this group of data points can also be observed in several other figures.

The test-to-prediction ratios in Table 23 and Table 24 are given for the data as a whole and for groups of data in ranges of unit weight. The mean ratio of the AASHTO LRFD expression for the sand-lightweight concrete data is near or less than unity for unit weights less than 0.110 kcf (1760 kg/m^3). The mean ratio for the all-lightweight concrete data is about 10% greater than unity for unit weights above 0.090 kcf (1440 kg/m^3). A test-to-prediction ratio greater than unity is an under-estimation of the splitting ratio and indicates a conservative prediction of concrete tensile strength when used for calculating nominal shear resistance or development length of mild reinforcement.

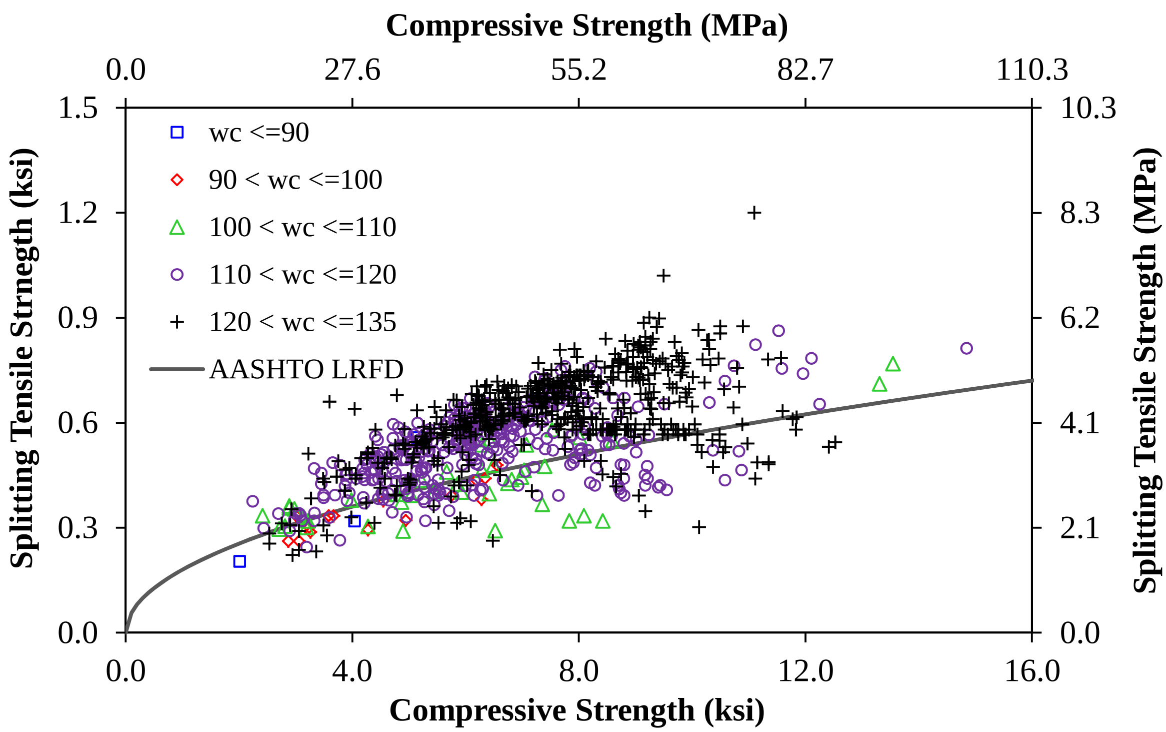


Figure 42. Graph. Splitting Tensile Strength Compared to Compressive Strength for Sand-Lightweight Concrete Showing Variation by Unit Weight.

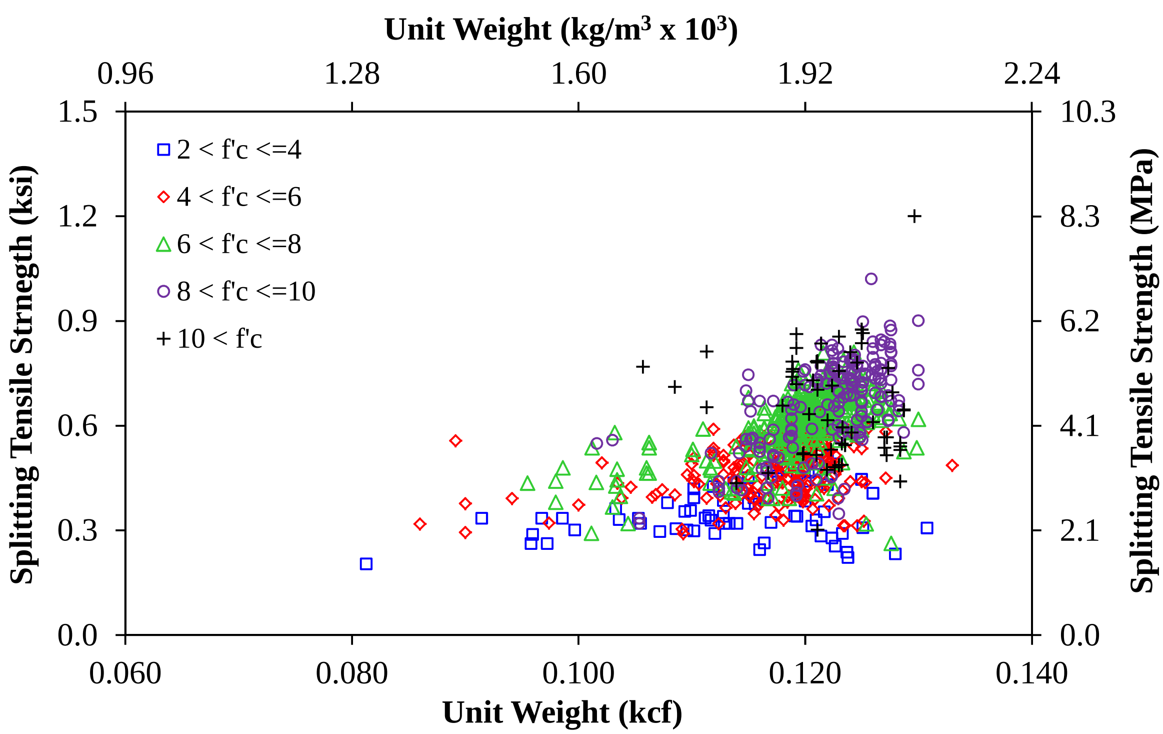


Figure 43. Graph. Splitting Tensile Strength Compared to Unit Weight for Sand-Lightweight Concrete Showing Variation by Compressive Strength.

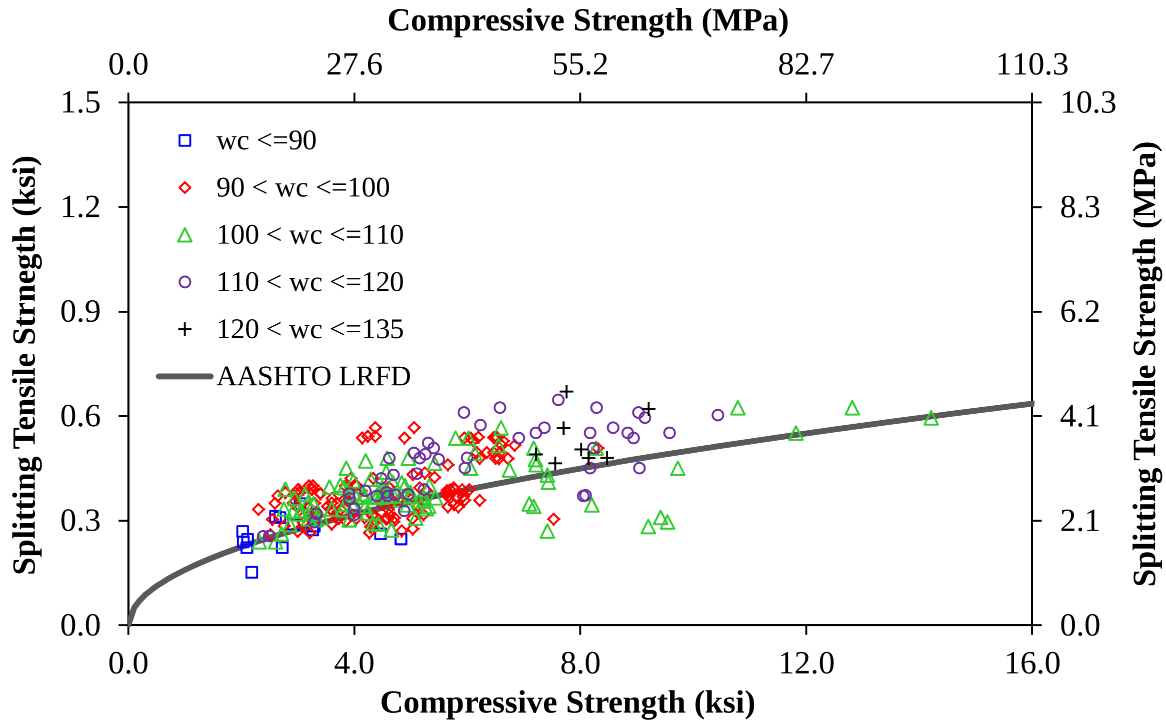


Figure 44. Graph. Splitting Tensile Strength Compared to Compressive Strength for All-Lightweight Concrete Showing Variation by Unit Weight.

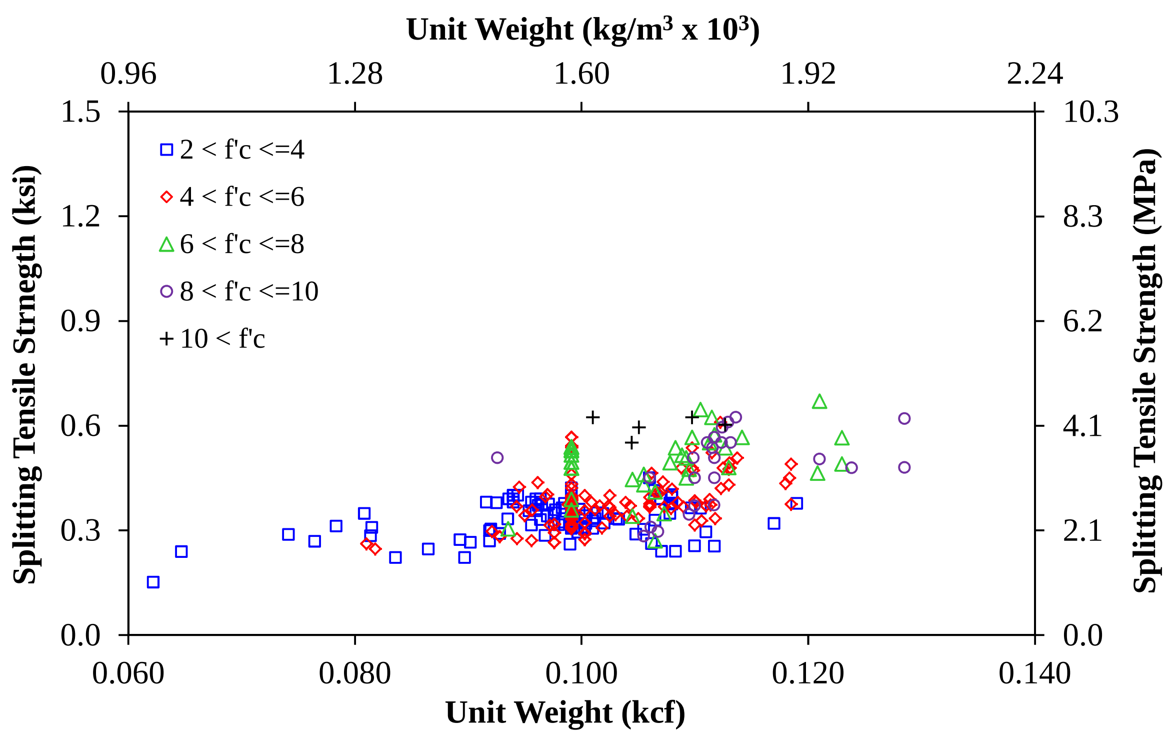


Figure 45. Graph. Splitting Tensile Strength Compared to Unit Weight for All-Lightweight Concrete Showing Variation by Compressive Strength.

Table 23. Test-to-Prediction Ratios of the Splitting Ratio for Sand-Lightweight Concrete using the AASHTO LRFD Expression (Eq. 22) and Potential Expressions 1 and 2 (Eq. 26 and Eq. 27).

F_{sp} Expression	Statistical Measure	Total	$w_c \leq 0.090$ kcf	$0.090 < w_c \leq 0.100$ kcf	$0.100 < w_c \leq 0.110$ kcf	$0.110 < w_c \leq 0.120$ kcf	$0.120 < w_c \leq 0.135$ kcf
AASHTO LRFD	No. Data Points	954	3	15	44	366	526
	Mean	1.222	1.011	0.920	0.992	1.181	1.279
	COV	17.2%	30.7%	8.5%	16.7%	18.4%	20.4%
	Maximum	2.000	1.363	1.069	1.295	1.519	2.000
	Minimum	0.526	0.794	0.788	0.610	0.732	0.526
	Percent ≥ 1.0	83.8%	33.3%	13.3%	52.3%	82.0%	89.9%
	Percent < 1.0	16.2%	66.7%	86.7%	47.7%	18.0%	10.1%
	Percent ≥ 1.2	59.9%	33.3%	0.0%	6.8%	53.6%	70.5%
	Percent < 0.8	3.8%	33.3%	6.7%	13.6%	3.8%	2.7%
Potential 1	No. Data Points	954	3	15	44	366	526
	Mean	1.135	1.146	1.000	1.010	1.115	1.162
	COV	16.1%	34.8%	9.2%	17.0%	16.9%	18.7%
	Maximum	1.788	1.544	1.139	1.348	1.422	1.788
	Minimum	0.485	0.900	0.860	0.621	0.682	0.485
	Percent ≥ 1.0	76.2%	33.3%	46.7%	56.8%	74.9%	79.8%
	Percent < 1.0	23.8%	66.7%	53.3%	43.2%	25.1%	20.2%
	Percent ≥ 1.2	44.1%	33.3%	0.0%	15.9%	37.4%	52.5%
	Percent < 0.8	6.0%	0.0%	0.0%	13.6%	5.7%	5.7%
Potential 2	No. Data Points	954	3	15	44	366	526
	Mean	1.165	1.146	1.043	1.070	1.152	1.186
	COV	15.9%	34.8%	9.7%	18.1%	17.3%	19.1%
	Maximum	1.834	1.544	1.211	1.439	1.476	1.834
	Minimum	0.497	0.900	0.894	0.658	0.701	0.497
	Percent ≥ 1.0	81.8%	33.3%	66.7%	77.3%	80.9%	83.5%
	Percent < 1.0	18.2%	66.7%	33.3%	22.7%	19.1%	16.5%
	Percent ≥ 1.2	52.6%	33.3%	6.7%	25.0%	48.6%	59.1%
	Percent < 0.8	5.2%	0.0%	0.0%	11.4%	5.2%	4.9%

Units: 0.001 kcf = 16.01 kg/m^3

Table 24. Test-to-Prediction Ratios of the Splitting Ratio for All-Lightweight Concrete using the AASHTO LRFD Expression (Eq. 22) and Potential Expressions 1 and 2 (Eq. 26 and Eq. 27).

F_{sp} Expression	Statistical Measure	Total	$w_c \leq 0.090$ kcf	$0.090 < w_c \leq 0.100$ kcf	$0.100 < w_c \leq 0.110$ kcf	$0.110 < w_c \leq 0.120$ kcf	$0.120 < w_c \leq 0.135$ kcf
AASHTO LRFD	No. Data Points	311	14	141	99	49	8
	Mean	1.129	0.991	1.143	1.094	1.190	1.188
	COV	17.6%	19.2%	20.6%	19.4%	17.0%	16.3%
	Maximum	1.707	1.256	1.707	1.472	1.573	1.514
	Minimum	0.587	0.642	0.699	0.587	0.820	1.037
	Percent ≥ 1.0	72.0%	50.0%	70.2%	67.7%	87.8%	100.0
	Percent < 1.0	28.0%	50.0%	29.8%	32.3%	12.2%	0.0%
	Percent ≥ 1.2	35.4%	14.3%	39.7%	26.3%	46.9%	37.5%
	Percent < 0.8	4.5%	21.4%	2.1%	8.1%	0.0%	0.0%
Potential 1	No. Data Points	311	14	141	99	49	8
	Mean	1.034	0.991	1.083	0.983	1.019	0.951
	COV	17.7%	19.2%	19.6%	16.6%	14.4%	13.6%
	Maximum	1.599	1.256	1.599	1.307	1.350	1.231
	Minimum	0.526	0.642	0.681	0.526	0.708	0.807
	Percent ≥ 1.0	52.4%	50.0%	58.9%	43.4%	55.1%	37.5%
	Percent < 1.0	47.6%	50.0%	41.1%	56.6%	44.9%	62.5%
	Percent ≥ 1.2	18.6%	14.3%	29.1%	9.1%	10.2%	12.5%
	Percent < 0.8	6.4%	21.4%	3.5%	10.1%	4.1%	0.0%
Potential 2	No. Data Points	311	14	141	99	49	8
	Mean	1.087	0.991	1.143	1.043	1.062	0.970
	COV	17.7%	19.2%	20.6%	17.4%	15.0%	14.1%
	Maximum	1.707	1.256	1.707	1.380	1.408	1.261
	Minimum	0.557	0.642	0.699	0.557	0.740	0.815
	Percent ≥ 1.0	65.9%	50.0%	70.2%	64.6%	65.3%	37.5%
	Percent < 1.0	34.1%	50.0%	29.8%	35.4%	34.7%	62.5%
	Percent ≥ 1.2	28.0%	14.3%	39.7%	19.2%	18.4%	12.5%
	Percent < 0.8	5.5%	21.4%	2.1%	9.1%	4.1%	0.0%

Units: 0.001 kcf = 16.01 kg/m^3

LINEAR EXPRESSIONS FOR THE SPLITTING RATIO USING UNIT WEIGHT

An expression for predicting the splitting ratio that is a function of unit weight is an alternative method to using constituent materials as the basis. This section describes the development of a piecewise continuous function for predicting F_{sp}. A conceptual illustration for the potential expression is shown in Figure 46. The expression consists of a constant predicted F_{sp} for unit weights less than or equal a lower limit on w_c. The prediction then assumes a linearly increasing F_{sp} with unit weight between the lower and upper limits on w_c. The basic form of the linear equation used is given by Eq. 23. The predicted F_{sp} then remains constant for unit weights greater than the upper limit on w_c. In this discussion, lower limits are denoted by "LL" and upper limits are denoted by "UL".

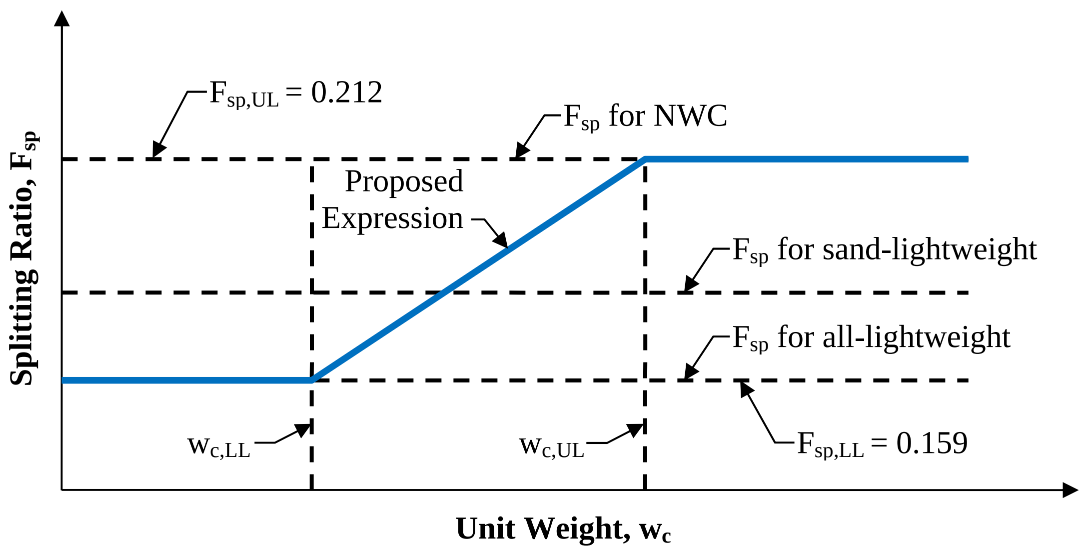


Figure 46. Illustration. Definitions for a Continuous Piecewise Expression for Predicting Splitting Ratio Based on Unit Weight.

$$\text{For } w_{c,LL} < w_c < w_{c,UL}\text{:} \quad F_{sp} = \frac{\left(F_{sp,UL} - F_{sp,LL}\right)}{\left(w_{c,UL} - w_{c,LL}\right)}\left(w_c - w_{c,LL}\right) + F_{sp,LL} \qquad \text{(Eq. 23)}$$

An upper limit of 0.212 on F_{sp} was selected because this value is currently specified in Article 5.8.2.2 as the largest F_{sp} that requires modification for LWC. A lower limit of 0.159 on F_{sp} was selected because this value is specified in Article 5.8.2.2 as the F_{sp} for all-lightweight concrete. An upper limit on w_c of 0.135 kcf (2160 kg/m^3) was selected because this value is the lower limit on w_c in the definition of NWC in the AASHTO LRFD Specifications.

