Synthesis and Evaluation of Lightweight Concrete Research Relevant to the AASHTO LRFD Bridge Design Specifications: Potential Revisions for Definition and 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 represents the document developed for and delivered to T-10 in September 2012 as part of their ongoing efforts to address the lightweight concrete provisions in the bridge design specifications. This document focuses on the definition of lightweight concrete and the mechanical properties thereof.

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15. Supplementary Notes

This document was developed by research staff at the Turner-Fairbank Highway Research Center. Portions of the work were completed by PSI, Inc. under contract DTFH61-10-D-00017. Gary Greene of PSI, Inc., who is the lead contract researcher on FHWA's lightweight concrete research efforts, and Ben Graybeal of FHWA, who manages the FHWA Structural Concrete Research Program, developed this document.

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. The purpose of this document is to give members of AASHTO Subcommittee on Bridges and Structures T-10 the opportunity to begin considering specific proposed 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 reduction factor relevant to LWC structural performance is discussed. This document served as supplemental information in support of the discussion that occurred at the September 2012 T-10 meeting in Nashville, Tennessee.

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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)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1. INTRODUCTION

INTRODUCTION

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 (ACI Committee 213 1967, Hanson 1961, Ivey and Buth 1967, Pauw 1960). 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 (2007), 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.

This document describes a database of mechanical property tests on LWC that has been collected, and the analysis of LWC 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

The objective of this document is to present potential revisions to the AASHTO LRFD Specifications relating to the mechanical properties of LWC to the members of AASHTO SCOBS T-10. The basis for the proposed expressions for mechanical properties is described in the document. The authors would like to solicit feedback on the proposed revisions.

OUTLINE OF DOCUMENT

The document is divided into four sections. The first section is an introduction, which includes 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 reduction factors. The second section describes the database of mechanical tests on LWC. Statistical information about the database is included. The third section compares the results of the LWC mechanical tests to design expressions and describes the development of prediction expressions. The fourth section presents potential revisions to the AASHTO LRFD Specifications. The units for stress and elastic modulus are ksi and the units for unit weight are kcf for all expressions unless stated otherwise. References to the paper and reports used in the LWC database are included in the last section of this document. An executive summary of this document is provided in the appendix.

SUMMARY OF PRELIMINARY RECOMMENDATIONS

Three 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, 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 reduction factor is proposed to potentially allow a more unified approach of accounting for the mechanical properties of LWC in the AASHTO LRFD Specifications. The proposed revisions are described in more detail in Chapter 5.

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 on the AASHTO LRFD Specifications, and the LWC reduction 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 (ACI Committee 213 2003).

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 (ACI Committee 213 2003).

EQUILIBRIUM DENSITY GAP IN AASHTO LRFD

The definition for LWC in AASHTO LRFD covers concrete having lightweight aggregate and an air-dry unit weight less than or equal to 0.120 kcf. Normal weight concrete is defined as having a unit weight from 0.135 to 0.155 kcf. Concretes in the gap of densities between 0.120 and 0.135 kcf 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. 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 course 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 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 should not be used in structural applications. The 2.0 ksi limit for the database was selected so as to include some data below the 2.4 ksi limit for structural concrete without allowing low strength LWC that is commonly used for insulating purposes to bias the analysis of mechanical properties.

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 1 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 particles for the coarse and fine aggregates. 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 1. 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.

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 and a unit weight that is less than or equal to 0.135 kcf. The 2.0 ksi limit on compressive strength was discussed previously. The 0.135 limit on unit weight was chosen because the AASHTO LRFD Specifications define NWC as having a unit weight as low as 0.135 kcf. Table 2 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. 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 3. 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 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 4. The variation of compressive strength and unit weight with E_c is shown in Figure 1 and Figure 2, respectively. The distribution of compressive strength, splitting tensile strength, and unit weight for specified ranges of f_{ct} is given in Table 5. The variation of compressive strength and unit weight with f_{ct} is shown in Figure 3 and Figure 4, respectively. The distribution of compressive strength, modulus of rupture, and unit weight for specified ranges of f_r is given in Table 6. The variation of compressive strength and unit weight with f_r is shown in Figure 5 and Figure 6, respectively. The distribution of compressive strength, Poisson’s Ratio, and unit weight for Poisson’s Ratio is given in Table 7. The variation of compressive strength and unit weight with Poisson’s Ratio is shown in Figure 7 and Figure 8, respectively.

Table 2. Mechanical Property and Unit weight Distribution in TFHRC LWC Database and Subset Databases.

Property	Range	No. of Data Lines				
		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

Table 3. 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	--

Table 4. 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

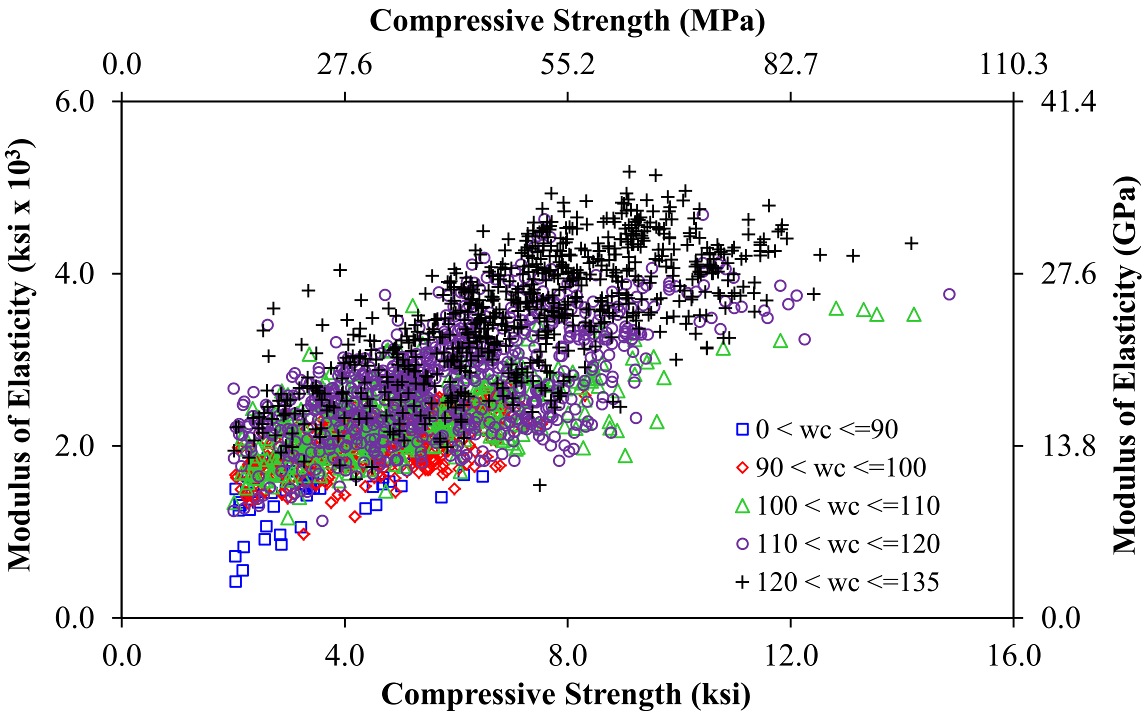

Figure 1. Graph. Modulus of Elasticity versus Compressive Strength in TFHRC LWC Database – E_c Subset Showing Variation by Unit Weight.

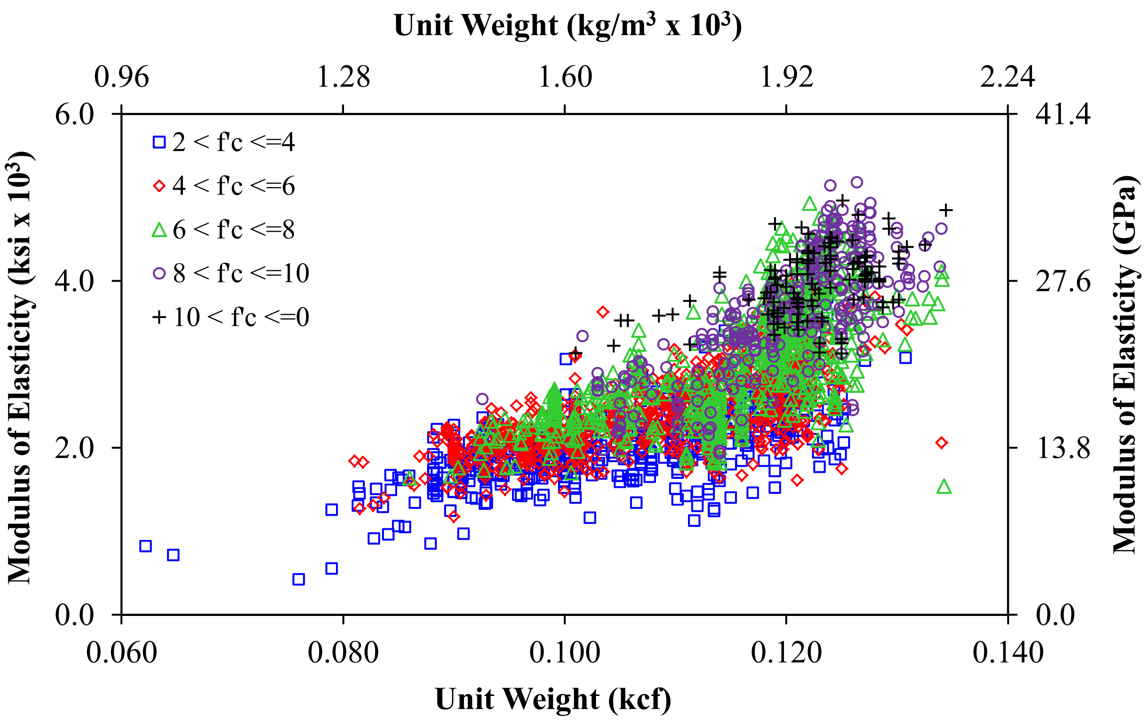

Figure 2. Graph. Modulus of Elasticity versus Unit Weight in TFHRC LWC Database – E_c Subset Showing Variation by Compressive Strength.

Table 5. 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

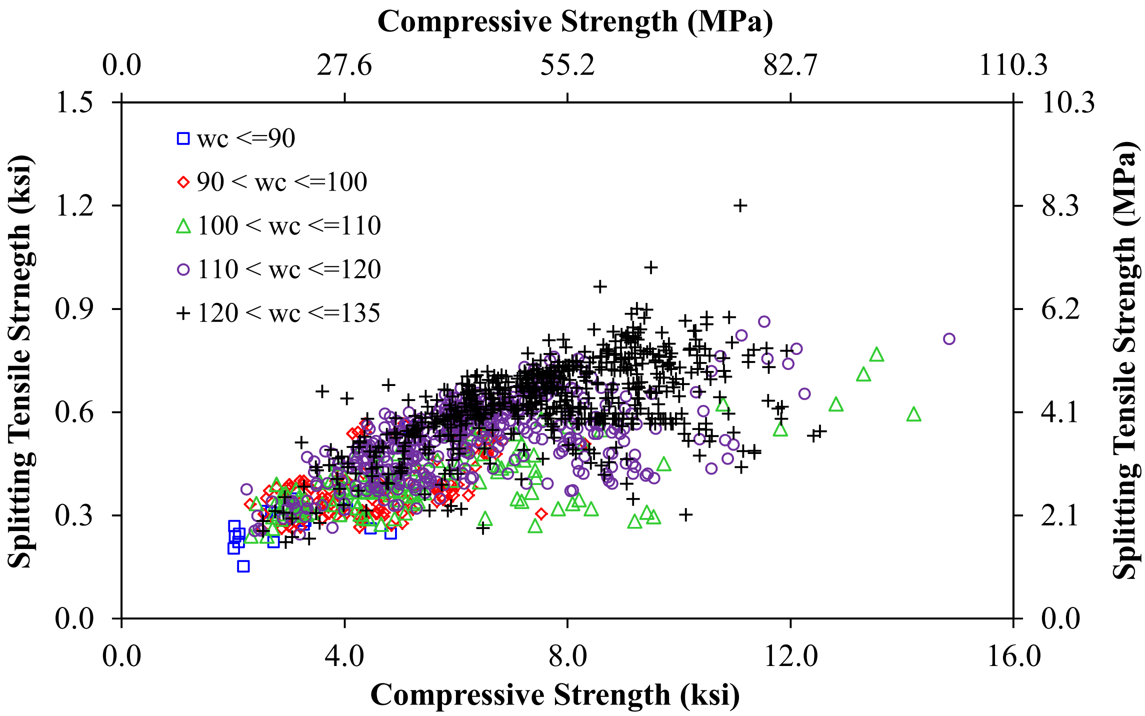

Figure 3. Graph. Splitting Tensile Strength versus Compressive Strength in TFHRC LWC Database – f_{ct} Subset Showing Variation by Unit Weight.

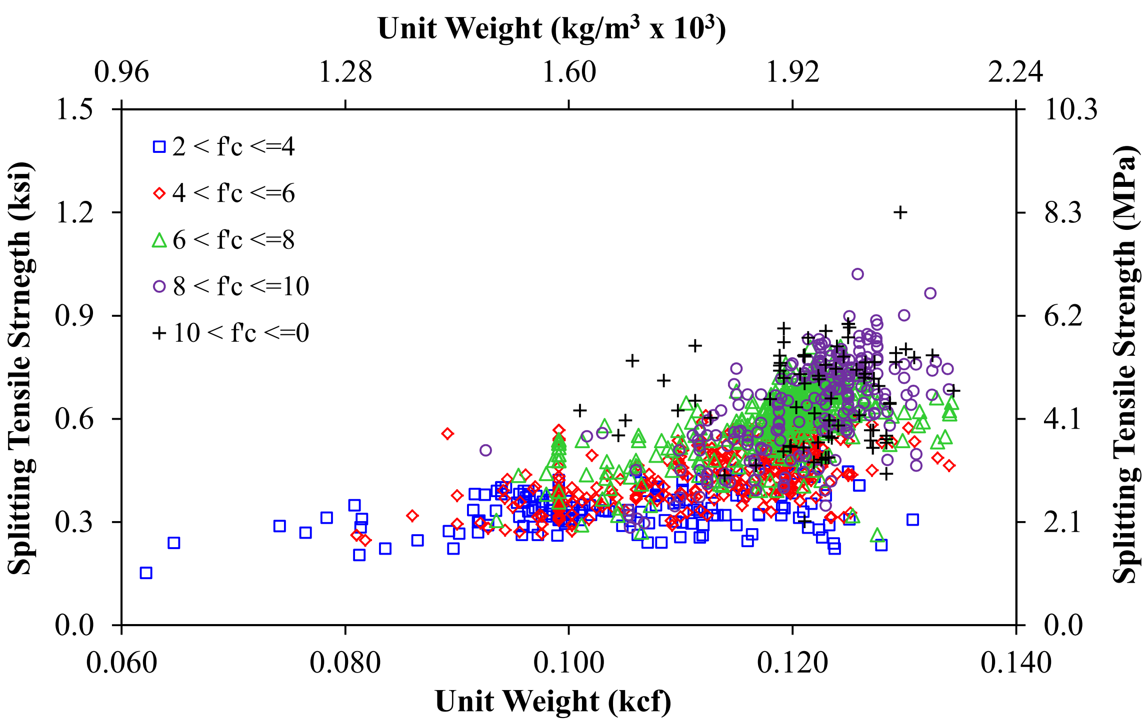

Figure 4. Graph. Splitting Tensile Strength versus Unit Weight in TFHRC LWC Database – f_{ct} Subset Showing Variation by Compressive Strength.

Table 6. 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

Table 7. 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

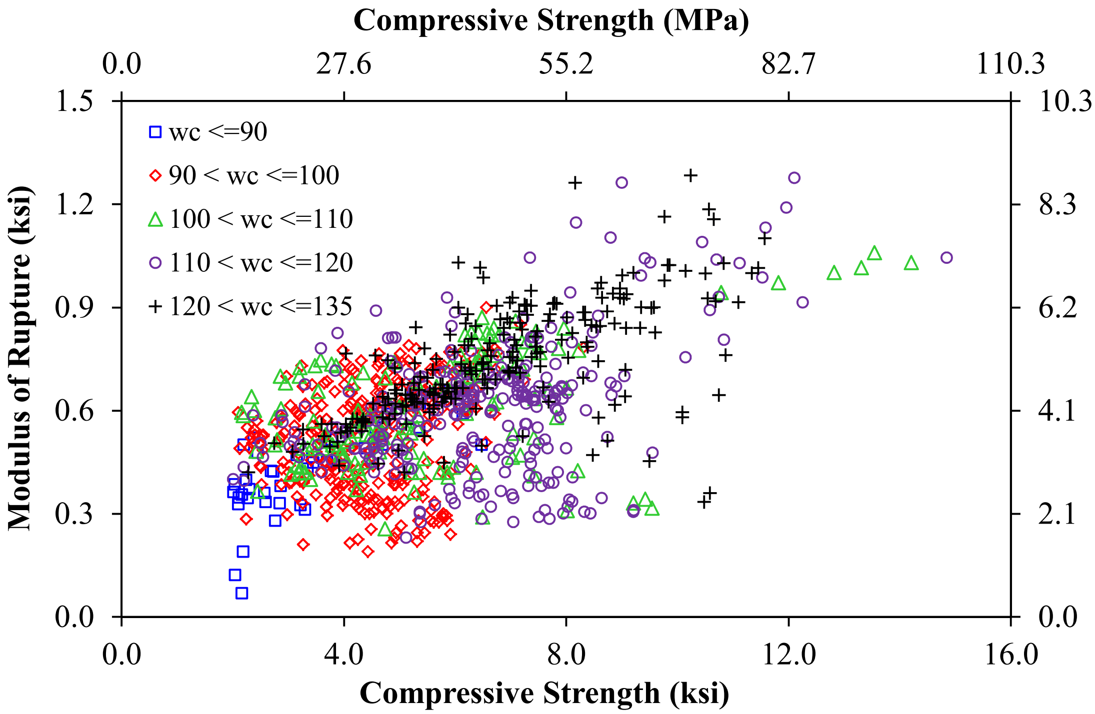

Figure 5. Graph. Modulus of Rupture versus Compressive Strength in TFHRC LWC Database – f_r Subset Showing Variation by Unit Weight.

