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Engineering and Design
PROPERTIES OF LOW-DENSITY CONCRETE

1. Purpose. This circular provides information on the major properties of low-density concrete (in contrast to the major properties of normal-density concrete), which is needed by those responsible for concrete construction in the U.S. Army Corps of Engineers (USACE).

2. Applicability. This circular applies to USACE Commands having responsibility for design of Civil Works projects.

3. Distribution Statement. Approval for public release; distribution unlimited.

4. References.

a. American Concrete Institute (ACI) (available from ACI, PO Box 9094, Farmington Hills, MI 48333)

(1) ACI 213R, Guide for Structural Lightweight Aggregate Concrete

(2) ACI 318, Building Code Requirements for Structural Concrete

b. American Society for Testing and Materials (ASTM) (available from ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959)

(1) ASTM C 33, Specification for Concrete Aggregates

(2) ASTM C 39, Test Method for Compressive Strength of Cylindrical Concrete Specimens

(3) ASTM C 138, Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Concrete

(4) ASTM C 330, Specification for Lightweight Aggregates for Structural Concrete

(5) ASTM C 469, Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression

(6) ASTM C 496, Method for Splitting Tensile Strength of Cylindrical Concrete Specimens

(7) ASTM C 512, Test Method for Creep of Concrete in Compression

(8) ASTM C 567, Test Method for Unit Weight of Structural Lightweight Concrete

(9) ASTM C 642, Test Method for Specific Gravity, Absorption, and Voids in Hardened Concrete

(10) ASTM C 666, Method for Resistance of Concrete to Rapid Freezing and Thawing

(11) ASTM E 119, Method for Fire Resistance of Building Construction and Materials

c. Bilodeau, A., Chevrier, R., Malhotra, V. M., and Hoff, G. C., 1995, "Mechanical properties, durability and fire resistance of high-strength lightweight concrete," *International Symposium on Structural Lightweight Aggregate Concrete*, Sandefjord, Norway, 432-43

d. Bremner, T. W., Boyd, A. J., Holm, T. A., and Boyd. S. R., 1998, "Indirect tensile testing to evaluate the effect of alkali-aggregate reaction in concrete," Paper No. T192-2, *Structural Engineering World Wide Conference*, San Francisco, Elsevier Science

e. Handbook for Concrete and Cement (http://www.wes.army.mil/SL/MTC/handbook/handbook.htm)

(1) CRD-C 36, Method of Test for Thermal Diffusivity of Concrete

(2) CRD-C 39, Test Method for Coefficient of Linear Thermal Expansion of Concrete

(3) CRD-C 44, Method for Calculation of Thermal Conductivity of Concrete

(4) CRD-C 124, Method of Test for Specific Heat of Aggregates, Concrete, and Other Materials (Method of Mixtures)

f. Hoff, G. C., 1994, "Observations on the fatigue behavior of high strength lightweight concrete," *Proceedings, ACI International Conference on High Performance Concrete*, Singapore, American Concrete Institute SP-149, Detroit, MI

g. Holm, T. A., and Bremner, T. W., 2000, "State-of-the-art report on high-strength, high-durability structural low-density concrete for application in severe marine environments," ERDC/SL TR-00-3, U.S. Army Engineer Research and Development Center, Vicksburg, MS (http://libweb.wes.army.mil/uhtbin/ hyperion/SL-TR-00-3.pdf)

h. Mindess, S., and Young, J. F., 1980, *Concrete*, Prentice Hall

i. Pauw, A., 1960, "Static modulus of elasticity of concrete as affected by density," *ACI Journal Proceedings* 57 (6), 679-88

j. Sugiyama, T., Bremner, T. W., and Holm, T. A., 1996, "Effect of stress on gas permeability in concrete," *ACI Materials Journal* 93(5), 443-50

5. Terminology and Abbreviations.

a. Normal-density concrete (NDC) is made from traditional materials. Densities are typically about 2,240 to 2,400 kg/m^3 (140 to 150 lb/ft^3). The term "normal-weight concrete" is also used; however, with changes toward use of SI units and attendant nomenclature, "normal-density concrete" is now the preferred term.

b. Normal density aggregate (NDA) is obtained from traditional sources (e.g., quarried or from natural deposits) and is covered by ASTM C 33. Specific gravities typically vary from about 2.5 to 2.8. This material is also called "normal-weight aggregate."

