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Structural Lightweight Concrete in the Building Code Requirements for Structural Concrete (ACI 318-19)

This Information Sheet aims to serve as an aid in locating and applying those provisions of "Building Code Requirements for Structural Concrete (ACI 318-19)", which specifically cover structural lightweight concrete. The remainder of the Standard is also applicable. Hence, the reader should be cautious about using this publication except in conjunction with a copy of the ACI Standard in combination with "Commentary on Building Code Requirements for Structural Concrete (ACI 318R-19)" reported by ACI Committee 318. Excerpts from the ACI 318 follow the same two-column format of the ACI Standard. Units, when applicable, reflect the ACI 318 with ACI 318M units in parenthesis. Additional notes represent the Expanded Shale, Clay and Slate Institute (ESCSI) remarks. ESCSI recommends consultation with the aggregate producers in various localities before design for advice on the range of structural and physical properties and practical applications of their products.

ESCSI NOTES ON

BUILDING CODE REQUIREMENTS FOR STRUCTURAL CONCRETE (ACI 318-19), AN ACI STANDARD; AND COMMENTARY ON BUILDING CODE REQUIREMENTS FOR STRUCTURAL CONCRETE (ACI 318R-19), REPORTED BY ACI COMMITTEE 318

Keywords

Lightweight Concretes

> ***Note:*** *The referenced keyword for structural lightweight aggregate concrete containing expanded shale, clay, and slate aggregates in the* ***ACI 318*** *is "lightweight concretes."* ***ACI CT-20: ACI Concrete Terminology*** *provides a comprehensive list of related terms.* ***ACI 213*** *provides additional information on lightweight aggregate and concrete.*

Chapter 2 Notation and Terminology

2.2 NOTATION

Code

w_c = density, unit weight, of normalweight concrete or equilibrium density of lightweight concrete, lb/ft^3 (kg/m^3)

Commentary

***Note: ACI 318** follows **ASTM C567** to determine the equilibrium density of lightweight concrete as the parallel term for the density of normalweight concrete. See **2.3-Terminology** for additional definitions.*

Code

λ = modification factor to reflect the reduced mechanical properties of lightweight concrete relative to normalweight concrete of the same compressive strength

λ_a = modification factor to reflect the reduced mechanical properties of lightweight concrete in certain concrete anchorage applications

Commentary

λ = in most cases, the reduction in mechanical properties is caused by the reduced ratio of tensile-to-compressive strength of lightweight concrete compared to normalweight concrete. There are instances in the Code where λ is used as a modifier to reduce expected performance of lightweight concrete where the reduction is not related directly to tensile strength.

***Note:** See **Chapter 19** for the determination of modification factors for reduction of mechanical properties, typically as a function of reduced ratio of tensile-to-compressive strength of lightweight concrete. The application of modification factors varies for different applications in each chapter and is sensitive to the availability of experimental data for each application.*

2.3 TERMINOLOGY

Code

aggregate, lightweight—aggregate meeting the requirements of ASTM C330 and having a loose bulk density of 70 lb/ft^3 (1120 kg/m^3) or less, determined in accordance with ASTM C29.

concrete, all-lightweight—lightweight concrete containing only lightweight coarse and fine aggregates that conform to ASTM C330.

concrete, lightweight—concrete containing lightweight aggregate and having an equilibrium density, as determined by ASTM C567, between 90 and 135 lb/ft^3 (1440 and 2160 kg/m^3).

concrete, sand-lightweight—lightweight concrete containing only normalweight fine aggregate that conforms to ASTM C33 and lightweight coarse aggregate that conforms to ASTM C330.

equilibrium density—density of lightweight concrete determined in accordance with ASTM C567.

Commentary

aggregate, lightweight—In some standards, the term "lightweight aggregate" is being replaced by the term "low-density aggregate."

concrete, sand-lightweight—By Code terminology, sand-lightweight concrete is lightweight concrete with all the fine aggregate replaced by sand. This definition may not be in agreement with usage by some material suppliers or contractors where the majority, but not all, of the lightweight fines are replaced by sand. For proper application of the Code provisions, the replacement limits should be stated, with interpolation if partial sand replacement is used.

Note: ACI 318 *follows* ***ACI 213*** *and referenced* ***ASTM*** *standards to define the density of various types of lightweight concrete and limit the density of lightweight aggregates. See* ***ACI CT-20: ACI Concrete Terminology*** *for related terms.*

The general lightweight concrete term, subject to defined limits of density, applies to other types not specifically mentioned in this section. An example is the reversed mixture, also known as all fine lightweight concrete, containing normalweight coarse aggregate that conforms to ***ASTM C33*** *and lightweight fine aggregate that conforms to* ***ASTM C330****.*

Internally cured concrete contains partial fine lightweight aggregates. But the small fraction of sand replacement for internal curing does not substantially reduce the equilibrium density of concrete; hence, the "lightweight concrete" definition does not apply to internally cured concrete.

Chapter 3 Referenced Standards

3.2 REFERENCED STANDARDS

3.2.4 ASTM International

Code

C330/C330M-17a—Standard Specification for Lightweight Aggregates for Structural Concrete

C567/C567M-14—Standard Test Method for Determining Density of Structural Lightweight Concrete

Commentary

Note: *See* ***ACI 213*** *for other* ***ASTM*** *standards applicable to lightweight aggregate and concrete.*

CHAPTER 7 ONE-WAY SLABS

7.3 DESIGN LIMITS

7.3.1 Minimum slab thickness

Code

Table 7.3.1.1—Minimum thickness of solid nonprestressed one-way slabs

Support condition	Minimum *h*[1]
Simply supported	*ℓ/20*
One end continuous	*ℓ/24*
Both ends continuous	*ℓ/28*
Cantilever	*ℓ/10*

[1] Expression applicable for normalweight concrete and f_y = 60,000 psi (420 MPa). For other cases, minimum *h* shall be modified in accordance with 7.3.1.1.1 through 7.3.1.1.3, as appropriate.

7.3.1.1.2 For nonprestressed slabs made of lightweight concrete having w_c in the range of 90 to 115 lb/ft^3 (1440 to 1840 kg/m^3), the expressions in Table 7.3.1.1 shall be multiplied by the greater of (a) and (b):

(a) $1.65 - 0.005w_c$ [w_c in lb/ft^3]
$1.65\text{-}0.0003w_c$ [w_c in kg/m^3]

(b) 1.09

7.3.1.1.3 For nonprestressed composite slabs made of a combination of lightweight and normalweight concrete, shored during construction, and where the lightweight concrete is in compression, the modifier of 7.3.1.1.2 shall apply.

