equal at least: 3500 psi for freezing and thawing; 4000 psi for exposure to fresh water; and 4500 psi if exposed to sea water.

DEFLECTION

Deflection control in terms of minimum thickness and additional long-term multipliers were specifically applicable to flexural members of normal weight concrete in ACI 318-63. Presumably, calculations were expected where flexural members contained lightweight aggregate concrete. In this connection a formula was included to determine the modulus of elasticity E_c for concretes weighing between 90 and 155 lb per cu ft. This formula for elastic modulus as a function of density and strength has been taken from the research reported by A. Pauw.[3] The forthcoming code does not propose any change in the formula for E_c, but does extend minimum thickness requirements and long-term deflection multipliers to include lightweight aggregate concretes, Sect. 9.5. Furthermore, a new method for computing immediate deflection using a so-called "effective moment of inertia" is included, as well as a table which details maximum allowable computed deflections.

The effective moment of inertia incorporates both the gross and the cracked moments of inertia as well as using a reduced modulus of rupture for lightweight concrete. Calculations of the immediate deflection of two slabs, identical in depth, reinforcement, and superimposed load, but with one containing a "sand-lightweight" concrete and the other normal weight concrete, are shown in Fig. 6-1. On the basis of these calculations, the lightweight slab would deflect about 10 percent more than the normal weight slab under the same superimposed loading. A computation based only on the moment of inertia of the transformed, cracked sections would indicate a differential of only about 3 percent.

The table of minimum thicknesses of beams or one-way slabs unless deflections are computed, Table 9.5 (a), requires a minimum increase of 9 percent in thickness for lightweight members over normal weight. Thus, using the values in this table, lightweight structural members are not expected to deflect more than normal weight members under the same superimposed load.

FLEXURAL STRENGTH

ACI 318-63 contained the statement: "Except in calculations for deflections, the value of n for lightweight concrete shall be assumed to be the same for normal weight concrete of the same strength." This was an engineering compromise that corrected an apparent inconsistency in the so-called working stress design of columns subjected to combined axial and bending stresses. This statement also had the effect of limiting the resisting moment of a lightweight aggregate concrete flexural member under working stress design to the same value as one out of normal weight concrete of the same strength.

Since the percentage of flexural reinforcement necessary for balanced design is slightly less for lightweight concrete than normal weight concrete of the same strength, this limitation was useful.

The forthcoming Code includes this statement regarding n-values, along with other working stress considerations, only as a working stress design alternate in Sect. 8.1.2. Otherwise the new code is based wholly on ultimate strength design concepts.

There is now the requirement, Sect. 10.3.2, that the reinforcement ratio p shall not exceed 0.75 of the ratio which produces balanced conditions under pure flexure, thus ensuring no flexural compression failures. The ultimate flexural capacity of two members, which fail due to yielding of the tensile reinforcement, will not be significantly different whether one has lightweight and the other normal weight concrete of the same strength.

SHEAR AND DIAGONAL TENSION

The requirements of ACI 318-63 were very specific regarding the shear capacity of structural lightweight concrete. The relationship between splitting ratio and the diagonal tension resistance of structural lightweight concrete was first reported by Hanson.[4] The test to determine the splitting ratio was outlined in the code and the limiting values of shear stress for lightweight concrete were modified by the splitting ratio. The factors used were such that a splitting ratio of 6.7 gave approximate parity with normal weight concrete. In the absence of test data, the splitting ratio was to be assumed as 4.0 regardless of whether the mix was sand-lightweight or all-lightweight concrete.

In the forthcoming code, the use of the splitting ratio F_{sp} has been dropped and in its place the actual splitting tensile strength f'_{sp} is used. This value of f'_{sp} is to be measured in accordance with ASTM C-330 and ASTM C-496. In the absence of tensile test data, the allowable shear in lightweight concrete using natural sand can be taken as 85 percent of normal weight concrete shear values, and as 75 percent if all-lightweight fine and coarse aggregates are used.

The fact that allowable shear or diagonal tensile stresses are now based upon actual splitting tensile tests, rather than a ficticious ratio, is an extremely important improvement to the code. Laboratory controlled split cylinder tests may be conducted to establish higher allowable values for shear, however, the simplified values of

75 and 85 percent will find ready acceptance among many designing engineers. Also, it is important to note, Sect. 4.2.9, that split cylinder tests are not to be made on field samples for concrete, which was not entirely clear in the old code. Values of f'_{sp} are to be determined only under laboratory test conditions. The value is primarily related to the properties of the aggregate and will, of course, be generally higher for a sanded 5000 psi mix than for an all-lightweight 3000 psi mix.