c. Low-density concrete (LDC) is made with low-density, structural-grade aggregates. Densities typically range from about 1,760 to 2,000 kg/m^3 (110 to 125 lb/ft^3). The density is controlled primarily by the properties of the low-density aggregate, although other factors include density of the other constituent materials and air content. This material is also called "light-weight concrete."

d. Low-density structural-grade aggregate (LDA) typically has specific gravities in the range of 1.3 to 1.7, although specifications are based on loose bulk density, as covered by ASTM C 330. This material is also called "light-weight aggregate." Low-density aggregates are primarily manufactured products, made by high-temperature processing of clay, shale, fly ash, slag, or slate, although natural products, such as pumice, scoria, and tuff, do exist.

e. Low-density high-strength concrete (HSLDC) is LDC that has a 28-day compressive strength greater than 35 MPa (5,070 psi). This strength level is not a specification requirement in any standard guidance, but rather a practical demarcation.

f. Specified-density concrete (SDC) is that in which partial replacement of normal density coarse aggregates with low-density, structural-grade coarse aggregate has been made.

6. Background.

a. The initial principal value of LDC is that considerable mass can be saved in a structure without sacrificing strength, at least over a wide range of strengths. LDC can easily be produced having densities 15 to 25 percent lower than those of typical NDC. Depending upon the specifics of the structure in question, this reduction in unit mass can result in a considerable impact on structural design and cost. While LDC can be produced using both coarse and fine LDA, in the United States, LDC is usually proportioned to use LDA to comprise 100 percent of the coarse aggregate together with a natural sand fine aggregate. The term SDC is normally used when the coarse aggregate in a concrete mixture consists of some combination of NDA and LDA.

b. The reduction in unit mass in LDC is accomplished primarily by use of LDA. Low-density aggregates have been processed at temperatures high enough to partially melt and decompose the material, driving off gases that cause particles to bloat. On cooling, the resultant particle has a very high porosity, causing the particle densities to be much lower than normal-density aggregate.

c. The first known evidence of the use of LDC was by the Romans, whereby the LDC was used to reduce mass in domes. In modern times, LDC has been successfully used in engineering practice since early in the 20th century. Applications include concrete ships constructed during World Wars I and II, high-rise buildings, and float-in concrete construction.

7. Physical Properties of Low-Density Concrete.

a. Density.

(1) The density of LDC typically ranges between 760 and 2,000 kg/m^3 (110 and 125 lb/ft^3) (Holm and Bremner 2000). Compressive strengths of 17 MPa (2,460 psi) or higher are easily attained, and are generally considered to be sufficient to qualify the material as a structural-grade concrete, although considerably higher strengths can be achieved within this density range. Sometimes, densities intermediate between NDC and LDC are created by mixing low- and normal-density aggregate.

(2) Although density levels are conspicuous throughout the discussion of LDC, there is *no standard specification* for this property. Specification requirements on density are developed on a project-specific basis. In practice, at least three density properties can be measured on LDC, as outlined below.

(a) Fresh density. This density measure (the density of concrete as delivered to the job site) should be specified for acceptance-testing purposes, since it can be measured easily and with reasonable precision at the job site.

(b) Equilibrium density. This is the density that should be used in structural design. As the concrete hardens and is exposed to air, it will slowly dry until it comes into equilibrium with its surroundings. This is not truly a constant condition, but the variation is not large. Equilibrium densities are typically about 80 kg/m^3 (5 lb/ft^3) lower than fresh densities.

(c) Oven-dry density. This density results when all free water is driven off at 110 °C (230 °F). It is typically about 50 kg/m^3 (3 lb/ft^3) lower than equilibrium density. While this condition rarely exists in structural concrete, it has practical value in that calculation equations exist from which oven-dry density of concrete can be calculated for a proposed mixture based on densities of individual materials (Holm and Bremner 2000).

b. Compressive strength. Up to about 35 MPa (5,070 psi), similar strengths in LDC and NDC can be achieved using similar mixture proportions. Differences in the details of mixture proportioning are needed to account for the higher absorption of LDA and for the sometimes-angular nature of the aggregate particles. Approximately equivalent strengths can be achieved even though LDA are weaker than NDA. This difference in aggregate strength does eventually become a limiting factor in developing compressive strength, but this usually occurs at strengths well above 35 MPa (see below). The performance of LDC is attributed to the fact that the lower modulus of elasticity of LDA results in a better matching with the elastic properties of the mortar fraction (Holm and Bremner 2000). The dissimilarities in modulus of elasticity and coefficient of thermal expansion between coarse aggregate and mortar have been thought to be a source of microstructural distress in NDC. It is also believed that the surface of LDA is somewhat pozzolanic, thus enhancing the interface between cement paste and aggregate, long known to be a weak zone in NDC.