Commentary

Note: Table 7.3.1.1 *provides the minimum thickness of solid nonprestressed one-way slabs. The minimum thickness is subject to modification for lightweight concrete due to lower modulus of elasticity as a function of equilibrium density in* ***7.3.1.1.2****. Figure 1* *shows the trend of minimum thickness multipliers as a function of equilibrium density. The soft conversion of units provided in **7.3.1.1.2** may cause errors in the International System of Units. Hence, the following equation is the precise form of equation **(a)** for equilibrium density in kg/m^3.*

7.3.1.1.2(a) *1.65-0.0003121wc*

*Designers who find the minimum thickness excessive may calculate the required thickness to satisfy the calculated deflection limits of **7.3.2**. Computing deflections is always preferable since it results in the necessary thickness to achieve the control desired at service loadings.*

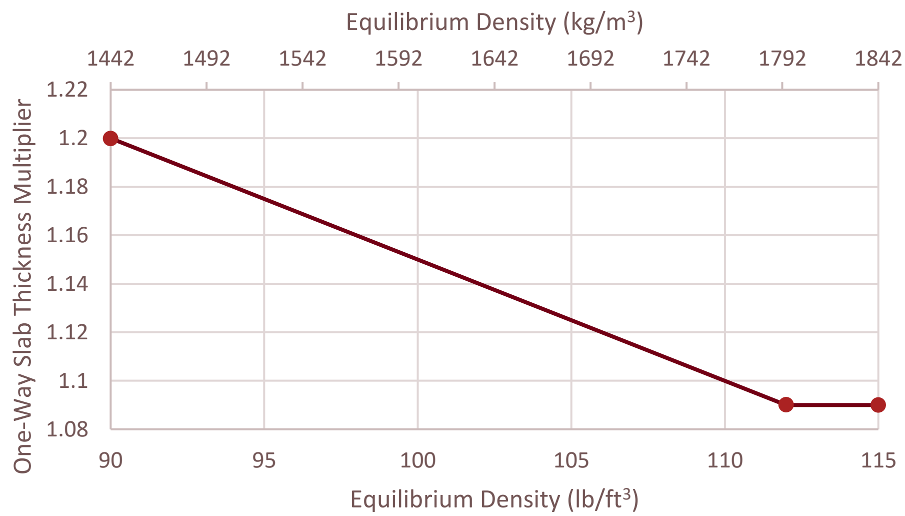

Figure 1 One-way slab thickness multiplier

Chapter 9 Beams

9.3 DESIGN LIMITS

9.3.1 Minimum beam depth

Code

Table 9.3.1.1—Minimum depth of nonprestressed beams

Support condition	Minimum h[1]
Simply supported	$\ell/16$
One end continuous	$\ell/18.5$
Both ends continuous	$\ell/21$
Cantilever	$\ell/8$

[1] Expression applicable for normalweight concrete and f_y = 60,000 psi (420 MPa). For other cases, minimum h shall be modified in accordance with 9.3.1.1.1 through 9.3.1.1.3, as appropriate.

9.3.1.1.2 For nonprestressed beams made of lightweight concrete having w_c in the range of 90 to 115 lb/ft^3 (1440 to 1840 kg/m^3), the expressions in Table 9.3.1.1 shall be multiplied by the greater of (a) and (b):

(a) $1.65 – 0.005w_c$ [w_c in lb/ft^3]
$1.65-0.0003w_c$ [w_c in kg/m^3]

(b) 1.09

9.3.1.1.3 For nonprestressed beams made of a combination of lightweight and normalweight concrete, shored during construction, and where the lightweight concrete is in compression, the modifier of 9.3.1.1.2 shall apply.

Commentary

R9.3.1.1.2 The modification for lightweight concrete is based on the results and discussions in ACI 213R. No correction is given for concretes with w_c greater than 115 lb/ft^3 (1840 kg/m^3) because the correction term would be close to unity in this range.

Note: Table 9.3.1.1 *provides the minimum depth of nonprestressed beams. The minimum thickness is subject to modification for lightweight concrete due to lower modulus of elasticity as a function of equilibrium density in* ***9.3.1.1.2****. Figure 2 shows the trend of minimum thickness multipliers as a function of equilibrium density. The soft conversion of units provided in* ***9.3.1.1.2*** *may cause errors in the International System of Units. Hence, the following equation is the precise form of equation* ***(a)*** *for equilibrium density in kg/m^3.*

9.3.1.1.2(a) $1.65-0.0003121w_c$

Designers who find the minimum depth excessive may calculate the required depth to satisfy the calculated deflection limits of 9.3.2. Computing deflections is always preferable since it results in the necessary thickness to achieve the control desired at service loadings.

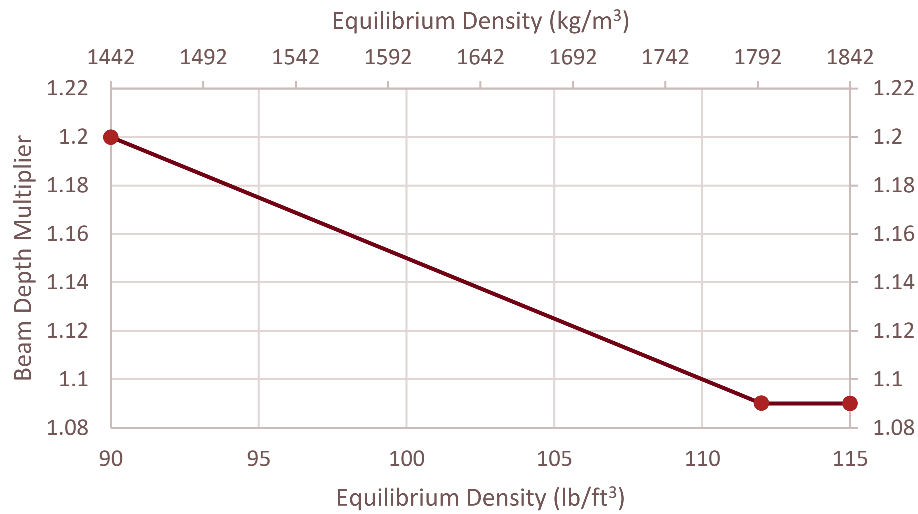

Figure 2 Beam depth multiplier

Chapter 14 Plain Concrete

14.5 DESIGN STRENGTH

14.5.1 General

Code

14.5.1.5 λ for lightweight concrete shall be in accordance with 19.2.4.

