Structural Lightweight Concrete for Composite Design

DANIEL P. JENNY

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ASTM Designation C330 defines lightweight aggregates for structural concrete in a number of ways: it names most available materials; it lists maximum permissible unit weights of coarse and fine fractions; it describes limiting aggregate tests; and it specifies tests for concrete-making ability.

The ACI Building Code defines structural concrete as having a compressive strength of 2,500 psi or more. ACI 613A-59, a standard for Mix Proportioning Lightweight Concrete, establishes a top unit weight for the concrete at 115 lbs per cu ft. Three other major factors work toward limiting which aggregates are considered truly structural lightweight aggregates—availability, cost, and proven performance.

The concrete-making properties of most lightweight aggregates are shown in a spectrum of concrete unit weights (Fig. 1). Vermiculite and perlite are extremely light materials used in insulating fill concrete ranging in density from 15 to 50 pcf and in strength from 300 to as high as 1,000 psi. Pumice and scoria are natural lightweight aggregates found in volcanic deposits; hence, they have limited availability. Concrete made with these aggregates is in an intermediate range as far as weight and strength are concerned. Coal cinders and expanded slag are by-product materials with limited availability; almost one-hundred percent of the aggregate is used for lightweight concrete block production. Expanded shale, clay or slate, processed in either rotary kilns or on sintering grates, are found in nearly all of the lightweight structural concrete projects built today. Unit weights range from 85 to 120 pcf and strengths range from 2,500 psi to more than 5,000 psi with economical concrete mixes.

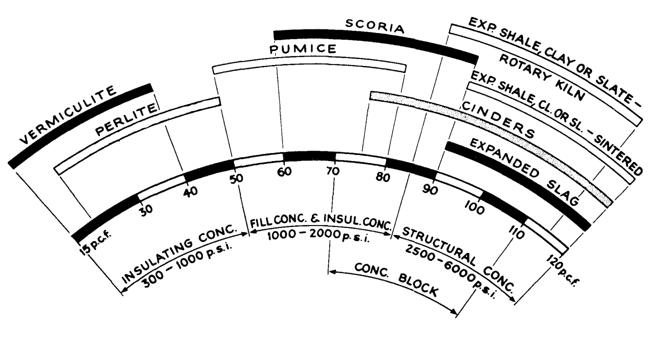

Fig. 1. Spectrum of concrete unit weights

Daniel P. Jenny is Chief Engineer of the Expanded Shale, Clay and Slate Institute, Washington, D. C.

PROPERTIES OF STRUCTURAL LIGHTWEIGHT CONCRETE

The most significant property is reduced weight at no sacrifice in strength. Structural lightweight concrete available today—basically the two materials pointed out on the spectrum in Fig. 1, rotary kiln expanded shale, clay or slate (roughly eighty percent of structural use) and sintered expanded shale or clay (twenty percent)—provides the same compressive strength as normal weight aggregates with approximately the same cement content. A typical performance chart of a given aggregate shows the various strengths attainable with different amounts of cement for both 7-day and 28-day tests (Fig. 2).

Composite design, except when beams are encased, assumes no bonding action between the concrete and the steel, even though there is a considerable amount of bond under most conditions of load and building usage. The interaction between the steel and the concrete is obtained through shear connectors, and the loading on the concrete is basically that of bearing, which is directly related to concrete's compressive strength.

If the lightweight concrete is comparable in compressive strength to normal weight concrete, the shear capacity (or, more correctly, the bearing capacity) of the connectors should be comparable. Pushout tests on shear connectors in lightweight concrete have indicated comparable values. However, because of some uncertainties of materials and a lack of complete test data to prove this point, many engineers and most connector manufacturers recommend some reduction in permissible load per connector when using lightweight concrete. Generally, eighty to ninety percent of normal