c. High-strength low-density concrete (HSLDC). LDC can be made with strength considerably greater than 35 MPa. Concretes with compressive strengths as high as about 75 MPa (11,000 psi) have been made. However, at some point above 35 MPa, the innate strength properties of the LDA can become limiting in compressive-strength development. This is called the *limiting strength*. The limiting strength varies considerably among sources and types of LDA and must be determined by laboratory testing.

d. Tensile strength.

(1) Tensile strength is commonly measured in LDC by ASTM C 496, which is a splitting tensile-strength test. Tensile strength is more affected by the properties of LDA than is compressive strength. The tensile strength of LDC averages about 15 percent lower than the tensile strength of NDC, but there is considerable variation. This effect is particularly evident in high-strength mixtures.

(2) It is recommended that equations in ACI 318, which generate estimates of tension and torsion properties of concrete structural elements, based on compressive-strength inputs, not be used for LDC calculations for compressive strengths greater than 35 MPa. These properties should be measured in a testing program, rather than by relying on the calculation.

e. Modulus of elasticity. The modulus of elasticity of concrete is a composite property derived from the modulus of the individual components. The modulus of NDA ranges from about 50 to 100 GPa (7.3 to 14.5 × 10^6 psi), resulting in a modulus for NDC ranging from about 25 to 50 GPa (3.6 to 7.3 × 10^6 psi). Because of the lower modulus of LDA, the modulus of LDC is lower than that of NDC. Typical values range from 15 to 25 GPa (2.2 to 3.6 × 10^6 psi), which is close to the modulus of the mortar fraction. For practical design considerations, the modulus of concretes with densities between 1,440 and 2,500 kg/m^3 (90 to 155 lb/ft^3) and within strength ranges up to 35 MPa (5,070 psi) can be represented by the standard formula (Pauw 1960)

$$E = 0.04\,\omega^{1.5}\sqrt{f_c'}$$

or

$$E = 33\omega^{1.5}\sqrt{f_c'}\ \text{(in non-SI)}$$

where

E = modulus of elasticity in MPa (psi)
ω = density in kg/m^3 (lb/ft^3)
f_c' = compressive strength in MPa of a 152- by 305-mm (6- by 12-in.) cylinder

This formula clearly overestimates the modulus for HSLDC. The formula has been modified to more reasonably estimate the modulus of HSLDC and is presented by ACI 213R as follows:

$$E = C\,\omega^{1.5}\sqrt{f_c'}$$

where

C = 0.040 for 35 MPa (5,000 psi)
= 0.038 for 41 MPa (6,000 psi)
ω = density (kg/m^3 or lb/ft^3)
f_c' = compressive strength (MPa or psi)

When design conditions require accurate elastic modulus data (e.g., deflections, buckling, etc.), however, laboratory tests should be conducted on specific concretes proposed for the project in accordance with the procedures of ASTM C 469.

f. Fatigue. Laboratory studies do not show a major difference in fatigue resistance of LDC and NDC, but some field evaluations of older structures suggest that LDC may perform a little better (Hoff 1994). This apparent performance improvement is attributed to the closer matching of the modulus of elasticity of LDA and mortar than usually exists in normal-density aggregate.

g. Reinforcing steel-bond strength and embedment length. LDC and NDC do not appear to differ much in bond strength to reinforcing steel. But, because splitting-tensile strength is sometimes lower for LDC, ACI 318 requires embedment lengths to be 1.3 times those required for NDC. There is some uncertainty about whether or not this is conservative enough for prestressed concrete with closely spaced and large-diameter strands. This technology apparently presents high splitting-tensile loads. A preconstruction testing program is recommended for such structures (Holm and Bremner 2000).