Commentary

Note: *See* ***Chapter 19*** *for the determination of modification factors for reduction of mechanical properties, typically as a function of reduced ratio of tensile-to-compressive strength of lightweight concrete. The application of modification factors varies for different applications in each chapter and is sensitive to the availability of experimental data for each application.*

Chapter 15 Beam-Column and Slab-Column Joints

15.4 STRENGTH REQUIREMENTS FOR BEAM-COLUMN JOINTS

15.4.2 Design shear strength

Code

15.4.2.3 V_n of the joint shall be calculated in accordance with Table 15.4.2.3.

Commentary

Table 15.4.2.3—Nominal joint shear strength V_n

Column	Beam in direction of V_n	Confinement by transverse beams according to 15.2.8	V_n, lb (N)[1]
Continuous or meets 15.2.6	Continuous or meets 15.2.7	Confined	$24\lambda\sqrt{f'_c}A_j \left(2.0\lambda\sqrt{f'_c}A_j\right)$
		Not confined	$20\lambda\sqrt{f'_c}A_j \left(1.7\lambda\sqrt{f'_c}A_j\right)$
	Other	Confined	$20\lambda\sqrt{f'_c}A_j \left(1.7\lambda\sqrt{f'_c}A_j\right)$
		Not confined	$15\lambda\sqrt{f'_c}A_j \left(1.3\lambda\sqrt{f'_c}A_j\right)$
Other	Continuous or meets 15.2.7	Confined	$20\lambda\sqrt{f'_c}A_j \left(1.7\lambda\sqrt{f'_c}A_j\right)$
		Not confined	$15\lambda\sqrt{f'_c}A_j \left(1.3\lambda\sqrt{f'_c}A_j\right)$
	Other	Confined	$25\lambda\sqrt{f'_c}A_j \left(1.3\lambda\sqrt{f'_c}A_j\right)$
		Not confined	$12\lambda\sqrt{f'_c}A_j \left(1.0\lambda\sqrt{f'_c}A_j\right)$

[1] λ shall be 0.75 for lightweight concrete and 1.0 for normalweight concrete.

Note: *Conservatively, a low value of 0.75 instead of the calculated modification factor from* ***Chapter 19*** *applies to* ***Table 15.4.2.3****. Regardless, designers typically rely on the significant contribution of transverse reinforcement compared with concrete for determination of the joint shear strength.*

Chapter 16 Connections Between Members

16.5 BRACKETS AND CORBELS

16.5.2 Dimensional limits

Code

16.5.2.5 For lightweight concrete, the bracket or corbel dimensions shall be selected such that V_u/φ shall not exceed the lesser of (a) and (b):

(a) $\left(0.2 - 0.07\frac{a_v}{d}\right) f'_c b_w d$

(b) $\left(800 - 280\frac{a_v}{d}\right) b_w d$ [lb]

$\left(5.5 - 1.9\frac{a_v}{d}\right) b_w d$ [N]

Commentary

R16.5.2.5 Tests (Mattock et al. 1976a) have shown that the maximum shear friction strength of lightweight concrete brackets and corbels is a function of both f_c' and a_v/d.

Note: *The shear friction strength limit of lightweight concrete in brackets and corbels applications decreases compared with normalweight concrete as the a_v/d ratio increases. The rate of decrease is higher for higher specified compressive strengths. Figure 3 shows the trend of bracket or corbel shear friction strength as a function of dimensional restrictions and specified compressive strength (f_c'). Equation (b) governs for f_c' values greater than 4000 psi (28 MPa).*

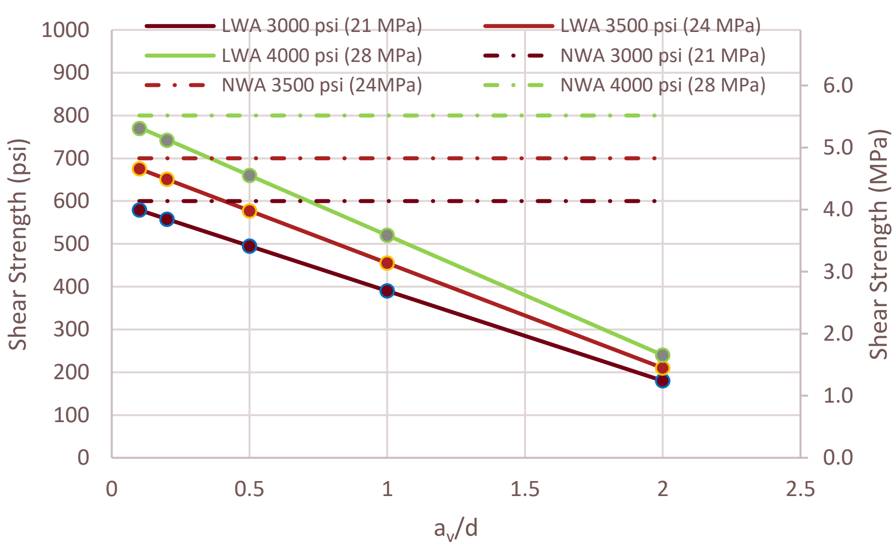

Figure 3 Bracket and corbel shear strength for various specified compressive strengths (f_c')

Chapter 17 Anchoring to Concrete

17.2 GENERAL

17.2.4 Lightweight concrete modification factor, λ_a

Code

17.2.4.1 Modification factor λ_a for lightweight concrete shall be in accordance with Table 17.2.4.1. It shall be permitted to use an alternate value of λ_a if tests are performed and evaluated in accordance with ACI 355.2 or ACI 355.4.

Table 17.2.4.1—Modification factor for lightweight concrete

Case	λ_a[1]
Cast-in and undercut anchor concrete failure	1.0λ
Expansion, screw, and adhesive anchor concrete failure	0.8λ
Adhesive anchor bond failure per Eq. (17.6.5.2.1)	0.6λ

[1] λ shall be in accordance with 19.2.4

Commentary

R17.2.4.1 The number of tests available to establish the strength of anchors in lightweight concrete is limited. Tests of headed studs cast in lightweight concrete indicate that the present reduction factor λ adequately represents the influence of lightweight concrete (Shaikh and Yi 1985; Anderson and Meinheit 2005). Anchor manufacturer data developed for evaluation reports on post-installed expansion, screw, undercut, and adhesive anchors indicate that a reduced λ is needed to provide the necessary safety factor for the respective design strength. ACI 355.2 and ACI 355.4 provide procedures whereby a specific value of λ_a can be used based on testing, assuming the lightweight concrete is similar to the reference test material.

Note: *The calculated modification factor from* ***19.2.4*** *applies to* ***Table 17.2.4.1****.*
Designers may contact ESCS producers on more recent experimental tests on anchorage to lightweight concrete containing ESCS aggregates.

Chapter 18 Earthquake-Resistant Structures

18.2 GENERAL

18.2.5 Concrete in special moment frames and special structural walls

Code

18.2.5.1 Specified compressive strength of concrete in special moment frames and special structural walls shall be in accordance with the special seismic systems requirements of Table 19.2.1.1.

Commentary

R18.2.5.1 Requirements of this section refer to concrete quality in frames and walls that resist earthquake-induced forces. The maximum specified compressive strength of lightweight concrete to be used in structural design calculations is limited to 5000 psi (35 MPa), primarily because of paucity of experimental and field data on the behavior of members made with lightweight concrete subjected to displacement reversals in the nonlinear range. If convincing evidence is developed for a specific application, the limit on maximum specified compressive strength of lightweight concrete may be increased to a level justified by the evidence.