DEVELOPMENT LENGTH

The concept of development length, rather than permissible bond stress, in flexure is new in the forthcoming code. ACI 318-63 did not differentiate between lightweight and normal weight concretes as far as bond was concerned. The proposed new code gives development length requirements for normal weight concrete, Sect. 12.5, which are to be increased for lightweight concrete by the ratio $6.7\sqrt{f'_c}/f'_{sp}$ but may never be decreased. In the event that the splitting tensile strength is not known, the required length of embedment for reinforcing steel to develop bond in lightweight mixes using natural sand is 1.18 times that required in normal weight concrete, or a factor of 1.33 if lightweight fine and coarse aggregates are used.

Since the advent of the ASTM specification for deformed reinforcing bars, bond has rarely been a factor in design. The question arises then as to why the proposed code inflicts more stringent design criteria for anchorage lengths. The proposed formulae, however, do not penalize lightweight aggregate concrete as much as the percentage increase in development length implies. Since the quantity of reinforcement in a flexural member depends on so many other requirements, such as minimum percentage, minimum laps, and minimum web reinforcement, the actual increase in cost due to extra development length will seldom be a factor.

A recent study* by a graduate student suggests that, for any particular lightweight concrete flexural member designed under the proposed new code, the increased costs due to increased development length would be less than 1 percent compared to the same member designed under ACI 318-63. Since a structure contains compression members as well as flexural members, the increased cost due to extra development length would be insignificant.

Fig. 6-2 shows diagrammatically the relationship between tensile splitting strength, development length, and shear as a comparison between lightweight and normal weight concretes. Since the splitting

*Gedizloglu, A. T., "Bond Requirements for Reinforced Concrete," A Thesis Submitted to the Faculty of the Graduate School, University of Missouri, Columbia, Private Communication.

tensile strength is more closely a function of the aggregate than it is the strength of concrete, a good aggregate in a 3500 psi mix will have an advantage over a slightly weaker aggregate in a 5000 psi mix. Under the best circumstance, a 3500 psi lightweight concrete with an f_{sp} of 396 psi would have parity with a 3500 psi normal weight concrete in both shear and development length. On the other hand a 5000 psi lightweight concrete with f_{sp} of 396 would require about 19 percent more shear capacity and development length than 5000 psi normal weight concrete. This represents a considerable departure from ACI 318-63 where the splitting ratio was related to the aggregate only.

The additional recognition of structural lightweight concrete in the forthcoming ACI Building Code, together with the clarification of many points, should lead to increasing usage.

Designers who are not presently familiar with lightweight concrete will have more confidence in incorporating it in their designs and specifying it.

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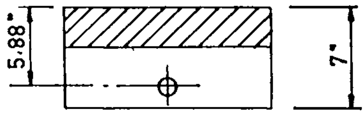
TYPICAL SLAB

7" CONCRETE SLAB

d = 7 − 1.12 = 5.88"

$A_s = 1.01\ in^2$



BASIC DATA

LT. WT.	NORM. WT.
WT. = 110 p.c.f.	WT = 145 p.c.f.
$E_c = 2.08 \times 10^6$	$E_c = 3.12 \times 10^6$
n = 13.9	n = 9.3
fr. $= (7.5 \times \sqrt{3000} \times .85) = 351$ p.s.i.	fr. $= (7.5 \times \sqrt{3000}) = 411$ p.s.i.
D.L. = 64	D.L = 85
PART. = 20	PART. = 20
L.L. = 40	L.L. = 40
124	145

Fig. 6-1—Proposed revision to ACI 318-63, immediate deflection

LOCATION OF NEUTRAL AXIS

LT. WT.

$$6(Kd)^2 = (1.01)13.9(5.88 - Kd)$$
$$Kd = 2.72''$$

NORM. WT.

$$6(Kd)^2 = (1.01)\,9.3\,(5.88 - Kd)$$
$$Kd = 2.35''$$

TRANSFORMED MOMENT OF INERTIA

LT. WT.

$$I_{CR} = 4(2.72)^2 = 29.6$$
$$(1.01)(13.9)(3.16)^2 = \underline{140.5}$$
$$170.1\ \text{IN}^4$$

NORM. WT.

$$4(2.35)^2 = 22.0$$
$$(1.01)(9.3)(3.53)^2 = \underline{117.0}$$
$$139.0\ \text{IN}^4$$

APPLICATION OF EQUATIONS 9 4 & 9 5 REVISED CODE

$$M_{CR}(\text{LT. WT.}) = 351 \times 2\,t^2 = 34\,400\,''\#$$
$$M_{CR}(\text{NORM. WT.}) = 40{,}300\,''\#$$
$$I_g = \frac{12 \times 7^3}{12} = 343\ (\text{LT. WT. \& NORM. WT.})\quad \text{ASSUME } M_{MAX.} = 100{,}000\,''\#$$
$$I_{EFF}(\text{LT. WT. or NORM. WT.}) = \left(\frac{M_{CR}}{M_{MAX.}}\right)^3 I_g + \left[1 - \left(\frac{M_{CR}}{M_{MAX.}}\right)^3\right] I_{CR}.$$