h. Drying shrinkage. The potential for drying shrinkage is determined by the amount and properties of the cementitious fraction of the concrete. The degree to which this potential is actually realized depends on the drying conditions and the amount of restraint to shrinkage. The internal restraint of the aggregate is an important component of the total restraint. LDC can exhibit up to about 15 percent more drying shrinkage than comparable NDC, apparently due to a lower level of restraint from the low-density aggregate (attributable to lower modulus of elasticity). This effect is somewhat negated in concrete that has been steam-cured for the first 24 hours (ACI 213R).

i. Creep. Creep of both LDC and NDC varies considerably with variations in materials, proportions, and conditions, particularly for concrete in the 20- to 30-MPa (3,000- to 5,000-psi) strength range. The envelope is so wide that any differences between LDC and NDC are difficult to generalize. It is recommended that creep be determined empirically for structures in which it is an important property (ACI 213R).

j. Coefficient of thermal expansion (CTE). The coefficient of thermal expansion of concrete is dominated by the coefficient of the aggregate. ACI 213R gives the range of coefficients for LDC of 7 to 11 × $10^{-6}/^{o}$C (4 to 6 × $10^{-6}/^{o}$F). Similar values (6 to 13 × $10^{-6}/^{o}$C) have been reported for high-strength LDC. These values are similar to the range of CTEs typical for NDC (7.4 to 13 × $10^{-6}/^{o}$C) reported in Mindess and Young (1980). Even though there is broad overlap in CTE between LDC and NDC, it is sometimes reported that the coefficients of LDC are lower than for NDC and differences in behavior attributed to this.

k. Other thermal properties. Specific heat, thermal conductivity, and thermal diffusivity are all properties that are strongly dependent on concrete density. Therefore, it follows that LDC differs significantly from NDC in these properties. Specific heat does not appear to be strongly affected, being about 10 percent higher in LDC than in NDC. Thermal conductivity and diffusivity are more strongly affected. Thermal conductivity of LDC ranges from about 150 to 200 percent lower than in NDC. Thermal diffusivity ranges from 70 to 400 percent lower in LDC than NDC. These differences are significant where heating and cooling of concrete are significant processes, such as in fire resistance, insulation, and in thermal stress problems associated with mass concrete and some structural concrete.

l. Fire resistance.

(1) LDC has been shown to have a higher "fire endurance" (ASTM E 119) than NDC, purportedly due to lower thermal conductivity, lower coefficient of thermal expansion, and greater stability of low-density aggregate to high temperatures (since the aggregate has already been pyro-processed during manufacture) (Holm and Bremner 2000).

(2) HSLDC tends to be more likely to be damaged by spalling during a fire than normal-strength LDC due to the higher levels of impermeability (Bilodeau and others 1995). The higher water content of the LDA is a source of potentially explosive pressure in a fire if the permeability is not high enough to relieve the steam pressure that develops. Incorporation of polypropylene fibers into the concrete is beneficial in this situation. The fibers decompose at high temperatures, leaving pathways for the steam to escape the interior of the concrete.

m. Durability properties.

(1) Water absorption and permeability. Permeability of concrete is considered to relate to several degradation mechanisms, and so is often viewed as a general measure of durability. Even though the low-density property of LDC is achieved by a large amount of porosity in the aggregate, LDC is not particularly permeable to water (Sugiyama and others 1996). This is attributed to the near absence of a discernible paste-aggregate zone in LDC. It is believed that the surface of low-density aggregate particles actually reacts with portland cement paste in a pozzolanic-type reaction, thus eliminating a major pathway by which water can penetrate concrete.

(2) Sulfate attack. Sulfate attack is a phenomenon that involves the cement paste's reaction with excess sulfate salts. Neither the density of the concrete nor the chemical properties of low-density aggregate are known to have any effect on the reaction. That LDC is less permeable, due to the paste-aggregate interface properties discussed above, has the effect of slowing down any sulfate attack potential that might exist (Holm and Bremner 2000). Water-cement ratios of ≤ 0.45 are often required in NDC to help resist the sulfates in seawater by this same mechanism.

(3) Abrasion resistance. Abrasion resistance of LDC is similar to NDC when abrasion is in the form of automobile traffic, or similar types of wear. However, LDC is less resistant to abrasion that has a significant impact component, such as might develop when steel-wheeled

vehicles are used on a concrete surface or in spillway stilling basins, where concrete absorbs a lot of impact from large rocks (Holm and Bremner 2000).