An obvious choice for the lower limit on w_c was less clear. A unit weight of 0.090 kcf (1440 kg/m^3) is stated as a lower limit in the definition of LWC in ACI 318-11. The unit weight of 0.090 kcf (1440 kg/m^3) is also stated as the lower limit for the applicability of the expression for E_c in Article 5.4.2.4 of the AASHTO LRFD Specifications. A lower limit on w_c of 0.090 kcf (1440 kg/m^3) was selected as a starting point for the development of an expression for F_{sp} and used in Potential Expression 1; however the value for this lower limit was changed in Potential Expression 2 to evaluate any improvement in the prediction of F_{sp}. The resulting linear equations between the upper and lower limits on w_c for Potential Expressions 1 and 2 are given by Eq. 24 and Eq. 25. These equations show how the upper and lower limits on F_{sp} and w_c were included.

$$\text{Potential 1: } F_{sp} = \frac{(0.212 - 0.159)}{(0.135 - 0.090)}(w_c - 0.090) + 0.159 \quad \text{(Eq. 24)}$$

$$\text{Potential 2: } F_{sp} = \frac{(0.212 - 0.159)}{(0.135 - 0.100)}(w_c - 0.100) + 0.159 \quad \text{(Eq. 25)}$$

Potential Expressions 1 and 2 for F_{sp} are given by Eq. 26 and Eq. 27 for the full range of unit weights. These equations are shown in Figure 47 for comparison with sand-lightweight and all-lightweight data only, and in Figure 48 for comparison with all the LWC data in the subset database for splitting tensile strength. There are horizontal lines in Figure 47 and Figure 48 that indicate the F_{sp} for NWC (0.212), the F_{sp} for sand-lightweight concrete (0.180), and the F_{sp} for all-lightweight concrete (0.159).

Potential Expression 1 for F_{sp} has a $w_{c,LL}$ of 0.090 kcf (1440 kg/m^3) and is given by:

$$\text{For } w_c \leq 0.090 \text{ kcf: } F_{sp} = 0.159 \quad \text{(Eq. 26a)}$$

$$\text{For } 0.090 < w_c < 0.135 \text{ kcf: } F_{sp} = 1.177w_c + 0.0530 \quad \text{(Eq. 26b)}$$

$$\text{For } w_c \geq 0.135 \text{ kcf: } F_{sp} = 0.212 \quad \text{(Eq. 26c)}$$

Potential Expression 2 for F_{sp} has a $w_{c,LL}$ of 0.100 kcf (1600 kg/m^3) and is given by:

$$\text{For } w_c < 0.100 \text{ kcf: } F_{sp} = 0.159 \quad \text{(Eq. 27a)}$$

$$\text{For } 0.100 < w_c < 0.135 \text{ kcf: } F_{sp} = 1.517w_c + 0.0076 \quad \text{(Eq. 27b)}$$

$$\text{For } w_c \geq 0.135 \text{ kcf: } F_{sp} = 0.212 \quad \text{(Eq. 27c)}$$

The test-to-prediction ratios for Potential Expressions 1 and 2 are given in Table 23 and Table 24 for sand-lightweight concrete and all-lightweight concrete, respectively. For sand-lightweight concrete, Potential Expressions 1 and 2 have greater mean test-to-prediction ratios than the expression in the AASHTO LRFD Specifications for unit weights up to 0.110 kcf (1760 kg/m^3). The mean ratio of 1.28 indicates that the AASHTO LRFD expression gave a very conservative prediction of F_{sp} in sand-lightweight concrete for unit weights greater than 0.120 kcf (1920 kg/m^3).

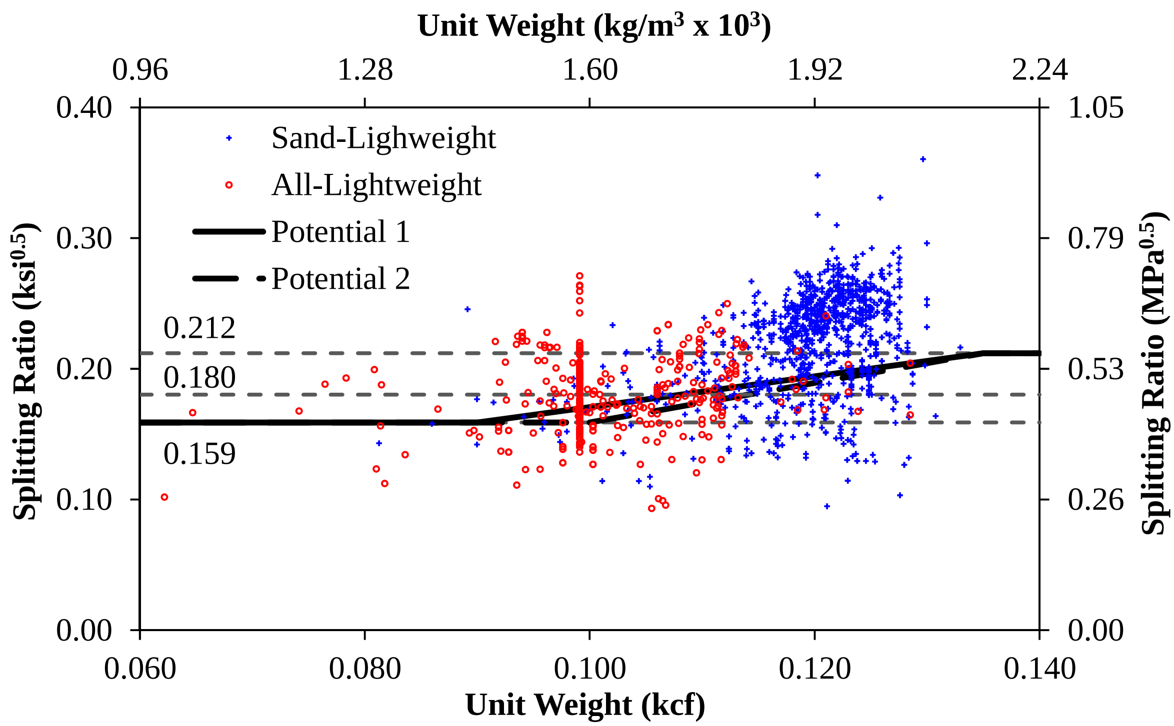


Figure 47. Graph. Splitting Ratio for Sand-Lightweight and All-Lightweight Concrete with Potential Expressions 1 and 2 (Eq. 26 and Eq. 27).

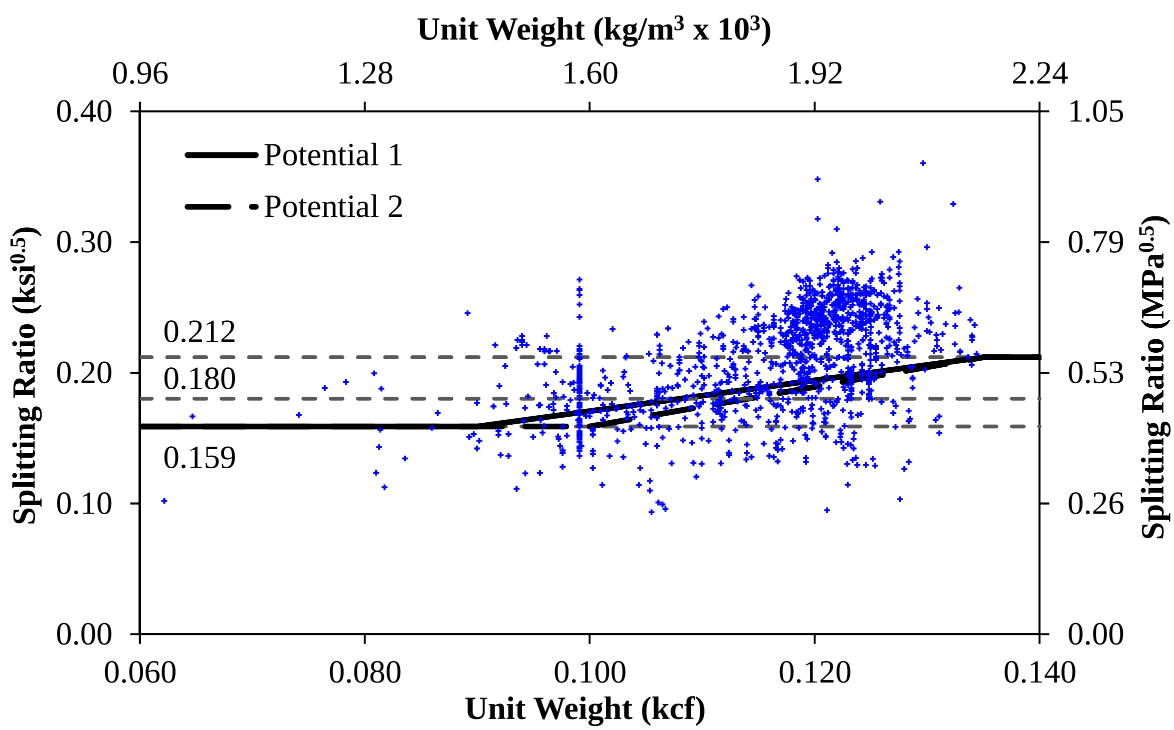


Figure 48. Graph. Splitting Ratio for TFHRC LWC Database with Potential Expressions 1 and 2 (Eq. 26 and Eq. 27).

In Table 24 for all-lightweight concrete, the potential expressions give the same result as the AASHTO LRFD prediction for unit weights below the lower limit on w_c. For unit weights above the lower limit on w_c, both potential expressions gave lower mean test-to-prediction ratios than the expression in AASHTO LRFD. Potential Expression 1 gave mean ratios that were greater than 0.98 except for the limited number of data points with a unit weight greater than 0.120 kcf (1920 kg/m^3). Potential Expression 2 had mean ratios greater than unity for unit weights up to 0.120 kcf (1920 kg/m^3). Most of the data from the tests on all-lightweight concrete had a unit weight between 0.090 kcf and 0.110 kcf (1440 and 1760 kg/m^3), while most of the tests on sand-lightweight concrete were between 0.110 kcf and 0.135 kcf (1760 and 2160 kg/m^3). This indicates that it is more likely for sand-lightweight concrete to be used to produce concrete with a unit weights greater than 0.120 kcf (1920 kg/m^3) and the test-to-prediction ratios for all-lightweight concrete that are less than unity at unit weights greater than 0.120 kcf (1920 kg/m^3) may not be a concern. The test-to-prediction ratios are shown graphically for the AASHTO LRFD expression in Figure 49 and for the Potential Equation 2 in Figure 50.

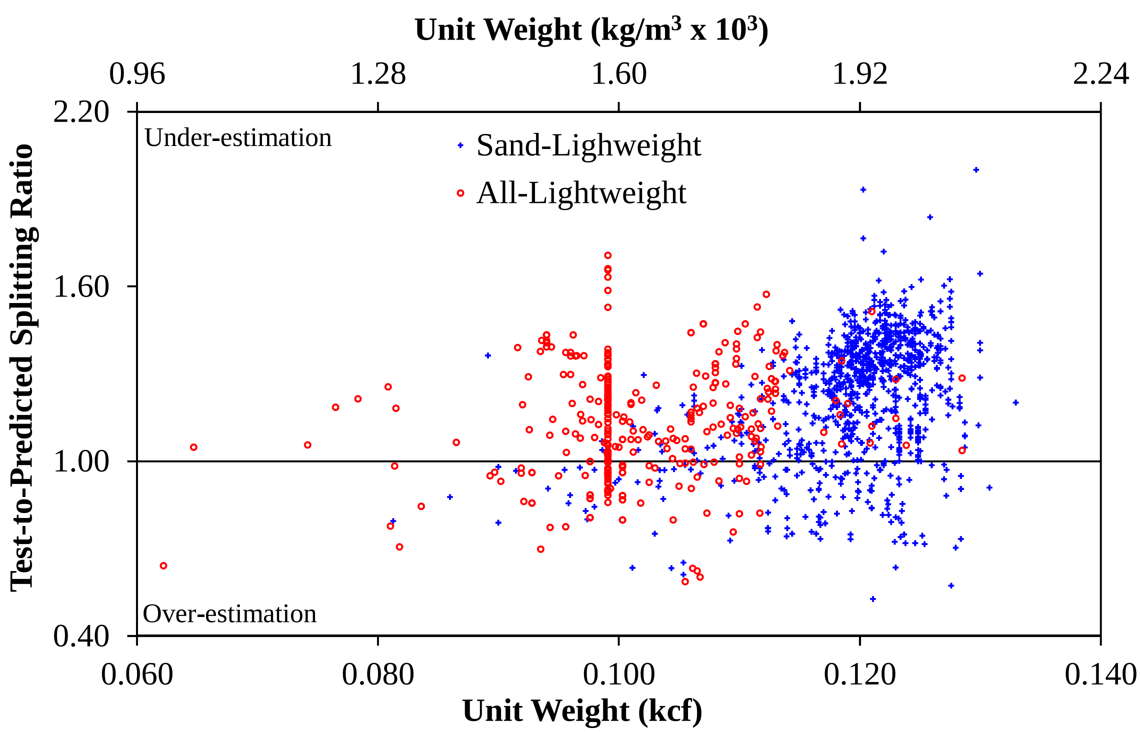


Figure 49. Graph. Test-to-Prediction Ratio for Splitting Ratio for Sand-Lightweight and All-Lightweight Concrete with AASHTO LRFD Expression (Eq. 22).

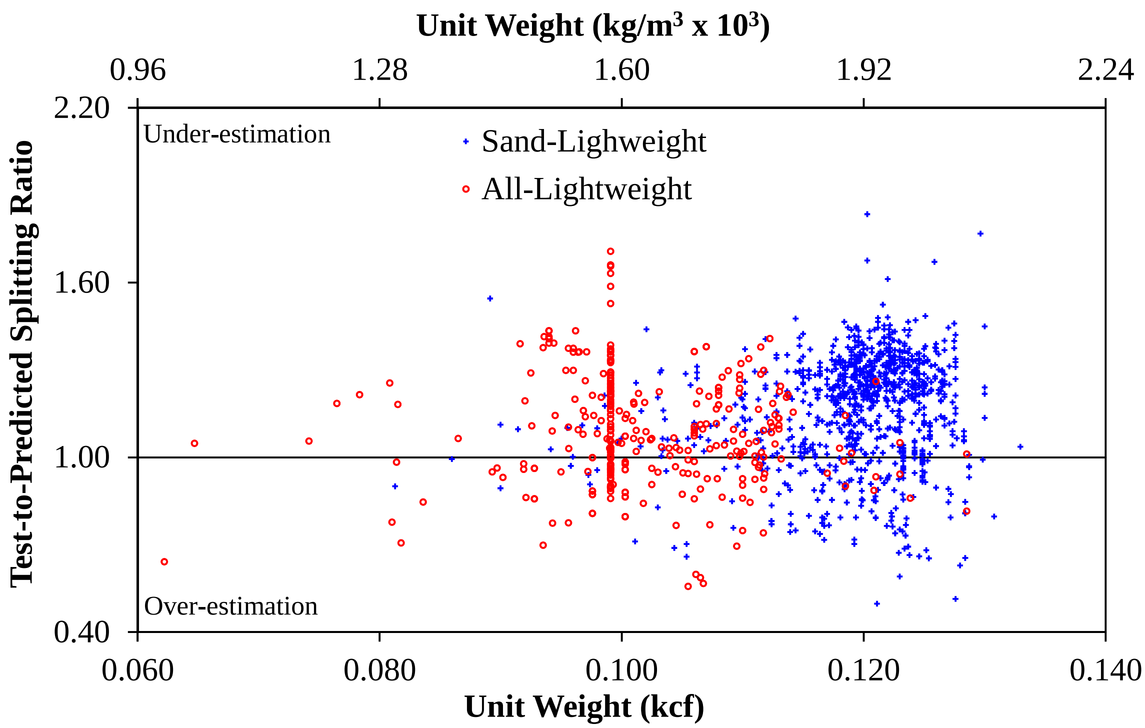


Figure 50. Graph. Test-to-Prediction Ratio for Splitting Ratio for Sand-Lightweight and All-Lightweight Concrete with Potential Expression 2 (Eq. 27).

Table 25 gives the test-to-prediction ratios for Potential Expressions 1 and 2 using the subset database for splitting tensile strength. This table shows that mean ratio for Potential Expression 1 over the entire range of unit weights included in the database is 1.11 and the only range in which the mean ratio slightly less than unity is between 0.100 kcf and 0.110 kcf (1600 and 1760 kg/m^3). Potential Expression 2 has a slightly higher mean test-to-prediction ratio of 1.14 and has a mean ratio in each range of unit weights that is greater than unity. The test-to-prediction ratios for the entire subset database are shown in Figure 51 for Potential Expression 2.

Additional expressions for predicting F_{sp} with a lower limit greater than 0.100 kcf (1600 kg/m^3) were not investigated for several reasons. As the lower limit on w_c increases, the total range in unit weights over which the transition from the lower to upper limit on F_{sp} can occur decreases. If the range becomes sufficiently small, the transition would resemble a step from lower to upper limit on F_{sp}. In the following section the effect of an expression for F_{sp} that incorporates an abrupt transition in the predicted F_{sp} based on unit weight was evaluated.

Table 25. Test-to-Prediction Ratios of the Splitting Ratio for the Subset Database using the Potential Expressions 1 and 2 (Eq. 26 and Eq. 27).

F_{sp} Expression	Statistical Measure	Total	$w_c \leq 0.090$ kcf	$0.090 < w_c \leq 0.100$ kcf	$0.100 < w_c \leq 0.110$ kcf	$0.110 < w_c \leq 0.120$ kcf	$0.120 < w_c \leq 0.135$ kcf
Potential 1	No. Data Points	1332	17	156	143	421	595
	Mean	1.109	1.018	1.075	0.991	1.102	1.154
	COV	16.7%	22.1%	19.0%	16.7%	16.9%	18.3%
	Maximum	1.788	1.544	1.599	1.348	1.422	1.788
	Minimum	0.485	0.642	0.681	0.526	0.682	0.485
	Percent ≥ 1.0	71.0%	47.1%	57.7%	47.6%	72.0%	80.2%
	Percent < 1.0	29.0%	52.9%	42.3%	52.4%	28.0%	19.8%
	Percent ≥ 1.2	36.5%	17.6%	26.3%	11.2%	33.7%	47.7%
	Percent < 0.8	5.9%	17.6%	3.2%	11.2%	5.7%	5.2%
Potential 2	No. Data Points	1332	17	156	143	421	595
	Mean	1.144	1.018	1.133	1.051	1.139	1.176
	COV	16.4%	22.1%	20.0%	17.6%	17.3%	18.7%
	Maximum	1.834	1.544	1.707	1.439	1.476	1.834
	Minimum	0.497	0.642	0.699	0.557	0.701	0.497
	Percent ≥ 1.0	78.2%	47.1%	69.9%	68.5%	78.4%	83.5%
	Percent < 1.0	21.8%	52.9%	30.1%	31.5%	21.6%	16.5%
	Percent ≥ 1.2	45.0%	17.6%	36.5%	21.0%	44.4%	54.1%
	Percent < 0.8	5.1%	17.6%	1.9%	9.8%	5.0%	4.5%

Units: 0.001 kcf = 16.01 kg/m^3

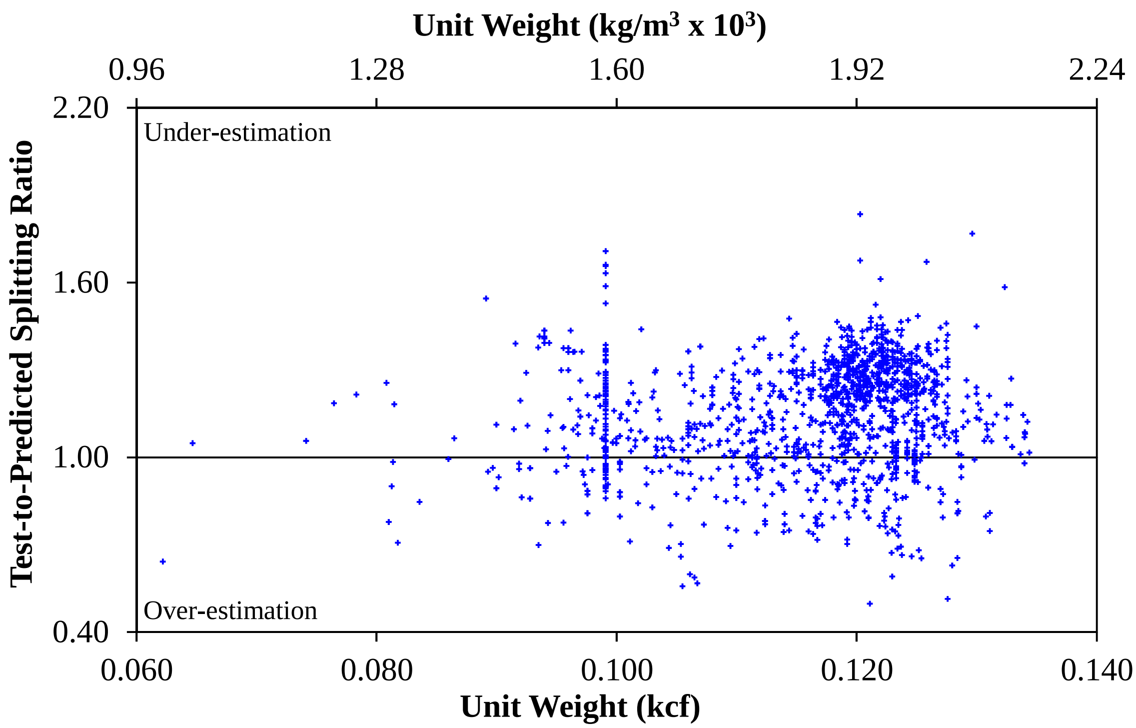


Figure 51. Graph. Test-to-Prediction Ratios of the Splitting Ratio for the Subset Database using Potential Expression 2 (Eq. 27).

EXPRESSIONS FOR THE SPLITTING RATIO USING A SINGLE ABRUPT TRANSITION

An expression including an abrupt change in predicted splitting ratio is an alternative method to using a piecewise continuous function. An abrupt change based on unit weight would result in a simple expression as illustrated in Figure 52. The predicted F_{sp} remains constant at the F_{sp} lower limit for unit weights less than the transition w_c. At the transition unit weight the predicted F_{sp} makes and abrupt change and the predicted F_{sp} remains constant at the F_{sp} upper limit for all w_c greater than the transition unit weight.