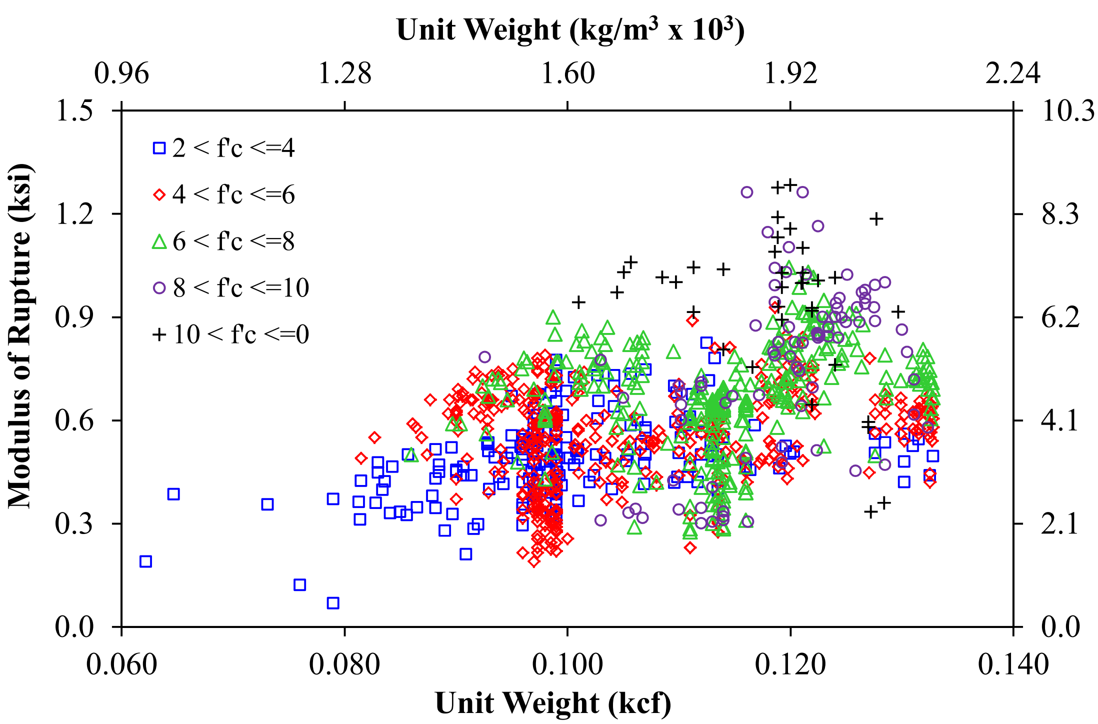

Figure 6. Graph. Modulus of Rupture versus Unit Weight in TFHRC LWC Database – f_r Subset Showing Variation by Compressive Strength.

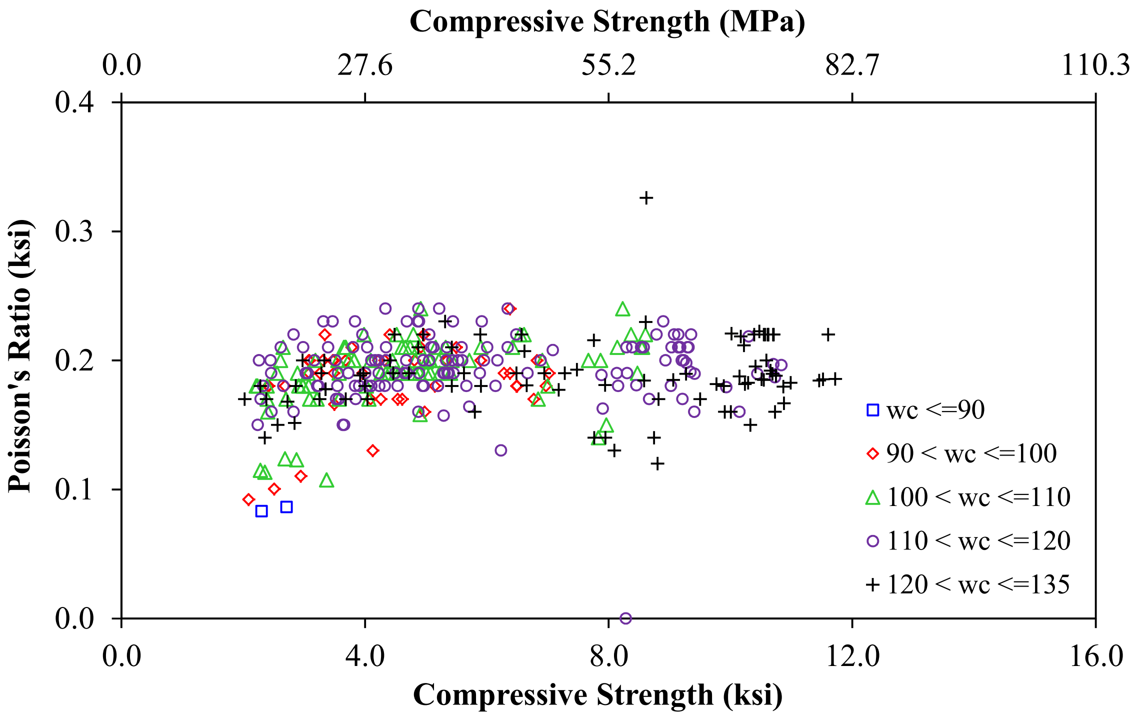

Figure 7. Graph. Poisson's Ratio versus Compressive Strength in TFHRC LWC Database – Poisson's Ratio Subset Showing Variation by Unit Weight.

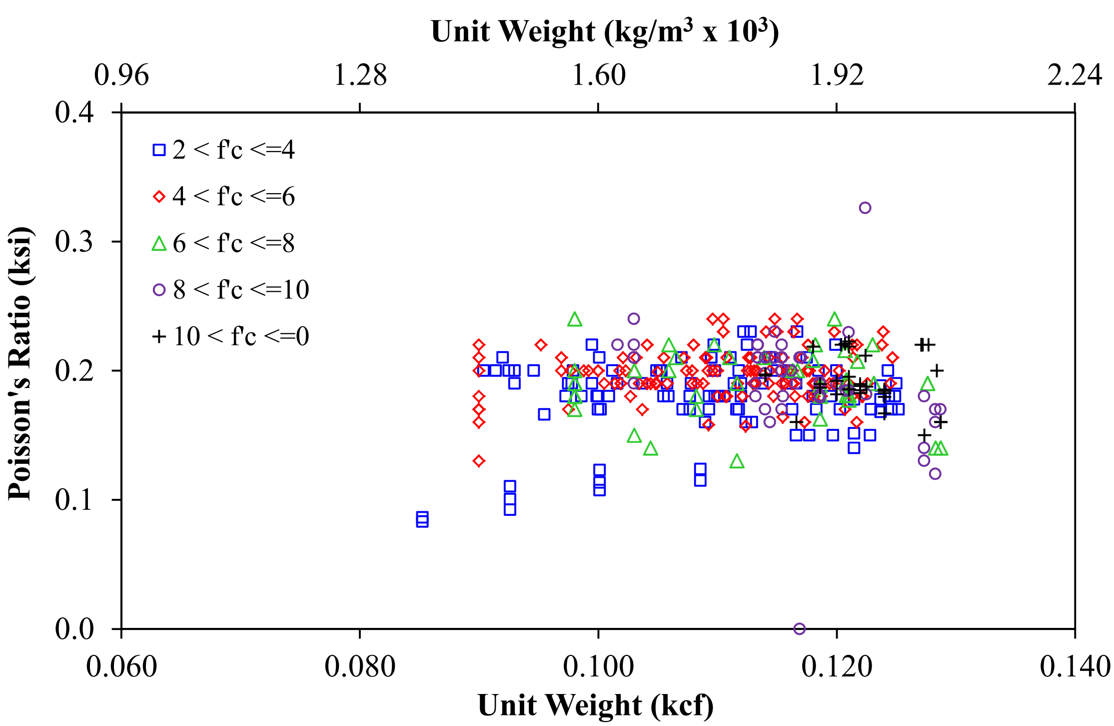

Figure 8. Graph. Poisson's Ratio versus Unit Weight in TFHRC LWC Database – Poisson's Ratio Subset Showing Variation by Compressive Strength.

CHAPTER 4. MECHANICAL PROPERTY ANALYSIS OF TFHRC LWC DATABASE

INTRODUCTION

This chapter compares the TFHRC LWC subset databases for modulus of elasticity and splitting tensile strength 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 reduction factor is developed and compared to the subset database.

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 will be offered to 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. 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 5.9.2.3), and if the refined estimate of losses is used (Art. 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 2. As discussed previously, the data lines were limited to those with a unit weight less than 0.135 kcf. 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 was utilized (Rizkalla et al. 2007). 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 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 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 limit was also selected because the LWC data in the TFHRC database uses a unit weight of 0.135 kcf 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. 1. NCHRP Project 12-64 proposed the expression given by Eq. 2 and was developed for concrete strengths up to 18 ksi using over 4400 data points. ACI Committee 363, High-Strength Concrete, gives Eq. 3 as a design expression for E_c in its document, "State-of-the-Art Report on High-Strength Concrete" (ACI 363 2010). The ratio of the tested E_c to the E_c predicted by the three design expressions is given in Table 8. 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 greater than unity indicates an over-estimation of E_c.

$$E_c = 33{,}000 K_1 w_c^{1.5} \sqrt{f_c'} \qquad \text{(Eq. 1)}$$

$$E_c = 310{,}000 K_1 w_c^{2.5} f_c'^{\,0.33} \qquad \text{(Eq. 2)}$$

$$E_c = 23 w_c^{1.5} \sqrt{f_c'} + 1{,}000{,}000 \qquad \text{(Eq. 3)}$$

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

Table 8. 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. 1)	NCHRP 12-64 (Eq. 2)	ACI 363 (Eq. 3)
NCHRP NWC and LWC	mean	0.968	1.039	1.066
	COV	17.5%	16.3%	16.6%
	maximum	1.765	2.455	2.051
	minimum	0.540	0.554	0.479
	Percent ≥ 1.0	37.4%	52.9%	55.6%
	Percent < 1.0	54.0%	38.5%	35.9%
	Percent ≥ 1.2	18.5%	29.7%	38.6%
	Percent < 0.8	34.2%	20.2%	15.5%
NCHRP LWC	mean	0.935	1.182	0.882
	COV	17.4%	17.8%	13.7%
	maximum	1.707	2.455	1.402
	minimum	0.595	0.755	0.479
	Percent ≥ 1.0	32.6%	79.0%	15.9%
	Percent < 1.0	67.4%	21.0%	84.1%
	Percent ≥ 1.2	5.7%	44.0%	0.8%
	Percent < 0.8	21.8%	0.3%	25.9%
NCHRP NWC	mean	0.972	1.007	1.095
	COV	17.3%	14.5%	14.8%
	maximum	1.765	1.778	2.051
	minimum	0.484	0.394	0.458
	Percent ≥ 1.0	41.9%	52.9%	68.7%
	Percent < 1.0	58.1%	47.1%	31.3%
	Percent ≥ 1.2	9.5%	9.1%	24.5%
	Percent < 0.8	17.9%	6.5%	1.9%

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 9 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 9 is very close to the mean test-to-prediction ratio for NCHRP LWC data in Table 8 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 and ACI 363-10 expressions over-estimate and the NCHRP 12-64 under-estimate the prediction of E_c.

Table 9. 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. 1)	NCHRP 12-64 (Eq. 2)	ACI 363 (Eq. 3)
TFHRC LWC and NCHRP NWC	mean	0.957	1.087	1.009
	COV	17.0%	18.8%	18.5%
	maximum	1.765	2.119	2.051
	minimum	0.346	0.386	0.249
	Percent ≥ 1.0	38.2%	65.0%	48.6%
	Percent < 1.0	61.8%	35.0%	51.4%
	Percent ≥ 1.2	7.2%	25.9%	15.2%
	Percent < 0.8	18.2%	4.9%	12.0%
TFHRC LWC	mean	0.936	1.206	0.881
	COV	16.3%	18.3%	16.0%
	maximum	1.643	2.119	1.392
	minimum	0.346	0.386	0.249
	Percent ≥ 1.0	32.6%	82.9%	18.7%
	Percent < 1.0	67.4%	17.1%	81.3%
	Percent ≥ 1.2	3.9%	50.9%	1.4%
	Percent < 0.8	18.6%	2.6%	27.0%

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 9 through Figure 14. The test-to-prediction ratios using the AASHTO LRFD expression is compared to compressive strength in Figure 9. This figure shows that the E_c for most of the NWC data with compressive strengths greater than 15.0 ksi is over-estimated by the AASHTO LRFD expression. Figure 10 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 11 and Figure 12, respectively. Figure 11 shows that a large number of LWC data points with a compressive strength less than 5.0 ksi are under-estimated by more than 50% (ratio > 1.5). Figure 12 shows that most of the LWC data with a unit weight less than 0.110 kcf 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 13 and Figure 14. These figures show that E_c is over-estimated for most of the LWC data. This trend is also given in Table 9 for the LWC data where 81% of the test-to-prediction ratios were less than unity (E_c over-estimated) and 27% of the E_c data was over-estimated by more than 20%.

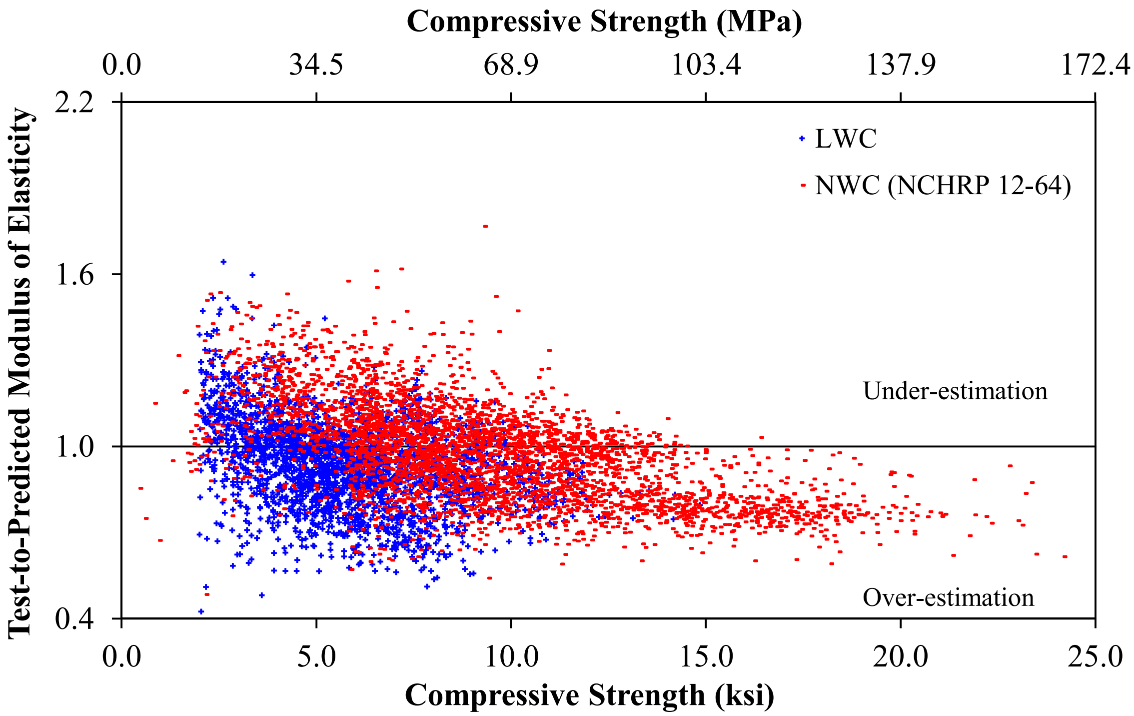

Figure 9. Graph. Modulus of Elasticity Test-to-Prediction Ratio Compared to Compressive Strength for AASHTO LRFD Equation (Eq. 1).

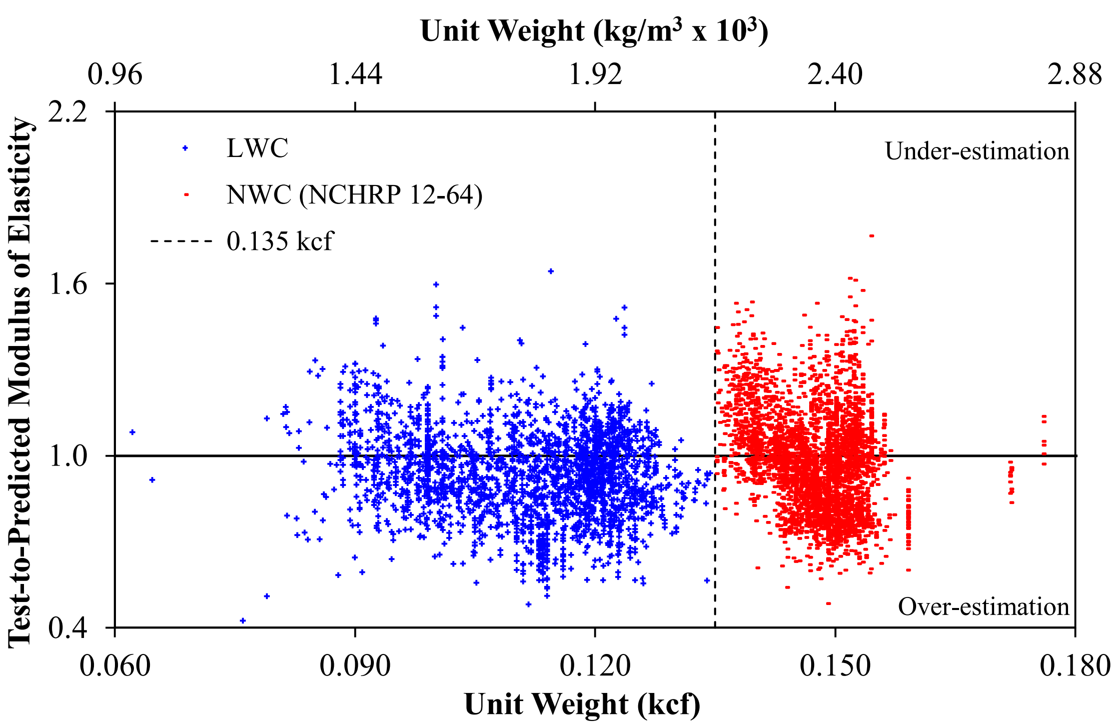

Figure 10. Graph. Modulus of Elasticity Test-to-Prediction Ratio Compared to Unit Weight for AASHTO LRFD Equation (Eq. 1).