(4) Freezing and thawing. LDA are capable of absorbing a large amount of water relative to normal-density aggregates. When LDC is made such that the aggregate is saturated, there does appear to be some degradation in performance in standard testing for durability to freezing and thawing (ACI 213R; ASTM C 666). However, these standard tests present relatively severe temperature gradients and results appear to be contradicted by service record. Examination of structures that have been exposed for many years to freezing and thawing under wet conditions shows insignificant damage. One possible explanation is that the pores in LDA do not completely fill up even when soaked for a relatively long time in water because most of the pores are not interconnected in a way that makes them readily accessible to permeation of water from the outside. Perhaps this empty pore space serves as relief mechanism to the high pressures generated during naturally occurring freezing events where the freezing gradient travels at a slow rate in a way analogous to air voids in cement paste. In contrast, the rapidly moving freezing gradient in an ASTM C 666 test may not allow enough time for the empty pore space to be effectively used (Holm and Bremner 2000).

(5) Alkali-silica reaction (ASR). The high-temperature processing of LDA results in the conversion of some of the silica into a glassy material. When silica in this form exists in normal-density aggregates, the aggregates are usually susceptible to reaction with the high-pH pore fluid that develops during the hydration of high-alkali cements. This reaction produces an expansive reaction product that can damage concrete. Laboratory testing of LDA shows no deleterious reaction. Two ameliorating effects are possible. One is that the surfaces of the aggregate particles are so reactive that they, in effect, act very much like a pozzolan. Pozzolans are believed to reduce damaging ASR by rapidly consuming the critical ingredients of the reaction before the concrete develops enough rigidity to be damaged by an expansive reaction (Bremner and others 1998). Another possibility is that the porosity of the particle serves as a repository for the ASR product to go into, so as not to cause expansion in the restrained area around the aggregate particle.

(6) Corrosion of reinforcing steel. Reinforcing steel can develop corrosion in concrete either as a result of the concrete around it becoming carbonated from atmospheric carbon dioxide or when sufficient chloride ion comes in contact with the steel. Both of these mechanisms proceed by the aggressive agent permeating the concrete. As mentioned above, LDC has been found to be at least as impermeable as NDC and, in some cases, to have superior impermeability. Consequently, the cover requirements for steel currently given in standard guidance should be adequate for LDC, as for NDC.

8. Summary. Properties that differ between LDC and NDC in a major way include density (by design), modulus of elasticity, thermal conductivity, and thermal diffusivity. Properties that differ in minor ways include tensile strength, drying shrinkage, specific heat, and coefficient of thermal expansion. Values shown in Table 1, taken from Holm and Bremner (2000), summarize some typical property comparisons.

Table 1 - Typical Mechanical and Physical Properties of Structural Low- and Normal-Density Concretes

Property	Unit	Structural Low-Density Aggregate	Normal-Density Aggregate
Design density	kg/m^3 (lb/ft^3)	1,160-2,000 (110-125)	2,240-2,400 (140-150)
Compressive strength	MPa (psi)	20-50 (3.000-7,500)	20-70 (3,000-10,000)
Tensile strength	MPa (psi)	2.5 (360)	3.0 (435)
Modulus of elasticity	GPa (psi*10^{-6})	17-28 (2.5-4.0)	20-40 (3 to 6)
Poisson's ratio		0.2	0.2
Shrinkage at 1 yr	microstrain	600	550
Specific creep	microstrain*10^{-6}/GPa (microstrain*10^{-6}/psi)	70-150 (0.5-1.0)	70-120 (0.5-0.8)
Specific heat	J/kg · K (cal/g · °C)	960 (0.23)	920 (0.22)
Thermal conductivity	W/m · K (Btu · in./hr · ft^2 · °F)	0.58-0.86 (4-6)	1.4-2.9 (10-20)
Thermal diffusivity	M^2/hr (ft^2/hr)	0.0015 (0.016)	0.0025-0.0079 (0.027-0.085)
Thermal expansion	microstrain*10^{-6}/°C (microstrain*10^{-6}/°F)	9± 5±	11± 6±

NOTE: Values shown are typical numbers that vary depending on mixture constituents and strength levels. Use for approximation purposes only.

8. Action Required. This EC should be used as interim guidance pending publication of the final EM. Any comments regarding improvements or clarification during this interim period should be submitted to HQUSACE (CECW-EWS), Washington, DC 20314-1000.

FOR THE COMMANDER:

Dwight A. Beranek, P.E.
Chief, Engineering and Construction Division
Directorate of Civil Works