LT. WT.

$$I_{EFF} = (.0408)\,343 + (.9592)\,170.1$$
$$I_{EFF} = 14.0 + 163.0 = 177.0$$

NORM. WT.

$$I_{EFF} = (.0656)\,343 + (.9344)\,139.0$$
$$I_{EFF} = 22.5 + 129.9 = 152.4\ \text{IN}^4$$

COMPARATIVE IMMEDIATE DEFECTIONS

$$\frac{\Delta_{LW}}{\Delta_{NW}} = \frac{(3.12)(152.4)(124)}{(2.08)(177.0)(145)} = 1.10$$

$$\frac{\Delta_{LW}}{\Delta_{NW}} = \frac{E_{NW}}{E_{LW}} \cdot \frac{I_{NW(EFF)}}{I_{LW(EFF)}} \cdot \frac{\text{TOTAL LOAD}_{LW}}{\text{TOTAL LOAD}_{NW}}$$

Fig. 6-1-(cont.)

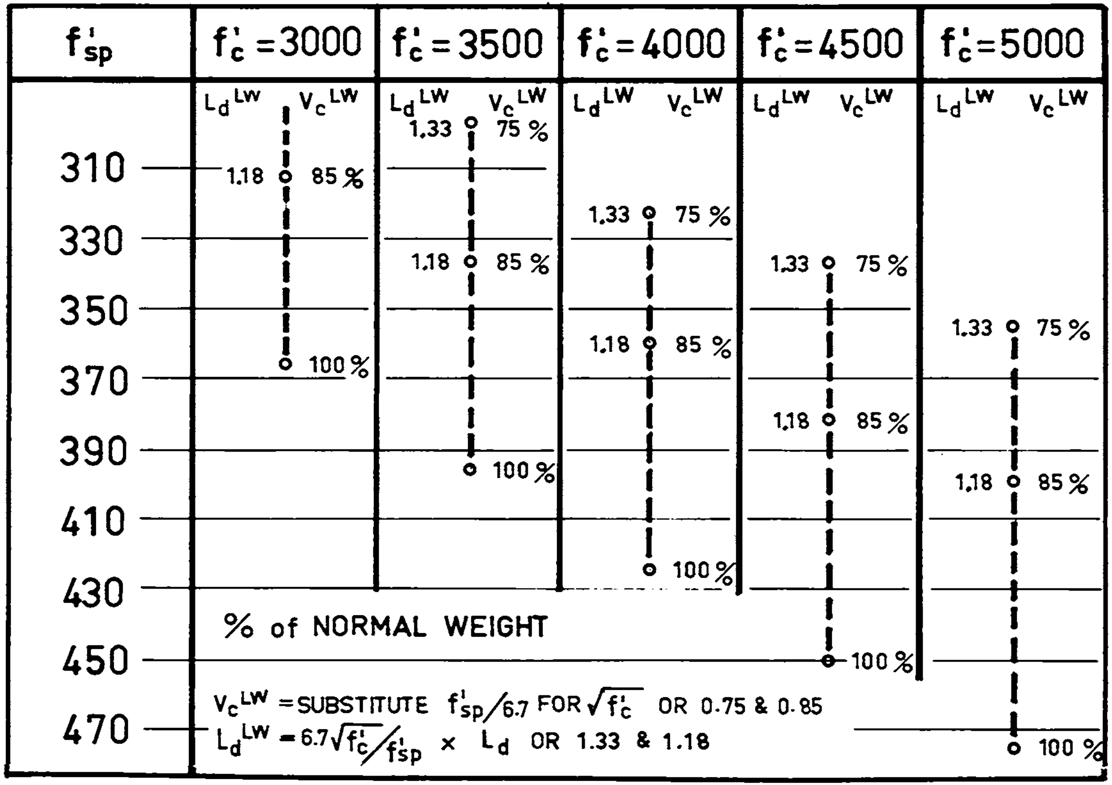


Fig. 6-2—Proposed revision to ACI 318-63, anchorage length and shear

Research report sponsored by the
Reinforced Concrete Research
Council

PAPER SP 29-7

LIGHTWEIGHT AGGREGATE REINFORCED CONCRETE COLUMNS

By BORIS BRESLER

The paper deals with deformation and strength of short lightweight aggregate reinforced concrete columns under combined axial load and bending. The experimental phase of this study was restricted to an investigation of a "complete" stress-strain diagram (defining ultimate strain) of plain concrete under axial compression. Concrete mixes of different strength levels with one lightweight aggregate and one conventional aggregate were used. It was found that the lightweight aggregate concretes may have significant variations in ultimate strain, varying for the concretes included in this study from 0.00224 to 0.00525, within a range of f_c' values from 3 to 5 ksi. The lower values of ultimate strain occurred in the higher strength concrete.