Note: *The calculated modification factor from **Chapter 19** applies to section **18.2.5.1**. Designers may contact ESCS producers on more recent experimental tests on high-strength lightweight concrete containing ESCS aggregates for earthquake-resistant applications.*

18.8 JOINTS OF SPECIAL MOMENT FRAMES

18.8.2 General

Code

18.8.2.3 Where longitudinal beam reinforcement extends through a beam-column joint, the depth *h* of the joint parallel to the beam longitudinal reinforcement shall be at least the greatest of (a) through (c):

(a) $\frac{20}{\lambda} d_b$ of the largest Grade 60 (Grade 420) longitudinal bar, where λ = 0.75 for lightweight concrete and 1.0 for all other cases

(b) $26d_b$ of the largest Grade 80 (Grade 550) longitudinal bar

(c) *h*/2 of any beam framing into the joint and generating joint shear as part of the seismic-force-resisting system in the direction under consideration

Commentary

R18.8.2.3 Tests demonstrate adequate behavior if the ratio of joint depth to maximum beam longitudinal bar diameter for Grade 60 (Grade 420) reinforcement is at least 20 for normalweight concrete and 26 for lightweight concrete. A joint depth of $26d_b$ for Grade 80 (Grade 550) reinforcement is intended to achieve similar performance to that of a joint depth of $20d_b$ for Grade 60 (Grade 420) reinforcement and normalweight concrete. The limits on joint depth provide reasonable control on the amount of slip of the beam bars in a beam-column joint, considering the number of anticipated inelastic excursions of the building frame during a major earthquake. A thorough treatment of this topic is given in Zhu and Jirsa (1983).

Note: *Conservatively, a low value of 0.75 instead of the calculated modification factor from* ***Chapter 19*** *applies to* ***18.8.2.3****. Regardless, designers typically rely on the significant contribution of transverse reinforcement compared with concrete for determination of the joint shear strength.*

Code

18.8.2.3.1 Concrete used in joints with Grade 80 (Grade 550) longitudinal reinforcement shall be normalweight concrete.

Commentary

R18.8.2.3.1 Test data justifying the combination of lightweight concrete and Grade 80 (Grade 550) longitudinal reinforcement in joints are not available.

Note: *Designers may contact ESCS producers to inquire about the availability of tests on high-grade longitudinal reinforcement in joints.*

18.8.4 Shear strength

Code

18.8.4.3 V_n of the joint shall be in accordance with Table 18.8.4.3.

Commentary

Table 18.8.4.3—Nominal joint shear strength V_n

Column	Beam in direction of V_n	Confinement by transverse beams according to 15.2.8	V_n, lb (N)[1]
Continuous or meets 15.2.6	Continuous or meets 15.2.7	Confined	$20\lambda\sqrt{f'_c}A_j \left(1.7\lambda\sqrt{f'_c}A_j\right)$
		Not confined	$15\lambda\sqrt{f'_c}A_j \left(1.2\lambda\sqrt{f'_c}A_j\right)$
	Other	Confined	$15\lambda\sqrt{f'_c}A_j \left(1.2\lambda\sqrt{f'_c}A_j\right)$
		Not confined	$12\lambda\sqrt{f'_c}A_j \left(1.0\lambda\sqrt{f'_c}A_j\right)$
Other	Continuous or meets 15.2.7	Confined	$15\lambda\sqrt{f'_c}A_j \left(1.2\lambda\sqrt{f'_c}A_j\right)$
		Not confined	$12\lambda\sqrt{f'_c}A_j \left(1.0\lambda\sqrt{f'_c}A_j\right)$
	Other	Confined	$12\lambda\sqrt{f'_c}A_j \left(1.0\lambda\sqrt{f'_c}A_j\right)$
		Not confined	$8\lambda\sqrt{f'_c}A_j \left(0.7\lambda\sqrt{f'_c}A_j\right)$

[1] λ shall be 0.75 for lightweight concrete and 1.0 for normalweight concrete. A_j shall be calculated in accordance with 15.4.2.4.

Note: *Conservatively, a low value of 0.75 instead of the calculated modification factor from* ***Chapter 19*** *applies to* ***Table 18.8.4.3****. Regardless, designers typically rely on the significant contribution of transverse reinforcement compared with concrete for determination of the joint shear strength.*

18.8.5 Development length of bars in tension

Code

18.8.5.1 For bar sizes No 3 (9 mm) through No. 11 (36 mm) terminating in a standard hook, ℓ_{dh} shall be calculated by Eq. (18.8.5.1), but ℓ_{dh} shall be at least the greater of $8d_b$ and 6 in. (150 mm) for normalweight concrete and at least the greater of $10d_b$ and 7-1/2 in. (190 mm) for lightweight concrete.

$\ell_{dh} = f_y d_b / \left(65\lambda\sqrt{f'_c}\right)$ [in.]

$\ell_{dh} = f_y d_b / \left(5.4\lambda\sqrt{f'_c}\right)$ [mm] (18.8.5.1)

The value of λ shall be 0.75 for concrete containing lightweight aggregate and 1.0 otherwise.

The hook shall be located within the confined core of a column or of a boundary element, with the hook bent into the joint.

Commentary

R18.8.5.1 Minimum embedment length in tension for deformed bars with standard hooks is determined using Eq. (18.8.5.1), which is based on the requirements of 25.4.3. The embedment length of a bar with a standard hook is the distance, parallel to the bar, from the critical section (where the bar is to be developed) to a tangent drawn to the outside edge of the hook. The tangent is to be drawn perpendicular to the axis of the bar (refer to Table 25.3.1).

Note: *Conservatively, a low value of 0.75 instead of the calculated modification factor from* ***Chapter 19*** *applies to* ***Table 18.8.5.1****. Designers may contact ESCS producers to inquire about the availability of tests on development length of bars in tension.*

Chapter 19 Concrete: Design and Durability Requirements

19.2 CONCRETE DESIGN PROPERTIES

19.2.1 Specified compressive strength

Code

19.2.1.1 The value of f_c' shall be in accordance with (a) through (d):

(a) Limits for f_c' in Table 19.2.1.1. Limits apply to both normalweight and lightweight concrete.
(b) Durability requirements in Table 19.3.2.1
(c) Structural strength requirements
(d) f_c' for lightweight concrete in special moment frames and special structural walls, and their foundations, shall not exceed 5000 psi (35 MPa), unless demonstrated by experimental evidence that members made with lightweight concrete provide strength and toughness equal to or exceeding those of comparable members made with normalweight concrete of the same strength.

Commentary

For design of special moment frames and special structural walls used to resist earthquake forces, the Code limits the maximum f_c' of lightweight concrete to 5000 psi (35 MPa). This limit is imposed primarily because of a paucity of experimental and field data on the behavior of members made with lightweight concrete subjected to displacement reversals in the nonlinear range.