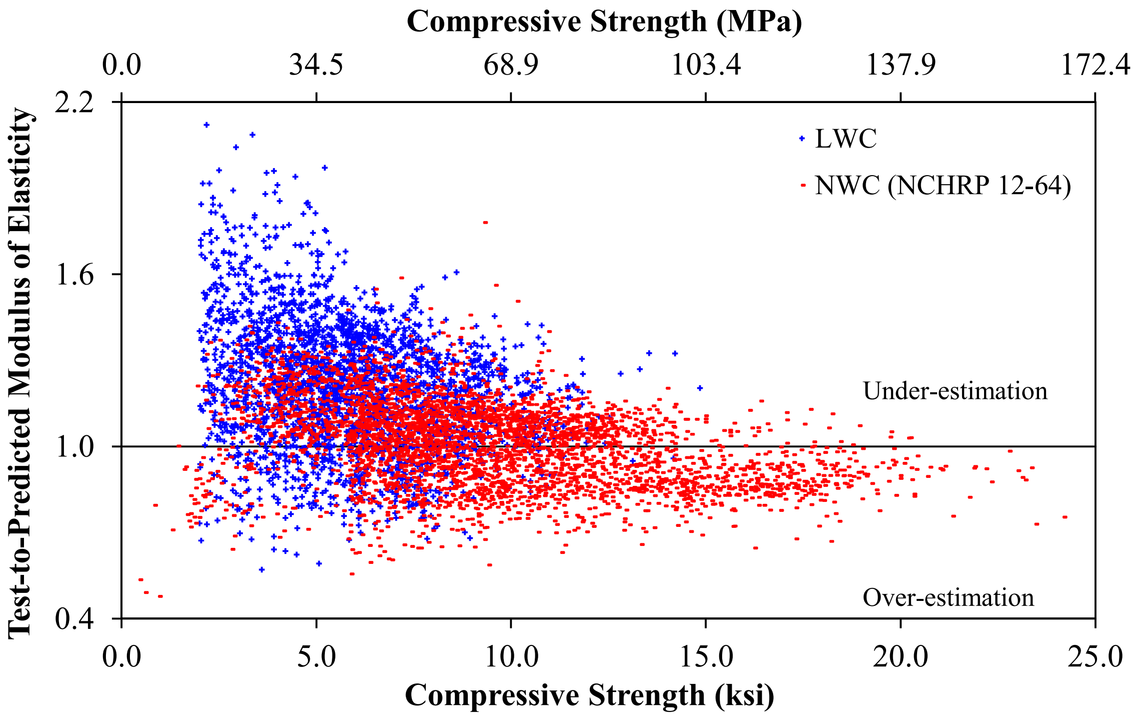

Figure 11. Graph. Modulus of Elasticity Test-to-Prediction Ratio Compared to Compressive Strength for NCHRP Project 12-64 Equation (Eq. 2).

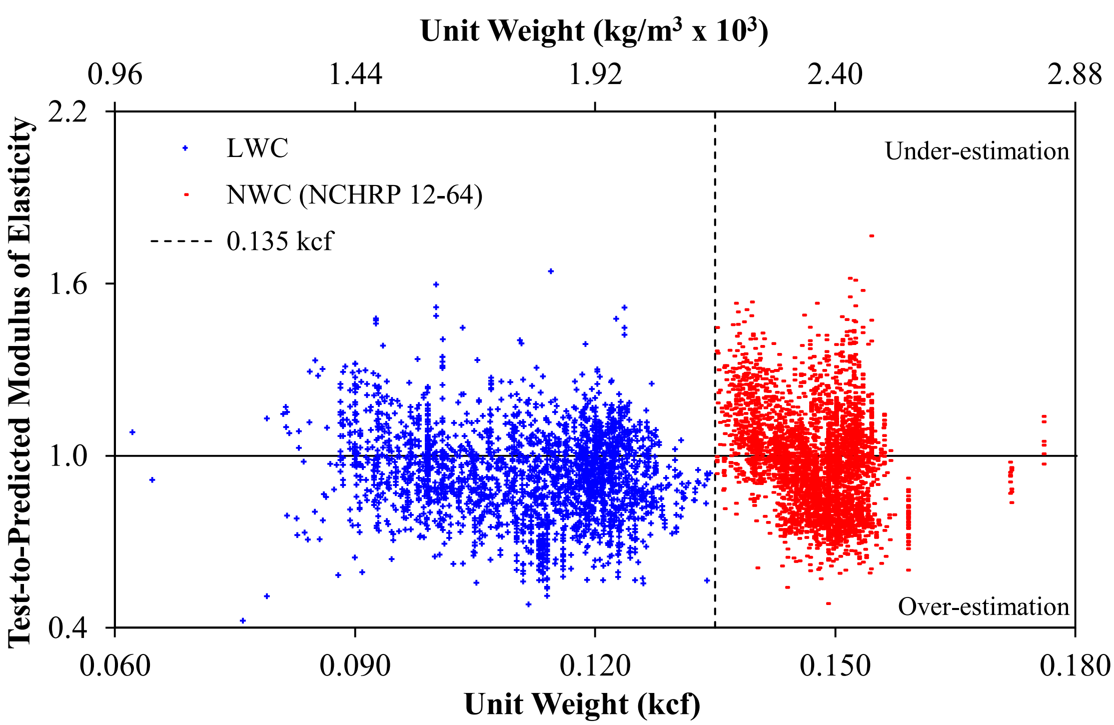

Figure 12. Graph. Modulus of Elasticity Test-to-Prediction Ratio Compared to Unit for NCHRP Project 12-64 Equation (Eq. 2).

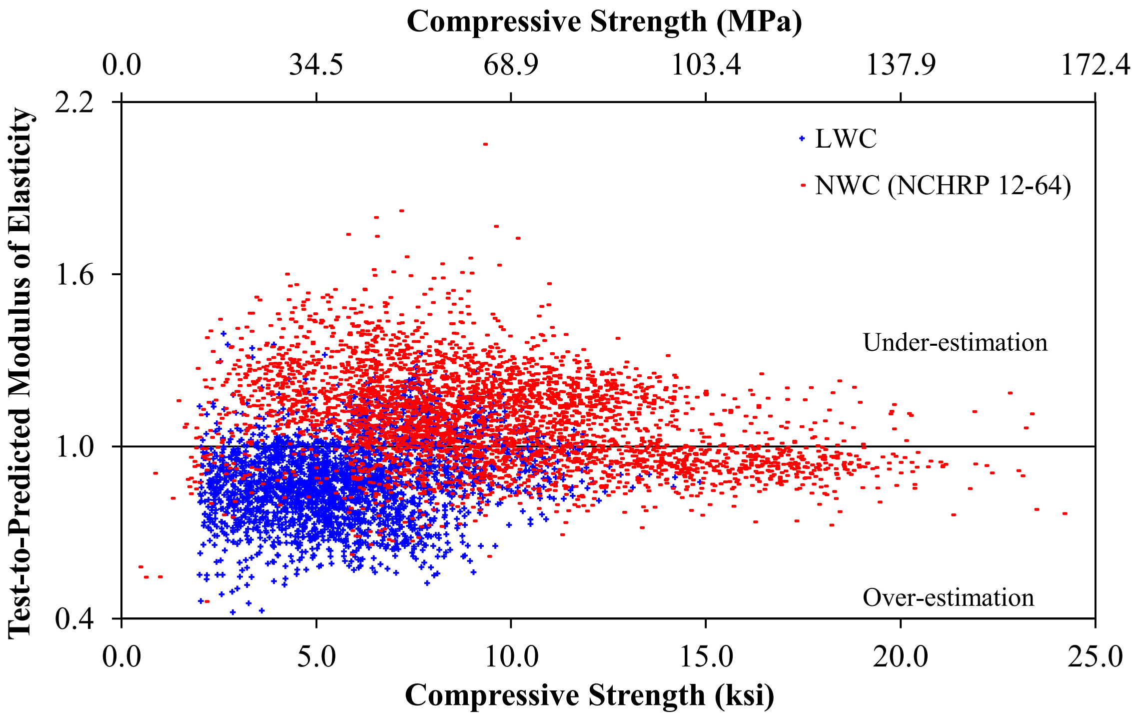

Figure 13. Graph. Modulus of Elasticity Test-to-Prediction Ratio Compared to Compressive Strength for ACI 363-10 Equation (Eq. 3).

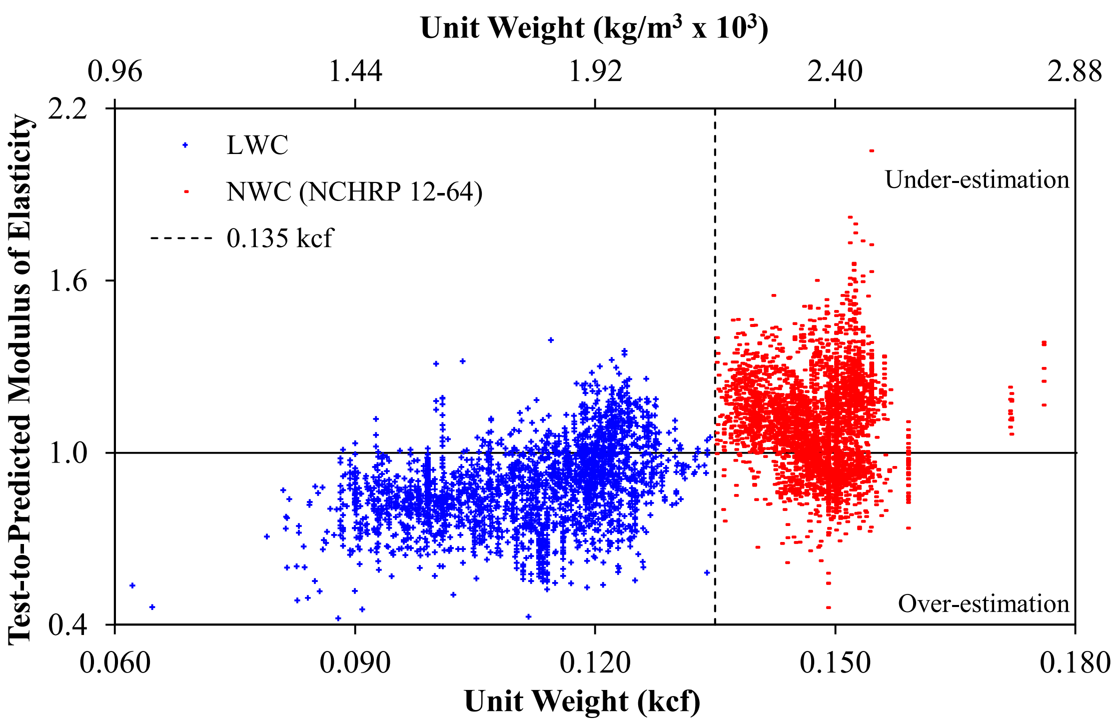

Figure 14. Graph. Modulus of Elasticity Test-to-Prediction Ratio Compared to Unit Weight for ACI 363-10 Equation (Eq. 3).

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. 4. 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. 4). In the second part, the exponent applied to the compressive strength term was varied (n_2 in Eq. 4). 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.

$$E_c = C(w_c)^{n_1}(f_c')^{n_2} + B \qquad \text{(Eq. 4)}$$

In all of the analyses, after the exponent was varied, the factor "C" in Eq. 4 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. 5. A comparison between the actual AASHTO LRFD expression and the Optimized Factor expression is given in Table 10. 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.

$$E_c = 31{,}580 w_c^{1.5} f_c'^{\,0.50} \qquad \text{(Eq. 5)}$$

A 1000 ksi E_c offset (factor "B" Eq. 4) 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. 6. The results of this comparison are given in Table 10 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 8 and Table 9.

$$E_c = 23{,}270 w_c^{1.5} f_c'^{\,0.50} + 1000 \qquad \text{(Eq. 6)}$$

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 10. 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. 1)	Optimize Factor (Eq. 5)	E_c Offset (Eq. 6)
LWC and NWC	mean	0.957	1.000	1.000
	COV	17.0%	17.0%	18.4%
	COV change[(2)]	--	0.0%	1.4%
	maximum	1.765	1.844	2.032
	minimum	0.346	0.361	0.247
	Percent ≥ 1.0	38.2%	49.6%	46.9%
	Percent < 1.0	61.8%	50.4%	53.1%
	Percent ≥ 1.2	7.2%	11.5%	13.8%
	Percent < 0.8	18.2%	11.6%	12.8%
LWC	mean	0.936	0.977	0.874
	COV	16.3%	16.3%	16.0%
	COV change[(2)]	--	0.0%	-0.3%
	maximum	1.643	1.716	1.383
	minimum	0.346	0.361	0.247
	Percent ≥ 1.0	32.6%	45.1%	17.3%
	Percent < 1.0	67.4%	54.9%	82.7%
	Percent ≥ 1.2	3.9%	7.3%	1.3%
	Percent < 0.8	18.6%	13.8%	28.7%
NWC	mean	0.972	1.015	1.085
	COV	17.3%	17.3%	14.8%
	COV change[(2)]	--	0.0%	-2.5%
	maximum	1.765	1.844	2.032
	minimum	0.484	0.505	0.455
	Percent ≥ 1.0	41.9%	52.6%	66.7%
	Percent < 1.0	58.1%	47.4%	33.3%
	Percent ≥ 1.2	9.5%	14.3%	22.2%
	Percent < 0.8	17.9%	10.1%	2.1%

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 11 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 11 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 over-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. 5). The three new expressions evaluated in this part of the analysis are given by Eq. 7, Eq. 8, and Eq. 9.

$$E_c = 4{,}200 w_c^{0.5} {f_c}'^{\,0.50} \qquad \text{(Eq. 7)}$$

$$E_c = 87{,}400 w_c^{2.0} {f_c}'^{\,0.50} \qquad \text{(Eq. 8)}$$

$$E_c = 243{,}700 w_c^{2.5} {f_c}'^{\,0.50} \qquad \text{(Eq. 9)}$$

The result of varying the exponent applied to compressive strength is given in Table 12. 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. 10, Eq. 11, and Eq. 12.

$$E_c = 51{,}600 w_c^{1.5} {f_c}'^{\,0.25} \qquad \text{(Eq. 10)}$$

$$E_c = 44{,}040 w_c^{1.5} {f_c}'^{\,0.33} \qquad \text{(Eq. 11)}$$

$$E_c = 19{,}620 w_c^{1.5} {f_c}'^{\,0.75} \qquad \text{(Eq. 12)}$$

Table 11. 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. 7)	Optimize Factor ($w_c^{1.5}$) (Eq. 5)	Increase w_c Exponent ($w_c^{2.0}$) (Eq. 8)	Increase w_c Exponent ($w_c^{2.5}$) (Eq. 9)
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 12. 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. 10)	Decrease f'_c Exponent ($f'_c{}^{0.33}$) (Eq. 11)	Optimize Factor ($f'_c{}^{0.50}$) (Eq. 5)	Increase f'_c Exponent ($f'_c{}^{0.75}$) (Eq. 12)
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 slightly under-estimated E_c 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 13 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 13 were previously evaluated in Table 10, Table 11, and Table 12. 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 15 through Figure 20 for Potential Expressions 1 through 3. In Figure 15 and Figure 16 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 17 and Figure 18. Figure 19 and Figure 20 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. 13. 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 21 and Figure 22, respectively.

$$E_c = 121{,}400 w_c^{2.0} f_c'^{\,0.33} \qquad \text{(Eq. 13)}$$

Table 13. 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. 5)	Potential Expression 2 ($w_c^{2.0}$ $f'_c{}^{0.50}$) (Eq. 8)	Potential Expression 3 ($w_c^{1.5}$ $f'_c{}^{0.33}$) (Eq. 11)	Potential Expression 4 ($w_c^{2.0}$ $f'_c{}^{0.33}$) (Eq. 13)
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

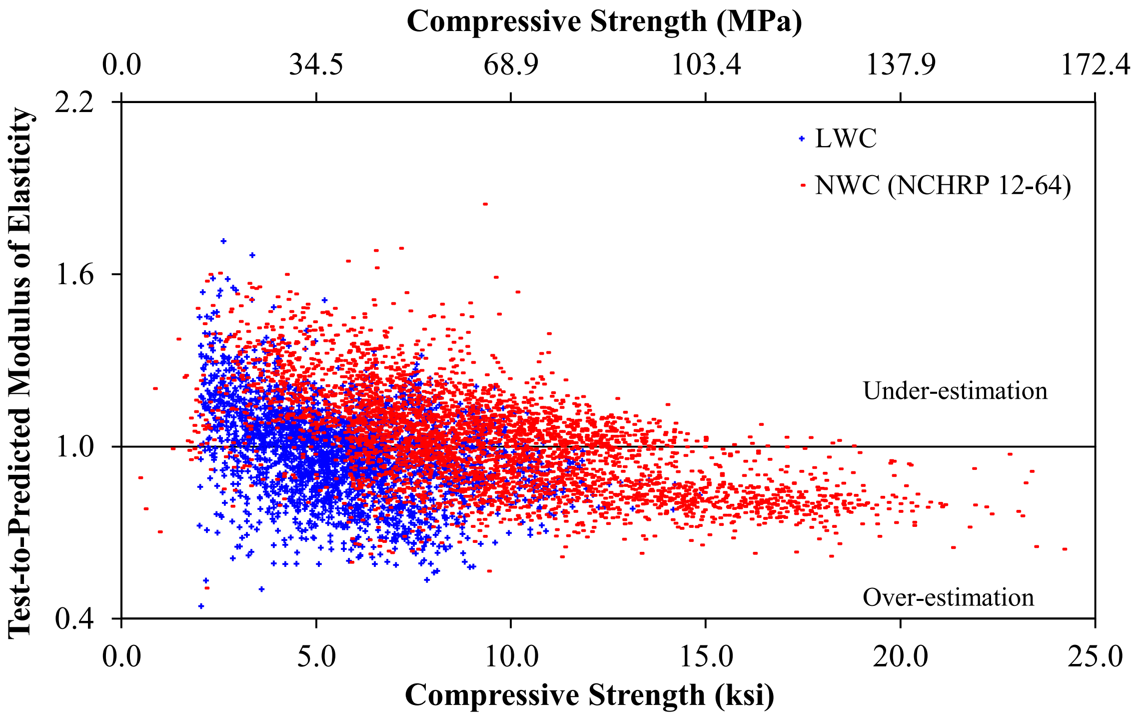

Figure 15. Graph. Modulus of Elasticity Test-to-Prediction Ratio Compared to Compressive Strength for Potential Expression 1 (Eq. 5).