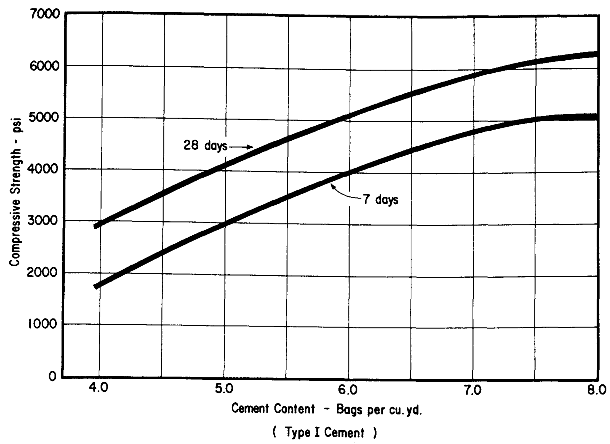

Fig. 2. Effect of cement content on compressive strength

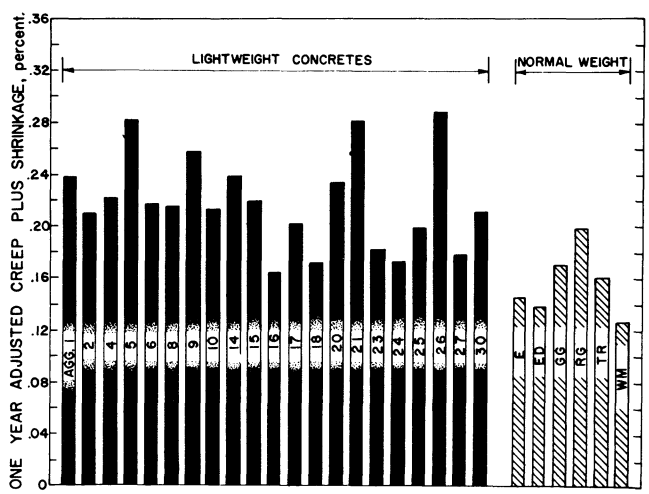

Fig. 3. Creep and drying shrinkage—lightweight and normal weight concretes

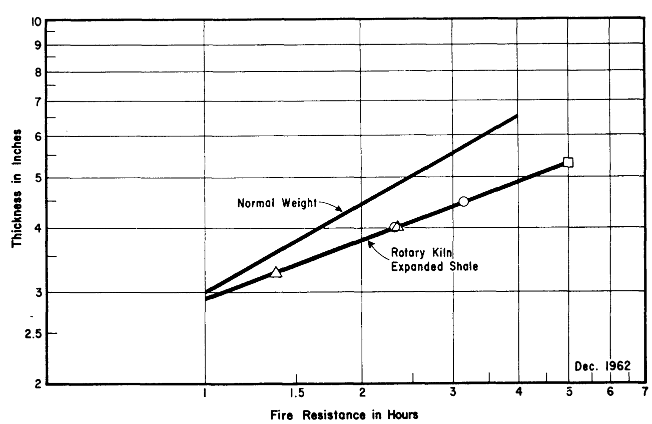

Fig. 4. Fire resistance of concrete floor slabs (ESCSI research)

weight concrete capacity is used. On the other hand, many engineers do not require any reduction in their designs.

The modulus of elasticity of lightweight concrete differs from normal weight concrete. It can range from one-half to three-fourths of the E-value of normal weight concrete at a given strength level, depending on the weight of the concrete. The ACI Building Code uses this formula for estimating the E-value of both types of concrete:

$$E_c = w^{1.5}33\sqrt{f_c'}$$

In composite design, the modular ratio, $n = E_s/E_c$, is important. For 3,000 psi, the n-value for normal weight concrete is 9; for lightweight concrete weighing 100 pcf, the n-value is 15; and at 115 pcf, the n-value is 12. In designing with lightweight concrete in composite design, it is recommended that no differentiation be made in n-values for preliminary design only. By using $n = 9$ for 3,000 psi lightweight concrete, the composite design tables in the *AISC Manual* and other sources can be used. However, in checking the actual stresses in the concrete and in computing deflections it is recommended that the applicable n-value be determined from the above formulas.

Higher n-values mean smaller transformed areas; hence, slighter smaller moments of inertia and, theoretically, greater deflections. This effect is offset by the reduced dead load due to lower concrete weight.

Other properties of lightweight concrete that may be of interest in composite design are the creep and shrinkage characteristics. Many engineers feel that lightweight concrete has much higher creep and shrinkage. Actually, a very extensive study of these properties—NBS Monograph 74, *Creep and Drying Shrinkage of Lightweight and Normal-Weight Concretes*—shows creep to be comparable to most normal weight concrete and, on an average, shrinkage to be only moderately greater (Fig. 3). Actually, in some areas of the country, lightweight structural concrete is being specified because it has *less* shrinkage cracking potential than normal weight concrete. Although there are no definitive values available, the feeling exists with some researchers that lightweight concrete under test performs better in composite design, possibly because the slightly higher creep and shrinkage may tend to distribute the V_h-load to more connectors than when normal weight composite beams are tested.

One other property merits attention. That is the better performance of lightweight concrete in fire tests, because of its improved insulation characteristics. Figure 4 shows that structural lightweight concrete provides a longer delay in reaching a critical temperature rise on the unexposed surface of a floor slab under test than an equal thickness of normal weight concrete. Put another way, an anticipated rating of 2 hours in lightweight concrete requires a 3¾-in. slab as opposed to a 4½-in. slab for normal weight concrete.

QUALITY CONTROL

To get good normal weight concrete, an engineer writes a good specification and sees that concrete quality is assured by proper control procedures at the job. With lightweight concrete, the engineer specifies a C330 aggregate and the 28-day strength and air-dry weight necessary to meet design requirements. Slump and air content should also be specified. The combination of strength and unit weight will, in most cases, eliminate undesirable or unsatisfactory materials. For example, suppose a lightweight aggregate has difficulty in achieving good strength. It will require an excess of cement to meet specifications, and this will boost both the unit weight and the cost. It will lose out on two counts. An engineer today can obtain reliable test data from aggregate producers on their material showing shrinkage values, modulus of elasticity, strength vs. cement content, and other properties.

More and more companies that provide aggregate for structural concrete have pushout test results on their material and will be able to provide an engineer this additional information. With such data, the specification can be closed to one type of aggregate or even to a given brand, taking into account all of the local conditions and the job requirements.

Quality lightweight concrete is achieved on a project by a few simple control tests: (1) Periodic slump measurements will control the amount of water being mixed with concrete and, since lightweight concrete is proportioned with a given cement content and mixed to a given slump, this will in effect control the net effective water-cement ratio and all subsequent concrete properties. (2) Fresh unit weight of the concrete, another simple check, is measured in half or quarter cubic foot containers. This weight should conform to the fresh unit weight determined from trial mixes and it is related to the 28-day air-dry weight, which is used as the basis for design. When the weight and slump are satisfactory, the mix and the yield are reasonably correct. (3) If the weight changes, the usual cause is a change in air content (entrained air is generally used in lightweight concrete to improve its workability and handling characteristics). Then the third control test is run, namely, an air content test using the volumetric method. If the percent of air is incorrect, an adjustment is made at the plant to get the air content back into line. (4) If the air content is satisfactory, further checks must then be made on gradation and specific gravity of the aggregate and possibly on the batching and handling procedures.

Generally, with attention to the basic principles of concrete mix design, good quality lightweight structural concrete is furnished to the field without difficulty. With increasing frequency, compressive strength evaluations of lightweight concrete have shown coefficients of variation under ten percent, rated excellent for job-furnished concrete.