The test-to-prediction splitting ratios for several possible transition unit weights are given in Table 26. Using a low transition w_c (0.000 kcf in the table), the predicted splitting ratio is at the F_{sp} upper limit (0.212) for all LWC. This means that LWC would be treated as NWC and the reduced tensile cracking strength of LWC would be ignored. This method is not recommended but is shown in the table for comparison purposes. A transition w_c of 0.135 kcf (2160 kg/m^3) uses an F_{sp} of 0.159 for LWC. This means treating all LWC as all-lightweight concrete.

The mean test-to-prediction splitting ratios from using constant values of F_{sp} for all LWC in the subset database are given in Table 27 by ranges of unit weight. Table 27 shows that using F_{sp} equal to 0.212 results in mean ratios that are less than unity for unit weights up to 0.120 kcf (1920 kg/m^3). An F_{sp} equal to 0.159 results in mean ratios that are greater than unity for all ranges of unit weight. For unit weights greater than 0.120 kcf (1920 kg/m^3), an F_{sp} equal to 0.159 results in a prediction that is very conservative with a mean of 1.44.

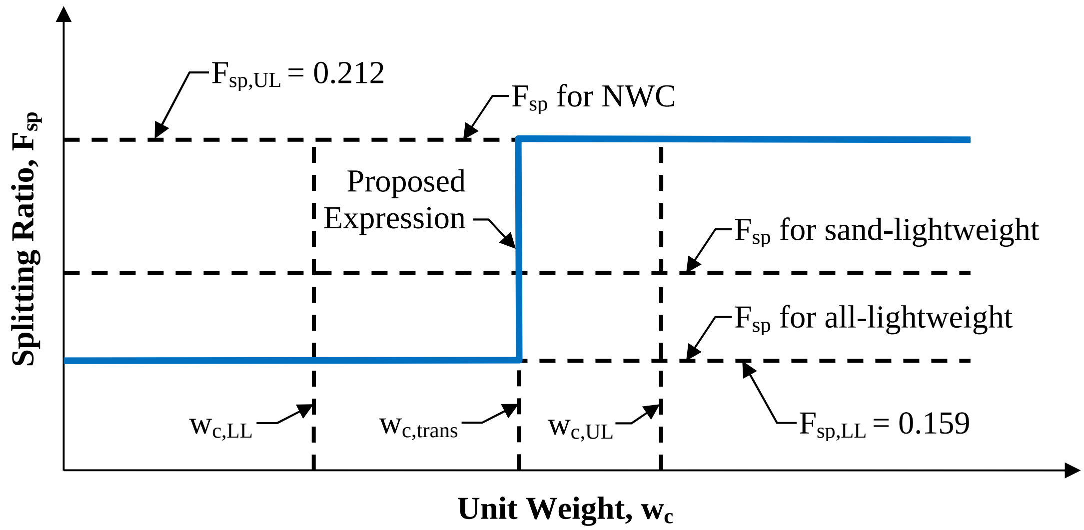


Figure 52. Illustration. Definitions for an Expression Predicting Splitting using a Single Abrupt Transition.

Table 26. Test-to-Prediction Ratios of the Splitting Ratios in the Subset Database for a Prediction Expression using Single and Multiple Abrupt Transitions.

	Single Transition				Multiple Transitions
Statistical Measure	**Transition w_c = 0.000 kcf: F_{sp} = 0.212 for all LWC**	**Transition w_c = 0.110 kcf: F_{sp} = 0.159 for $w_c < w_{c,trans}$ and F_{sp} = 0.212 for $w_c \geq w_{c,trans}$ kcf**	**Transition w_c = 0.120 kcf: F_{sp} = 0.159 for $w_c < w_{c,trans}$ and F_{sp} = 0.212 for $w_c \geq w_{c,trans}$**	**Transition w_c = 0.135 kcf: F_{sp} = 0.159 for all LWC**	**First Transition w_c = 0.110 kcf F_{sp} = 0.159 for $w_c < w_{c,trans}$ and F_{sp} = 0.180 for $w_c \geq w_{c,trans}$**
No. Data Points	1332	1332	1332	1332	1332
Mean	0.994	1.060	1.164	1.325	1.200
COV	18.9%	17.0%	18.7%	18.9%	17.2%
Maximum	1.700	1.706	1.722	2.266	2.000
Minimum	0.440	0.447	0.447	0.586	0.526
Percent ≥ 1.0	52.9%	65.6%	78.3%	88.1%	81.6%
Percent < 1.0	47.1%	34.4%	21.7%	11.9%	18.4%
Percent ≥ 1.2	12.9%	20.1%	40.3%	68.1%	54.2%
Percent < 0.8	17.2%	8.8%	4.7%	1.7%	3.6%

Units: 0.001 kcf = 16.01 kg/m^3

Table 27. Test-to-Prediction Ratios of the Splitting Ratios in the Subset Database for a Prediction Expression using a Constant Value for Splitting Ratio.

Constant F_{sp} Value	Statistical Measure	Total	$w_c \leq 0.090$ kcf	$0.090 < w_c \leq 0.100$ kcf	$0.100 < w_c \leq 0.110$ kcf	$0.110 < w_c \leq 0.120$ kcf	$0.120 < w_c \leq 0.135$ kcf
$F_{sp} = 0.212$	No. Data Points	1332	17	156	143	421	595
	Mean	0.994	0.764	0.850	0.827	0.988	1.082
	COV	18.9%	16.6%	15.0%	14.4%	15.7%	17.0%
	Maximum	1.700	1.158	1.280	1.104	1.291	1.700
	Minimum	0.440	0.481	0.524	0.440	0.615	0.447
	Percent ≥ 1.0	52.9%	5.9%	19.2%	13.3%	51.8%	73.3%
	Percent < 1.0	47.1%	94.1%	80.8%	86.7%	48.2%	26.7%
	Percent ≥ 1.2	12.9%	0.0%	2.6%	0.0%	6.2%	23.9%
	Percent < 0.8	17.2%	70.6%	42.3%	36.4%	13.1%	7.4%
$F_{sp} = 0.180$	No. Data Points	1332	17	156	143	421	595
	Mean	1.169	0.898	1.000	0.973	1.163	1.273
	COV	18.9%	19.5%	17.6%	17.0%	18.5%	19.9%
	Maximum	2.000	1.363	1.506	1.299	1.519	2.000
	Minimum	0.517	0.566	0.616	0.517	0.723	0.526
	Percent ≥ 1.0	75.6%	29.4%	46.2%	44.1%	78.6%	90.1%
	Percent < 1.0	24.4%	70.6%	53.8%	55.9%	21.4%	9.9%
	Percent ≥ 1.2	49.7%	5.9%	17.3%	8.4%	48.9%	69.9%
	Percent < 0.8	5.7%	29.4%	13.5%	14.0%	3.8%	2.4%
$F_{sp} = 0.159$	No. Data Points	1332	17	156	143	421	595
	Mean	1.325	1.018	1.133	1.103	1.318	1.443
	COV	18.9%	22.1%	20.0%	19.2%	21.0%	22.6%
	Maximum	2.266	1.544	1.706	1.472	1.722	2.266
	Minimum	0.586	0.642	0.698	0.586	0.820	0.597
	Percent ≥ 1.0	88.1%	47.1%	69.9%	72.0%	91.9%	95.3%
	Percent < 1.0	11.9%	52.9%	30.1%	28.0%	8.1%	4.7%
	Percent ≥ 1.2	68.1%	17.6%	36.5%	28.0%	70.1%	86.1%
	Percent < 0.8	1.7%	17.6%	1.9%	8.4%	0.0%	0.7%

Units: 0.001 kcf = 16.01 kg/m^3

The effect on the mean test-to-prediction ratios of using transition unit weights of 0.110 kcf and 0.120 kcf (1760 and 1920 kg/m^3) is given in Table 26. The table shows that both transition unit weights have mean ratios greater than unity and that increasing the transition w_c results in an increase in the mean ratio. The mean test-to-prediction ratios for different ranges of w_c can be determined from Table 27. Transition unit weights of 0.110 kcf and 0.120 kcf (1760 and 1920 kg/m^3) were selected because a preliminary examination of the mean ratios for a transition w_c of 0.100 kcf (1600 kg/m^3) was only 1.03, about a 3% difference between the mean ratios at unit weights of 0.090 kcf and 0.110 kcf (1440 and 1760 kg/m^3). The difference between the mean ratios at 0.110 kcf and 0.120 kcf (1760 and 1920 kg/m^3) was much larger.

EXPRESSIONS FOR THE SPLITTING RATIO USING MULTIPLE ABRUPT TRANSITIONS

An alternative to using only a single abrupt change in the expression for predicting splitting ratios is to use multiple changes in F_{sp}. Figure 53 illustrates an expression with one intermediate transition w_c and a second transition w_c from representing the change from LWC to NWC. The predicted F_{sp} makes an abrupt change from the existing F_{sp} for all-lightweight concrete (F_{sp} lower limit) to the existing F_{sp} for sand-lightweight concrete at the first transition w_c. The predicted F_{sp} makes another abrupt change at the upper limit on w_c.

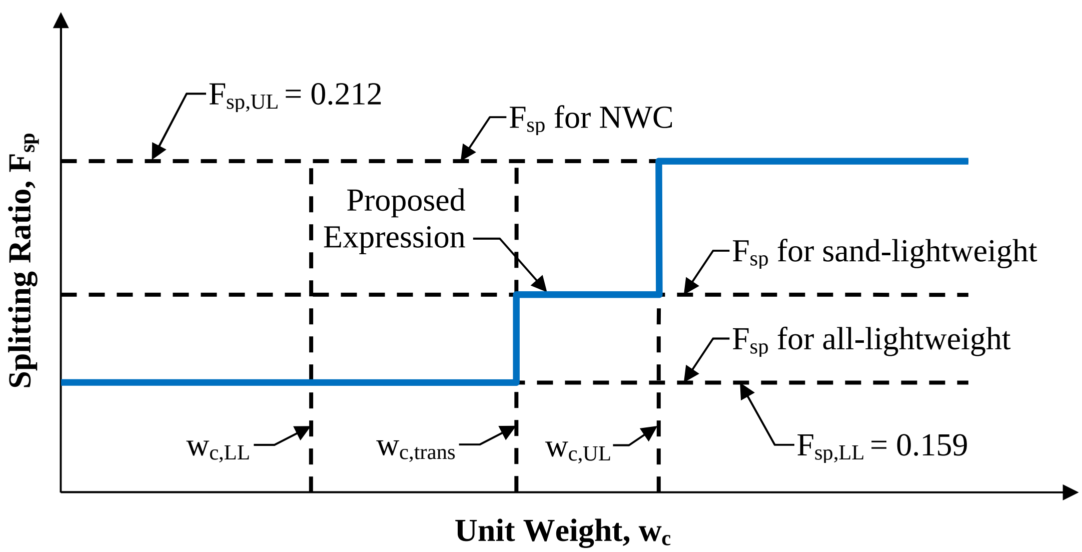


Figure 53. Illustration. Definitions for an Expression Predicting Splitting Ratio including Multiple Abrupt Transitions.

A potential expression for F_{sp} using the method of multiple abrupt changes was examined with a transition w_c of 0.110 kcf (1760 kg/m^3). The mean test-to-prediction ratio for this expression is 1.20 and is given in Table 26. The transition w_c of 0.110 kcf (1760 kg/m^3) was selected based on an examination of the mean test-to-prediction ratios for a constant F_{sp} of 0.180 and 0.159 in Table 27. There is a significant increase in the mean ratio (from 1.10 to 1.32) for a constant F_{sp}

of 0.159 for ranges of w_c greater and less than 0.110 kcf (1760 kg/m^3). There is a similar increase in the mean ratio (0.97 to 1.16) at 0.110 kcf (1760 kg/m^3) for a constant F_{sp} of 0.180. The mean ratios for a constant F_{sp} of 0.180 were less than or equal to unity for unit weights less than 0.110 kcf (1760 kg/m^3). Although the mean test-to-prediction ratios for different ranges of unit weight could be determined from Table 27, the ratios are given again in Table 28 for clarity.

Table 28. Test-to-Prediction Ratios of the Splitting Ratios in the Subset Database for a Prediction Expression using Multiple Abrupt Transitions.

		Use F_{sp} = 0.159			Use F_{sp} = 0.180	
Statistical Measure	**Total**	**$w_c \leq$ 0.090 kcf**	**0.090 < $w_c \leq$ 0.100 kcf**	**0.100 < $w_c \leq$ 0.110 kcf**	**0.110 < $w_c \leq$ 0.120 kcf**	**0.120 < $w_c \leq$ 0.135 kcf**
No. Data Points	1332	17	156	143	421	595
Mean	1.200	1.018	1.133	1.103	1.163	1.273
COV	17.2%	22.1%	20.0%	19.2%	18.5%	19.9%
Maximum	2.000	1.544	1.707	1.472	1.519	2.000
Minimum	0.526	0.642	0.699	0.587	0.723	0.526
Percent $\geq$ 1.0	81.6%	47.1%	69.9%	72.0%	78.6%	90.1%
Percent < 1.0	18.4%	52.9%	30.1%	28.0%	21.4%	9.9%
Percent $\geq$ 1.2	54.2%	17.6%	36.5%	28.0%	48.9%	69.9%
Percent < 0.8	3.6%	17.6%	1.9%	8.4%	3.8%	2.4%

Units: 0.001 kcf = 16.01 kg/m^3

The expressions for F_{sp} using single or multiple abrupt changes can result in test-to-prediction ratios that are similar to those observed with piecewise continuous functions. Although the expressions with abrupt changes result in conceptually simple design expressions, a concern with using them is that designs using LWC with unit weights on opposite sides of the abrupt change would have a very different predicted nominal resistance, even though the difference in their unit weight was small and the difference in their actual resistance is also likely very small. The selection of the transition w_c could potentially influence the unit weight specified for a design because a w_c slightly less than the transition w_c would use a smaller F_{sp} and as a result have a lower predicted resistance.

DESIGN EXPRESSION FOR THE LWC MODIFICATION FACTOR

Potential expressions for F_{sp} were described previously in the form of piecewise continuous functions and expressions with one or more abrupt changes. These expressions for F_{sp} can be converted to LWC modification factors by dividing them by the upper limit on F_{sp} as shown in Eq. 28. In this document, the term λ-factor will be used to refer to LWC modification factors. This section will describe the conversion of Potential Expressions 1 and 2 (Eq. 26 and Eq. 27), both piecewise continuous functions for F_{sp}, into expressions for λ-factors. A simplified expression for λ-factors will be given and evaluated. The conversion of the expressions for F_{sp} using abrupt changes with F_{sp} values of 0.212, 0.180 and 0.159 results in λ-factors with a value of 1.00, 0.85, and 0.75, respectively.

$$\text{LWC modification factor:} \quad \lambda = \frac{F_{sp,Prediction}}{F_{sp,UL}} \qquad \text{(Eq. 28)}$$

LWC modification factors based on Potential Expressions 1 and 2 for F_{sp} are given by Eq. 29 and Eq. 30. Potential Expression 2 for F_{sp} gave slightly more conservative predictions (higher mean test-to-prediction ratio) than Potential Expression 1.

Expression for the λ-factor converted from Potential Expression 1 with a $w_{c,LL}$ of 0.090 kcf (1440 kg/m^3):

$$\text{For } w_c \leq 0.090 \text{ kcf:} \quad \lambda = 0.75 \qquad \text{(Eq. 29a)}$$

$$\text{For } 0.090 < w_c < 0.135 \text{ kcf:} \quad \lambda = 5.556w_c + 0.250 \qquad \text{(Eq. 29b)}$$

$$\text{For } w_c \geq 0.135 \text{ kcf:} \quad \lambda = 1.00 \qquad \text{(Eq. 29c)}$$

Expression for the λ-factor converted from Potential Expression 2 with a $w_{c,LL}$ of 0.100 kcf (1600 kg/m^3):

$$\text{For } w_c \leq 0.100 \text{ kcf:} \quad \lambda = 0.75 \qquad \text{(Eq. 30a)}$$

$$\text{For } 0.100 < w_c < 0.135 \text{ kcf:} \quad \lambda = 7.143w_c + 0.036 \qquad \text{(Eq. 30b)}$$

$$\text{For } w_c \geq 0.135 \text{ kcf:} \quad \lambda = 1.00 \qquad \text{(Eq. 30c)}$$

The linear equation for unit weights between the upper and lower limit on w_c in Potential Expression 2 has a small vertical axis intercept as indicated by the value of 0.036. Potential Expression 2 can be simplified by ignoring the intercept and adjusting the factor multiplied by w_c. The resulting expression is given by Eq. 31 and results in a λ-factor of 0.75 at a w_c of 0.100 kcf (1600 kg/m^3) and a λ-factor of 1.00 at a w_c of approximately 0.133 kcf (2130 kg/m^3).

An inequality is added to the expression to limit the λ-factor to 1.00 for the limited range of unit weights between 0.133 kcf and 0.135 kcf (2130 and 2160 kg/m^3).

$$\text{For } w_c \leq 0.100 \text{ kcf: } \lambda = 0.75 \qquad \text{(Eq. 31a)}$$

$$\text{For } 0.100 < w_c < 0.135 \text{ kcf: } \lambda = 7.5w_c \leq 1.00 \qquad \text{(Eq. 31b)}$$

$$\text{For } w_c \geq 0.135 \text{ kcf: } \lambda = 1.00 \qquad \text{(Eq. 31c)}$$

In order to compare the predictions made by the simplified expression for λ-factor, the expression was converted back to an expression for F_{sp} and is given by Eq. 32 for Potential Expression 3. The mean test-to-prediction ratios for the Potential Expression 3 are given in Table 29 and are very similar to mean ratios for Potential Expression 2. The splitting ratio predicted by Potential Expression 3 is shown graphically in Figure 54, and the test-to-prediction ratios are shown in Figure 55.

$$\text{For } w_c < 0.100 \text{ kcf: } F_{sp} = 0.16 \qquad \text{(Eq. 32a)}$$

$$\text{For } 0.100 < w_c < 0.135 \text{ kcf: } F_{sp} = 1.589w_c \leq 0.21 \qquad \text{(Eq. 32b)}$$

$$\text{For } w_c \geq 0.135 \text{ kcf: } F_{sp} = 0.21 \qquad \text{(Eq. 32c)}$$

Table 29. Test-to-Prediction Ratios of the Splitting Ratio for the Subset Database using Potential Expression 3 (Eq. 32).

Data Source	Statistical Measure	Total	$w_c \le 0.090$ kcf	$0.090 < w_c \le 0.100$ kcf	$0.100 < w_c \le 0.110$ kcf	$0.110 < w_c \le 0.120$ kcf	$0.120 < w_c \le 0.135$ kcf
LWC	No. Data Points	1332	17	156	143	421	595
	Mean	1.150	1.254	1.163	1.051	1.139	1.176
	COV	16.4%	26.3%	20.6%	17.6%	17.3%	18.7%
	Maximum	1.834	1.722	1.721	1.439	1.476	1.834
	Minimum	0.497	0.855	0.744	0.557	0.701	0.497
	Percent ≥ 1.0	79.5%	88.2%	76.3%	68.5%	78.4%	83.5%
	Percent < 1.0	20.5%	11.8%	23.7%	31.5%	21.6%	16.5%
	Percent ≥ 1.2	45.7%	47.1%	39.7%	21.0%	44.4%	54.1%
	Percent < 0.8	4.7%	0.0%	0.6%	9.8%	5.0%	4.5%
Sand-lightweight	No. Data Points	954	3	15	44	366	526
	Mean	1.150	1.138	1.036	1.061	1.137	1.169
	COV	15.9%	34.6%	9.6%	18.0%	17.1%	18.9%
	Maximum	1.809	1.534	1.203	1.429	1.458	1.809
	Minimum	0.490	0.894	0.888	0.652	0.692	0.490
	Percent ≥ 1.0	79.2%	33.3%	60.0%	75.0%	78.7%	80.8%
	Percent < 1.0	20.8%	66.7%	40.0%	25.0%	21.3%	19.2%
	Percent ≥ 1.2	47.6%	33.3%	6.7%	20.5%	43.4%	54.0%
	Percent < 0.8	5.8%	0.0%	0.0%	11.4%	5.7%	5.5%
All-lightweight	No. Data Points	311	14	141	99	49	8
	Mean	1.078	0.984	1.135	1.034	1.050	0.956
	COV	17.7%	19.1%	20.4%	17.2%	14.8%	13.9%
	Maximum	1.695	1.247	1.695	1.367	1.392	1.244
	Minimum	0.552	0.638	0.694	0.552	0.732	0.803
	Percent ≥ 1.0	63.3%	50.0%	68.8%	61.6%	61.2%	25.0%
	Percent < 1.0	36.7%	50.0%	31.2%	38.4%	38.8%	75.0%
	Percent ≥ 1.2	27.0%	14.3%	39.0%	18.2%	16.3%	12.5%
	Percent < 0.8	5.5%	21.4%	2.1%	9.1%	4.1%	0.0%

Units: 0.001 kcf = 16.01 kg/m^3

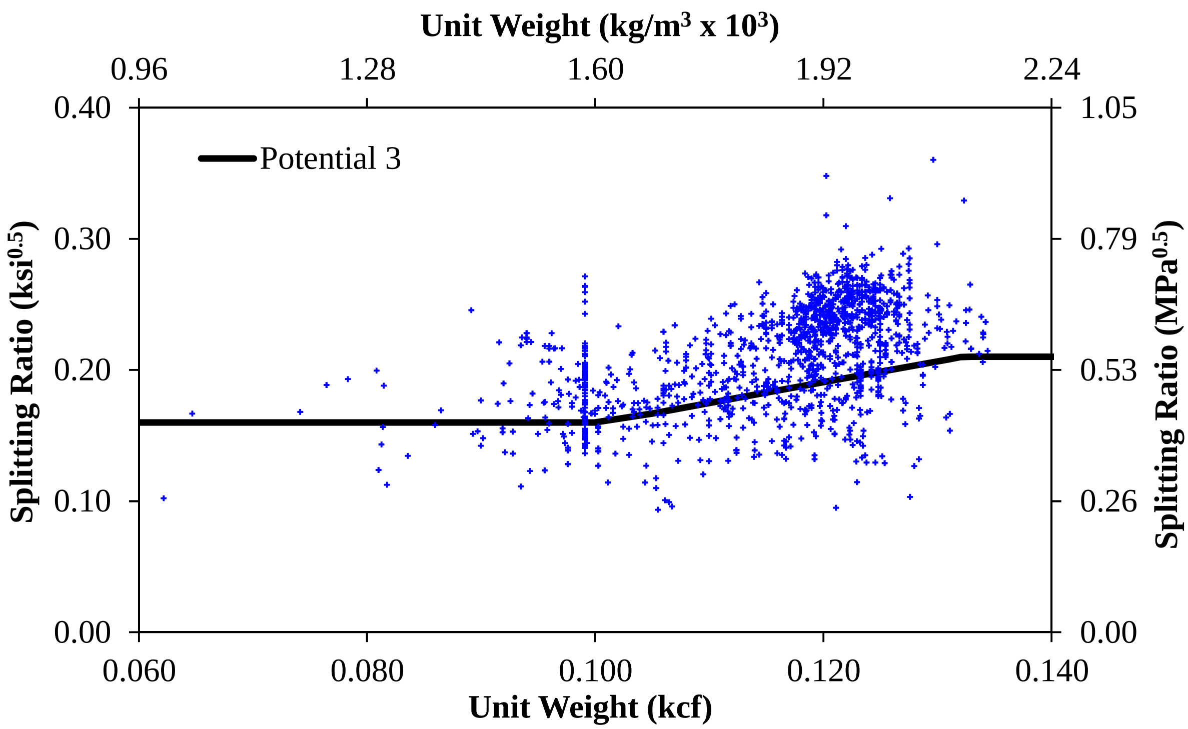


Figure 54. Graph. Splitting Ratio for the Subset Database with Potential Expression 3 (Eq. 32).