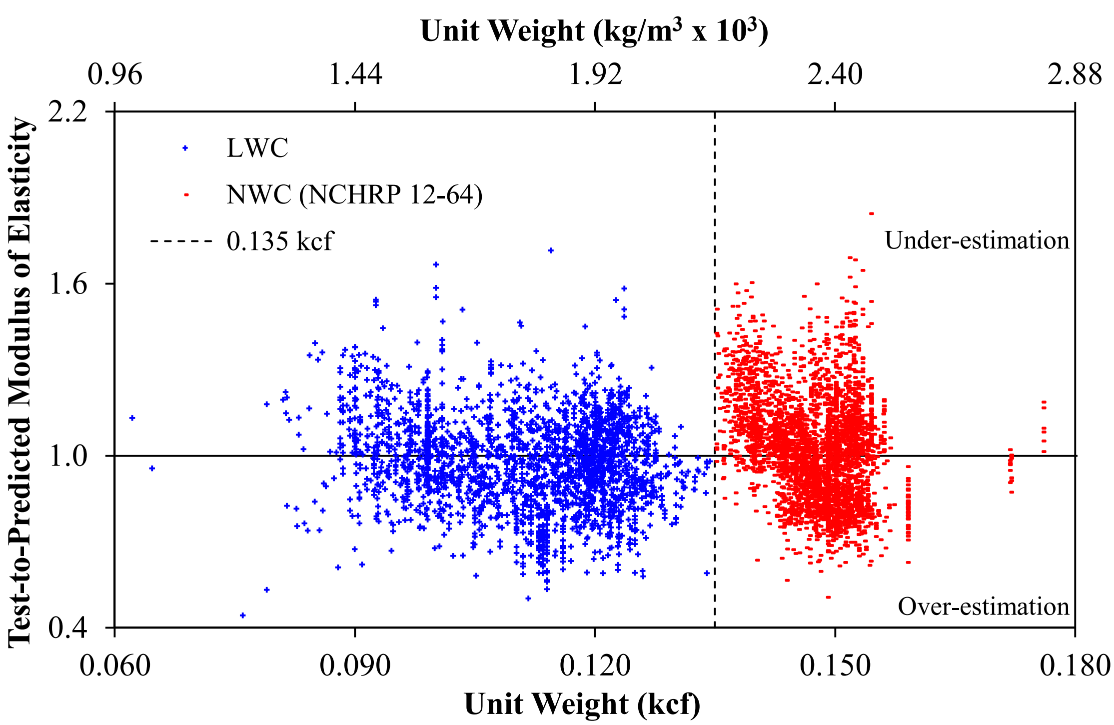

Figure 16. Graph. Modulus of Elasticity Test-to-Prediction Ratio Compared to Unit Weight for Potential Expression 1 (Eq. 5).

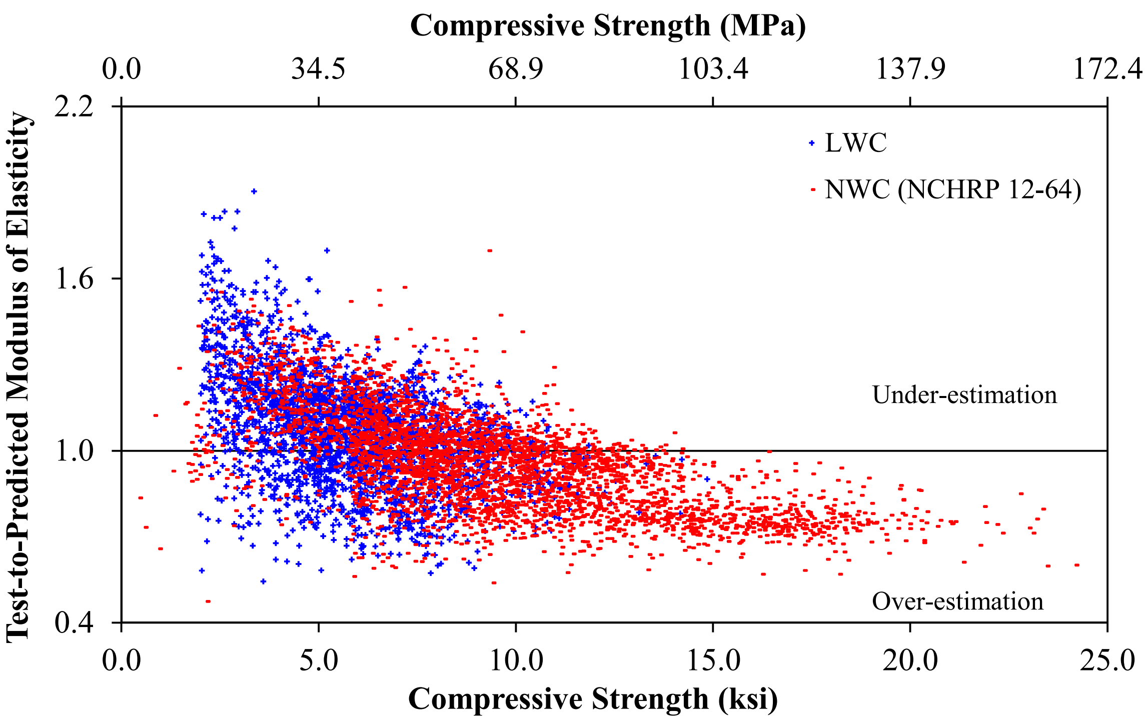

Figure 17. Graph. Modulus of Elasticity Test-to-Prediction Ratio Compared to Compressive Strength for Potential Expression 2 (Eq. 8).

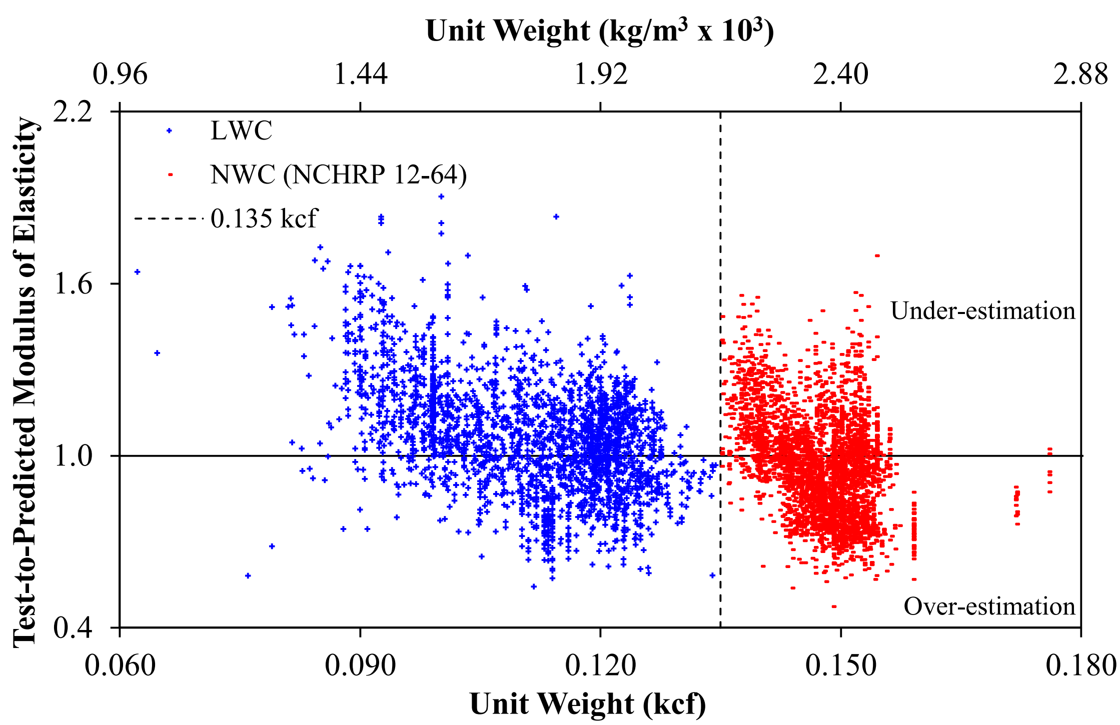

Figure 18. Graph. Modulus of Elasticity Test-to-Prediction Ratio Compared to Unit Weight for Potential Expression 2 (Eq. 8).

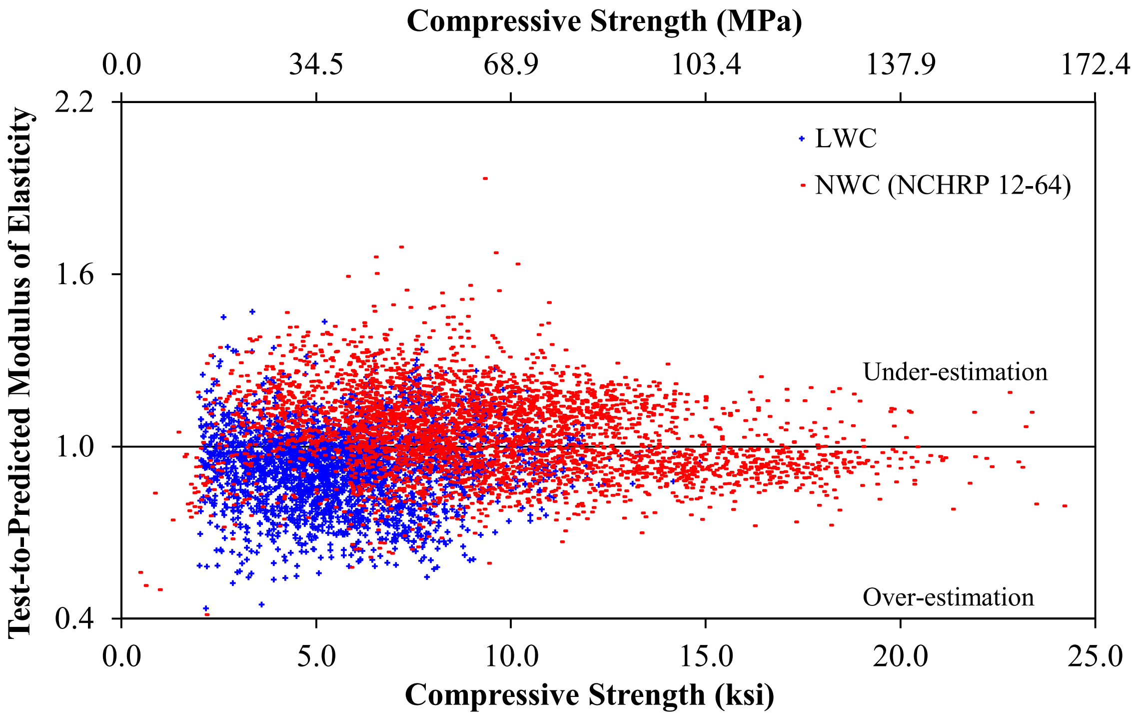

Figure 19. Graph. Modulus of Elasticity Test-to-Prediction Ratio Compared to Compressive Strength for Potential Expression 3 (Eq. 11).

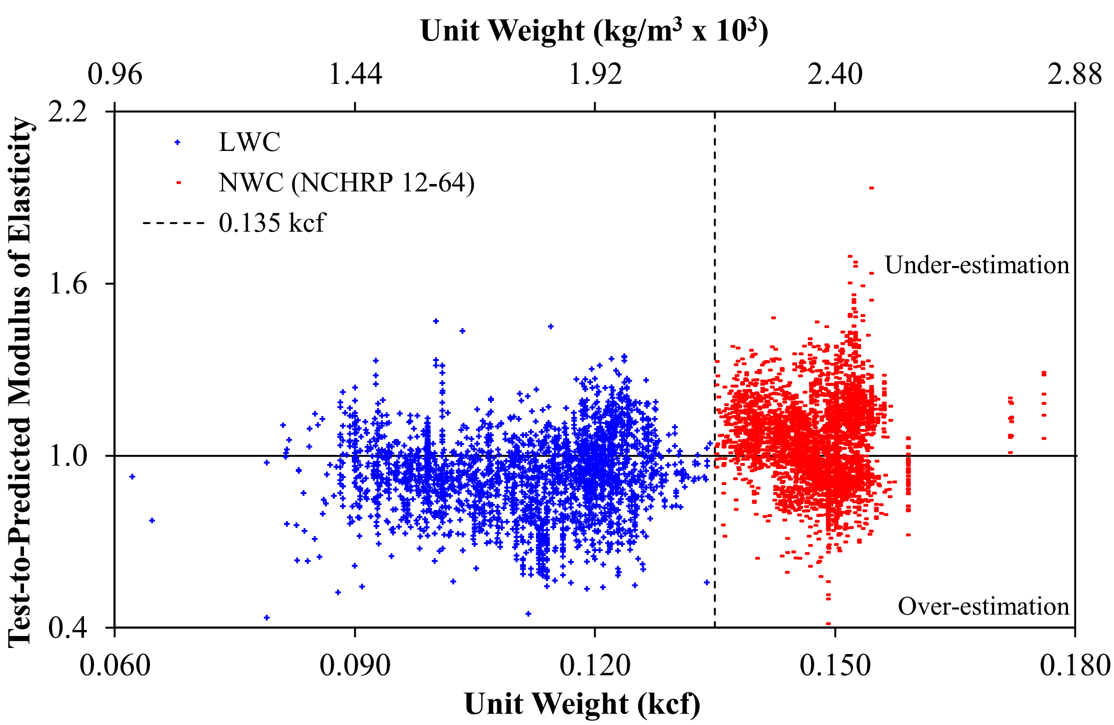

Figure 20. Graph. Modulus of Elasticity Test-to-Prediction Ratio Compared to Unit Weight for Potential Expression 3 (Eq. 11).

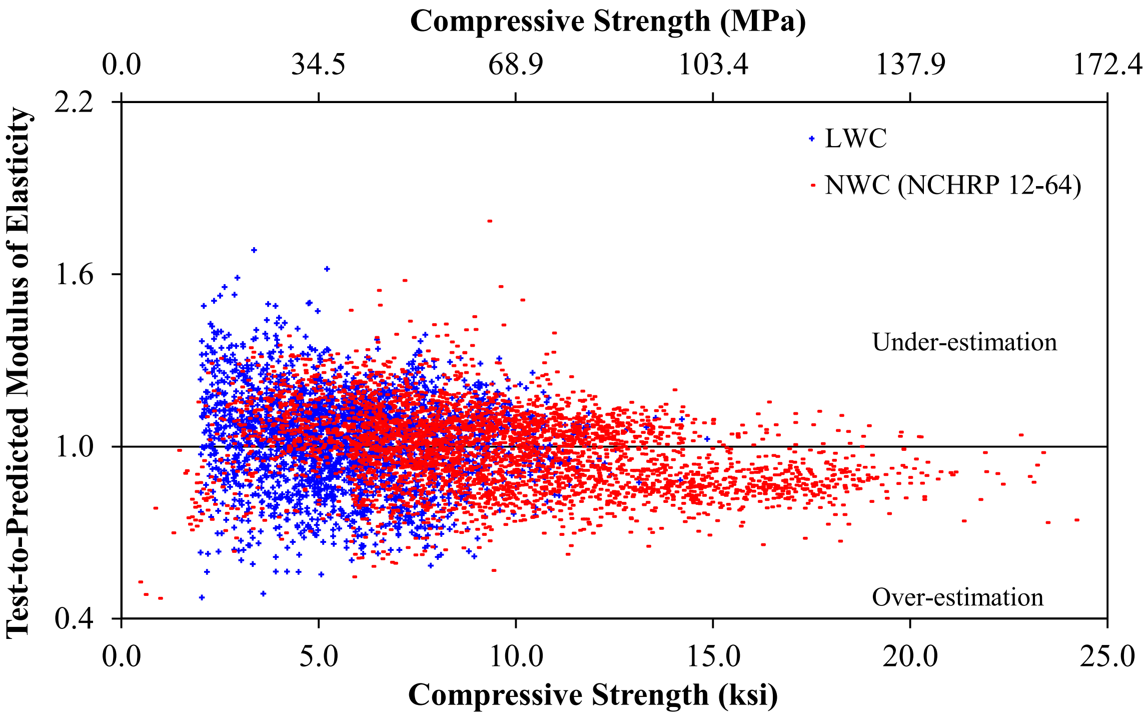

Figure 21. Graph. Modulus of Elasticity Test-to-Prediction Ratio Compared to Compressive Strength for Potential Expression 4 (Eq. 13).