Table 19.2.1.1—Limits for f_c'

Application	Minimum f_c', psi (MPa)
General	2500 (17)
Foundations for structures assigned to SDC A, B, or C	2500 (17)
Foundations for Residential and Utility use and occupancy classification with stud bearing wall construction two stories or less assigned to SDC D, E, or F	3000 (21)
Special moment frames Special structural walls with Grade 60 or 80 (Grade 420 or 550) reinforcement	3000 (21)
Special structural walls with Grade 100 (Grade 690) reinforcement	5000 (35)
Precast-nonprestressed driven piles Drilled shafts	4000 (28)
Precast-prestressed driven piles	5000 (35)

Note: *Designers may contact ESCS producers to inquire about the availability of any recent tests on high-strength lightweight concrete containing ESCS to justify alternative values.*

19.2.2 Modulus of elasticity

Code

19.2.2.1 It shall be permitted to calculate E_c in accordance with (a) or (b):

(a) For values of w_c between 90 and 160 lb/ft^3 (1440 and 2560 kg/m^3)

$$E_c = w_c{}^{1.5} 33\sqrt{f'_c} \text{ (in psi)}$$

$$E_c = w_c{}^{1.5} 0.043\sqrt{f'_c} \text{ (in MPa)}$$

(19.2.2.1.a)

(b) For normalweight concrete

$$E_c = 57{,}000\sqrt{f'_c} \text{ (in psi)}$$

$$E_c = 4700\sqrt{f'_c} \text{ (in MPa)}$$

(19.2.2.1.b)

Commentary

The modulus of elasticity is sensitive to a number of variables including aggregate type, concrete constituents, mixture proportions, bond between paste and aggregate, and the age of the concrete. This sensitivity, coupled with the inherent variability in the properties of the constituent materials and quality control exercised during construction, can result in differences between measured and calculated values for deflection, drift, periods of vibration, and other quantities that depend on E_c. Refer to ACI 435R for more information on the use of E_c, especially when used in deflection calculations.

Modulus of elasticity determined by calculation using the Code equations has been shown to be appropriate for most applications based on many years of use. For some applications, however, these equations may not provide sufficiently accurate estimates of actual values. Larger differences between measured and calculated values of E_c have been observed for high-strength concrete (fc' > 8000 psi (55 MPa)), lightweight concrete, and for mixtures with low coarse aggregate volume, as can occur with self-consolidating concrete. Refer to ACI 363R, ACI 213R, and ACI 237R for more information.

Note: *Designers may contact ESCS producers to inquire about the availability of any recent tests on the modulus of elasticity of lightweight concrete containing ESCS to justify alternative values.*

19.2.4 Lightweight Concrete

Code

19.2.4.1 Except as required in Table 25.4.2.5, the value of λ shall be determined using Table 19.2.4.1(a) based on the equilibrium density, w_c, of the concrete mixture used in design, or Table 19.2.4.1(b) based on the composition of the aggregate in the concrete mixture assumed in the design.

Table 19.2.4.1(a)—Values of λ for lightweight concrete based on equilibrium density

w_c, lb/ft^3 (kg/m^3)	λ	
≤ 100 (≤ 1600)	0.75	(a)
$100 < w_c \leq 135$ ($1600 < w_c \leq 2160$)	$0.0075w_c \leq 1.0$ ($0.00047w_c \leq 1.0$)	(b)
> 135 (> 2160)	1.0	(c)

Table 19.2.4.1(b)—Values of λ for lightweight concrete based on composition of aggregates

Concrete	Composition of aggregates	λ
All-lightweight	Fine: ASTM C330 Coarse: ASTM C330	0.75
Lightweight, fine blend	Fine: Combination of ASTM C330 and C33 Coarse: ASTM C330	0.75 to 0.85[1]
Sand-lightweight	Fine: ASTM C33 Coarse: ASTM C330	0.85
Sand-lightweight, coarse blend	Fine: ASTM C33 Coarse: Combination of ASTM C330 and C33	0.85 to 1[1]

[1]Linear interpolation from 0.75 to 0.85 is permitted based on the absolute volume of normalweight fine aggregate as a fraction of the total absolute volume of fine aggregate.

[2]Linear interpolation from 0.85 to 1 is permitted based on the absolute volume of normalweight coarse aggregate as a fraction of the total absolute volume of aggregate.

Commentary

R19.2.4 The modification factor λ is used to account for the reduced mechanical properties of lightweight concrete compared with normalweight concrete of the same compressive strength. For design using lightweight concrete, shear strength, friction properties, splitting resistance, bond between concrete and reinforcement, and development length requirements are not taken as equivalent to normalweight concrete of the same compressive strength.

The methodology for determining λ was changed in the 2019 Code to include a new method that is based on the equilibrium density of the lightweight concrete. The new method allows the designer to select a value for λ based on the equilibrium density of the lightweight concrete that is used in design. Laboratory testing on the specific mixture to be used in the structure can be accomplished if the designer desires to determine a more accurate value of λ (Ivey and Buth 1967; Hanson 1961). Table 19.2.4.1 is based on data from tests (Graybeal 2014; Greene and Graybeal 2013, 2015) of concrete made with many types of structural lightweight aggregate and having a wide range of mixture proportions that resulted in equilibrium densities over a range of 90 to 135 lb/ft^3 (1440 to 2160 kg/m^3).

Code

19.2.4.2 It shall be permitted to take λ as 0.75 for lightweight concrete.

19.2.4.3 The value of λ shall be taken as 1.0 for normalweight concrete.

Commentary

The second method for determining λ, which is retained from the previous code, is based on the composition of aggregates. In most cases, local concrete and aggregate suppliers have standard lightweight concrete mixtures and can provide the volumetric fractions to determine the value of λ. In the absence of such data, it is permissible to use the lower-bound value of λ for the type of lightweight concrete specified. This method is based on the assumption that, for equivalent compressive strength levels, the tensile strength of lightweight concrete is a fixed fraction of the tensile strength of normalweight concrete (Ivey and Buth 1967). The multipliers used for λ are based on data from tests on concrete made with many types of structural lightweight aggregate.

A previously included method to calculate λ based on splitting tensile strength and the corresponding value of measured compressive strength was removed from the Code in 2019.

In editions of the Code prior to 2019, the upper limit on the equilibrium density for lightweight concrete was 115 lb/ft^3 (1840 kg/m^3). With the lower limit for normalweight concrete established at 135 lb/ft^3 (2160 kg/m^3), a 20 lb/ft^3 (320 kg/m^3) range remained that was undefined. In practice, to achieve an equilibrium density in the range of 115 to 135 lb/ft^3 (1840 to 2160 kg/m^3), the use of some amount of lightweight aggregate is required. The 2019 Code removes this undefined range by defining lightweight concrete as having an equilibrium density from 90 to 135 lb/ft^3 (1440 to 2160 kg/m^3).