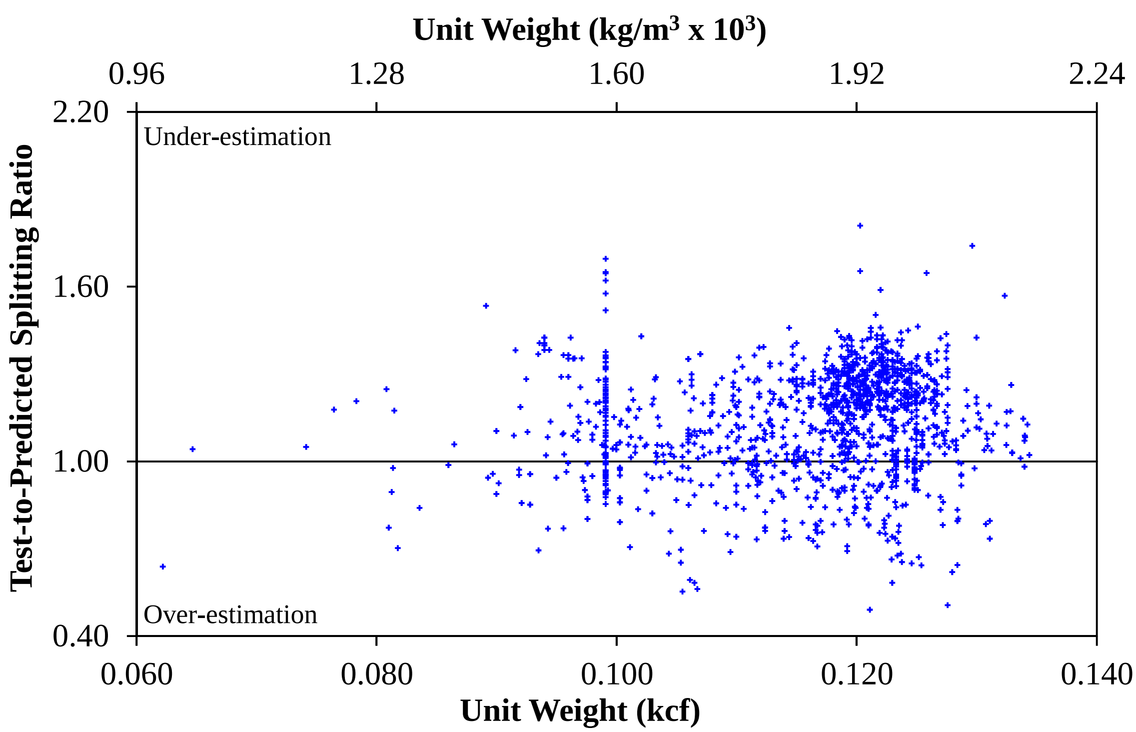


Figure 55. Graph. Test-to-Prediction Ratios of the Splitting Ratio for the Subset Database using Potential Expression 3 (Eq. 32).

MODULUS OF RUPTURE

This section gives the design expressions for the modulus of rupture in the AASHTO LRFD Specifications and briefly describes how the modulus of rupture is used. Modulus of rupture data in the TFHRC LWC database is compared to the design expressions the AASHTO LRFD Specifications and to a new expression incorporating the LWC modification factor proposed in the previous section.

IMPORTANCE OF THE PREDICTED MODULUS OF RUPTURE

The accuracy of the modulus of rupture expression is important for the strength, serviceability, and ductility of structural concrete bridges. In the AASHTO LRFD Specifications (1), the modulus of rupture is used for calculating the nominal shear resistance through the calculation of the cracking moment for V_{ci} ("Simplified Procedure" in Article 5.8.3.4.3). The modulus of rupture is used for serviceability in the calculation of deflection through the effective moment of inertia (Article 5.7.3.6.2) and cracking control requirements (Article 5.7.3.4). The modulus of rupture is used for ductility through the calculation of the minimum area of flexural reinforcement in prestressed and non-prestressed members (Article 5.7.3.3.2).

DESIGN EXPRESSIONS FOR MODULUS OF RUPTURE

The AASHTO LRFD Specifications have different expressions for the modulus of rupture depending upon the use of the calculation and the type of concrete. For normal-weight concrete, Eq. 33 is used when f_r is used to calculate V_{ci} (Article 5.8.3.4.3). For all other calculations using normal-weight concrete such as effective moment of inertia, cracking control, and minimum flexural reinforcement, Eq. 34 is used. The modulus of rupture for lightweight concrete is given by Eq. 35 and Eq. 36 for sand-lightweight concrete and all-lightweight concrete, respectively. Unlike for NWC, the AASHTO LRFD Specifications do not give different expressions for the modulus of rupture of LWC depending upon the use of the concrete. This creates varying levels of conservatism in the calculations of cracking control, effective moment of inertia, and cracking moment for V_{ci} when used in members made from LWC.

$$f_r = 0.20\sqrt{f_c'} \qquad \text{(Eq. 33)}$$

$$f_r = 0.24\sqrt{f_c'} \qquad \text{(Eq. 34)}$$

$$f_r = 0.20\sqrt{f_c'} \qquad \text{(Eq. 35)}$$

$$f_r = 0.17\sqrt{f_c'} \qquad \text{(Eq. 36)}$$

Expressions for modulus of rupture other than the ones in the AASHTO LRFD Specifications have also been proposed in literature.[18,21] For NWC, these expressions are typically in the form of a factor multiplied by $\sqrt{f_c'}$. Evaluation of these alternate expressions is beyond the scope of this report.

SPECIAL CONSIDERATIONS FOR THE MODULUS OF RUPTURE SUBSET DATABASE

The statistical information by ranges of compressive strength, modulus of rupture, and unit weight for the modulus of rupture is given in Table 15 for the f_r subset database. The variation of f_r with compressive strength and unit weight is shown in Figure 24 and Figure 25, respectively.

Some of the tests in the f_r subset database were performed on specimens that were allowed to dry. The drying causes a gradient of moisture and more shrinkage on the surface of the specimens than in the core. The drying shrinkage results in tensile strains on the outside of the specimen and a reduction in the tested modulus of rupture.[3]

An alternate f_r subset database was created to include only specimens that were indicated as remaining wet until tested. These tests were indicated in the literature as being stored in a moist room, sealed in bags, or submerged in a bath until tested. The variation of the f_r data with compressive strength and unit weight from the "wet f_r subset database" is shown in Figure 56 and Figure 57 for sand-lightweight concrete and in Figure 58 and Figure 59 for all-lightweight concrete.

The ratio of f_r to $\sqrt{f_c'}$ for the sand-lightweight and all-lightweight data in the wet f_r subset database is shown in Figure 60. Lines indicating the AASHTO LRFD design values of 0.24 for NWC, 0.20 for sand-lightweight concrete, and 0.17 for all-lightweight concrete are also shown in the figure. A value of 0.24 for NWC is used in all calculations of f_r except those for V_{ci}.

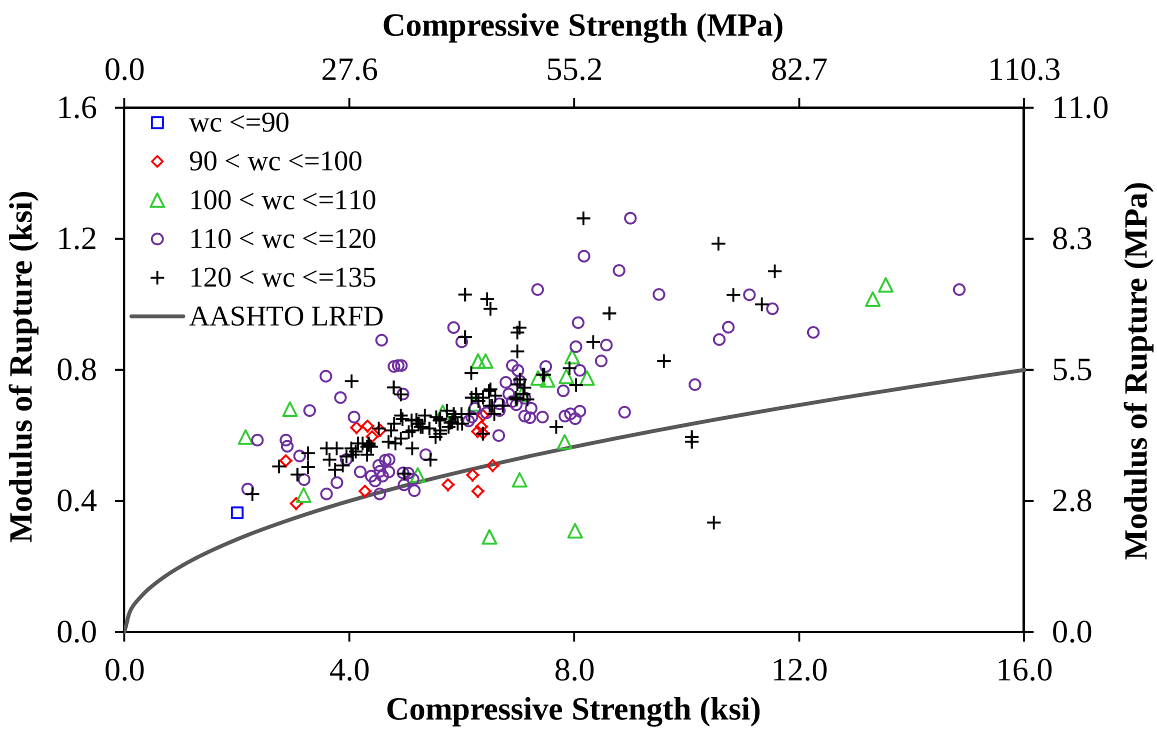


Figure 56. Graph. Modulus of Rupture Compared to Compressive Strength for Sand-Lightweight Concrete Showing Variation by Unit Weight.

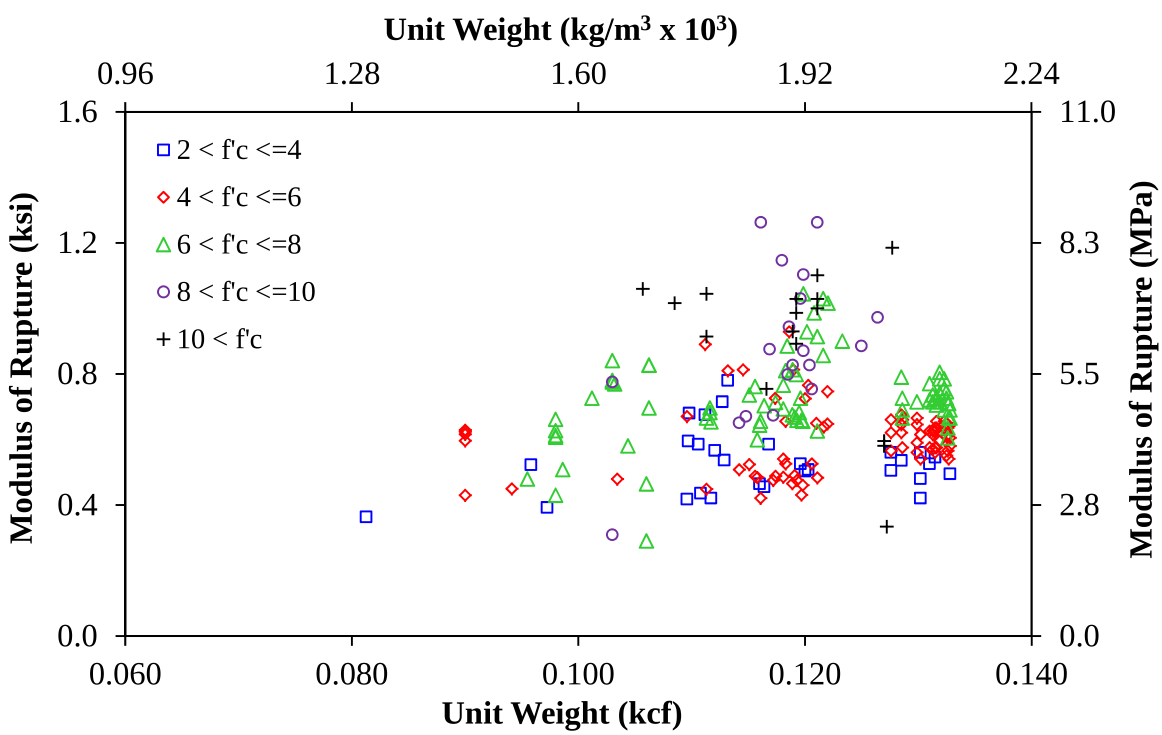


Figure 57. Graph. Modulus of Rupture Compared to Unit Weight for Sand-Lightweight Concrete Showing Variation by Compressive Strength.

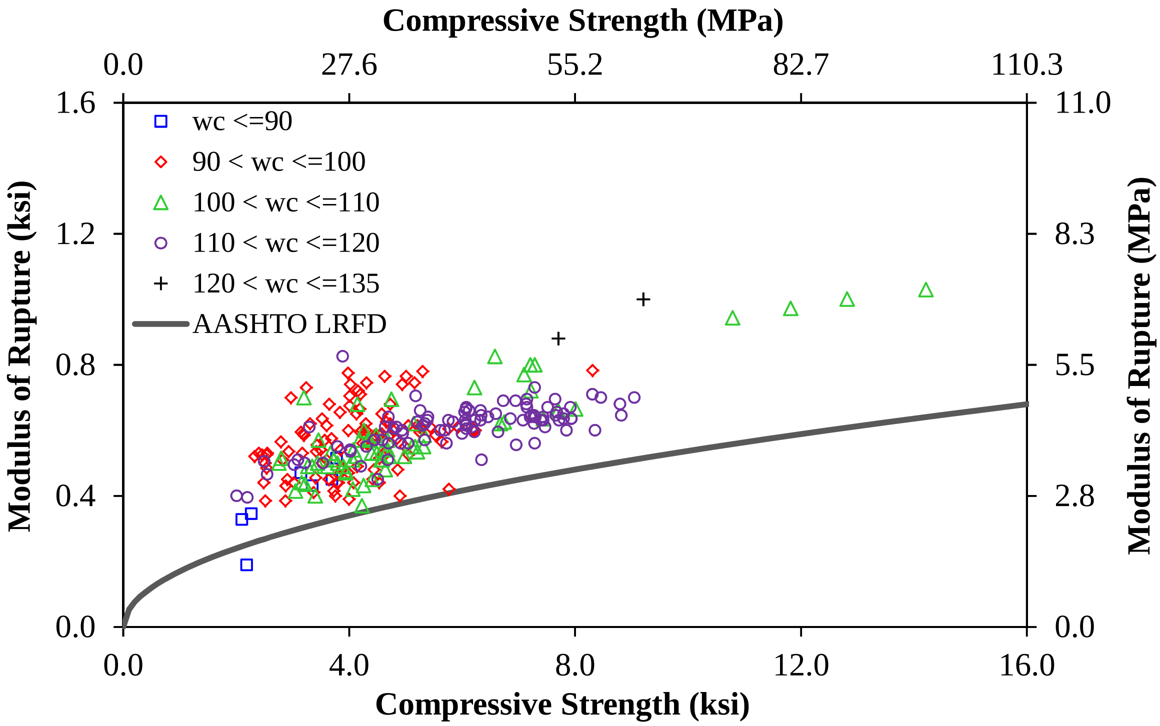


Figure 58. Graph. Modulus of Rupture Compared to Compressive Strength for All-Lightweight Concrete Showing Variation by Unit Weight.

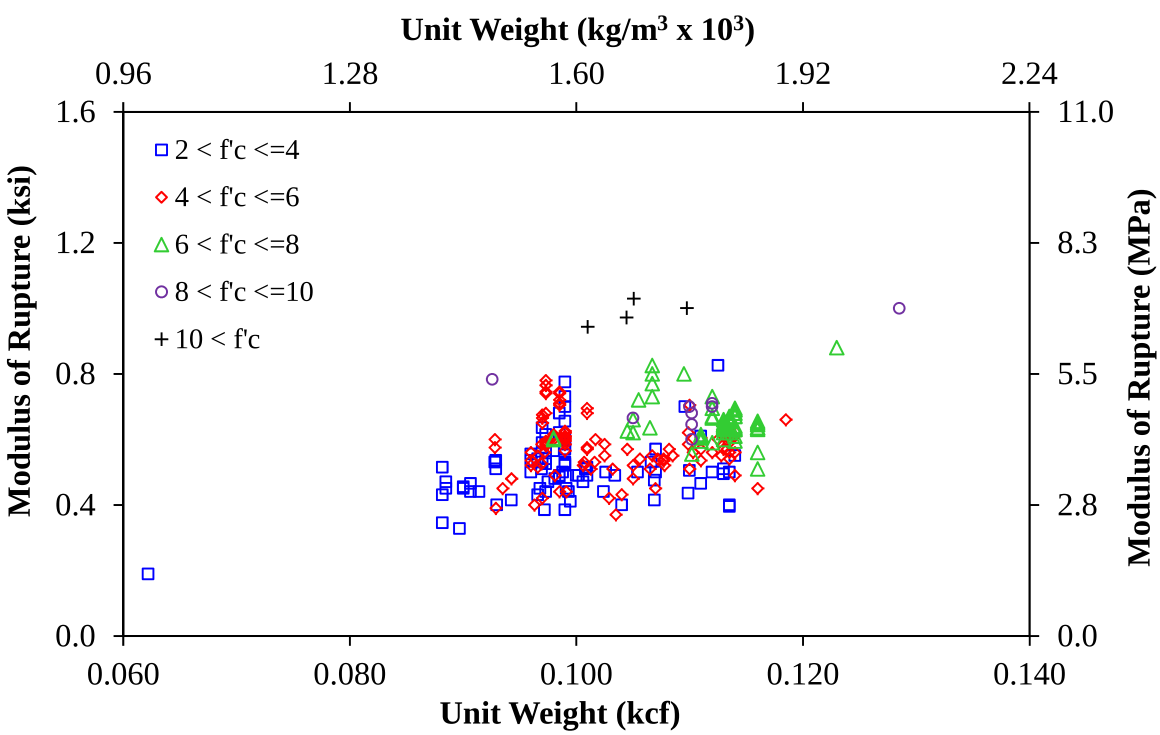


Figure 59. Graph. Modulus of Rupture Compared to Unit Weight for All-Lightweight Concrete Showing Variation by Compressive Strength.