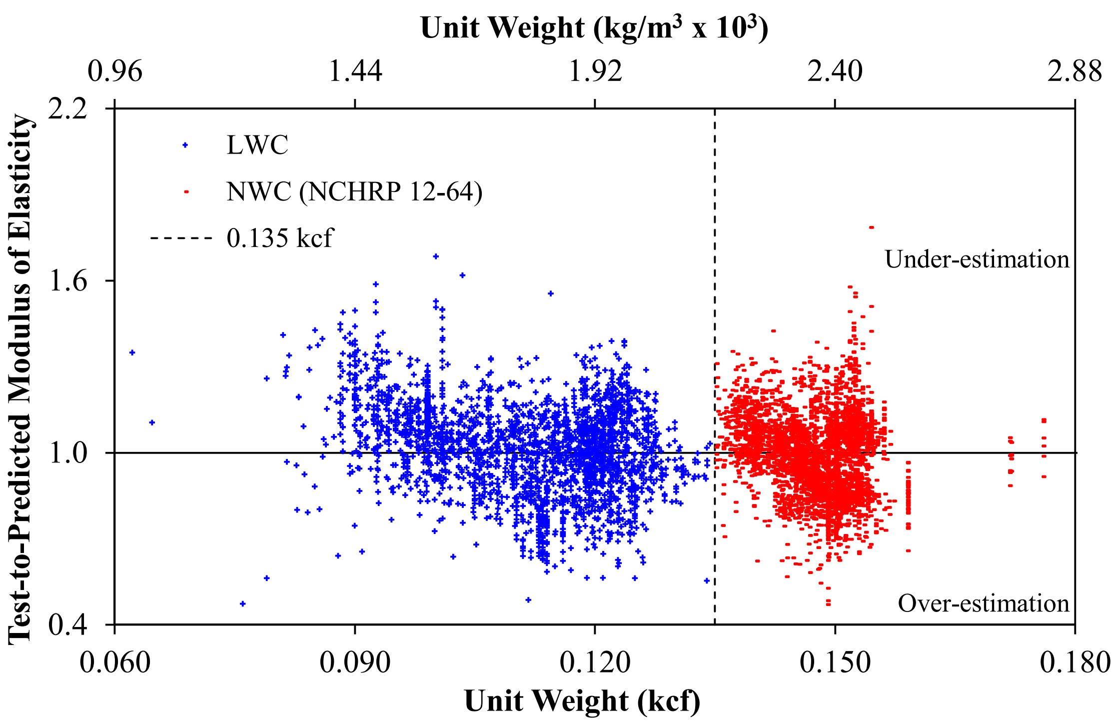

Figure 22. Graph. Modulus of Elasticity Test-to-Prediction Ratio Compared to Unit Weight for Potential Expression 4 (Eq. 13).

LIGHTWEIGHT CONCRETE REDUCTION FACTOR

The AASHTO LRFD Specifications 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 reduction 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 LWC reduction factor based on unit weight, a mix property typically specified for LWC. 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 reduction 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 (1961) and ACI Committee 318 (1962). 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. 14. 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.

$$\text{Splitting Ratio: } \frac{f_{ct}}{\sqrt{f_c'}} = \frac{1}{4.7} = 0.212 \qquad \text{(Eq. 14)}$$

The splitting ratios implied by the AASHTO LRFD Specifications for sand-lightweight concrete and all-lightweight concrete are given by Eq. 20 and are based on the 0.85 and 0.75 reduction factors described in Articles 5.8.2.

$$\text{Splitting Ratio for Sand-Lightweight: } 0.85\frac{f_{ct}}{\sqrt{f_c'}} = 0.85 \times 0.212 = 0.180 \quad \text{(Eq. 20a)}$$

$$\text{Splitting Ratio for All-Lightweight: } 0.75\frac{f_{ct}}{\sqrt{f_c'}} = 0.75 \times 0.212 = 0.159 \quad \text{(Eq. 20b)}$$

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 23 and Figure 24 and compared to compressive strength and unit weight, respectively. Figure 25 and Figure 26 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 23 for sand-lightweight concrete and in Figure 25 for all-lightweight concrete. The test-to-prediction ratios for the AASHTO LRFD expression for F_{sp} are given in Table 14 for sand-lightweight concrete and in Table 15 for all-lightweight concrete.

In Figure 26, some of the data points are arranged along a vertical line near a unit weight of 0.100 kcf. 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 14 and Table 15 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. The mean ratio for the all-lightweight concrete data is about 10% greater than unity for unit weights above 0.100 kcf. A test-to-prediction ratio greater than unity is an over-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.

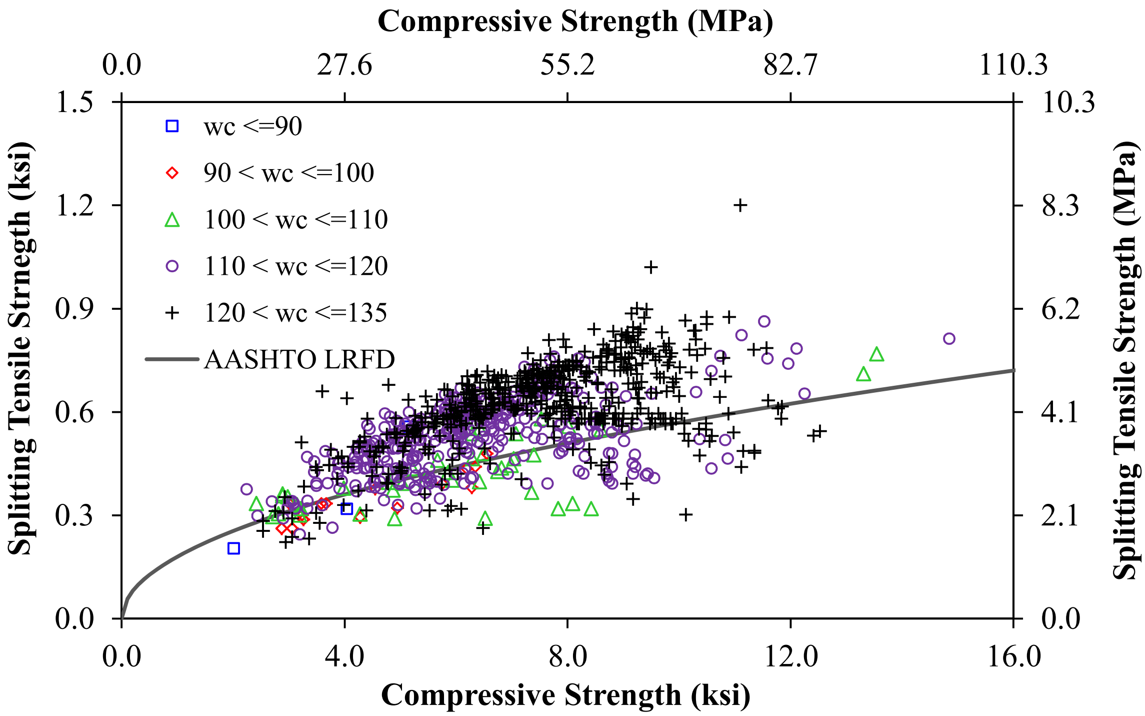

Figure 23. Graph. Splitting Tensile Strength Compared to Compressive Strength for Sand-Lightweight Concrete Showing Variation by Unit Weight.

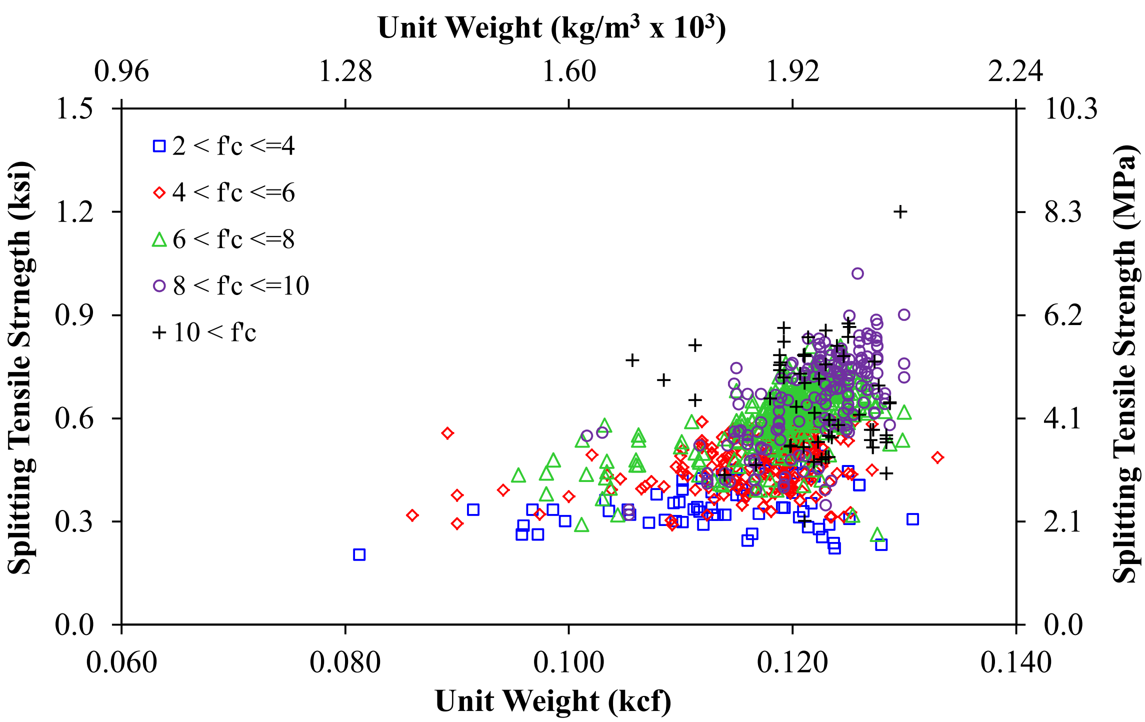

Figure 24. Graph. Splitting Tensile Strength Compared to Unit Weight for Sand-Lightweight Concrete Showing Variation by Compressive Strength.

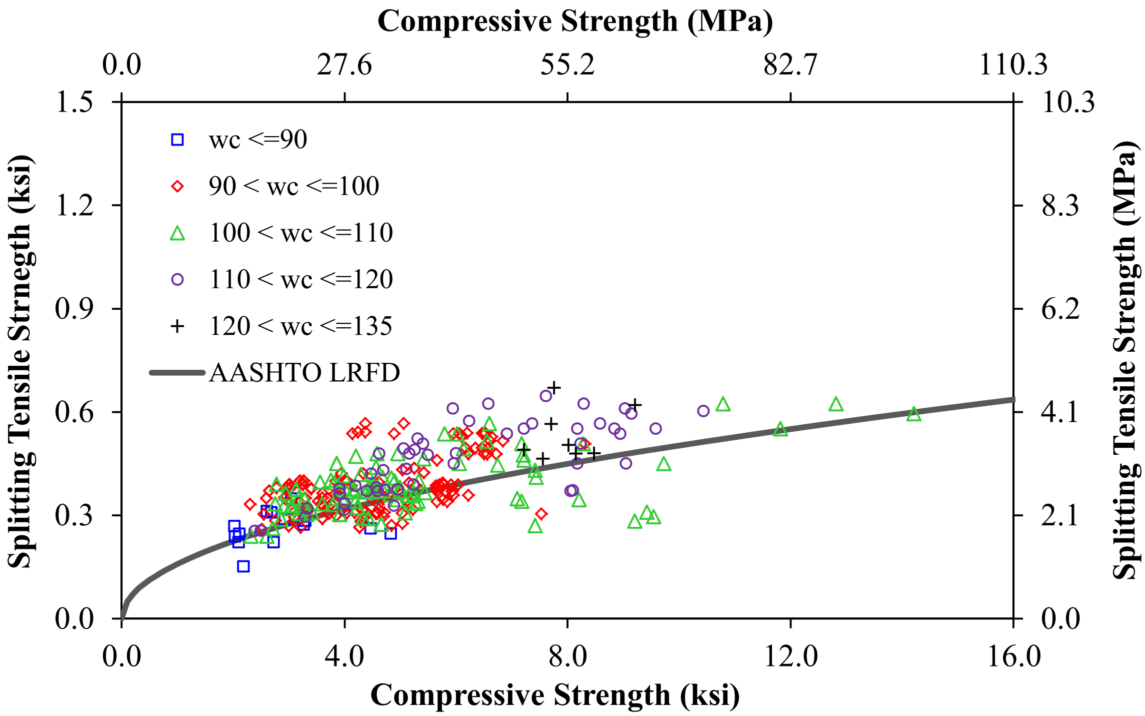

Figure 25. Graph. Splitting Tensile Strength Compared to Compressive Strength for All-Lightweight Concrete Showing Variation by Unit Weight.

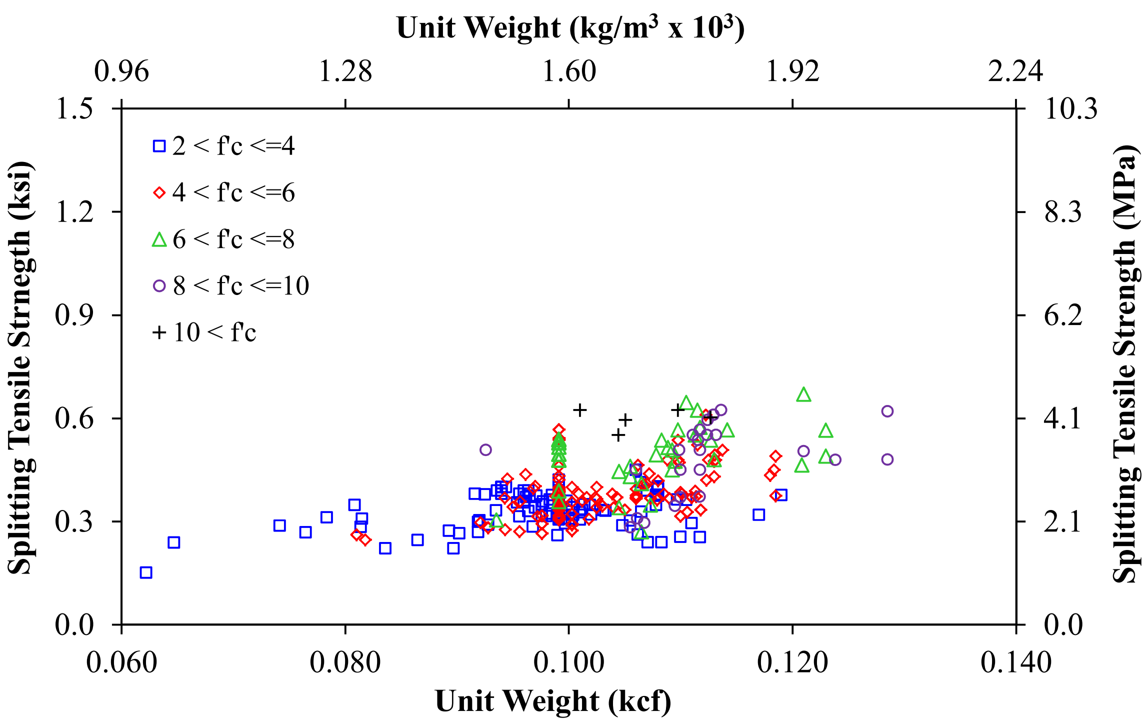

Figure 26. Graph. Splitting Tensile Strength Compared to Unit Weight for All-Lightweight Concrete Showing Variation by Compressive Strength.

Table 14. Test-to-Prediction Ratios of the Splitting Ratio for Sand-Lightweight Concrete using the AASHTO LRFD Expression (Eq. 20) and Potential Expressions 1 and 2 (Eq. 24 and Eq. 25).

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%

Table 15. Test-to-Prediction Ratios of the Splitting Ratio for All-Lightweight Concrete using the AASHTO LRFD Expression (Eq. 20) and Potential Expressions 1 and 2 (Eq. 24 and Eq. 25).

F_{sp} Expression	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
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%

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 will describe the development of a piecewise continuous function for predicting F_{sp}. A conceptual illustration for the potential expression is shown in Figure 27. 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. 21. The predicted F_{sp} then remains constant for unit weights greater than the upper limit on w_c.