The analytical studies deal with the evaluation of influences of material characteristics, amount of reinforcement, and magnitude of axial load or flexural strength, stiffness, and rotational capacity. Eighty column sections with different parameters were studied. It was found that properly designed lightweight aggregate reinforced concrete columns can develop the same strength and rotational capacity as similar columns with normal weight aggregate concrete. Reductions in ultimate strain capacity of concrete limit the effective use of high strength steel reinforcement and the ductility (rotational capacity) of reinforced concrete members.

Keywords: axial loads; bending; columns (supports); compressive strength; ductility; lightweight aggregate concretes; plain concrete; reinforced concrete; reinforcing steels; research; short columns; stiffness; strains; stress-strain relationships.

Use of lightweight aggregate concrete in building construction has become increasingly economical in recent years. While at first lightweight aggregate concrete found its principal use in slabs and beams, it is now used for the entire frame, including columns.[1]

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Mr. Bresler's practical experience included structural design for Kaiser Shipyards, Richmond, California, and for Convair Corporation in San Diego. He has been active in research and in 1959 was awarded the ACI Wason Medal for research, and in 1968 received the ASCE State-of-the-Art of Civil Engineering Award.

He is a member of ACI, ASCE, SEAONC, IABSE, BRI, and RCRC.

The capacity of flexural members made of lightweight reinforced concrete and failing either as a result of pure flexure or flexure combined with shear has been studied both analytically and experimentally, and results of these studies have been incorporated in the 1963 ACI Building Code design criteria. Experimental studies of lightweight aggregate reinforced concrete columns, particularly under varying combinations of compression and bending, have not been extensive, and none have been published prior to 1965, the date of initiating the project reported here. Some studies have been carried out recently,[2,3] but these have been limited in scope and require further verification.

One of the primary considerations in determining the capacity of reinforced concrete columns subjected to combined compression and bending is the shape of the concrete stress-strain diagram. This diagram includes an ascending branch up to maximum stress and a branch descending to failure strain. Although data on the shapes of the complete stress-strain diagrams for lightweight aggregate concretes are meager, it has been shown that the ascending portion of the diagram generally has a smaller slope (lower modulus of elasticity) than that for conventional concrete of the same strength.[4]

Both ascending and descending branches of the stress-strain curve, and in some cases the strain at failure of the concrete, may have a significant influence on the mode of failure and on capacity and ductility of the column. For example, the strain in lightweight concrete at a stress level of about half the strength would be 50 to 100 percent greater than the strain in conventional concrete of the same strength and at the same stress level. Therefore, a lightweight aggregate column, all other characteristics being the same, would have a lower stiffness than one of normal weight concrete. Because capacity of long slender columns depends on stiffness, calculations would indicate that slender lightweight aggregate reinforced concrete columns would have a lower capacity than that of normal weight aggregate concrete columns containing identical reinforcement.

On the other hand, if the value of ultimate strain for lightweight reinforced concrete columns is greater than that for conventional concrete members, as might appear reasonable in consequence of the lower elastic modulus, short lightweight aggregate columns with small eccentricities might have greater capacity and ductility than columns of conventional concrete, and the "balanced failure" condition would develop at a lower eccentricity and higher axial load than that for normal weight concrete.

These suppositions have only been substantiated by somewhat meager experimental data and the 1963 ACI Code did not distinguish between lightweight aggregate reinforced concrete columns and similar conventional concrete columns. In order to develop a more rational design criteria for design of lightweight aggregate concrete columns, additional data on the shape of the complete stress-strain diagrams and on the magnitude of ultimate strain in lightweight concrete, as well as test results for lightweight concrete columns, were needed.

The objective of this investigation was to determine the characteristics of the stress-strain curve of plain lightweight concrete beyond the maximum stress, and to apply the basic experimental data in an analytical study of the capacity of lightweight aggregate reinforced concrete columns. The analytical study was limited to behavior of short columns under short duration of loading with special attention to deformation and capacity under combined axial load and bending.

SCOPE OF THE EXPERIMENTAL INVESTIGATION

The experimental phase of this study was restricted to an investigation of a "complete" stress-strain diagram (both its ascending and descending branches and ultimate strain capacity) of plain concrete. The standard compression test on concrete cylinders cannot be used for determining the complete stress-strain diagram. As soon as a critical stress or strain level is attained the cylinder begins to fail, and the energy stored in the testing machine is released rapidly. If the specimen is unable to absorb this released energy, it fails quickly and the resulting descending branch of the stress-strain curve varies greatly with the stiffness of the testing machine and with the particular mode of failure of a given specimen. The stiffness of the testing machine partly determines the amount of energy stored, and the mode of failure partly determines the rate of dissipation of the stored energy.