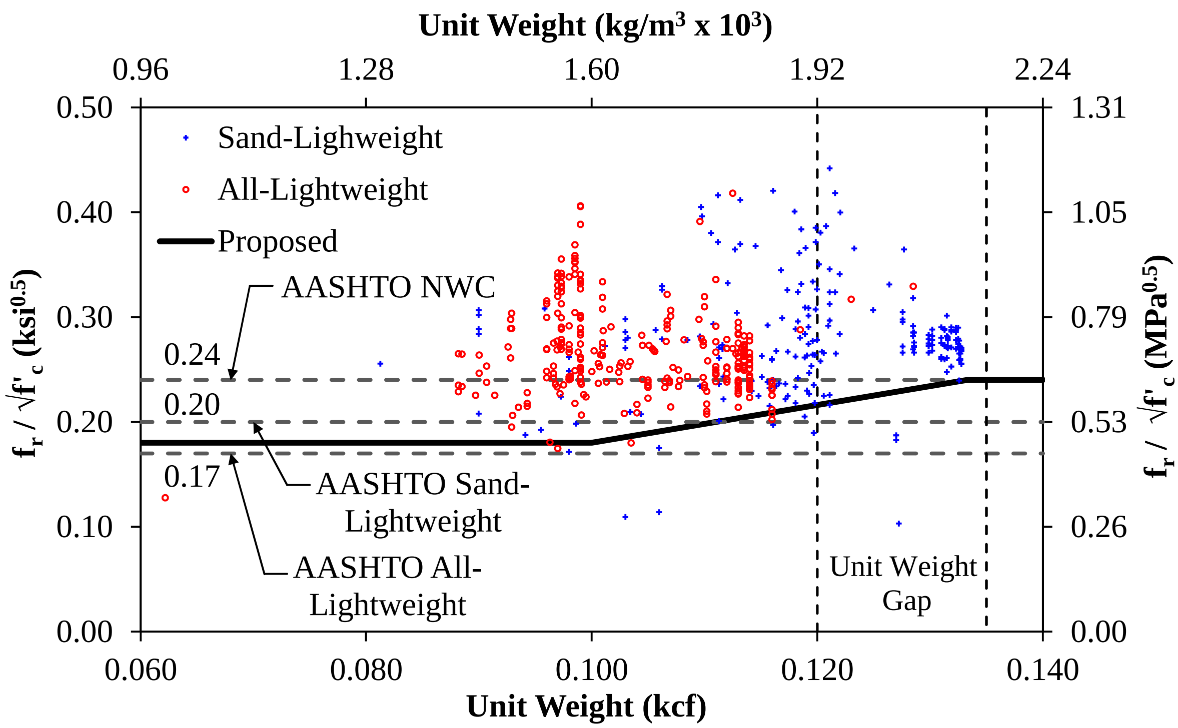


Figure 60. Graph. Modulus of Rupture to $\sqrt{f'_c}$ Ratio for Sand-Lightweight and All-Lightweight Concrete with Proposed Expression (Eq. 40).

COMPARISON OF MODULUS OF RUPTURE TO SPLITTING TENSILE STRENGTH

In the following section, an expression for the modulus of rupture that incorporates the proposed λ-factor is introduced. The λ-factor was previously correlated to splitting tensile in this document. In this section, the modulus of rupture will be compared to the splitting tensile strength in order to justify defining the material property f_r in terms of another material property f_{ct} (through the λ-factor).

For this comparison, a new subset was created for concrete mixes with tests results in both the f_{ct} subset and the wet f_r subset. The statistical information by ranges of compressive strength, modulus of rupture, splitting tensile strength, and unit weight is given in Table 30 for this combined f_{ct} and wet f_r subset database. A graphical comparison of f_r and f_{ct} is shown in Figure 61 and Figure 62 by range of compressive strength and unit weight. Of significance, these figures show a trend of f_r increasing proportional to f_{ct}, which supports the observations of previous research on a limited number of data points.(3)

Table 30. Distribution of Mechanical Properties in the Combined Subset Databases for Wet Modulus of Rupture Tests and Splitting Tensile Strength.

Range (ksi)	Property	No. of Data Lines	Mean	COV	Max.	Min.
$0 < f_r \leq 0.2$	f'_c (ksi)	1	2.190	--	--	--
	f_{ct} (ksi)	1	0.151	--	--	--
	f_r (ksi)	1	0.189	--	--	--
	w_c (kcf)	1	0.062	--	--	--
$0.2 < f_r \leq 0.4$	f'_c (ksi)	7	4.958	68.2%	10.486	2.016
	f_{ct} (ksi)	7	0.364	44.7%	0.566	0.203
	f_r (ksi)	7	0.343	11.2%	0.392	0.290
	w_c (kcf)	7	0.100	14.4%	0.127	0.081
$0.4 < f_r \leq 0.6$	f'_c (ksi)	42	4.985	32.9%	10.095	2.500
	f_{ct} (ksi)	42	0.393	20.0%	0.566	0.244
	f_r (ksi)	42	0.497	10.0%	0.599	0.418
	w_c (kcf)	42	0.112	8.1%	0.127	0.090
$0.6 < f_r \leq 0.8$	f'_c (ksi)	46	6.735	18.7%	9.050	3.300
	f_{ct} (ksi)	46	0.527	16.5%	0.689	0.295
	f_r (ksi)	46	0.693	7.5%	0.798	0.610
	w_c (kcf)	46	0.113	6.8%	0.122	0.090
$0.8 < f_r$	f'_c (ksi)	38	9.244	29.8%	14.852	4.873
	f_{ct} (ksi)	38	0.619	18.9%	0.862	0.435
	f_r (ksi)	38	0.943	10.3%	1.185	0.800
	w_c (kcf)	38	0.116	6.0%	0.129	0.101

Units: 1.0 ksi = 6.89 MPa, 0.001 kcf = 16.01 kg/m^3

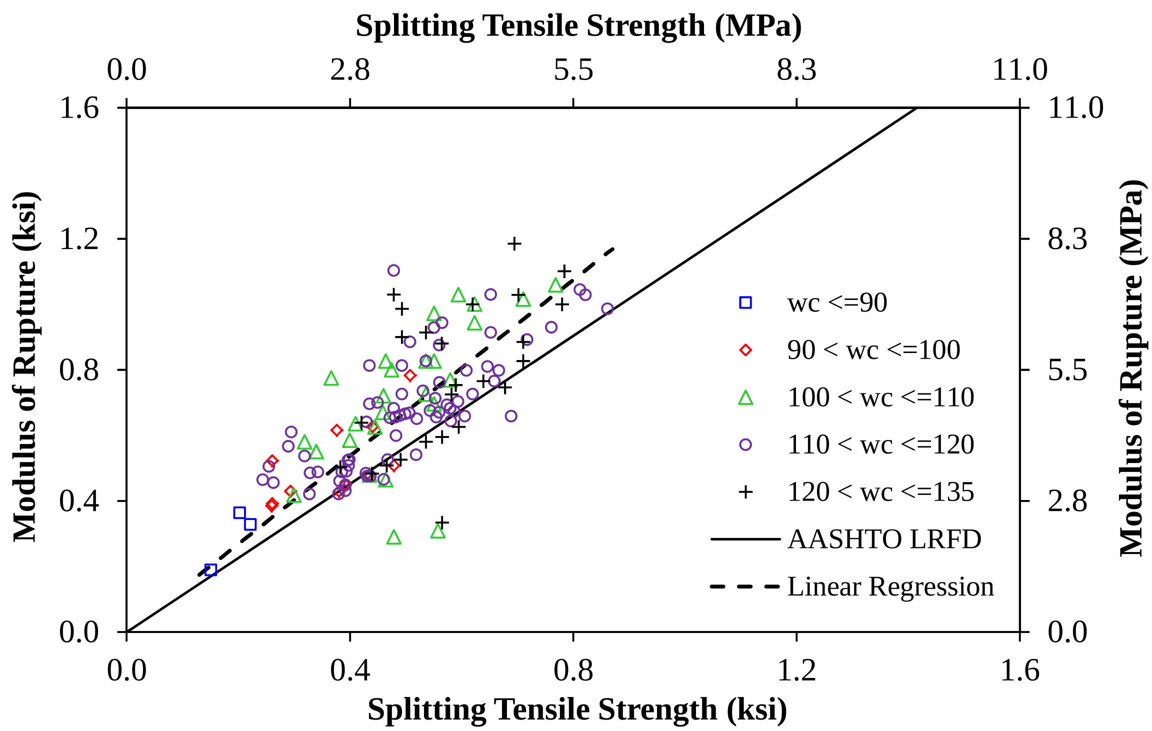


Figure 61. Graph. Modulus of Rupture Compared to Splitting Tensile Strength for the Combined f_{ct} and Wet f_r Subset Showing Variation by Unit Weight with AASHTO LRFD Expression (Eq. 37) and Linear Regression (Eq. 38).

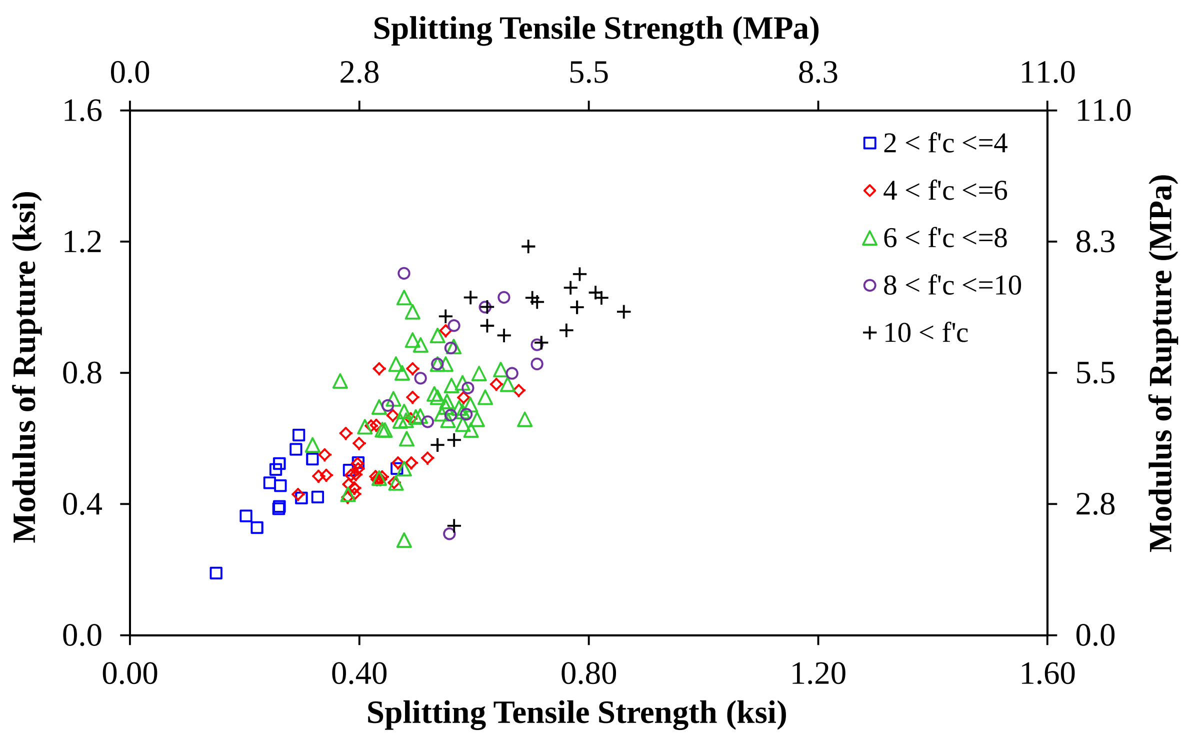


Figure 62. Graph. Modulus of Rupture Compared to Splitting Tensile Strength for the Combined f_{ct} and Wet f_r Subset Showing Variation by Compressive Strength.

A linear expression for the relationship between f_r and f_{ct} based on the individual expressions in the AASHTO LRFD Specifications for f_r and f_{ct} is given by Eq. 37. This expression is a ratio of f_r given by Eq. 34 and f_{ct} given by Eq. 5. The combined f_{ct} and wet f_r subset database is compared to Eq. 37 in Figure 61. This figure shows that Eq. 37 under-estimates the modulus of rupture for most of the data. An expression for a least squares linear regression with vertical-axis offset equal to zero is given by Eq. 38 and is also shown in Figure 61. The ratio of the slope given by the slope given by the linear regression expression (from Eq. 38) and the slope calculated from the AASHTO LRFD Expressions for f_r and f_{ct} (from Eq. 37) is 1.19 and implies that a larger factor multiplied by $\sqrt{f_c'}$ in the expression for f_r may be appropriate for predicting the modulus of rupture for specimens kept wet. When used to predict the cracking stress of flexural cracking strength of members allowed to dry, the smaller slope given by Eq. 37 seems adequate. An analysis of the data for members allowed to dry is included in the next section.

$$\frac{f_r}{f_{ct}} = \frac{0.24\sqrt{f_c'}}{0.212\sqrt{f_c'}} = 1.13 \qquad \text{(Eq. 37)}$$

$$f_r = 1.34 f_{ct} \qquad \text{(Eq. 38)}$$

PROPOSED DESIGN EXPRESSION FOR MODULUS OF RUPTURE

A new expression for f_r including the proposed LWC modification factor λ is given by Eq. 39. The λ-factor is given by Eq. 31. The proposed expression for f_r given by Eq. 39 is applicable to the calculation of the effective moment of inertia (Article 5.7.3.6.2), cracking control requirements (Article 5.7.3.4), and minimum area of flexural reinforcement (Article 5.7.3.3.2). The prediction of f_r can be rearranged as a ratio of f_r to $\sqrt{f_c'}$ as given by Eq. 40. Figure 60 shows a comparison of Eq. 40 with unit weight for the data from the wet f_r subset. Almost all of the sand-lightweight and all-lightweight concrete data is above the prediction curve given by Eq. 40 indicating an under-estimation of the modulus of rupture.

$$f_r = 0.24\lambda\sqrt{f_c'} \qquad \text{(Eq. 39)}$$

$$f_r/\sqrt{f_c'} = 0.24\lambda \qquad \text{(Eq. 40)}$$

The ratio of the tested modulus of ruptures from the wet f_r subset database to the f_r predicted by Eq. 39 is given in Table 31 for sand-lightweight concrete and Table 32 for all lightweight concrete. Table 31 and Table 32 also show test-to-prediction ratios for f_r predicted by the AASHTO LRFD Specifications. The AASHTO LRFD expressions gave slightly more conservative predictions than those from Eq. 39; however the mean test-to-prediction ratios for Eq. 39 were still 1.30 for sand-lightweight concrete and 1.41 for all-lightweight concrete. The test-to-prediction ratios for sand-lightweight concrete and all-lightweight concrete are shown graphically in Figure 63 for comparison with the current AASHTO LRFD expression and in Figure 64 for comparison with the prediction given by Eq. 39.

The remainder of the modulus of ruptures tests in the f_r subset database that were not explicitly stated in the literature as maintained wet until the time of testing were also compared to the f_r predicted by Eq. 39. These tests are referred to as the "dry f_r subset database" although some of the tests may have been tested wet, but were not adequately described in the literature to determine their moisture state at the time they were tested. The test-to-prediction ratios for the dry f_r subset is given in Table 33 and shown graphically in Figure 65.

The test-to-prediction ratios for the wet f_r subset, dry f_r subset, and the full f_r subset are given in Table 33. The mean test-to-prediction ratios for the wet and dry f_r subsets are similar for most ranges of unit weight. For three out of five ranges of unit weight, the mean ratios for the dry f_r subset is actually greater than mean ratios for the wet f_r subset. What is more significant is the number of tests that were over-estimated and had a test-to-prediction ratio less than unity or were significantly over-estimated with a ratio less than 0.8. In the wet f_r subset with unit weights greater than 0.090 kcf (1440 kg/m^3), the percentage of tests that were over-estimated was less than 5% in each range of unit weights. In comparison, the percentage of tests over-estimated in each range of unit weight for the dry f_r subsets was from 12 to 56%, and the percentage significantly over-estimated was from 5 to 36%. The large percentage of over-estimated f_r in the dry subset is not surprising given that the tested modulus of rupture can decrease with concrete age for specimens allowed to dry.[22-24] The measured f_r on a specimen allowed to dry includes the effects of both concrete flexural tensile strength and the tensile strains induced by drying shrinkage. The reduction in measured f_r shows the importance of comparing the design expression for f_r to test results on specimens kept continuously wet until the time of test order to only measure the effect of concrete flexural tensile strength.

Table 31. Test-to-Prediction Ratios of the Modulus of Rupture for Sand-Lightweight Concrete in the Wet f_r Subset using the AASHTO LRFD Expression (Eq. 34) and Proposed Expression (Eq. 39).

f_r Expression	Statistical Measure	Total	$w_c \leq 0.090$ kcf	$0.090 < w_c \leq 0.100$ kcf	$0.100 < w_c \leq 0.110$ kcf	$0.110 < w_c \leq 0.120$ kcf	$0.120 < w_c \leq 0.135$ kcf
AASHTO LRFD	No. Data Points	221	1	15	21	79	105
	Mean	1.394	1.277	1.222	1.344	1.415	1.414
	COV	19.1%	--	23.3%	37.8%	29.1%	21.6%
	Maximum	2.208	1.277	1.541	2.024	2.102	2.208
	Minimum	0.515	1.277	0.857	0.546	0.946	0.515
	Percent ≥ 1.0	94.6%	100.0	73.3%	85.7%	97.5%	97.1%
	Percent < 1.0	5.4%	0.0%	26.7%	14.3%	2.5%	2.9%
	Percent ≥ 1.2	81.0%	100.0	60.0%	71.4%	70.9%	93.3%
	Percent < 0.8	1.4%	0.0%	0.0%	9.5%	0.0%	1.0%
Proposed	No. Data Points	221	1	15	21	79	105
	Mean	1.299	1.419	1.357	1.412	1.351	1.227
	COV	20.8%	--	25.8%	38.4%	28.5%	21.3%
	Maximum	2.077	1.419	1.712	2.050	2.077	2.026
	Minimum	0.450	1.419	0.952	0.588	0.878	0.450
	Percent ≥ 1.0	95.0%	100.0	93.3%	85.7%	96.2%	96.2%
	Percent < 1.0	5.0%	0.0%	6.7%	14.3%	3.8%	3.8%
	Percent ≥ 1.2	54.8%	100.0	66.7%	71.4%	64.6%	41.9%
	Percent < 0.8	1.8%	0.0%	0.0%	9.5%	0.0%	1.9%

Units: 0.001 kcf = 16.01 kg/m^3

Table 32. Test-to-Prediction Ratios of the Modulus of Rupture for All-Lightweight Concrete in the Wet f_r Subset using the AASHTO LRFD Expression (Eq. 34) and Proposed Expression (Eq. 39).

f_r Expression	Statistical Measure	Total	$w_c \leq 0.090$ kcf	$0.090 < w_c \leq 0.100$ kcf	$0.100 < w_c \leq 0.110$ kcf	$0.110 < w_c \leq 0.120$ kcf	$0.120 < w_c \leq 0.135$ kcf
AASHTO LRFD	No. Data Points	277	7	108	63	97	2
	Mean	1.571	1.328	1.664	1.538	1.498	1.901
	COV	15.7%	27.2%	28.6%	19.9%	17.3%	5.2%
	Maximum	2.461	1.558	2.389	2.302	2.461	1.938
	Minimum	0.751	0.751	1.028	1.058	1.191	1.864
	Percent ≥ 1.0	99.6%	85.7%	100.0	100.0	100.0	100.0
	Percent < 1.0	0.4%	14.3%	0.0%	0.0%	0.0%	0.0%
	Percent ≥ 1.2	97.8%	85.7%	97.2%	98.4%	99.0%	100.0
	Percent < 0.8	0.4%	14.3%	0.0%	0.0%	0.0%	0.0%
Proposed	No. Data Points	277	7	108	63	97	2
	Mean	1.409	1.254	1.571	1.387	1.253	1.428
	COV	18.0%	25.7%	27.0%	18.0%	14.9%	0.5%
	Maximum	2.257	1.472	2.257	1.983	2.066	1.431
	Minimum	0.709	0.709	0.971	0.966	0.969	1.425
	Percent ≥ 1.0	98.2%	85.7%	99.1%	98.4%	97.9%	100.0
	Percent < 1.0	1.8%	14.3%	0.9%	1.6%	2.1%	0.0%
	Percent ≥ 1.2	81.6%	85.7%	93.5%	90.5%	61.9%	100.0
	Percent < 0.8	0.4%	14.3%	0.0%	0.0%	0.0%	0.0%

Units: 0.001 kcf = 16.01 kg/m^3

Table 33. Test-to-Prediction Ratios of the Modulus of Rupture Ratio for All-Lightweight Concrete in the Wet, Dry, and Full f_r Subset using the Proposed Expression (Eq. 39).

f_r Expression	Statistical Measure	Total	$w_c \leq 0.090$ kcf	$0.090 < w_c \leq 0.100$ kcf	$0.100 < w_c \leq 0.110$ kcf	$0.110 < w_c \leq 0.120$ kcf	$0.120 < w_c \leq 0.135$ kcf
Proposed - Wet	No. Data Points	498	8	123	84	176	107
	Mean	1.360	1.275	1.545	1.393	1.297	1.231
	COV	19.6%	24.5%	27.7%	24.4%	22.5%	21.3%
	Maximum	2.257	1.472	2.257	2.050	2.077	2.026
	Minimum	0.450	0.709	0.952	0.588	0.878	0.450
	Percent ≥ 1.0	96.8%	87.5%	98.4%	95.2%	97.2%	96.3%
	Percent < 1.0	3.2%	12.5%	1.6%	4.8%	2.8%	3.7%
	Percent ≥ 1.2	69.7%	87.5%	90.2%	85.7%	63.1%	43.0%
	Percent < 0.8	1.0%	12.5%	0.0%	2.4%	0.0%	1.9%
Proposed - Dry	No. Data Points	512	32	189	65	115	111
	Mean	1.240	1.303	1.273	1.435	0.995	1.307
	COV	31.8%	33.2%	41.9%	45.6%	34.1%	23.4%
	Maximum	2.281	1.873	2.281	2.235	1.714	1.856
	Minimum	0.257	0.257	0.502	0.532	0.480	0.479
	Percent ≥ 1.0	68.9%	87.5%	67.7%	75.4%	44.3%	87.4%
	Percent < 1.0	31.1%	12.5%	32.3%	24.6%	55.7%	12.6%
	Percent ≥ 1.2	58.4%	75.0%	56.1%	67.7%	31.3%	80.2%
	Percent < 0.8	16.0%	6.3%	14.8%	9.2%	35.7%	4.5%
Proposed - Full	No. Data Points	1010	40	312	149	291	218
	Mean	1.299	1.298	1.381	1.412	1.177	1.270
	COV	26.3%	31.4%	39.3%	35.2%	31.3%	22.7%
	Maximum	2.281	1.873	2.281	2.235	2.077	2.026
	Minimum	0.257	0.257	0.502	0.532	0.480	0.450
	Percent ≥ 1.0	82.7%	87.5%	79.8%	86.6%	76.3%	91.7%
	Percent < 1.0	17.3%	12.5%	20.2%	13.4%	23.7%	8.3%
	Percent ≥ 1.2	64.0%	77.5%	69.6%	77.9%	50.5%	61.9%
	Percent < 0.8	8.6%	7.5%	9.0%	5.4%	14.1%	3.2%

Units: 0.001 kcf = 16.01 kg/m^3

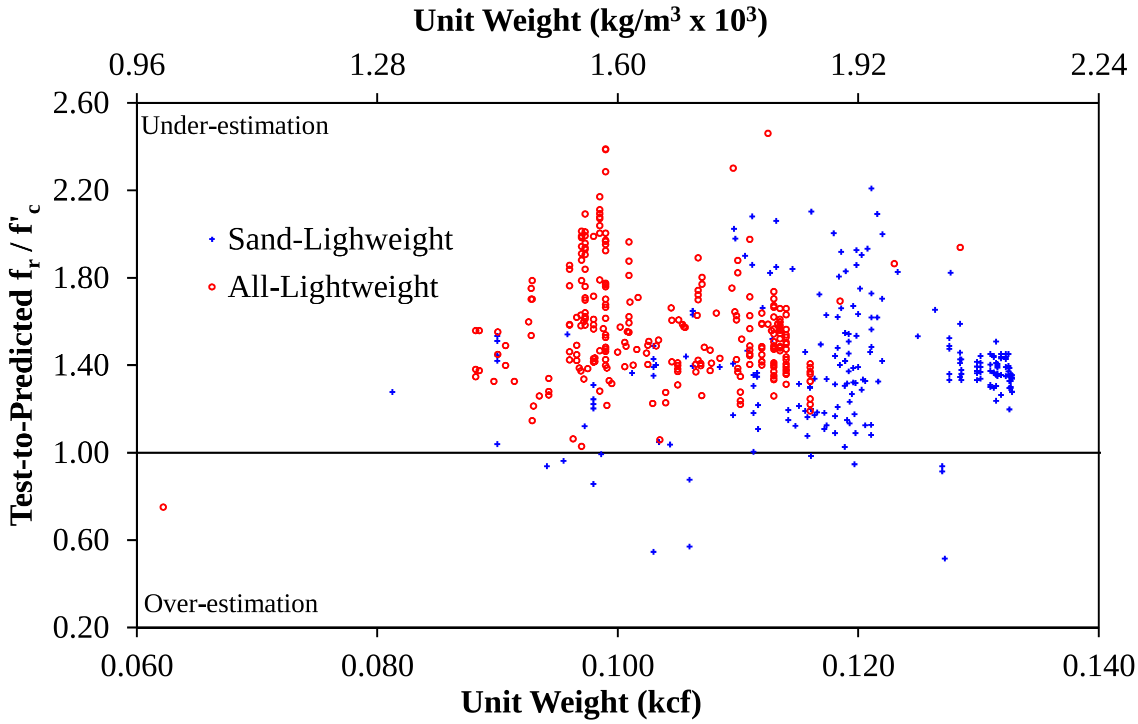


Figure 63. Graph. Test-to-Prediction Ratio for Modulus of Rupture for Sand-Lightweight and All-Lightweight Concrete in Wet f_r Subset with AASHTO LRFD Expression (Eq. 34).