Note: *Designers may contact ESCS producers to inquire about mixture design, equilibrium density, and other related criteria for determining the modification factor.*

19.3 CONCRETE DURABILITY REQUIREMENTS

19.3.2 Requirements for concrete mixtures

Code

19.3.2.1 Based on the exposure classes assigned from Table 19.3.1.1, concrete mixtures shall conform to the most restrictive requirements in Table 19.3.2.1.

Footnote to Table 19.3.2.1—Requirements for concrete by exposure class

[2]The maximum *w/cm* limits do not apply to lightweight concrete.

Commentary

As stated in the footnote to Table 19.3.2.1, maximum *w/cm* limits are not specified for lightweight concrete because the amount of mixing water that is absorbed by the lightweight aggregates makes calculation of *w/cm* uncertain. Therefore, only a minimum f_c' is specified to achieve the required durability.

Note: *An accurate w/cm calculation is possible when the water absorbed by lightweight aggregate is determined and accounted for following applicable* ***ASTM*** *standards, similar to those of normalweight aggregate, with aggregates in saturated surface dry conditions. Hence, designers may specify durability criteria related to the w/cm. ESCS producers can provide additional information about the properties of ESCS aggregates, including water content and saturation state.*

19.3.3 Additional requirements for freezing-and-thawing exposure

Code

19.3.3.2 Concrete shall be sampled in accordance with ASTM C172, and air content shall be measured in accordance with ASTM C231 or ASTM C173.

Commentary

R19.3.3.2 The sampling of fresh concrete for acceptance based on air content is usually performed as the concrete is discharged from a mixer or a transportation unit (for example, a ready mixed concrete truck) to the conveying equipment used to transfer the concrete to the forms. ASTM C172 primarily covers sampling of concrete as it is discharged from a mixer or a transportation unit but recognizes that specifications may require sampling at other points such as discharge from a pump. Table 19.3.3.1 was developed for testing as-delivered concrete. ASTM C231 is applicable to normalweight concrete and ASTM C173 is applicable to normalweight or lightweight concrete.

Note: *Consult with ESCS producers for additional information related to freeze-thaw, pumping, and other related topics. See* ***ESCSI 7300.093*** *and* ***ESCSI 4770.0*** *for more details.*

Chapter 20 Steel Reinforcement Properties, Durability, & Embedments

20.5 PROVISIONS FOR DURABILITY OF STEEL REINFORCEMENT

20.5.1 Specified concrete cover

20.5.1.4 Specified concrete cover requirements for corrosive environments

Code

20.5.1.4.1 In corrosive environments or other severe exposure conditions, the specified concrete cover shall be increased as deemed necessary. The applicable requirements for concrete based on exposure categories in 19.3 shall be satisfied, or other protection shall be provided.

Commentary

R20.5.1.4.1 Where concrete will be exposed to external sources of chlorides in service, such as deicing salts, brackish water, seawater, or spray from these sources, concrete should be proportioned to satisfy the requirements for the applicable exposure class in Chapter 19. These include maximum *w/cm*, minimum strength for normalweight and lightweight concrete, and maximum chloride ion in the concrete. Additionally, for corrosion protection, a specified concrete cover for reinforcement not less than 2 in. (50 mm) for walls and slabs and not less than 2-1/2 in. (65 mm) for other members is recommended. For precast concrete members manufactured under plant control conditions, a specified concrete cover not less than 1-1/2 in. (40 mm) for walls and slabs and not less than 2 in. (50 mm) for other members is recommended.

Note: *Consult with ESCS producers on recent experimental studies on the durability of lightweight concrete using chloride ion transport properties. See* ***ESCSI 4363-2020*** *for more information.*

Chapter 22 Sectional Strength

22.9 SHEAR FRICTION

22.9.4 Nominal shear strength

Code

22.9.4.2 If shear-friction reinforcement is perpendicular to the shear plane, nominal shear strength across the assumed shear plane shall be calculated by:

$$V_n = \mu A_{vf} f_y \qquad (22.9.4.2)$$

where A_{vf} is the area of reinforcement crossing the assumed shear plane to resist shear, and μ is the coefficient of friction in accordance with Table 22.9.4.2.

Table 22.9.4.2—Coefficients of friction

Contact surface condition	Coefficient of friction μ[1]	
Concrete placed monolithically	1.4λ	(a)
Concrete placed against hardened concrete that is clean, free of laitance, and intentionally roughened to a full amplitude of approximately 1/4 in. (6 mm)	1.0λ	(b)
Concrete placed against hardened concrete that is clean, free of laitance, and not intentionally roughened	0.6λ	(c)
Concrete placed against as-rolled structural steel that is clean, free of paint, and with shear transferred across the contact surface by headed studs or by welded deformed bars or wires.	0.7λ	(d)

[1]λ = 1.0 for normalweight concrete. For lightweight concrete, λ is calculated as given in 19.2.4, but shall not exceed 0.85.

Commentary

R22.9.4.2 The required area of shear-friction reinforcement, A_{vf}, is calculated using:

$$A_{vf} = \frac{V_u}{\phi f_y \mu} \qquad (R22.9.4.2)$$

The upper limit on shear strength that can be achieved using Eq. (22.9.4.2) is given in 22.9.4.4.

In the shear-friction method of calculation, it is assumed that all the shear resistance is due to the friction between the crack faces. It is therefore necessary to use artificially high values of the coefficient of friction in the shear-friction equations so that the calculated shear strength will be in reasonable agreement with test results.

For concrete cast against hardened concrete not roughened in accordance with 22.9.4.2, shear resistance is primarily due to dowel action of the reinforcement. Test results (Mattock 1977) indicate that the reduced value of μ = 0.6λ specified for this case is appropriate.

For concrete placed against as-rolled structural steel, the shear-transfer reinforcement may be either reinforcing bars or headed studs. The design of shear connectors for composite action of concrete slabs and steel beams is not covered by these provisions. AISC 360 contains design provisions for these systems.

***Note:** Conservatively, this section limits the calculated modification factor from **Chapter 19** to 0.85 in the absence of other evidence.*

Chapter 25 Reinforcement Details

25.4 DEVELOPMENT OF REINFORCEMENT

25.4.2 Development of deformed bars and deformed wires in tension

Code

25.4.2.5 For the calculation of ℓd, modification factors shall be in accordance with Table 25.4.2.5.

Commentary

R25.4.2.5 The lightweight factor λ for calculating development length of deformed bars and deformed wire in tension is the same for all types of lightweight concrete. Research does not support the variations of this factor in Codes prior to 1989 for all-lightweight and sand-lightweight concrete (ACI 408R).