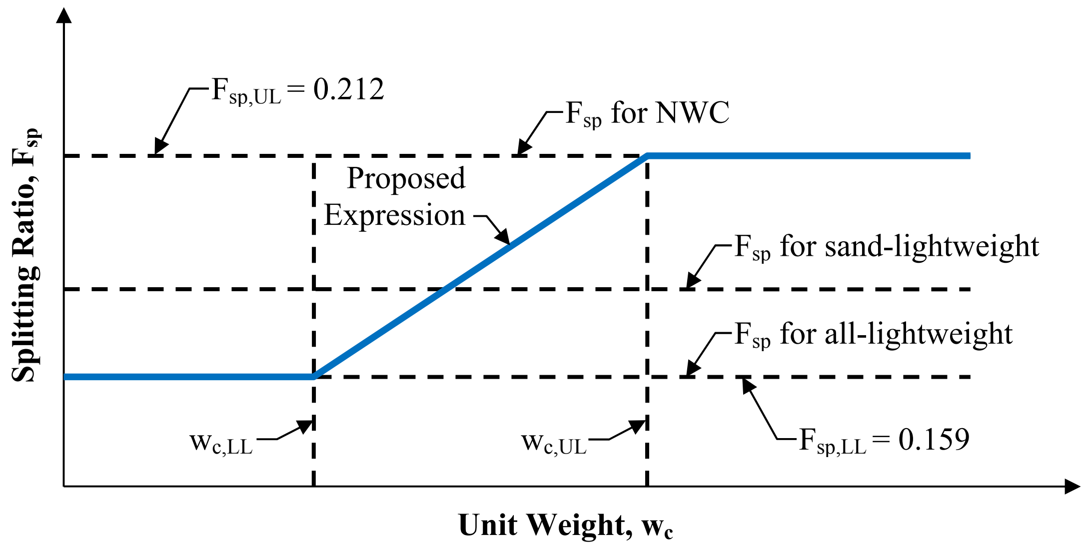

Figure 27. Illustration. Definitions for a Continuous Piecewise Expression for Predicting Splitting Ratio Based on Unit Weight.

$$\text{For } w_{c,LL} < w_c < w_{c,UL}\text{:}\ \ F_{sp} = \frac{\left(F_{sp,UL} - F_{sp,LL}\right)}{\left(w_{c,UL} - w_{c,LL}\right)}\left(w_c - w_{c,LL}\right) + F_{sp,LL} \qquad \text{(Eq. 21)}$$

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 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 is stated as a lower limit in the definition of LWC in ACI 318-11. The unit weight of 0.090 kcf 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 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. 22 and Eq. 23. These equations show how the upper and lower limits on F_{sp} and w_c were included.

$$\text{Potential 1: } F_{sp} = \frac{(0.212 - 0.159)}{(0.135 - 0.090)}(w_c - 0.090) + 0.159 \quad \text{(Eq. 22)}$$

$$\text{Potential 2: } F_{sp} = \frac{(0.212 - 0.159)}{(0.135 - 0.100)}(w_c - 0.100) + 0.159 \quad \text{(Eq. 23)}$$

Potential Expressions 1 and 2 for F_{sp} are given by Eq. 24 and Eq. 25 for the full range of unit weights. These equations are shown in Figure 28 for comparison with sand-lightweight and all-lightweight data only, and in Figure 29 for comparison with all the LWC data in the subset database for splitting tensile strength. There are horizontal lines in Figure 28 and Figure 29 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 and is given by:

$$\text{For } w_c \leq 0.090 \text{ kcf: } F_{sp} = 0.159 \quad \text{(Eq. 24a)}$$

$$\text{For } 0.090 < w_c < 0.135 \text{ kcf: } F_{sp} = 1.177w_c + 0.0530 \quad \text{(Eq. 24b)}$$

$$\text{For } w_c \geq 0.135 \text{ kcf: } F_{sp} = 0.212 \quad \text{(Eq. 24c)}$$

Potential Expression 2 for F_{sp} has a $w_{c,LL}$ of 0.100 kcf and is given by:

$$\text{For } w_c < 0.100 \text{ kcf: } F_{sp} = 0.159 \quad \text{(Eq. 25a)}$$

$$\text{For } 0.100 < w_c < 0.135 \text{ kcf: } F_{sp} = 1.517w_c + 0.0076 \quad \text{(Eq. 25b)}$$

$$\text{For } w_c \geq 0.135 \text{ kcf: } F_{sp} = 0.212 \quad \text{(Eq. 25c)}$$

The test-to-prediction ratios for Potential Expressions 1 and 2 are given in Table 14 and Table 15 for sand-lightweight concrete and all-lightweight concrete, respectively. Potential Expressions 1 and 2 have greater mean test-to-prediction ratios (over-estimated F_{sp}) than the expression in the AASHTO LRFD Specifications for unit weights up to 0.110 kcf. 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.

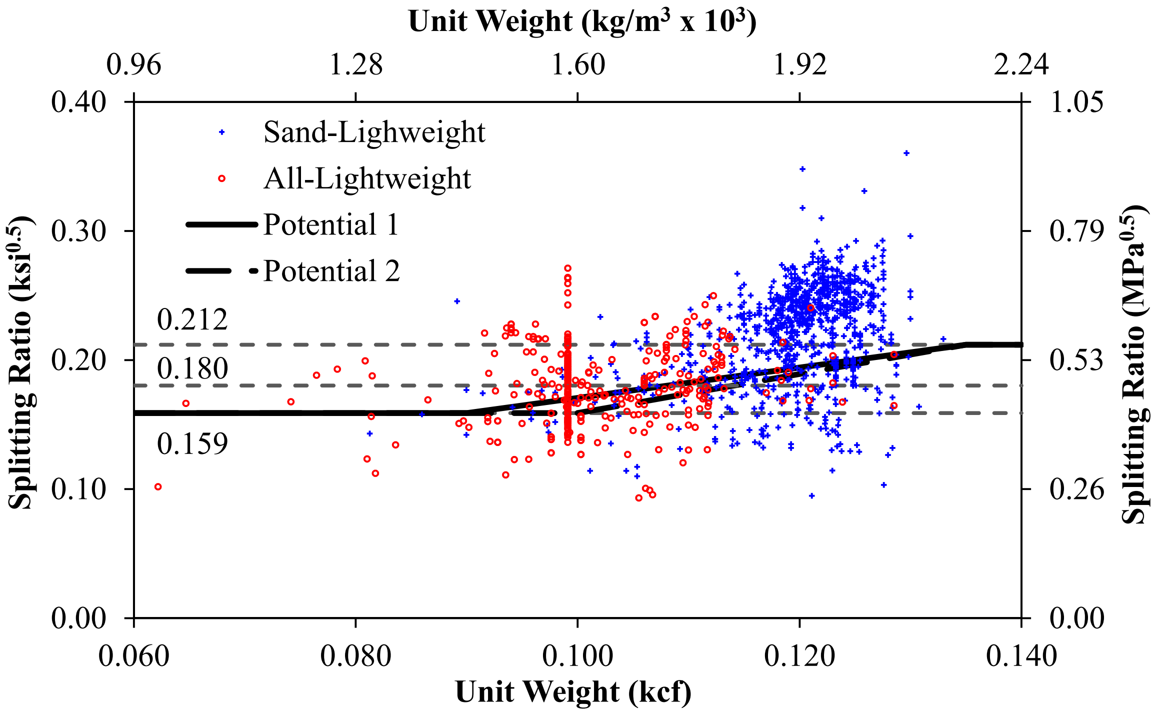

Figure 28. Graph. Splitting Ratio for Sand-Lightweight and All-Lightweight Concrete with Potential Expressions 1 and 2 (Eq. 24 and Eq. 25).

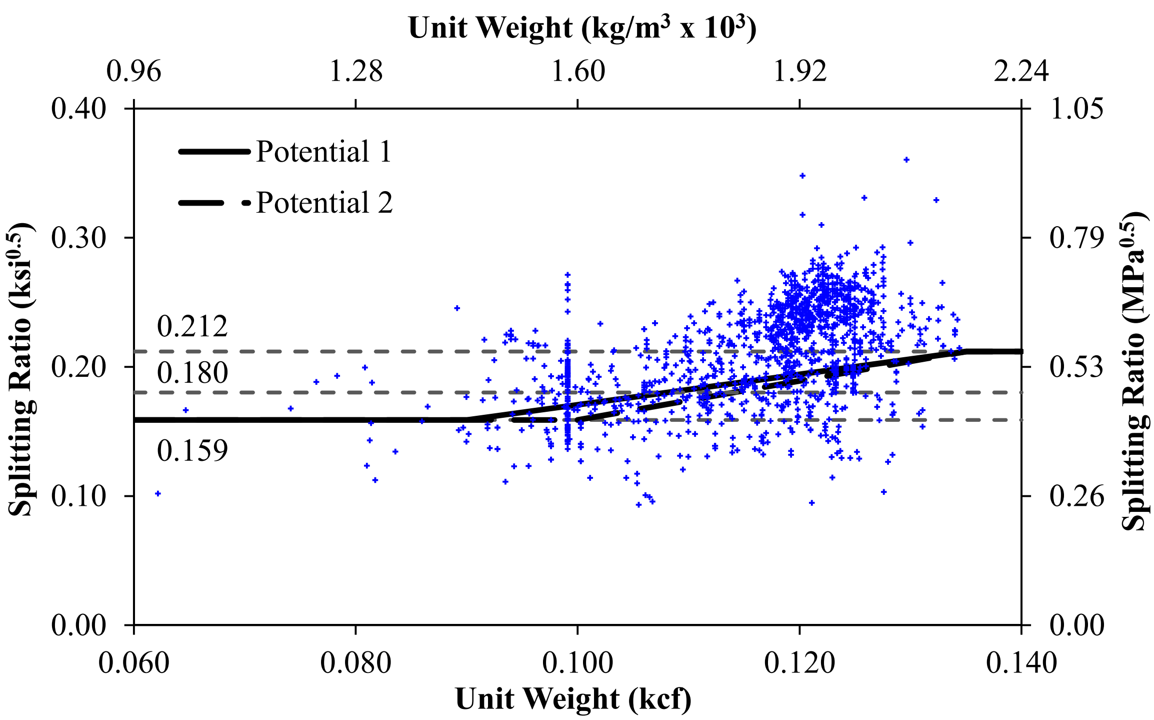

Figure 29. Graph. Splitting Ratio for TFHRC LWC Database with Potential Expressions 1 and 2 (Eq. 24 and Eq. 25).

In Table 15 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. Potential Expression 2 had mean ratios greater than unity for unit weights up to 0.120 kcf. Most of the data from the tests on all-lightweight concrete had a unit weight between 0.090 kcf and 0.110 kcf, while most of the tests on sand-lightweight concrete were between 0.110 kcf and 0.135 kcf. 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 and the test-to-prediction ratios for all-lightweight concrete that are less than unity at unit weights greater than 0.120 kcf may not be a concern. The test-to-prediction ratios are shown graphically for the AASHTO LRFD expression in Figure 30 and for the Potential Equation 2 in Figure 31.

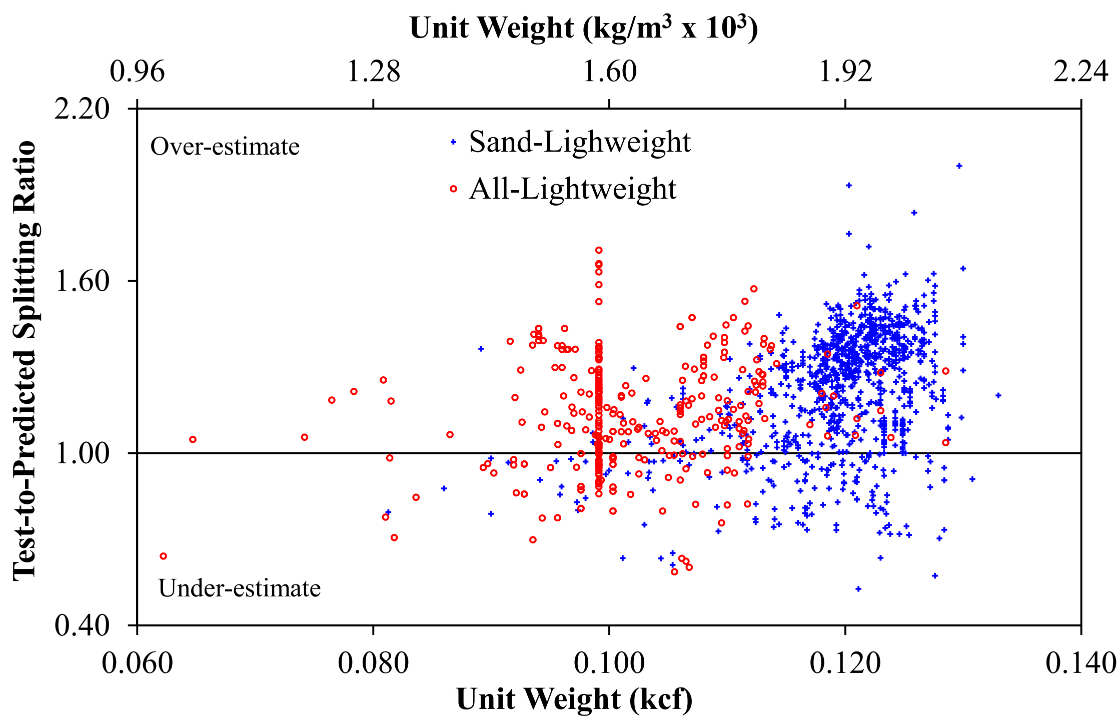

Figure 30. Graph. Test-to-Prediction Ratio for Splitting Ratio for Sand-Lightweight and All-Lightweight Concrete with AASHTO LRFD Expression (Eq. 20).

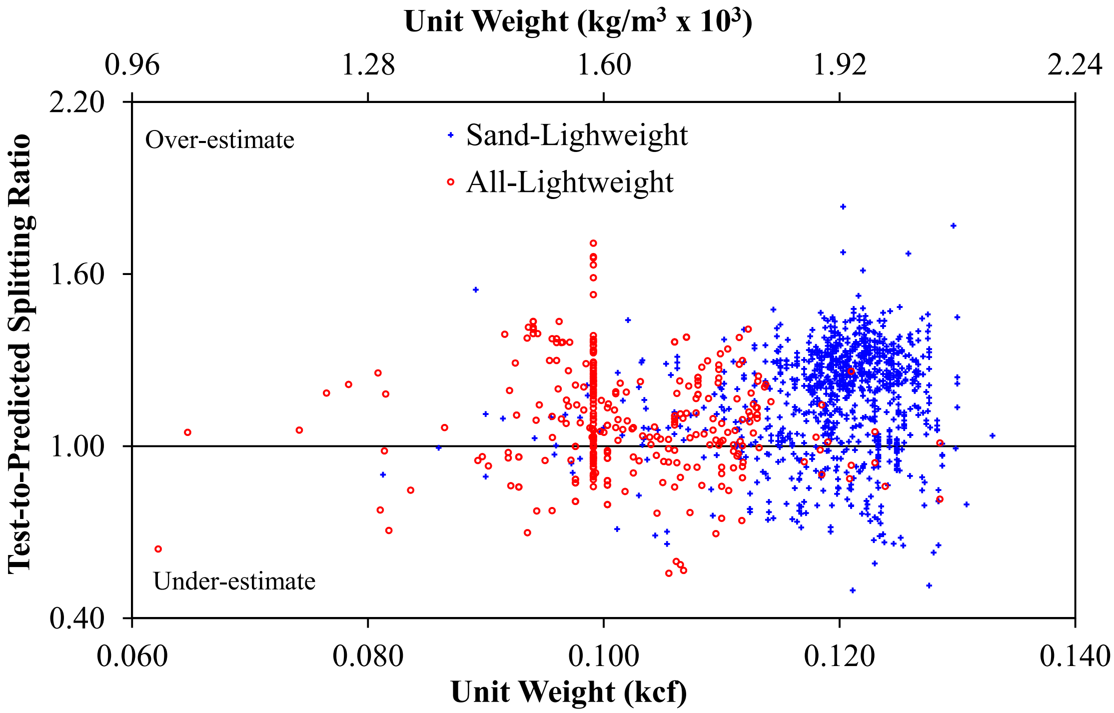

Figure 31. Graph. Test-to-Prediction Ratio for Splitting Ratio for Sand-Lightweight and All-Lightweight Concrete with Potential Expression 2 (Eq. 25).

Table 16 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. 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 32 for Potential Expression 2.

Additional expressions for predicting F_{sp} with a lower limit exceeding 0.100 kcf 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 16. Test-to-Prediction Ratios of the Splitting Ratio for the Subset Database using the Potential Expressions 1 and 2 (Eq. 24 and Eq. 25).

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%

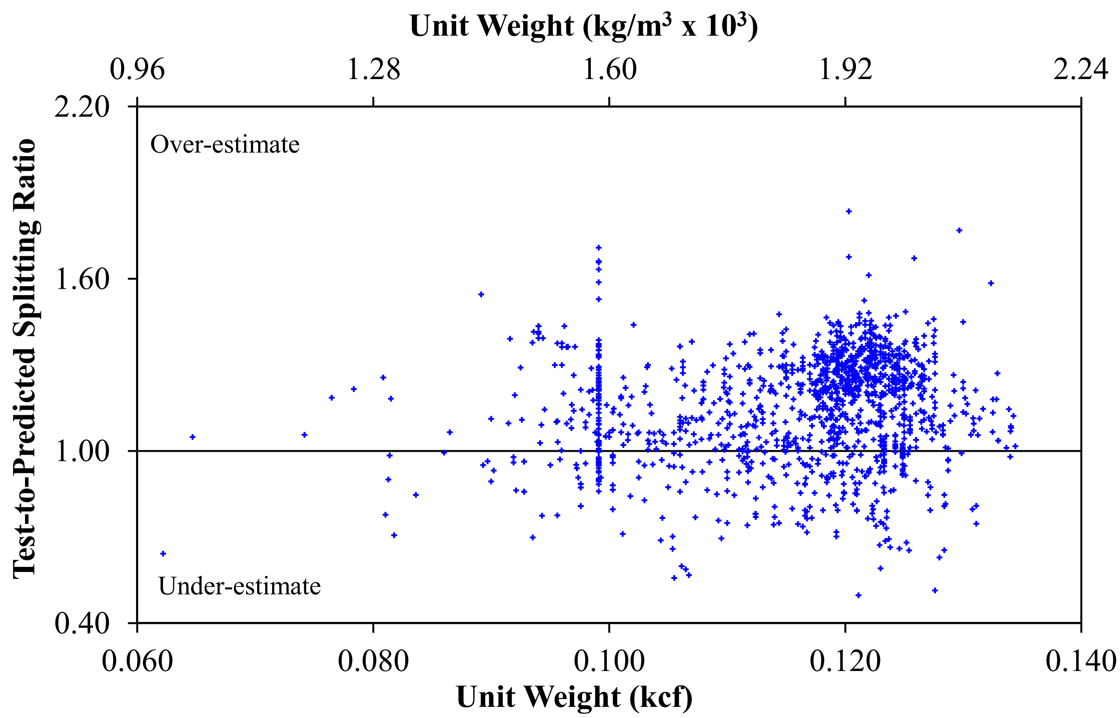

Figure 32. Graph. Test-to-Prediction Ratios of the Splitting Ratio for the Subset Database using Potential Expression 2 (Eq. 25).