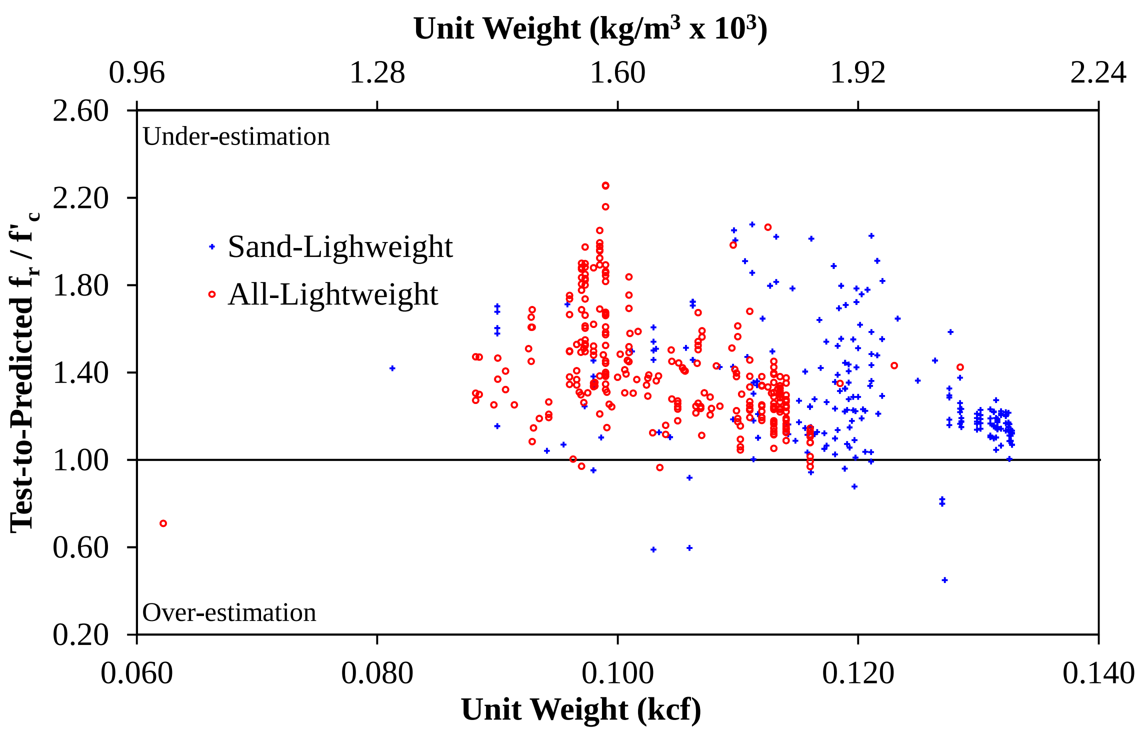


Figure 64. Graph. Test-to-Prediction Ratio for Modulus of Rupture for Sand-Lightweight and All-Lightweight Concrete in Wet f_r Subset with Proposed Expression (Eq. 39).

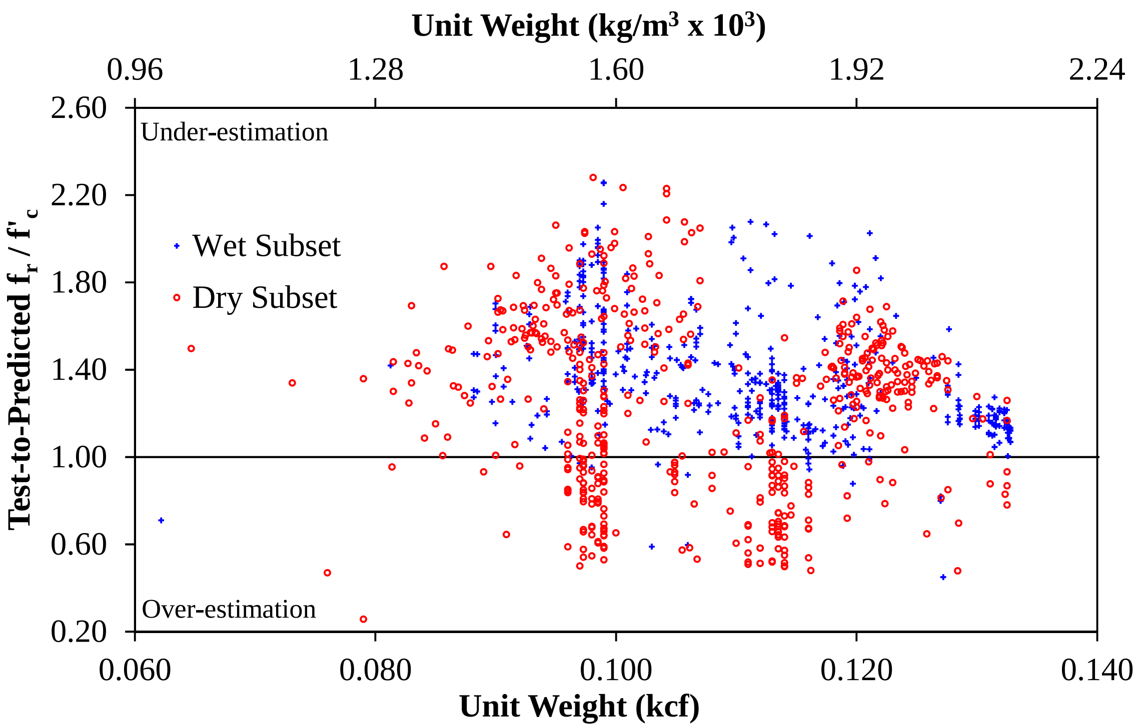


Figure 65. Graph. Test-to-Prediction Ratio for Modulus of Rupture for Full f_r Subset with Proposed Expression (Eq. 39).

CHAPTER 6. PRELIMINARY RECOMMENDATIONS FOR AASHTO LRFD SPECIFICATIONS

INTRODUCTION

This chapter summarizes several preliminary recommended changes to the AASHTO LRFD Specifications. This document has only considered the analysis of tests on the mechanical properties of LWC. Additional analysis on the structural performance of LWC members is needed before final recommendations can be made. The areas needing additional analysis include the development of mild reinforcement in tension, the transfer and development length of prestressing strands, and the shear resistance of reinforced and prestressed members. The effects of the preliminary recommendations made in this document will be included in those further analyses.

The analysis of the TFHRC LWC Database using the subset database for modulus of elasticity, the subset database for splitting tensile strength, and the subset database for modulus of rupture has resulted in several new expressions for E_c, LWC modification factor (λ-factor), and f_r. The new expressions are not based on the proportions of constituent materials and include tests from types of mix designs that are not explicitly permitted by the current edition of the AASHTO LRFD Specifications.[(1)] These mix types include specified density LWC (typically a blend of lightweight and normal weight coarse aggregate) and inverted mixes (normal weight coarse and lightweight fine aggregate). The new expressions are instead based on unit weight and as a result the definitions of sand-lightweight concrete and all-lightweight concrete would no longer be needed. This chapter proposes a revised definition of LWC that does not include the terms sand-lightweight concrete or all-lightweight concrete.

PROPOSED DEFINITION FOR LWC

The definition for lightweight concrete in the AASHTO LRFD Specifications (AASHTO 2012) is in Article 5.2 and states the following:

> *Lightweight Concrete* – Concrete containing lightweight aggregate and having an air-dry unit weight not exceeding 0.120 kcf, as determined by ASTM C567. Lightweight Concrete without natural sand is termed "all-lightweight concrete" and lightweight concrete in which all of the fine aggregate consists of normal weight sand is termed "sand-lightweight concrete."

This definition limits the unit weight for LWC to 0.120 kcf (1920 kg/m^3) and includes definitions for sand-lightweight and all-lightweight concrete. The proposed definition for LWC expands the range of unit weights and eliminates the definitions for terms relating to the constituent materials in LWC. The proposed definition for LWC is as follows:

Lightweight Concrete – Concrete containing lightweight aggregate and having an equilibrium density not exceeding 0.135 kcf, as determined by ASTM C567.

The term "air-dry unit weight" is used in the existing definition; however this term is not found in ASTM C567 (Standard Test Method for Determining Density of Structural Lightweight Concrete).(16) The AASHTO LRFD term "air-dry unit weight" is interpreted to be equivalent to the ASTM C567 term "equilibrium density". A statement could be added to the commentary to clarify the term "air-dry unit weight" or the term "equilibrium density" could be used in the definition for LWC.

PROPOSED EXPRESSION FOR MODULUS OF ELASTICITY

The expression for modulus of elasticity in the AASHTO LRFD Specifications is in Article 5.4.2.4 and states the following:

In the absence of measured data, the modulus of elasticity, E_c, for concretes with unit weights between 0.090 and 0.155 kcf and specified compressive strengths up to 15.0 ksi may be taken as:

$$E_c = 33{,}000\, K_1\, w_c^{1.5} \sqrt{f'_c} \qquad (5.4.2.4\text{-}1)$$

The proposed new expression for E_c would have the same limits on unit weight and specified compressive strength. The only proposed change is the expression for E_c itself. The proposed expression for modulus of elasticity is as follows:

$$E_c = 121{,}000\, K_1\, w_c^{2.0}\, f'^{\,0.33}_c \qquad (5.4.2.4\text{-}1)$$

The derivation for this expression for E_c is described previously in this document. The expression was given as Eq. 20 and Figure 66 shows the expression compared to the current AASHTO LRFD expression for an assumed unit weight of 0.110 kcf (1760 kg/m^3) and K_1 equal to unity.

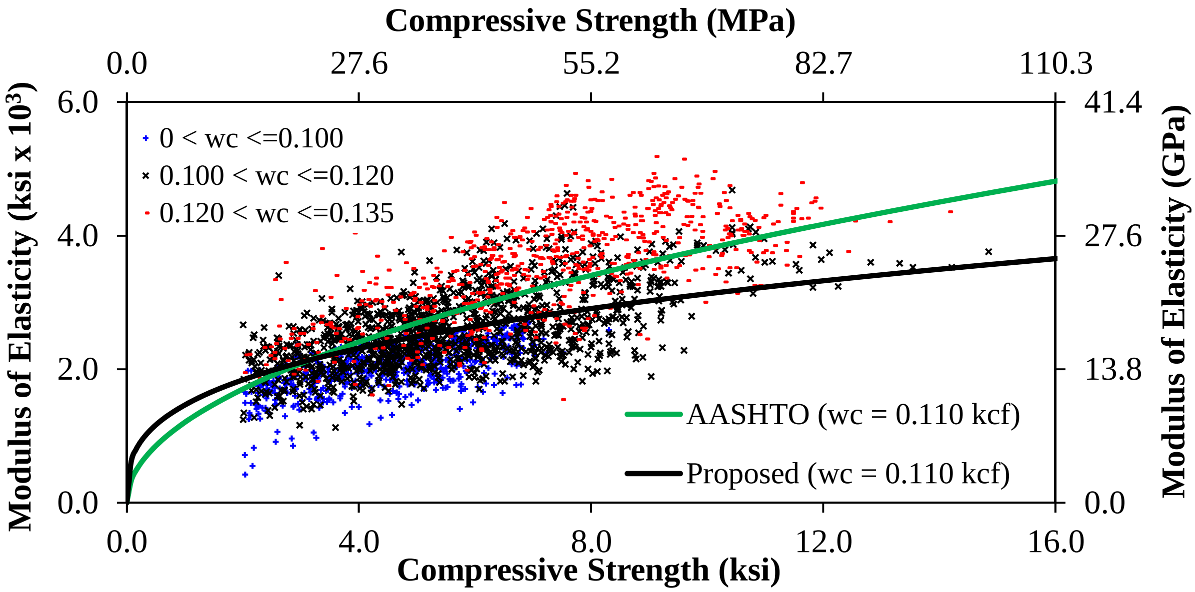


Figure 66. Graph. Modulus of Elasticity for Proposed Expression.

PROPOSED EXPRESSION FOR LWC MODIFICATION FACTOR

The concept of including a modification factor for LWC in expressions for predicting nominal resistance is included in many articles of the AASHTO LRFD Specifications. However, a single unified expression or LWC modification factor is not specified. This section proposes a new term, the λ-factor, to quantify the reduction in nominal resistance that could be included in any expression for nominal resistance. The language for the LWC modification factor, or λ-factor, could be based on the existing language for the modification factor for shear in Article 5.8.2.2 which states the following:

> Where lightweight aggregate concretes are used, the following modifications shall apply in determining resistance to torsion and shear:
>
> Where the average splitting tensile strength of lightweight concrete, f_{ct}, is specified, the term $\sqrt{f'_c}$ in the expressions given in Articles 5.8.2 and 5.8.3 shall be replaced by: $4.7\ f_{ct} \le \sqrt{f'_c}$
>
> Where f_{ct} is not specified, the term $0.75\ \sqrt{f'_c}$ for all lightweight concrete, and $0.85\ \sqrt{f'_c}$ for sand-lightweight concrete shall be substituted for $\sqrt{f'_c}$ in the expressions given in Articles 5.8.2 and 5.8.3
>
> Linear interpolation may be employed when partial sand replacement is used.

Article 5.8.2.2 specifically relates to torsion and shear, so a general λ-factor would not specifically reference those actions in its definition. The terms sand-lightweight concrete and all-lightweight concrete would not be used because the proposed new definition for LWC does not include them. The λ-factor relates to the material properties of structural LWC so the new Article for the definition for the λ-factor could be located in Article 5.4.2 "Normal Weight and Structural Lightweight Concrete". The λ-factor will be referred to as Article 5.4.2.8 in the present document. The proposed text for the λ-factor is as follows:

> Where lightweight aggregate concretes are used, the lightweight concrete modification factor, λ, shall be determined as:
>
> Where the average splitting tensile strength of lightweight concrete, f_{ct}, is specified, λ may be taken as: $4.7 f_{ct} / \sqrt{f'_c} \leq 1.0$
>
> Where f_{ct} is not specified, λ may be taken as:
>
> $$0.75 \leq \lambda = 7.5\, w_c \leq 1.0 \qquad (5.4.2.8\text{-}1)$$

The language for the λ-factor expression when f_{ct} is not specified follows the format of the ϕ-factor for flexure for prestressed and nonprestressed members in Article 5.5.4.2.1.

An illustration of the proposed expression for the λ-factor is shown in Figure 67 and the predicted splitting ratios (λ-factor × 0.212) are shown in Figure 68. The λ-factors implied in AASHTO LRFD for sand-lightweight concrete and all-lightweight concrete are also shown in Figure 68. Figure 68 shows that a considerable amount of the sand-lightweight concrete data is in the gap of unit weights not defined in the current AASHTO LRFD Specifications.

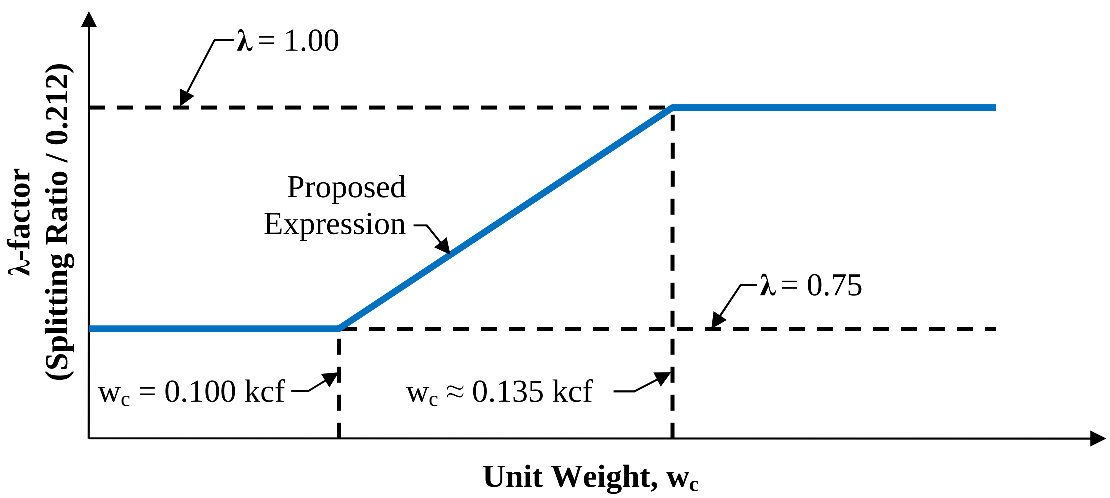


Figure 67. Illustration. Proposed Expression for λ-Factor.

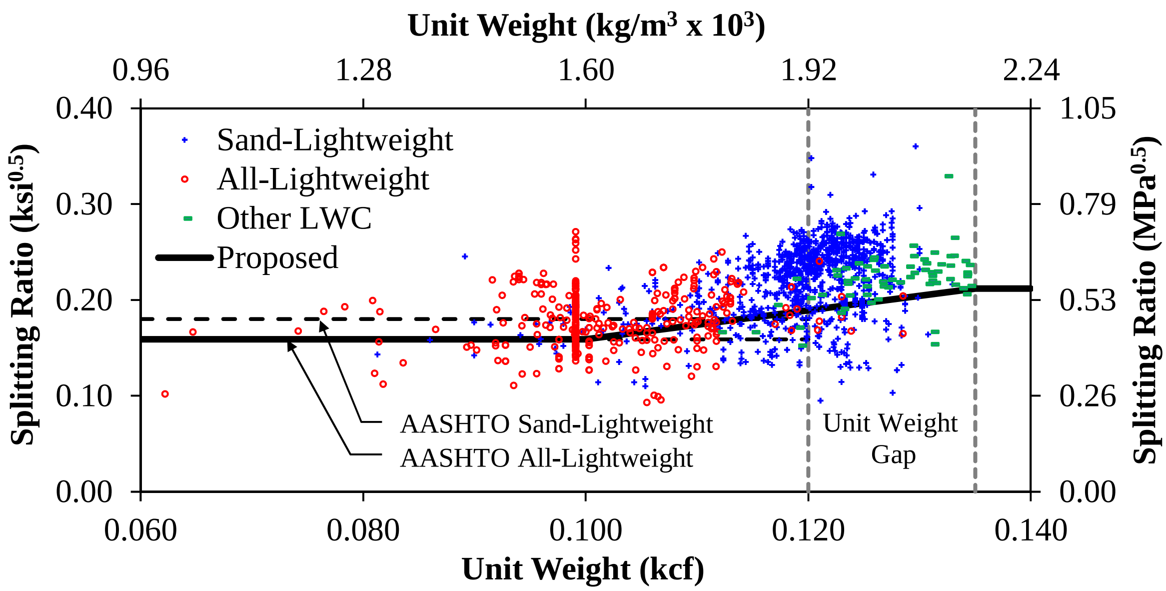


Figure 68. Graph. Splitting Ratio (f_{ct} / √f'$_c$) for the Proposed Expression (λ-factor × 0.212).