Parts of Table 25.4.2.5—Modification factors for development of deformed bars and deformed wires in tension

Modification factor	Condition	Value of factor
Lightweight λ	Lightweight concrete	0.75
	Normalweight concrete	1.0

Note: *Conservatively, the calculated modification factor from* ***Chapter 19*** *does not apply to this section. Instead, a minimum value of 0.75 applies in the absence of other evidence.*

25.4.3 Development of standard hooks in tension

Code

25.4.3.2 For the calculation of ℓdh, modification factors ψe, ψr, ψo, ψc, and λ shall be in accordance with Table 25.4.3.2. At discontinuous ends of members, 25.4.3.4 shall apply.

Commentary

Parts of Table 25.4.3.2—Modification factors for development of hooked bars in tension

Modification factor	Condition	Value of factor
Lightweight λ	Lightweight concrete	0.75
	Normalweight concrete	1.0

Note: *Conservatively, the calculated modification factor from* ***Chapter 19*** *does not apply to this section. Instead, a minimum value of 0.75 applies in the absence of other evidence.*

25.4.4 Development of headed deformed bars in tension

Code

25.4.4.1 Use of a head to develop a deformed bar in tension shall be permitted if conditions (a) through (f) are satisfied:

(a) Bar shall conform to 20.2.1.6
(b) Bar size shall not exceed No. 11 (36 mm)
(c) Net bearing area of head A_{brg} shall be at least $4A_b$
(d) Concrete shall be normalweight
(e) Clear cover for bar shall be at least $2d_b$
(f) Center-to-center spacing between bars shall be at least $3d_b$.

Commentary

R25.4.4.1

The provisions for headed deformed bars were formulated with due consideration of the provisions for anchorage in Chapter 17 (Shao et al. 2016). Chapter 17 contains provisions for headed anchors related to the individual failure modes of concrete breakout, side-face blowout, and pullout. These failure modes were considered in the formulation of 25.4.4.2. The restrictions to maximum bar size of No. 11 (36 mm) and normalweight concrete are based on a lack of data for larger bars or lightweight concrete (Thompson et al. 2005, 2006a,b; Shao et al. 2016). The upper limit of 60,000 psi (420 MPa) on f_y that appeared prior to the 2019 Code has been removed.

Note: *Designers may contact ESCS producers to inquire about the availability of tests on lightweight concrete containing ESCS aggregates.*

25.4.9 Development of deformed bars and deformed wires in compression

Code

25.4.9.1 Development length ℓ_{dc} for deformed bars and deformed wires in compression shall be the greater of (a) and (b)

(a) Length calculated in accordance with 25.4.9.2
(b) 8 in. (200 mm)

25.4.9.2 ℓ_{dc} shall be the greater of (a) and (b), using the modification factors of 25.4.9.3:

(a) $\left(\frac{f_y \psi_r}{50\lambda\sqrt{f'_c}}\right) d_b$ (in.)

$\left(\frac{0.24 f_y \psi_r}{\lambda\sqrt{f'_c}}\right) d_b$ (mm)

(b) $0.0003 f_y \psi_r d_b$ (in.)

$0.043 f_y \psi_r d_b$ (mm)

25.4.9.3 For the calculation of ℓ_{dc}, modification factors shall be in accordance with Table 25.4.9.3, except ψ_r shall be permitted to be taken as 1.0.

Table 25.4.9.3—Modification factors for deformed bars and wires in compression

Modification factor	Condition	Value of factor
Lightweight λ	Lightweight concrete	0.75
	Normalweight concrete	1.0

Commentary

R25.4.9.1 The weakening effect of flexural tension cracks is not present for bars and wires in compression, and usually end bearing of the bars on the concrete is beneficial. Therefore, shorter development lengths are specified for compression than for tension.

R25.4.9.2 The constant 0.0003 (0.043) has units of in.^{2}/lb (mm^2/N). The term λ is provided in the expression for development in 25.4.9.2 recognizing that there are no known test data on compression development in lightweight concrete, but that splitting is more likely in lightweight concrete.

R25.4.9.3 The development length may be reduced 25 percent when the reinforcement is enclosed within closely spaced spirals, ties, or hoops.

***Note:** Conservatively, the calculated modification factor from Chapter 19 does not apply to this section. Instead, a minimum value of 0.75 applies in the absence of other evidence.*

25.9.4 General zone

25.9.4.4 Reinforcement limits

Code

25.9.4.4.6 For monostrand anchorage devices for 1/2 in. (12.7 mm) or smaller diameter strands in normalweight concrete slabs, reinforcement satisfying (a) and (b) shall be provided in the anchorage zone, unless a detailed analysis in accordance with 25.9.4.3 shows that this reinforcement is not required:

(a) Two horizontal bars at least No. 4 (13 mm) in size shall be provided within the local zone parallel to the slab edge ahead of the bearing face of the anchorage device. They shall be permitted to be in contact with the bearing face of the anchorage device, the center of the bars shall be no farther than 4 in. (100 mm) ahead of the bearing face of the device, and the bars shall extend at least 6 in. (150 mm) either side of the outer edges of the device.

(b) If the center-to-center spacing of anchorage devices is 12 in. (300 mm) or less, the anchorage devices shall be considered as a group. For each group of six or more anchorage devices, at least $n + 1$ hairpin bars or closed stirrups at least No. 3 (10 mm) in size shall be provided, where n is the number of anchorage devices. One hairpin bar or stirrup shall be placed between adjacent anchorage devices and one on each side of the group. The hairpin bars or stirrups shall be placed with the horizontal legs extending into the slab perpendicular to the edge. The center line of the vertical leg of the hairpin bars, or the vertical leg of stirrups closest to the anchorage device, shall be placed $3h/8$ to $h/2$ ahead of the bearing face of the anchorage device. Hairpin bars or stirrups shall be detailed in accordance with 25.7.1.1 and 25.7.1.2.

Commentary

R25.9.4.4.6 The tests on which the recommendations of Breen et al. (1994) were based were limited to anchorage devices for 1/2 in. (12.7 mm) diameter, Grade 270 (Grade 1860) strand, and unbonded tendons in normalweight concrete. For larger strand anchorage devices or for use in lightweight concrete slabs, ACI Committee 423 recommends that the amount and spacing of reinforcement should be conservatively adjusted to provide for the larger anchorage force and smaller splitting tensile strength of lightweight concrete (ACI 423.3R).

Note: *Refer to other* ***ACI*** *documents and consult with ESCS producers for more information.*

25.9.4.5 Limiting stresses in general zones

Code

25.9.4.5.2 Compressive stress in concrete at nominal strength shall not exceed $0.7\lambda f_{ci}'$, where λ is defined in 19.2.4.