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 33. 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 17. 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 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 18 by ranges of unit weight. Table 18 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. 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, an F_{sp} equal to 0.159 results in a prediction that is very conservative with a mean of 1.44.

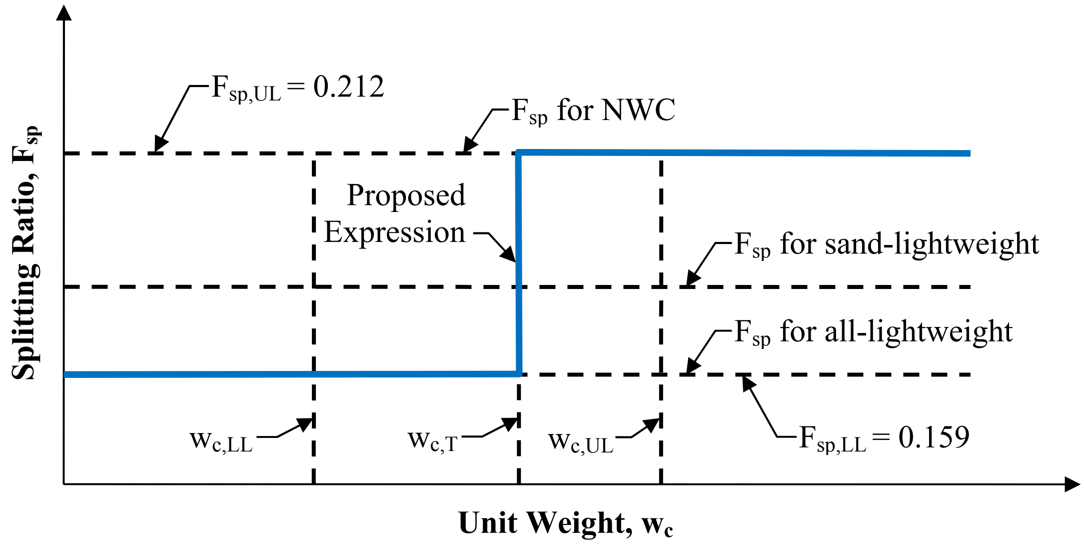

Figure 33. Illustration. Definitions for an Expression Predicting Splitting using a Single Abrupt Transition.

Table 17. 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%

Table 18. 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%

The effect on the mean test-to-prediction ratios of using transition unit weights of 0.110 kcf and 0.120 kcf is given in Table 17. 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 18. Transition unit weights of 0.110 kcf and 0.120 kcf were selected because a preliminary examination of the mean ratios for a transition w_c of 0.100 kcf was only 1.03, about a 3% difference between the mean ratios at unit weights of 0.090 kcf and 0.110 kcf. The difference between the mean ratios at 0.110 kcf and 0.120 kcf 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 34 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.

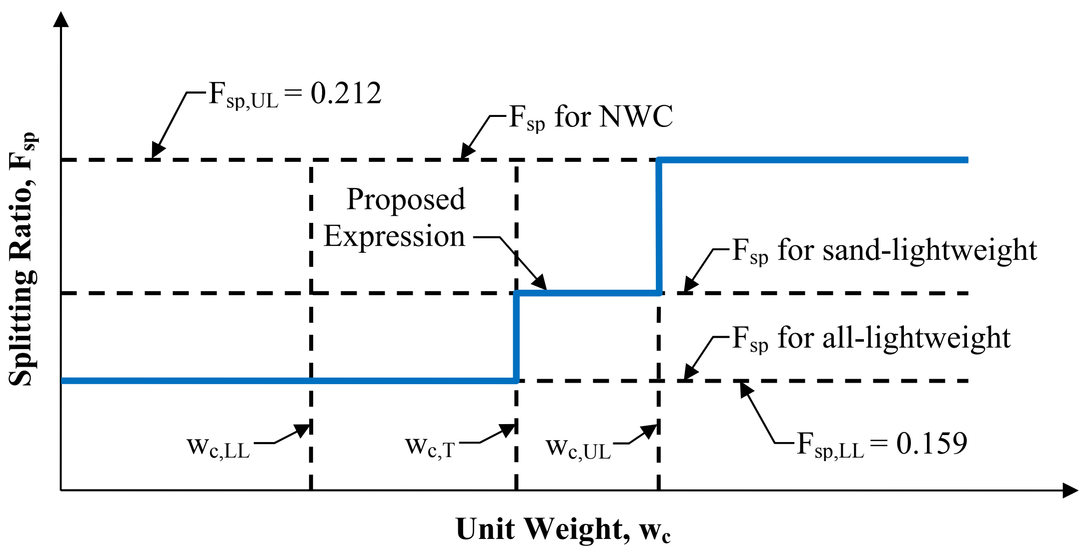

Figure 34. Illustration. Definitions for an Expression Predicting Splitting Ratio including Multiple Abrupt Transitions.

A potential expression for F_{sp} using the method of multiple abrupt changes was examined with a transition w_c of 0.110 kcf. The mean test-to-prediction ratio for this expression is 1.20 and is given in Table 17. The transition w_c of 0.110 kcf 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 18. 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. There is a similar increase in the mean ratio (0.97 to 1.16) at 0.110 kcf 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. Although the mean test-to-prediction ratios for different ranges of unit weight could be determined from Table 18, the ratios are given again in Table 19 for clarity.

Table 19. 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**	**$w_c \le 0.090$ 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**
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 ≥ 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 ≥ 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%

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 REDUCTION 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 reduction factors by dividing them by the upper limit on F_{sp} as shown in Eq. 26. In this document, the term λ-factor will be used to refer to LWC reduction factors. This section will describe the conversion of Potential Expressions 1 and 2 (Eq. 24 and Eq. 25), 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.

$$\text{LWC reduction factor:} \quad \lambda = \frac{F_{sp,Prediction}}{F_{sp,UL}} \tag{Eq. 26}$$

LWC reduction factors based on Potential Expressions 1 and 2 for F_{sp} are given by Eq. 27 and Eq. 28. 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:

$$\text{For } w_c \leq 0.090 \text{ kcf:} \quad \lambda = 0.75 \tag{Eq. 27a}$$

$$\text{For } 0.090 < w_c < 0.135 \text{ kcf:} \quad F_{sp} = 5.556 w_c + 0.250 \tag{Eq. 27b}$$

$$\text{For } w_c \geq 0.135 \text{ kcf:} \quad F_{sp} = 1.00 \tag{Eq. 27c}$$

Expression for the λ-factor converted from Potential Expression 2 with a $w_{c,LL}$ of 0.100 kcf:

$$\text{For } w_c \leq 0.100 \text{ kcf:} \quad \lambda = 0.75 \tag{Eq. 28a}$$

$$\text{For } 0.100 < w_c < 0.135 \text{ kcf:} \quad F_{sp} = 7.143 w_c + 0.036 \tag{Eq. 28b}$$

$$\text{For } w_c \geq 0.135 \text{ kcf:} \quad F_{sp} = 1.00 \tag{Eq. 28c}$$

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. 29 and results in a λ-factor of 0.75 at a w_c of 0.100 kcf and a λ-factor of 1.00 at a w_c of approximately 0.133 kcf. 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.

$$\text{For } w_c \leq 0.100 \text{ kcf: } \lambda = 0.75 \tag{Eq. 29a}$$

$$\text{For } 0.100 < w_c < 0.135 \text{ kcf: } \lambda = 7.5w_c \leq 1.00 \tag{Eq. 29b}$$

$$\text{For } w_c \geq 0.135 \text{ kcf: } \lambda = 1.00 \tag{Eq. 29c}$$

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. 30 for Potential Expression 3. The mean test-to-prediction ratios for the Potential Expression 3 are given in Table 20 and are very similar to mean ratios for Potential Expression 2. The splitting ratio predicted by Potential Expression 3 is shown graphically in Figure 35, and the test-to-prediction ratios are shown in Figure 36.

$$\text{For } w_c < 0.100 \text{ kcf: } F_{sp} = 0.16 \tag{Eq. 30a}$$

$$\text{For } 0.100 < w_c < 0.135 \text{ kcf: } F_{sp} = 1.589w_c \leq 0.21 \tag{Eq. 30b}$$

$$\text{For } w_c \geq 0.135 \text{ kcf: } F_{sp} = 0.21 \tag{Eq. 30c}$$

Table 20. Test-to-Prediction Ratios of the Splitting Ratio for the Subset Database using Potential Expression 3 (Eq. 30).

Data Source	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
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%

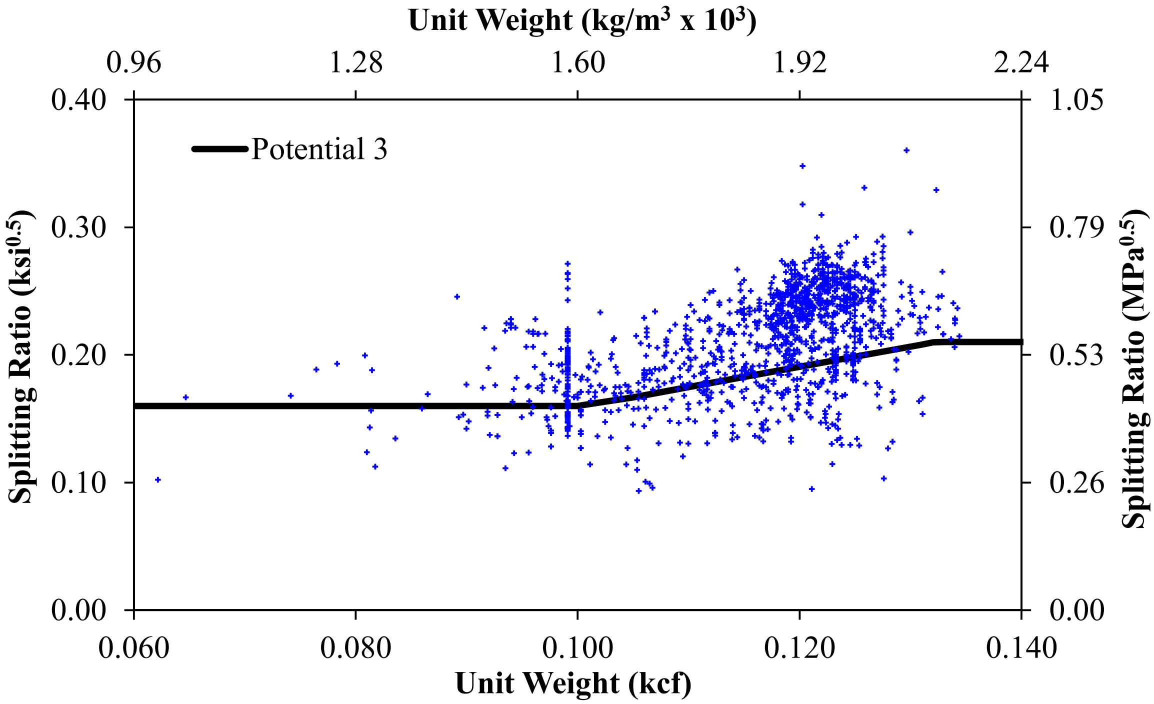

Figure 35. Graph. Splitting Ratio for the Subset Database with Potential Expression 3 (Eq. 30).

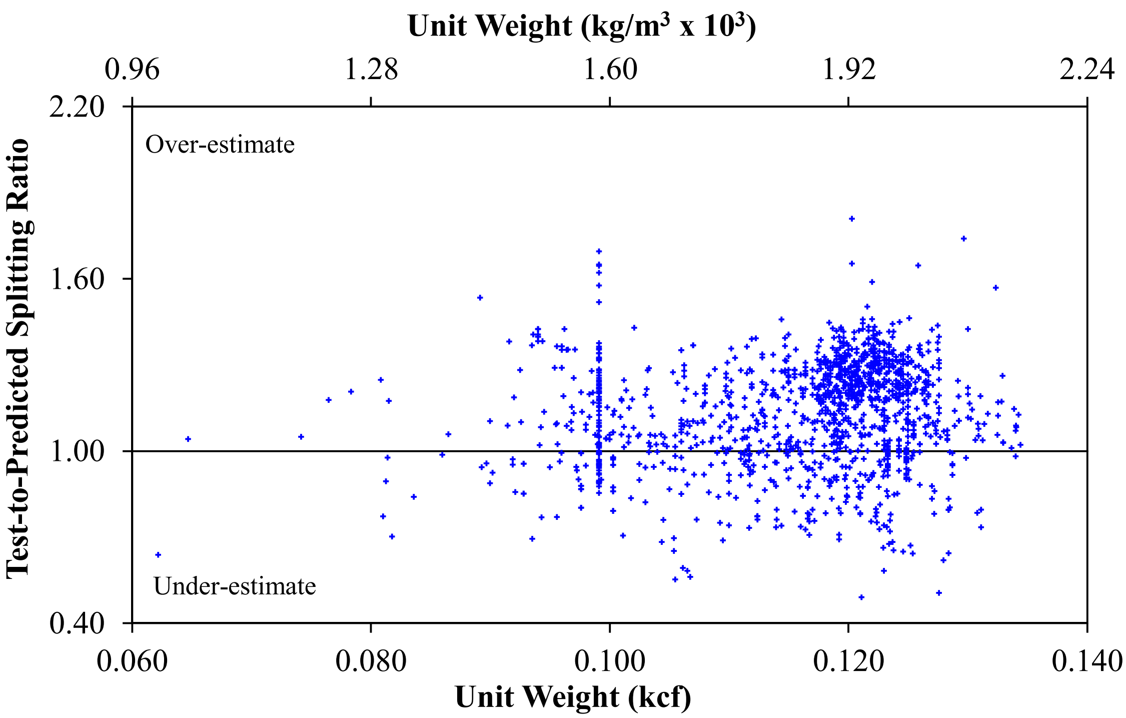

Figure 36. Graph. Test-to-Prediction Ratios of the Splitting Ratio for the Subset Database using Potential Expression 3 (Eq. 30).

CHAPTER 5. 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 the analysis.

The analysis of the TFHRC LWC Database using the subset database for modulus of elasticity and the subset database for splitting tensile strength has resulted in several new expressions for E_c and LWC reduction factor (λ-factor). 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. These mix types include specified density LWC 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 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 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 air-dry unit weight not exceeding 0.135 kcf, as determined by ASTM C567.

The term "air-dry unit weight" is used in the existing and proposed definitions; however this term is not found in ASTM C567 (Standard Test Method for Determining Density of Structural Lightweight Concrete). 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 concrete with unit weight 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 w_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 is described previously in this document. The expression was given as Eq. 13 and Figure 37 shows the expression compared to the current AASHTO LRFD expression for an assumed unit weight of 0.110 kcf and K_1 equal to unity.

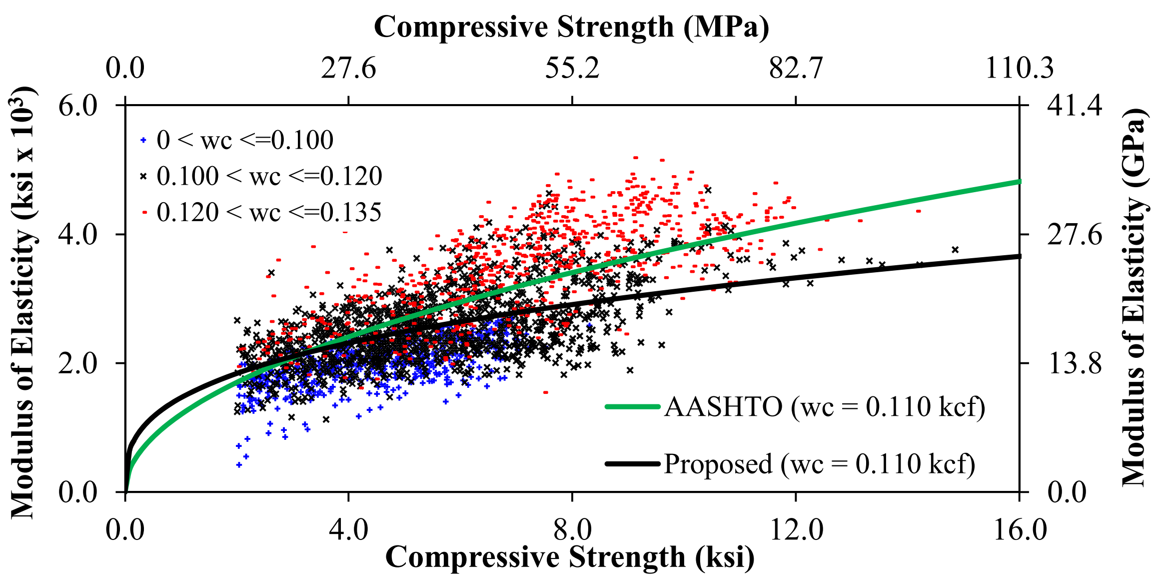

Figure 37. Graph. Modulus of Elasticity for Proposed Expression.