As stated previously, the effect of using the λ-factor in expressions for nominal resistance will need to be evaluated. The proposed λ-factor could then be included in the expressions for nominal resistance in the AASHTO LRFD Specifications. For example, the λ-factor could be added directly to design expressions for nominal shear resistance in Articles 5.8.2 and 5.8.3 and would replace the existing modification factor for LWC.

PROPOSED EXPRESSION FOR MODULUS OF RUPTURE

The expression for modulus of rupture in the AASHTO LRFD Specifications is in Article 5.4.2.6 and states the following:

> Unless determined by physical tests, the modulus of rupture, f_r, for specified compressive strengths up to 15.0 ksi may be taken as:
>
> For normal-weight concrete:
>
> Except as specified below: 0.24 √f'$_c$
>
> When used to calculate the cracking moment of a member in Article 5.8.3.4.3: 0.20 √f'$_c$
>
> For lightweight concrete:
>
> For sand-lightweight concrete: 0.20 √f'$_c$
>
> For all-lightweight concrete: 0.17 √f'$_c$

The proposed expression for modulus of rupture is as follows:

For normal-weight and light-weight concrete:

Except as specified below: $0.24 \lambda \sqrt{f'_c}$

When used to calculate the cracking moment of a member in Article 5.8.3.4.3: $0.20 \lambda \sqrt{f'_c}$

The proposed new expressions for f_r include the proposed λ-factor and would be applicable to both NWC and LWC. The expression for f_r used to calculate the cracking moment of a member in Article 5.8.3.4.3 (V_{ci}) includes the proposed λ-factor for consistency. The f_r expression for use with Article 5.8.3.4.3 will need to be validated on shear test data from LWC members available in the literature before it is proposed for inclusion into the AASHTO LRFD Specifications

The ratio of the predicted f_r (i.e., $0.24 \lambda\sqrt{f_c'}$) to $\sqrt{f_c'}$ is shown in Figure 69 with sand-lightweight and all-lightweight concrete data. Figure 69 shows that most of the test data is above the predicted f_r (under-estimation) and that a considerable amount of the sand-lightweight concrete data is in the gap of unit weights not defined in the current AASHTO LRFD Specifications.

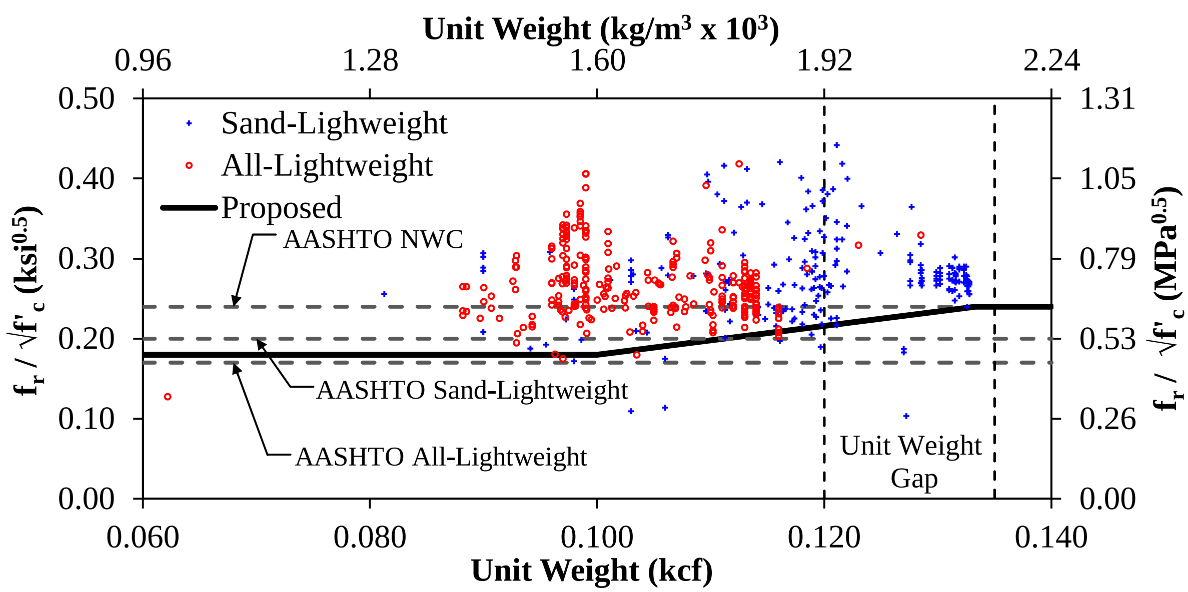


Figure 69. Graph. f_r / $\sqrt{f'_c}$ for the Proposed Expression ($0.24 \lambda\sqrt{f_c'}$).

CHAPTER 7. CONCLUDING REMARKS

INTRODUCTION

This document describes mechanical property tests on specified density concrete, describes a LWC mechanical property database, and presents potential revisions to the AASHTO LRFD Specifications relating to the definition and mechanical properties of LWC. The proposed design expressions for modulus of elasticity, LWC modification factor, and modulus of rupture were compared to tested values in a LWC database collected as part of this research effort. A description of the database and the development and evaluation of prediction expressions is included in this document.

Future phases of this research compilation and analysis effort will include synthesis of past work on structural performance of LWC. The test results will be compared to the prediction expressions for nominal resistance in the AASHTO LRFD Specifications incorporating appropriate proposed revisions for LWC mechanical properties as presented in this document.

ACKNOWLEDGEMENTS

This document presents results from a research program and is intended to both facilitate broader understanding of the performance of lightweight concrete and to assist AASHTO SCOBS T-10 as they consider relevant revisions to Chapter 5 of the AASHTO LRFD Bridge Design Specification.(1) It does not constitute a policy statement or a recommendation from FHWA. Additionally, the publication of this article does not necessarily indicate approval or endorsement of the findings, opinions, conclusions, or recommendations either inferred or specifically expressed herein by FHWA or the United States Government. This document was created by PSI on behalf of FHWA as part of contract DTFH61-10-D-00017.

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CHAPTER 8. REFERENCES

INTRODUCTION

This chapter gives the references for the document in three parts. The first part consists of references cited in the document text. The second part consists of references for the mechanical test data used in the TFHRC LWC Database. At the end of each reference in this section, the number of data lines obtained from the reference is included in brackets. The third part consists of references on LWC that were reviewed, but did not have test data that was included in the database. Taken together, the references in the second and third sections constitute a bibliography on LWC.

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APPENDIX A

This appendix contains tables of the batch quantities for the concrete produced at the precaster's facility. The information was collected by the precaster's personnel and reproduced here for informational purposes only.

Table 34. Batch Quantities for HG Mix on 5/14/2008, Batch 1 of 4.75 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	2519 lb	2520 lb
Lightweight Coarse	13.4	10.3	3922 lb	3990 lb
Normal Weight Sand	4.40	0.51	5857 lb	5850 lb
Type III Portland Cement			3563 lb	3522 lb
Air Entrainer			10 oz	9 oz
High Range Water Reducer			160 oz	164 oz
Water Reducer			53 oz	55 oz
Water added				718 lb
Water from Aggregate				456 lb
Total Water			1268 lb	1174 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 35. Batch Quantities for HG Mix on 5/14/2008, Batch 2 of 4.75 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	2519 lb	2690 lb
Lightweight Coarse	13.4	10.3	3922 lb	3930 lb
Normal Weight Sand	4.66	0.51	5872 lb	5860 lb
Type III Portland Cement			3563 lb	3554 lb
Air Entrainer			10 oz	10 oz
High Range Water Reducer			160 oz	164 oz
Water Reducer			53 oz	55 oz
Water added				702 lb
Water from Aggregate				492 lb
Total Water			1268 lb	1194 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 36. Batch Quantities for SG Mix on 5/14/2008, Batch 1 of 4.5 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	1147 lb	1170 lb
Lightweight Coarse	11.4	9.0	4057 lb	4080 lb
Normal Weight Sand	3.94	0.51	5690 lb	5640 lb
Type III Portland Cement			3600 lb	3592 lb
Air Entrainer			10 oz	12 oz
High Range Water Reducer			162 oz	165 oz
Water Reducer			36 oz	36 oz
Water added				676 lb
Water from Aggregate				430 lb
Total Water			1125 lb	1106 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 37. Batch Quantities for SG Mix on 5/14/2008, Batch 2 of 4.5 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	1147 lb	1160 lb
Lightweight Coarse	11.4	9.0	4057 lb	4020 lb
Normal Weight Sand	3.97	0.51	5692 lb	5690 lb
Type III Portland Cement			3600 lb	3592 lb
Air Entrainer			10 oz	12 oz
High Range Water Reducer			162 oz	163 oz
Water Reducer			36 oz	38 oz
Water added				678 lb
Water from Aggregate				386 lb
Total Water			1125 lb	1064 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 38. Batch Quantities for SG Mix on 5/14/2008, Batch 3 of 4.0 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	1020 lb	1020 lb
Lightweight Coarse	11.4	9.0	3607 lb	3610 lb
Normal Weight Sand	4.19	0.51	5071 lb	5030 lb
Type III Portland Cement			3200 lb	3198 lb
Air Entrainer			9 oz	11 oz
High Range Water Reducer			144 oz	145 oz
Water Reducer			32 oz	31 oz
Water added				606 lb
Water from Aggregate				354 lb
Total Water			1000 lb	960 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 39. Batch Quantities for UG Mix on 5/14/2008, Batch 1 of 4.75 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	1865 lb	2030 lb
Lightweight Coarse	16.9	14.5	3601 lb	3770 lb
Normal Weight Sand	4.48	0.51	6267 lb	6240 lb
Type III Portland Cement			2850 lb	2784 lb
Class F Fly Ash			713 lb	706 lb
Air Entrainer			11 oz	12 oz
High Range Water Reducer			160 oz	162 oz
Water Reducer			62 oz	60 oz
Water added				706 lb
Water from Aggregate				378 lb
Total Water			1231 lb	1084 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 40. Batch Quantities for UG Mix on 5/14/2008, Batch 2 of 4.75 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	1865 lb	1900 lb
Lightweight Coarse	16.9	14.5	3601 lb	3660 lb
Normal Weight Sand	4.47	0.51	6267 lb	6270 lb
Type III Portland Cement			2850 lb	2808 lb
Class F Fly Ash			713 lb	696 lb
Air Entrainer			11 oz	12 oz
High Range Water Reducer			160 oz	162 oz
Water Reducer			62 oz	63 oz
Water added				682 lb
Water from Aggregate				414 lb
Total Water			1230 lb	1096 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 41. Batch Quantities for UG Mix on 5/14/2008, Batch 3 of 2.0 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	785 lb	780 lb
Lightweight Coarse	16.9	14.5	1516 lb	1500 lb
Normal Weight Sand	4.42	0.51	2637 lb	2670 lb
Type III Portland Cement			1200 lb	1128 lb
Class F Fly Ash			300 lb	256 lb
Air Entrainer			5 oz	5 oz
High Range Water Reducer			68 oz	71 oz
Water Reducer			26 oz	28 oz
Water added				238 lb
Water from Aggregate				172 lb
Total Water			518 lb	410 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 42. Batch Quantities for HG Mix on 5/29/2008, Batch 1 of 5.0 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	2652 lb	2790 lb
Lightweight Coarse	13.4	10.3	4128 lb	4110 lb
Normal Weight Sand	4.31	0.51	6159 lb	6130 lb
Type III Portland Cement			3750 lb	3720 lb
Air Entrainer			10 oz	11 oz
High Range Water Reducer			169 oz	171 oz
Water Reducer			94 oz	95 oz
Water added				648 lb
Water from Aggregate				504 lb
Total Water			1335 lb	1152 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 43. Batch Quantities for HG Mix on 5/29/2008, Batch 2 of 5.0 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	2652 lb	3000 lb
Lightweight Coarse	13.4	10.3	4128 lb	4120 lb
Normal Weight Sand	4.36	0.51	6162 lb	6110 lb
Type III Portland Cement			3750 lb	3736 lb
Air Entrainer			10 oz	11 oz
High Range Water Reducer			169 oz	172 oz
Water Reducer			94 oz	94 oz
Water added				644 lb
Water from Aggregate				536 lb
Total Water			1335 lb	1180 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 44. Batch Quantities for SG Mix on 5/29/2008, Batch 1 of 4.75 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	1211 lb	1400 lb
Lightweight Coarse	11.4	9.0	4283 lb	4340 lb
Normal Weight Sand	4.37	0.51	6032 lb	6000 lb
Type III Portland Cement			3800 lb	3772 lb
Air Entrainer			11 oz	13 oz
High Range Water Reducer			171 oz	173 oz
Water Reducer			76 oz	77 oz
Water added				554 lb
Water from Aggregate				463 lb
Total Water			1187 lb	1017 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 45. Batch Quantities for SG Mix on 5/29/2008, Batch 2 of 4.75 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	1211 lb	1270 lb
Lightweight Coarse	11.4	9.0	4283 lb	4310 lb
Normal Weight Sand	4.29	0.51	6028 lb	5990 lb
Type III Portland Cement			3800 lb	3768 lb
Air Entrainer			11 oz	13 oz
High Range Water Reducer			171 oz	172 oz
Water Reducer			76 oz	77 oz
Water added				560 lb
Water from Aggregate				458 lb
Total Water			1187 lb	1018 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 46. Batch Quantities for UG Mix on 5/29/2008, Batch 1 of 5.0 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	1963 lb	2010 lb
Lightweight Coarse	16.9	14.5	3791 lb	3860 lb
Normal Weight Sand	4.17	0.51	6576 lb	6540 lb
Type III Portland Cement			3000 lb	2968 lb
Class F Fly Ash			750 lb	748 lb
Air Entrainer			11 oz	13 oz
High Range Water Reducer			169 oz	170 oz
Water Reducer			94 oz	95 oz
Water added				652 lb
Water from Aggregate				431 lb
Total Water			1295 lb	1083 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 47. Batch Quantities for UG Mix on 5/29/2008, Batch 2 of 5.0 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	1963 lb	2440 lb
Lightweight Coarse	16.9	14.5	3791 lb	3870 lb
Normal Weight Sand	3.76	0.51	6548 lb	6570 lb
Type III Portland Cement			3000 lb	2980 lb
Class F Fly Ash			750 lb	718 lb
Air Entrainer			11 oz	13 oz
High Range Water Reducer			169 oz	171 oz
Water Reducer			94 oz	94 oz
Water added				678 lb
Water from Aggregate				409 lb
Total Water			1295 lb	1087 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 48. Batch Quantities for UG Mix on 5/30/2008, Batch 1 of 5.0 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	1963 lb	1990 lb
Lightweight Coarse	16.9	14.5	3791 lb	3900 lb
Normal Weight Sand	5.90	0.51	6584 lb	6660 lb
Type III Portland Cement			3000 lb	2984 lb
Class F Fly Ash			750 lb	730 lb
Air Entrainer			11 oz	12 oz
High Range Water Reducer			169 oz	170 oz
Water Reducer			94 oz	94 oz
Water added				480 lb
Water from Aggregate				552 lb
Total Water			1295 lb	1032 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 49. Batch Quantities for UG Mix on 5/30/2008, Batch 2 of 5.0 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	1963 lb	2500 lb
Lightweight Coarse	16.9	14.5	3791 lb	3860 lb
Normal Weight Sand	5.57	0.51	6673 lb	6690 lb
Type III Portland Cement			3000 lb	2958 lb
Class F Fly Ash			750 lb	736 lb
Air Entrainer			11 oz	14 oz
High Range Water Reducer			169 oz	171 oz
Water Reducer			94 oz	94 oz
Water added				504 lb
Water from Aggregate				567 lb
Total Water			1295 lb	1071 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 50. Batch Quantities for UG Mix on 5/30/2008, Batch 3 of 5.0 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	1963 lb	2500 lb
Lightweight Coarse	16.9	14.5	3791 lb	3860 lb
Normal Weight Sand	5.57	0.51	6673 lb	6690 lb
Type III Portland Cement			3000 lb	2958 lb
Class F Fly Ash			750 lb	736 lb
Air Entrainer			11 oz	14 oz
High Range Water Reducer			169 oz	171 oz
Water Reducer			94 oz	94 oz
Water added				504 lb
Water from Aggregate				567 lb
Total Water			1295 lb	1071 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 51. Batch Quantities for HG Mix on 6/3/2008, Batch 1 of 5.0 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	2652 lb	2630 lb
Lightweight Coarse	13.4	10.3	4128 lb	4090 lb
Normal Weight Sand	4.09	0.51	6145 lb	6090 lb
Type III Portland Cement			3750 lb	3734 lb
Air Entrainer			10 oz	11 oz
High Range Water Reducer			169 oz	170 oz
Water Reducer			94 oz	95 oz
Water added				612 lb
Water from Aggregate				567 lb
Total Water			1335 lb	1179 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 52. Batch Quantities for HG Mix on 6/3/2008, Batch 2 of 5.0 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	2652 lb	2840 lb
Lightweight Coarse	13.4	10.3	4128 lb	4110 lb
Normal Weight Sand	4.03	0.51	6141 lb	6130 lb
Type III Portland Cement			3750 lb	3724 lb
Air Entrainer			10 oz	10 oz
High Range Water Reducer			169 oz	172 oz
Water Reducer			94 oz	96 oz
Water added				616 lb
Water from Aggregate				569 lb
Total Water			1335 lb	1185 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 53. Batch Quantities for HG Mix on 6/3/2008, Batch 3 of 5.0 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	2652 lb	2630 lb
Lightweight Coarse	16.9	14.5	4128 lb	4120 lb
Normal Weight Sand	5.57	0.51	6143 lb	6090 lb
Type III Portland Cement			3750 lb	3728 lb
Air Entrainer			10 oz	13 oz
High Range Water Reducer			169 oz	171 oz
Water Reducer			94 oz	94 oz
Water added				738 lb
Water from Aggregate				571 lb
Total Water			1335 lb	1309 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 54. Batch Quantities for SG Mix on 6/9/2008, Batch 1 of 4.75 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	1211 lb	1210 lb
Lightweight Coarse	11.4	9.0	4283 lb	4250 lb
Normal Weight Sand	4.18	0.51	6021 lb	6010 lb
Type III Portland Cement			3800 lb	3764 lb
Air Entrainer			11 oz	11 oz
High Range Water Reducer			171 oz	173 oz
Water Reducer			76 oz	76 oz
Water added				542 lb
Water from Aggregate				439 lb
Total Water			1187 lb	981 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 55. Batch Quantities for SG Mix on 6/9/2008, Batch 2 of 4.75 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	1211 lb	1200 lb
Lightweight Coarse	11.4	9.0	4283 lb	4240 lb
Normal Weight Sand	4.17	0.51	6020 lb	6000 lb
Type III Portland Cement			3800 lb	3784 lb
Air Entrainer			11 oz	12 oz
High Range Water Reducer			171 oz	173 oz
Water Reducer			76 oz	76 oz
Water added				542 lb
Water from Aggregate				545 lb
Total Water			1188 lb	1087 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 56. Batch Quantities for UG Mix on 6/9/2008, Batch 1 of 5.0 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	1963 lb	2080 lb
Lightweight Coarse	16.9	14.5	3791 lb	3860 lb
Normal Weight Sand	4.01	0.51	6565 lb	6560 lb
Type III Portland Cement			3000 lb	2926 lb
Class F Fly Ash			750 lb	684 lb
Air Entrainer			11 oz	13 oz
High Range Water Reducer			169 oz	172 oz
Water Reducer			94 oz	95 oz
Water added				612 lb
Water from Aggregate				434 lb
Total Water			1295 lb	1046 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 57. Batch Quantities for UG Mix on 6/9/2008, Batch 2 of 5.0 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	1963 lb	2110 lb
Lightweight Coarse	16.9	14.5	3791 lb	3860 lb
Normal Weight Sand	4.13	0.51	6573 lb	6530 lb
Type III Portland Cement			3000 lb	2950 lb
Class F Fly Ash			750 lb	722 lb
Air Entrainer			11 oz	12 oz
High Range Water Reducer			169 oz	171 oz
Water Reducer			94 oz	95 oz
Water added				604 lb
Water from Aggregate				431 lb
Total Water			1295 lb	1035 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 58. Batch Quantities for UG Mix on 6/9/2008, Batch 3 of 5.0 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	1963 lb	2030 lb
Lightweight Coarse	16.9	14.5	3791 lb	3860 lb
Normal Weight Sand	4.30	0.51	6584 lb	6570 lb
Type III Portland Cement			3000 lb	2986 lb
Class F Fly Ash			750 lb	742 lb
Air Entrainer			11 oz	12 oz
High Range Water Reducer			169 oz	172 oz
Water Reducer			94 oz	94 oz
Water added				590 lb
Water from Aggregate				473 lb
Total Water			1295 lb	1063 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 59. Batch Quantities for HG Mix on 6/10/2008, Batch 1 of 5.0 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	2652 lb	2860 lb
Lightweight Coarse	13.4	10.3	4128 lb	4170 lb
Normal Weight Sand	4.01	0.51	6140 lb	6120 lb
Type III Portland Cement			3750 lb	3720 lb
Air Entrainer			10 oz	10 oz
High Range Water Reducer			169 oz	170 oz
Water Reducer			94 oz	94 oz
Water added				740 lb
Water from Aggregate				478 lb
Total Water			1335 lb	1218 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 60. Batch Quantities for UG Mix on 6/10/2008, Batch 1 of 5.0 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	1963 lb	2010 lb
Lightweight Coarse	16.9	14.5	3791 lb	3800 lb
Normal Weight Sand	4.01	0.51	6565 lb	6510 lb
Type III Portland Cement			3000 lb	2974 lb
Class F Fly Ash			750 lb	732 lb
Air Entrainer			11 oz	13 oz
High Range Water Reducer			169 oz	170 oz
Water Reducer			94 oz	94 oz
Water added				608 lb
Water from Aggregate				454 lb
Total Water			1296 lb	1062 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 61. Batch Quantities for HG Mix on 6/13/2008, Batch 1 of 5.0 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	2652 lb	2620 lb
Lightweight Coarse	13.4	10.3	4128 lb	--
Normal Weight Sand	0.51	0.51	5925 lb	--
Type III Portland Cement			3750 lb	--
Air Entrainer			10 oz	11 oz
High Range Water Reducer			169 oz	171 oz
Water Reducer			94 oz	94 oz
Water added				--
Water from Aggregate				--
Total Water			1335 lb	--