Commentary

R25.9.4.5.2 Some inelastic deformation of concrete within general zones is expected because anchorage zone design is based on a strength approach. Unless shown by tests, the λ factor for lightweight concrete should be applied to reflect a lower tensile strength, which is an indirect factor in limiting compressive stresses, as well as the wide scatter and brittleness exhibited in some lightweight concrete anchorage zone tests.

Note: *Refer to other* ***ACI*** *documents and consult with ESCS producers for more information.*

CHAPTER 26 CONSTRUCTION DOCUMENTS AND INSPECTION

26.4 CONCRETE MATERIALS AND MIXTURE REQUIREMENTS

26.4.1 Concrete materials

26.4.1.2 Aggregates

Code

26.4.1.2.1 Compliance requirements:

(a) Aggregates shall conform to (1) or (2):

(1) Normalweight aggregate: ASTM C33.
(2) Lightweight aggregate: ASTM C330.

Commentary

Note: *Contact ESCS producers to obtain documents on ASTM C330 compliance and available gradation.*

26.4.2 Concrete mixture requirements

Code

26.4.2.1 Design information:

(a) Requirements (1) through (17) for each concrete mixture, based on assigned exposure classes or design of members:

(14) Equilibrium density of lightweight concrete.

(15) Requirement for submittal of the volumetric fractions of aggregate in lightweight concrete mixtures if Table 19.2.4.1(b) is used as the basis for λ in design.

Commentary

R26.4.2.1(a)(14 and 15) Equilibrium density is an estimate of the density of lightweight concrete assuming some degree of drying after initial construction. The equilibrium density of lightweight concrete is determined in accordance with ASTM C567. Acceptance of lightweight concrete at the time of delivery is based on a fresh density determined by the concrete supplier that has been correlated with the equilibrium density. The range of fresh densities can vary based on variations in moisture and air content, mixture proportion, and type of lightweight aggregate, and should be considered when establishing the fresh density that will result in the required equilibrium density. Acceptance of lightweight concrete based on density as well as strength is necessary because the value of λ and self-weight used for design is a function of equilibrium density.

Note: *Contact ESCS producers to obtain information about mixture design and equilibrium density of lightweight concrete containing ESCS aggregates.*

Code

26.4.2.2 Compliance requirements:

(h) For lightweight concrete, fresh density shall be determined in accordance with ASTM C138 that corresponds with the specified equilibrium density determined in accordance with ASTM C567. The fresh density corresponding to the specified equilibrium density shall be used as the basis of acceptance.

Commentary

R26.4.2.2(h) ASTM C567 provides two methods for determining equilibrium density. To measure equilibrium density, specimens are maintained at 73°F (23°C) and 50 percent relative humidity until they achieve constant mass. This measurement can take in excess of 2 months. Alternatively, the calculated equilibrium density can be more rapidly estimated from the oven-dry density. The licensed design professional can require the measurement of equilibrium density in accordance with ASTM C567.

Note: *Contact ESCS producers to obtain information about mixture design and equilibrium density of lightweight concrete containing ESCS aggregates.*

26.7 ANCHORING TO CONCRETE

Code

26.7.1 Design information:

(h) For post-installed anchors, parameters associated with the design strength in accordance with 17.5, including anchor category, concrete strength, aggregate type, type of lightweight concrete, required installation torque, and requirements for hole drilling and preparation.
(i) For adhesive anchors in tension, parameters associated with the characteristic bond stress used for design in accordance with 17.6.5, including concrete temperature range, moisture condition of concrete at time of installation, type of lightweight concrete, if applicable, and requirements for hole drilling and preparation.

Commentary

R26.7.1(h) Certain types of anchors can be sensitive to variations in hole diameter, cleaning conditions, orientation of the axis, magnitude of the installation torque, crack width, and other variables. Some of this sensitivity is indirectly accounted for in the assigned φ values for the different anchor categories, which depend in part on the results of the installation safety tests. If anchor components are altered or if anchor installation procedures deviate from those specified, the anchor may fail to comply with the acceptance criteria of ACI 355.2 or 355.4.

R26.7.1(i) Due to the sensitivity of bond strength to installation, on-site quality control is important for adhesive anchors. The construction documents must provide all parameters relevant to the characteristic bond stress used in design. These parameters may include, but are not limited to:

(a) Acceptable anchor installation environment (dry or saturated concrete; concrete temperature range)
(b) Acceptable drilling methods
(c) Required hole cleaning procedures
(d) Anchor type and size range (threaded rod or reinforcing bar)

Note: *Contact ESCS producers to obtain information about anchoring to lightweight concrete containing ESCS aggregates.*

26.12 EVALUATION AND ACCEPTANCE OF HARDENED CONCRETE

26.12.5 Acceptance criteria for density of lightweight concrete

Code

26.12.5.1 Compliance requirements:

(a) Frequency of sampling for determining fresh density shall be according to 26.12.2.
(b) Sampling of lightweight concrete for determining fresh density shall be at the point of delivery in accordance with ASTM C172.
(c) Fresh density of lightweight concrete shall be determined in accordance with ASTM C138.
(d) Unless otherwise permitted by the licensed design professional, fresh density of lightweight concrete shall be acceptable if within ±4.0 lb/ft3 of the fresh density corresponding to the specified equilibrium density.

Commentary

R26.12.5(d) The permitted tolerance for fresh concrete density for a mixture designed for the specified equilibrium density, w_c, is intended to account for variations in aggregate moisture, air content, and batch quantities. The impact of the tolerance in density on the value of λ assumed in design is minimal and deemed to be acceptable. The Licensed Design Professional can consider permitting a larger tolerance on fresh density to accommodate these expected variations when appropriate.

Note: *Structural lightweight concrete is typically proportioned to meet the specified properties of the plastic and hardened concrete. The general practice with lightweight aggregates is to proportion the mix and to assess probable physical characteristics of the concrete based on a given cement content at a given slump for particular aggregates.*

For projects with a known source(s) of supply, consult with the aggregate producer(s) to obtain suggested aggregate mix designs for achieving the desired concrete properties.

Chapter 27 Strength Evaluation of Existing Structures

27.4 STRENGTH EVALUATION BY LOAD TEST

27.4.6 Test load arrangement and load factors

Code

27.4.6.5 Unless documentation or tests are available to confirm the density of normalweight concrete used in the structure, the density shall be taken as 150 lb/ft^3 (2400 kg/m^3). For other types of concrete materials, the density shall be determined based upon test results or from other documentation.

Commentary

R27.4.6.5 Documentation to support a different unit weight may include test results showing concrete unit weight during placement or measured unit weight of concrete core samples. For other types of concrete materials (such as lightweight concrete), the unit weight should be determined based upon concrete core test results or other documentation. The calculation of D_w may include determination of the weight of bonded concrete materials, such as a topping slab to be placed on precast members, not present during a load test. D_s may also include the weight from structural framing members.

Note: *For projects with a known source(s) of supply, consult with the aggregate producer(s) to obtain suggested concrete properties.*