PROPOSED EXPRESSION FOR LWC REDUCTION FACTOR

The concept of including a reduction 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 reduction factor is not specified. This section will propose 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 reduction 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: $4.7\ f_{ct} < \sqrt{f'_c}$
>
> 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 following modifications shall apply in determining nominal resistance:
>
> Where the average splitting tensile strength of lightweight concrete, f_{ct}, is specified, λ may be taken as: $0.21\ f_{ct} / \sqrt{f'_c} \leq 1.0$
>
> 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 38 and the predicted splitting ratios (λ-factor × 0.212) are shown in Figure 39. The λ-factors implied in AASHTO LRFD for sand lightweight concrete and all-lightweight concrete are also shown in Figure 39. Figure 39 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.

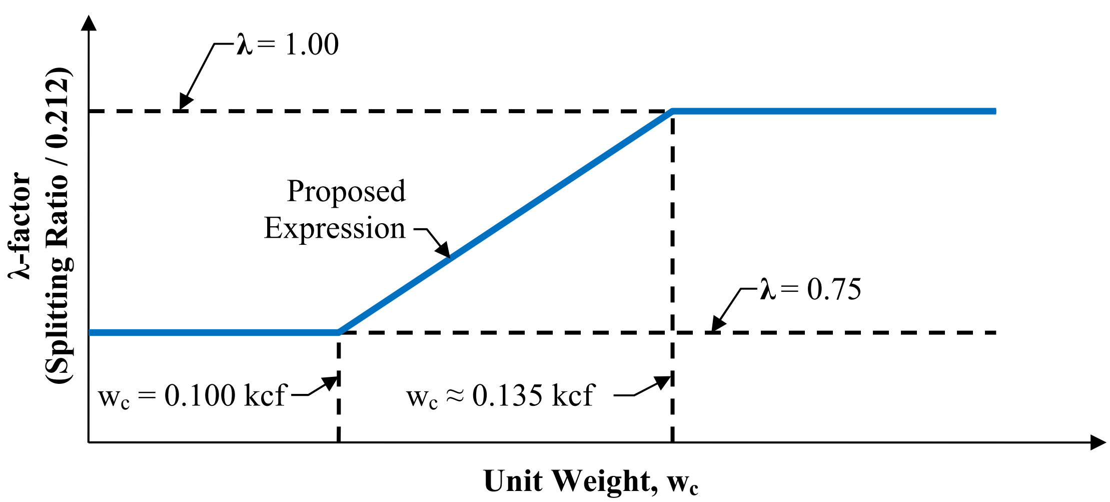

Figure 38. Illustration. Proposed Expression for λ-Factor.

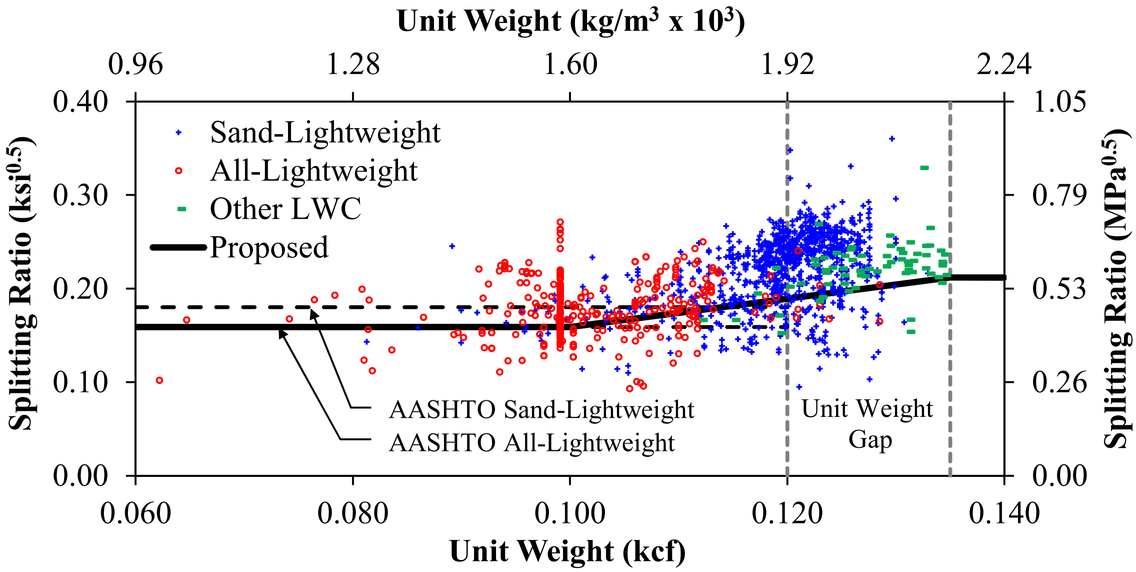

Figure 39. Graph. Splitting Ratio (f_{ct} / $\sqrt{f'_c}$) for the Proposed Expression (λ-factor × 0.212).

As state 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.

CHAPTER 6. CONCLUDING REMARKS

INTRODUCTION

This document 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 and LWC reduction factor 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 was developed to assist AASHTO SCOBS T-10 as they consider revisions to Chapter 5 of the AASHTO LRFD Bridge Design Specification. 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 7. NOTATION

AASHTO = American Association of State Highway and Transportation Officials

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

COV = coefficient of variation

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

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

LWC = lightweight concrete

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

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

NWC = normal weight concrete

SCOBS = Highway Subcommittee on Bridges and Structures

SDC = specified density concrete

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 reduction factor

ϕ = resistance factor

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: EXECUTIVE SUMMARY

This appendix contains an executive summary of this document. This executive summary, along with the full document presented in the body of this report, was provided to AASHTO SCOBS T-10 for their September 2012 meeting. The body of the report was condensed for the summary; however the section on Preliminary Recommendations for AASHTO Specifications closely resembles Chapter 5 in the full document.

SYNTHESIS AND EVALUATION OF LIGHTWEIGHT CONCRETE RESEARCH RELEVANT TO THE AASHTO LRFD BRIDGE DESIGN SPECIFICATIONS: *POTENTIAL REVISIONS FOR DEFINITION AND MECHANICAL PROPERTIES*

Executive Summary

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INTRODUCTION

This document describes a database of mechanical property tests on LWC that has been collected, and the analysis of LWC 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

The objective of this document is to present potential revisions to the AASHTO LRFD Specifications relating to the mechanical properties of LWC to the members of AASHTO SCOBS T-10. The basis for the proposed expressions for mechanical properties is summarized in this document and described in more detail in the full report. The authors would like to solicit feedback on the proposed revisions.

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. The recorded mechanical tests included compressive strength, modulus of elasticity, splitting tensile test, modulus of rupture, and Poisson's Ratio. Concrete mix information was recorded including the type of course 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.

TFHRC DATABASE SUBSETS

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 and a unit weight that is less than or equal to 0.135 kcf.

DESIGN EXPRESSIONS FOR MODULUS OF ELASTICITY

A total of 2556 data lines are in the TFHRC subset database for modulus of elasticity. As discussed previously, the data lines were limited to those with a unit weight less than 0.135 kcf. 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 was utilized. 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 is termed the "NCHRP LWC data", and the rest of data for a total of 3795 data lines is termed the "NCHRP NWC data".

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. 1. NCHRP Project 12-64 proposed the expression given by Eq. 2 and was developed for concrete strengths up to 18 ksi using over 4400 data points. For Eq. 1 and Eq. 2, the units of E_c and f'_c are ksi and w_c is kcf. ACI Committee 363, High-Strength Concrete, gives Eq. 3 as a design expression for E_c in its document, "State-of-the-Art Report on High-Strength Concrete". For Eq. 3, the units of E_c and f'_c are psi and w_c is pcf.

$$E_c = 33{,}000 K_1 w_c^{1.5} \sqrt{f_c'} \qquad \text{(Eq. 1)}$$

$$E_c = 310{,}000 K_1 w_c^{2.5} {f_c'}^{0.33} \qquad \text{(Eq. 2)}$$

$$E_c = 23 w_c^{1.5} \sqrt{f_c'} + 1{,}000{,}000 \qquad \text{(Eq. 3)}$$

LIGHTWEIGHT CONCRETE REDUCTION FACTOR

Article 5.8.2.2 in the AASHTO LRFD Specifications accounts for the reduced tensile strength of LWC using a modification for LWC. 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. Unfortunately, the amount of sand replacement 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 reduction factor based on a specified mix property, such as concrete density, would be easier for a designer to use.

PRELIMINARY RECOMMENDATIONS FOR AASHTO SPECIFICATIONS

This section summarizes several preliminary recommended changes to the AASHTO LRFD Specifications. The recommendations are based on an analysis of tests on the mechanical properties of LWC only. 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 the analysis.

The analysis of the TFHRC LWC Database using the subset database for modulus of elasticity (including TFHRC LWC and NCHRP NWC) and the subset database for splitting tensile strength has resulted in several new expressions for E_c and LWC reduction factor (λ-factor). 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. 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 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 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 air-dry unit weight not exceeding 0.135 kcf, as determined by ASTM C567.

The term "air-dry unit weight" is used in the existing and proposed definitions; however this term is not found in ASTM C567 (Standard Test Method for Determining Density of Structural Lightweight Concrete). 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 concrete with unit weight 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 w_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:

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

Figure 40 shows the proposed expression compared to the current AASHTO LRFD expression for an assumed unit weight of 0.110 kcf and K_1 equal to unity. Table 21 gives the test-to-prediction ratios for the AASHTO LRFD expression, the AASHTO LRFD expression with a modified factor, and the proposed expressions. The modified factor was selected to give a mean test-to-prediction ratio of unity. The percentage of E_c data points that were under-estimated by 20% (ratio ≥ 1.2) or over-estimated by 20% (ratio <0.8) is also given in Table 21.

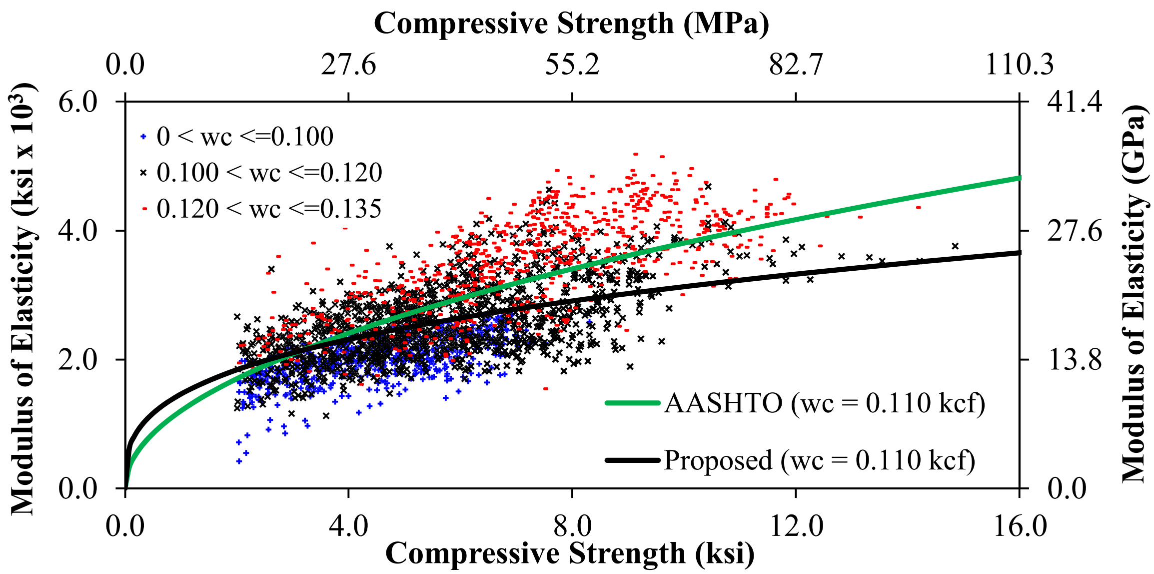

Figure 40. Graph. Modulus of Elasticity for Proposed Expression.

Table 21. Test-to-Prediction Ratios for Modulus of Elasticity for AASHTO LRFD, AASHTO LRFD with Optimized Factor, and Proposed Expression.

Data Source(1)	Statistical Measure	**AASHTO LRFD** (Eq. 1)	**Optimize Factor ($31{,}580 w_c^{1.5} f'_c{}^{0.50}$)**	**Proposed Expression ($121{,}400 w_c^{2.0} f'_c{}^{0.33}$)**
LWC and NWC	mean	0.957	1.000	1.000
	COV	17.0%	17.0%	14.8%
	Percent ≥ 1.2	7.2%	11.5%	7.9%
	Percent < 0.8	18.2%	11.6%	8.6%
LWC	mean	0.936	0.977	1.019
	COV	16.3%	16.3%	15.6%
	Percent ≥ 1.2	3.9%	7.3%	11.0%
	Percent < 0.8	18.6%	13.8%	9.4%
NWC	mean	0.972	1.015	0.987
	COV	17.3%	17.3%	14.1%
	Percent ≥ 1.2	9.5%	14.3%	5.8%
	Percent < 0.8	17.9%	10.1%	8.0%

Notes: 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

PROPOSED EXPRESSION FOR LWC REDUCTION FACTOR

The concept of including a reduction 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 reduction factor is not specified. This section will propose 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 reduction factor, or λ-factor, could be based on the language in 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: $4.7 f_{ct} < \sqrt{f'_c}$

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 this document. The proposed text for the λ-factor is as follows:

Where lightweight aggregate concretes are used, the following modifications shall apply in determining nominal resistance:

Where the average splitting tensile strength of lightweight concrete, f_{ct}, is specified, λ may be taken as: $0.21\, f_{ct} / \sqrt{f'_c} \leq 1.0$

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 41 and the predicted splitting ratios (λ-factor × 0.212) are shown in Figure 42. The λ-factors implied in AASHTO LRFD for sand lightweight concrete and all-lightweight concrete are also shown in Figure 42. Figure 42 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.

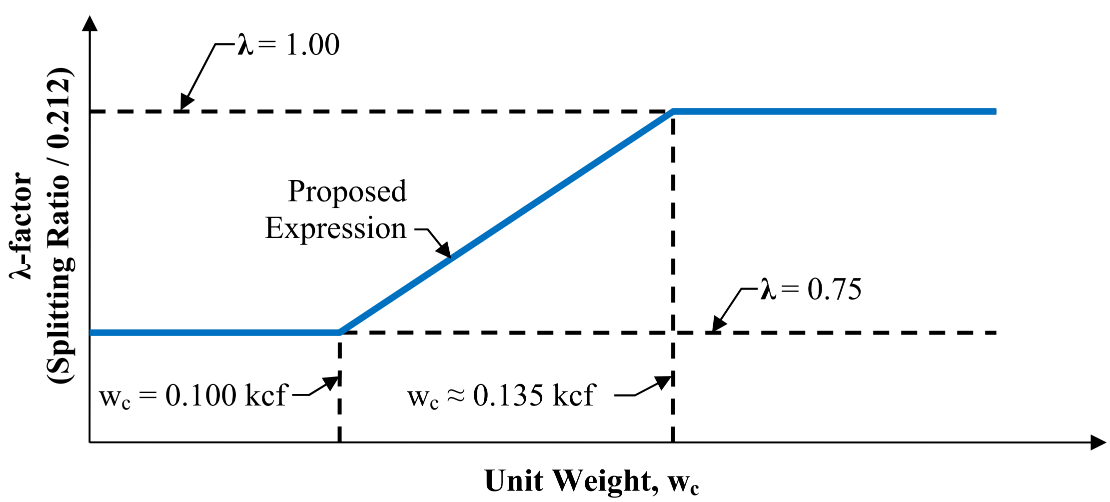

Figure 41. Illustration. Proposed Expression for λ-Factor.

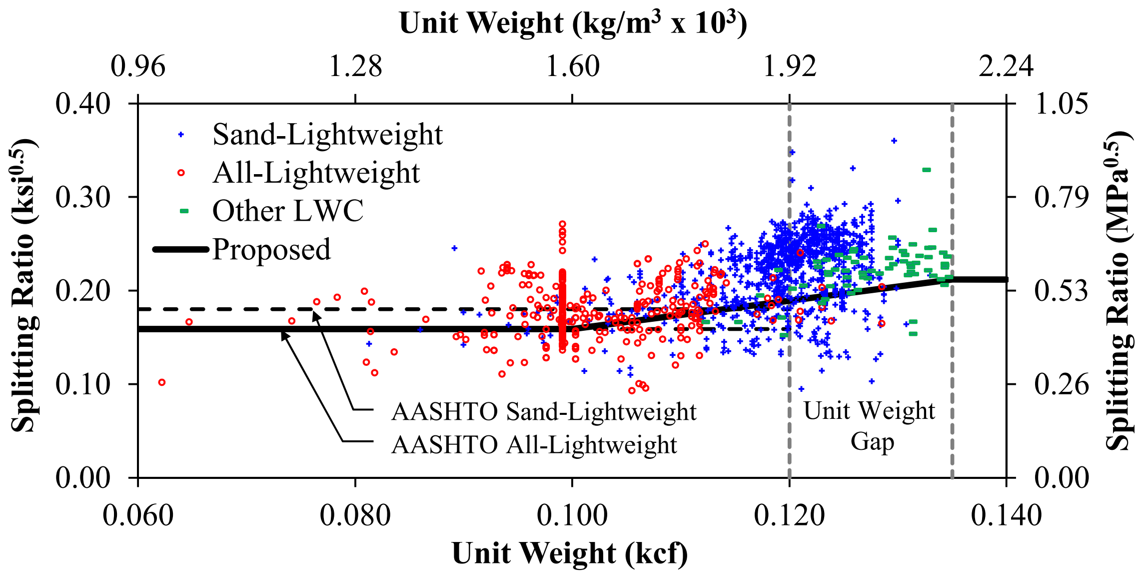

Figure 42. Graph. Splitting Ratio (f_{ct} / √f'$_c$) for the Proposed Expression (λ-factor × 0.212).

As state 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 of LWC.

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