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 62. Batch Quantities for HG Mix on 6/13/2008, Batch 2 of 5.0 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	1061 lb	1330 lb
Lightweight Coarse	13.4	10.3	1651 lb	1640 lb
Normal Weight Sand	4.73	0.51	2475 lb	2460 lb
Type III Portland Cement			1500 lb	1456 lb
Air Entrainer			4 oz	4 oz
High Range Water Reducer			68 oz	71 oz
Water Reducer			38 oz	37 oz
Water added				158 lb
Water from Aggregate				254 lb
Total Water			534 lb	412 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 63. Batch Quantities for UG Mix on 6/13/2008, Batch 1 of 5.0 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	1963 lb	2350 lb
Lightweight Coarse	16.9	14.5	3791 lb	3890 lb
Normal Weight Sand	4.70	0.51	6612 lb	6550 lb
Type III Portland Cement			3000 lb	2978 lb
Class F Fly Ash			750 lb	738 lb
Air Entrainer			11 oz	11 oz
High Range Water Reducer			169 oz	172 oz
Water Reducer			94 oz	95 oz
Water added				564 lb
Water from Aggregate				509 lb
Total Water			1295 lb	1073 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 64. Batch Quantities for HG Mix on 6/20/2008, Batch 1 of 5.0 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	2652 lb	2840 lb
Lightweight Coarse	13.4	10.3	4128 lb	4150 lb
Normal Weight Sand	4.84	0.51	6193 lb	6250 lb
Type III Portland Cement			3750 lb	3720 lb
Air Entrainer			10 oz	10 oz
High Range Water Reducer			169 oz	171 oz
Water Reducer			94 oz	95 oz
Water added				588 lb
Water from Aggregate				541 lb
Total Water			1335 lb	1129 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 65. Batch Quantities for HG Mix on 6/20/2008, Batch 2 of 5.0 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	2652 lb	2630 lb
Lightweight Coarse	13.4	10.3	4128 lb	4100 lb
Normal Weight Sand	4.81	0.51	6191 lb	6180 lb
Type III Portland Cement			3750 lb	3734 lb
Air Entrainer			10 oz	10 oz
High Range Water Reducer			169 oz	172 oz
Water Reducer			94 oz	95 oz
Water added				590 lb
Water from Aggregate				535 lb
Total Water			1335 lb	1125 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 66. Batch Quantities for HG Mix on 6/20/2008, Batch 3 of 5.0 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	2652 lb	2740 lb
Lightweight Coarse	13.4	10.3	4128 lb	4110 lb
Normal Weight Sand	4.82	0.51	6192 lb	6140 lb
Type III Portland Cement			3750 lb	3726 lb
Air Entrainer			10 oz	10 oz
High Range Water Reducer			169 oz	172 oz
Water Reducer			94 oz	95 oz
Water added				590 lb
Water from Aggregate				611 lb
Total Water			1335 lb	1201 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 67. Batch Quantities for HG Mix on 6/20/2008, Batch 4 of 5.0 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	2652 lb	2660 lb
Lightweight Coarse	13.4	10.3	4128 lb	4100 lb
Normal Weight Sand	4.56	0.51	6175 lb	6190 lb
Type III Portland Cement			3750 lb	3718 lb
Air Entrainer			10 oz	11 oz
High Range Water Reducer			169 oz	171 oz
Water Reducer			94 oz	94 oz
Water added				606 lb
Water from Aggregate				620 lb
Total Water			1335 lb	1226 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 68. Batch Quantities for SG Mix on 6/20/2008, Batch 1 of 5.0 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	1275 lb	1270 lb
Lightweight Coarse	11.4	9.0	4508 lb	4500 lb
Normal Weight Sand	5.06	0.51	6396 lb	6360 lb
Type III Portland Cement			4000 lb	3982 lb
Air Entrainer			11 oz	13 oz
High Range Water Reducer			180 oz	184 oz
Water Reducer			80 oz	80 oz
Water added				476 lb
Water from Aggregate				533 lb
Total Water			1250 lb	1009 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 69. Batch Quantities for SG Mix on 6/20/2008, Batch 2 of 5.0 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	1211 lb	1200 lb
Lightweight Coarse	11.4	9.0	4283 lb	4240 lb
Normal Weight Sand	4.17	0.51	6020 lb	6000 lb
Type III Portland Cement			3800 lb	3784 lb
Air Entrainer			11 oz	12 oz
High Range Water Reducer			171 oz	173 oz
Water Reducer			76 oz	76 oz
Water added				542 lb
Water from Aggregate				545 lb
Total Water			1188 lb	1087 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

Table 70. Batch Quantities for UG Mix on 6/20/2008, Batch 1 of 5.0 CY.

Material	Measured Moisture (percent)	Moisture at SSD (percent)	Target Amount	Measured Amount
Normal Weight Coarse	2.85	0.90	1963 lb	2240 lb
Lightweight Coarse	16.9	14.5	3791 lb	3880 lb
Normal Weight Sand	5.02	0.51	6569 lb	6670 lb
Type III Portland Cement			3000 lb	2958 lb
Class F Fly Ash			750 lb	762 lb
Air Entrainer			11 oz	12 oz
High Range Water Reducer			169 oz	172 oz
Water Reducer			94 oz	94 oz
Water added				542 lb
Water from Aggregate				554 lb
Total Water			1296 lb	1096 lb

Units: 1.0 yd^3 (CY) = 0.836 m^3, 1.0 lb = 4.45 N, 1.0 oz = 29.6 mL

APPENDIX B

This appendix contains tables of the results of compressions tests performed for the purpose of quality control. The cylinders were cast, tested, and reported by the precaster's personnel and reproduced here for informational purposes only.

Table 71. Concrete Properties Tested by Precaster on 4x8 inch Cylinders, HG Mix.

Cast Date	Purpose of Test	Specimen Age (days)	Compressive Strength (ksi)
5/14/2008	RELEASE	1	6.19
	7DAY	7	8.33
	28DAY	28	9.46
5/29/2008	RELEASE	1	6.33
	7DAY	7	8.48
	28DAY	31	9.58
6/3/2008	RELEASE	1	5.80
	7DAY	7	7.84
	28DAY	28	9.35
6/10/2008	RELEASE	1	6.29
	7DAY	7	8.48
	28DAY	28	9.65
6/14/2008	RELEASE	2	7.44
	7DAY	6	7.67
	28DAY	27	8.84
6/20/2008	RELEASE	1	5.76
	7DAY	7	7.34
	28DAY	31	8.84

Units: 1.0 ksi = 6.89 MPa

Table 72. Concrete Properties Tested by Precaster on 4x8 inch Cylinders, SG Mix.

Cast Date	Purpose of Test	Specimen Age (days)	Compressive Strength (ksi)
5/14/2008	RELEASE	1	7.82
	7DAY	7	9.54
	28DAY	28	10.29
5/21/2008	RELEASE	1	7.53
	7DAY	7	7.56
	28DAY	28	7.58
5/29/2008	RELEASE	1	4.01
	7DAY	7	8.45
	28DAY	28	9.64
6/9/2008	SHORT	2	6.86
	7DAY	7	8.06
	28DAY	28	8.60
6/14/2008	RELEASE	2	6.74
	7DAY	6	7.18
	28DAY	27	8.61
6/20/2008	RELEASE	1	6.80
	7DAY	3	8.43
	28DAY	31	9.52

Units: 1.0 ksi = 6.89 MPa

Table 73. Concrete Properties Tested by Precaster on 4x8 inch Cylinders, UG Mix.

Cast Date	Purpose of Test	Specimen Age (days)	Compressive Strength (ksi)
5/14/2008	RELEASE	1	4.65
	7DAY	7	7.05
	28DAY	28	8.58
5/29/2008	RELEASE	1	5.20
	7DAY	7	7.34
	28DAY	28	8.69
5/30/2008	RELEASE	3	6.83
	7DAY	7	7.27
	28DAY	28	8.74
6/9/2008	RELEASE	1	5.24
	7DAY	7	7.33
	28DAY	28	8.82
6/10/2008	RELEASE	1	4.27
	7DAY	7	5.61
	28DAY	28	7.07
6/14/2008	RELEASE	2	5.56
	7DAY	6	604
	28DAY	27	8.06
6/20/2008	RELEASE	3	4.80
	7DAY	7	5.29
	28DAY	31	6.84

Units: 1.0 ksi = 6.89 MPa

APPENDIX C

This appendix contains tables of detailed results of mechanical tests performed by FHWA personnel at the precaster's facility, and at TFHRC in McLean, Virginia. This appendix also contains the detailed results of the oven dry and air-dry density tests.

Table 74. Tested Concrete Properties on 4x8 inch Cylinders, HG Mix.

Cast Date	Specimen Age (days)	Compressive Strength (ksi)	Air-Dry Density (kcf)	Splitting Tensile Strength (ksi)	Elastic Modulus (ksi)
5/14/2008	3	7.50	0.134	0.65	-
	27	10.20	0.133	0.78	4430
	1044	11.94	0.131	0.78	4410
5/29/2008	2	7.44	0.134	0.62	4110
	32	10.08	0.134	0.68	4850
	1083	10.95	0.130	0.80	4270
6/3/2008	1	6.21	0.132	0.59	3550
	29	8.79	0.130	-	-
	29	8.91	0.131	-	-
	29	8.82	0.131	0.68	4040
	528	9.85	-	-	-
	548	9.67	0.128	-	-
	766	10.38	0.126	0.74	4010
6/10/2008	1	6.66	0.134	0.55	3730
	28	9.83	0.133	0.74	4420
	28	10.11	0.134	-	-
	604	11.36	0.132	-	-
	668	10.37	0.129	0.79	4750
6/14/2008	2	7.31	0.131	0.62	3780
	27	9.21	0.131	0.76	4130
	467	9.95	0.128	-	-
6/20/2008	3	7.30	0.134	0.61	4020
	28	9.28	0.134	0.68	4620
	28	8.04	0.132	-	-
	854	9.57	0.134	0.74	4170

Units: 1.0 ksi = 6.89 MPa, 0.001 kcf = 16.01 kg/m^3

Table 75. Tested Concrete Properties on 4x8 inch Cylinders, SG Mix.

Cast Date	Specimen Age (days)	Compressive Strength (ksi)	Air-Dry Density (kcf)	Splitting Tensile Strength (ksi)	Elastic Modulus (ksi)
5/14/2008	3	8.20	0.127	0.61	3950
	27	10.51	0.127	0.72	4300
	27	10.64	0.126	-	-
	975	11.62	0.126	0.73	4790
5/21/2008	1	6.35	0.126	0.61	3630
	28	9.48	0.125	0.66	3890
	28	9.32	0.125	-	-
	28	9.61	0.124	-	-
	436	10.65	0.123	-	-
	427	10.81	0.122	-	-
	427	11.11	0.122	-	-
	797	11.25	0.124	0.75	4450
5/29/2008	2	7.72	0.125	0.55	3560
	32	9.63	0.126	0.62	4280
	1090	10.37	0.123	0.66	4410
6/9/2008	2	7.12	0.123	0.59	3670
	29	9.64	0.123	0.67	4150
	29	9.77	0.125	-	-
	417	9.90	0.121	-	-
	669	10.34	0.122	0.72	3960
6/14/2008	2	6.80	0.123	0.61	4070
	27	9.27	0.125	0.67	3920
	479	9.71	0.121	-	-
6/20/2008	3	7.73	0.124	0.66	3740
	28	9.71	0.125	0.73	4280
	872	9.86	0.122	0.72	4160

Units: 1.0 ksi = 6.89 MPa, 0.001 kcf = 16.01 kg/m^3

Table 76. Tested Concrete Properties on 4x8 inch Cylinders, UG Mix.

Cast Date	Specimen Age (days)	Compressive Strength (ksi)	Air-Dry Density (kcf)	Splitting Tensile Strength (ksi)	Elastic Modulus (ksi)
5/14/2008	3	6.08	0.133	0.53	3570
	27	9.10	0.132	0.67	4050
	1052	11.24	0.129	0.76	4620
5/29/2008	2	5.80	0.130	0.57	3480
	32	8.40	0.129	0.74	3990
	971	10.81	0.126	0.72	4230
5/30/2008	5	7.11	0.131	0.58	3560
	31	8.73	0.131	0.64	4320
	31	9.34	0.132	-	-
	31	9.13	0.131	-	-
	523	10.66	0.127	-	-
	538	9.10	0.128	-	-
	759	10.55	0.127	0.76	4220
6/9/2008	2	6.22	0.133	0.66	3790
	28	7.70	0.125	-	-
	29	9.64	0.133	0.76	4520
	29	9.63	0.131	-	-
	542	10.46	0.130	-	-
	651	9.22	0.123	0.82	3970
6/14/2008	2	5.86	0.131	0.53	3410
	27	8.34	0.130	0.67	3930
	465	10.04	0.129	-	-
6/20/2008	3	5.16	0.129	0.53	3200
	28	7.37	0.129	0.61	3680
	826	8.79	0.126	0.72	3740

Units: 1.0 ksi = 6.89 MPa, 0.001 kcf = 16.01 kg/m^3

Table 77. Tested Concrete Properties on 4x8 inch Cylinders, SD Mix.

Cast Date	Specimen Age (days)	Compressive Strength (ksi)	Air-Dry Density (kcf)	Splitting Tensile Strength (ksi)	Elastic Modulus (ksi)
5/14/2008	28	5.67	0.138	--	--

Table 78. Tested Concrete Properties on 6x12 inch Cylinders

Mix Design	Cast Date	Specimen Age (days)	Compressive Strength (ksi)	Air-Dry Density (kcf)
HG	5/29/2008	32	10.17	0.134
	6/3/2008	29	8.98	0.131
	6/10/2008	28	9.78	0.134
	6/14/2008	27	9.46	0.132
	6/20/2008	28	9.15	0.133
SG	5/14/2008	27	9.62	0.126
	5/14/2008	27	10.44	0.127
	5/21/2008	28	9.32	0.126
	5/29/2008	32	9.74	0.127
	6/9/2008	29	9.39	0.124
	6/14/2008	27	9.27	0.125
	6/20/2008	28	9.67	0.125
UG	5/14/2008	27	9.32	0.134
	5/29/2008	32	8.87	0.132
	5/30/2008	31	9.33	0.133
	6/9/2008	29	9.50	0.135
	6/14/2008	27	8.70	0.133
	6/20/2008	28	7.39	0.129
SD	5/14/2008	28	5.86	0.137

Units: 1.0 ksi = 6.89 MPa, 0.001 kcf = 16.01 kg/m^3

Table 79. Density of 6 x 12 inch Cylinders by Days of Air Drying.

Cast Date	Girder Mix	Cylinder Density (kcf) by Drying Time (days)				
		0	114	271	404	516
5/14/2008	SG	0.126	0.125	0.125	0.125	0.124
	UG †	0.134	0.133	0.133	0.132	0.132
5/21/2008	SG	0.127	0.125	0.125	0.125	0.124
5/29/2008	HG	0.134	0.133	0.132	0.131	0.131
	SG	0.128	0.127	0.127	0.126	0.126
	UG	0.132	0.131	0.131	0.130	0.130
5/30/2008	UG	0.133	0.132	0.132	0.131	0.131
6/3/2008	HG	0.133	0.130	0.130	0.129	0.129
6/9/2008	SG	0.123	0.122	0.121	0.121	0.121
	UG	0.133	0.132	0.131	0.131	0.131
6/10/2008	HG	0.135	0.133	0.132	0.132	0.131
6/13/2008	HG	0.133	0.131	0.130	0.129	0.129
	SG	0.126	0.124	0.124	0.123	0.123
	UG	0.133	0.132	0.132	0.131	0.131
6/20/2008	HG	0.135	0.133	0.132	0.132	0.131
	SG	0.126	0.125	0.124	0.124	0.124
	UG	0.131	0.129	0.128	0.127	0.127

Note: † Calculated using two cylinders
Units: 1.0 ksi = 6.89 MPa, 0.001 kcf = 16.01 kg/m^3

Table 80. Density of 6 x 12 inch Cylinders by Days of Oven Drying.

Cast Date	Girder Mix	Cylinder Density (kcf) by Drying Time (days)				
		0	27	33	47	58
5/14/2008	SG	0.134	0.125	0.125	0.125	0.125
	UG †	0.143	0.133	0.132	0.131	0.131
5/21/2008	SG	0.135	0.126	0.126	0.125	0.125
5/29/2008	HG	0.141	0.132	0.131	0.131	0.131
	SG	0.136	0.128	0.128	0.128	0.127
	UG	0.141	0.131	0.130	0.130	0.130
5/30/2008	UG	0.143	0.133	0.132	0.131	0.131
6/3/2008	HG	0.141	0.130	0.130	0.129	0.129
6/9/2008	SG	0.133	0.125	0.125	0.124	0.124
	UG	0.136	0.131	0.130	0.128	0.127
6/10/2008	HG	0.134	0.128	0.126	0.125	0.125
6/13/2008	HG	0.132	0.125	0.123	0.122	0.122
	SG	0.126	0.120	0.119	0.117	0.117
	UG	0.133	0.128	0.126	0.124	0.124
6/20/2008	HG	0.135	0.129	0.127	0.126	0.126
	SG	0.126	0.121	0.119	0.118	0.118
	UG	0.131	0.125	0.123	0.121	0.121

Note: † Calculated using two cylinders
Units: 1.0 ksi = 6.89 MPa, 0.001 kcf = 16.01 kg/m^3

APPENDIX D

This appendix contains a copy of the presentation slides presented by Meyer to ACI Committee 213 showing his concept for a lightweight concrete modification factor based on unit weight.[19]

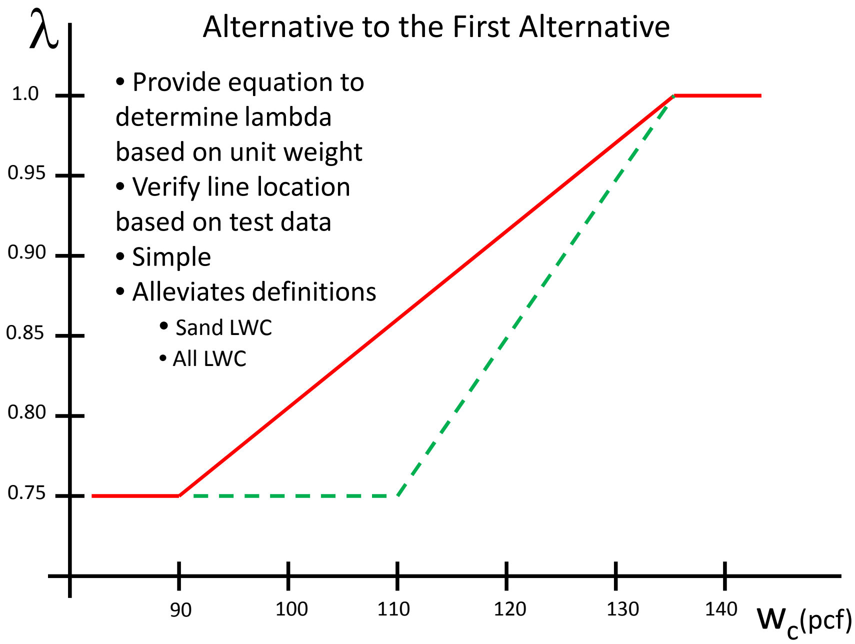

Figure 70. Graph. Slide 1.

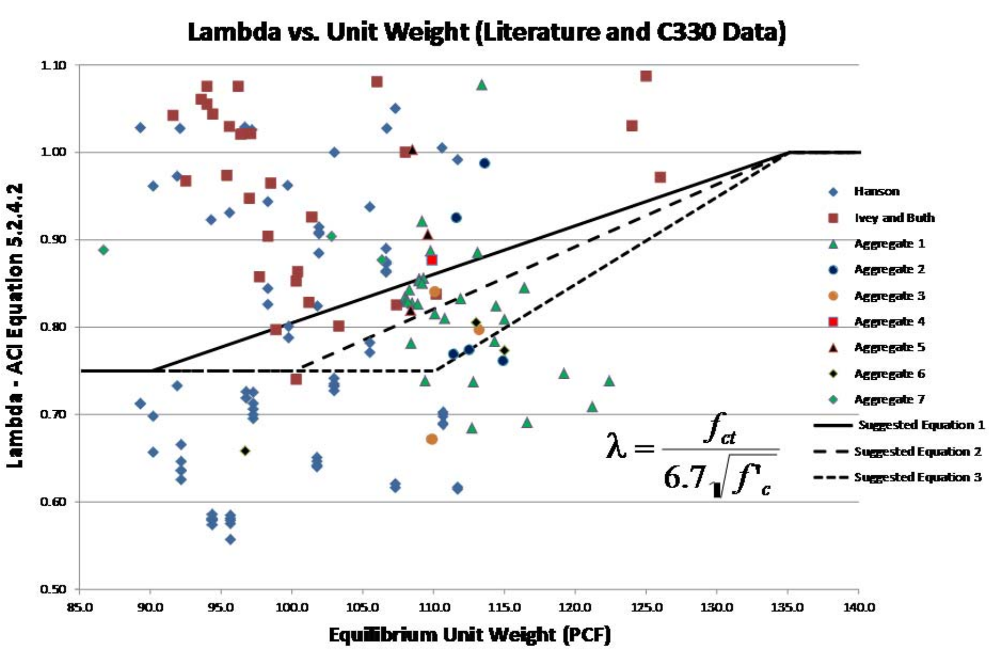

Figure 71. Graph. Slide 2.