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Incremental Loading of Reinforced Lightweight Concrete Columns

Accroissement différentiel de la charge dans les colonnes en béton armé léger

Differentieller Lastzuwachs bei Leichtstahlbetonsäulen

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INTRODUCTION

A recent experimental investigation[1] has shown that high quality structural lightweight aggregate concrete can safely be used in reinforced concrete columns, including ultra-highrise buildings. Their creep and shrinkage characteristics differ little from those of columns containing normal weight concrete. In both cases, elastic and time-dependent column shortenings were found to be governed primarily by reinforcing steel percentage, the influence of concrete type was relatively minor.

The previous study involved the typical laboratory procedure of moist curing the specimen for 28 days and then applying the full design load at that age. This loading technique bears little semblance to the actual incremental loading of concrete columns as construction of a tall structure proceeds. At the suggestion of Dr. Fazlur Khan of Skidmore, Owings and Merrill, laboratory tests dealing with incremental loadings were therefore undertaken. The main objective being comparison with the shortening characteristics of columns loaded in the typical laboratory manner.

DESCRIPTION OF LABORATORY INVESTIGATION

General -- These tests were made to determine the elastic and time-dependent shortenings of reinforced lightweight concrete columns which were fabricated and loaded to simulate conditions encountered in a 50-story concrete building 714 ft. (218 m) tall. The investigation primarily concerns columns loaded in weekly increments to simulate the actual construction schedule. These columns required 50 equal weekly increments, each 2 percent of full load. Companion reinforced columns were also instantaneously loaded to full load when the columns were 1, 4, 35, and 50 weeks old.

Tests were also undertaken on non-reinforced concretes to determine compressive strength, elastic deformation, creep, and drying shrinkage characteristics as functions of time.

Materials -- The coarse lightweight aggregate, No. 14 in the PCA numbering series, is an expanded shale produced in a rotary kiln that has been studied extensively in previous investigations.(1) Normal weight Elgin, Illinois sand was used as all the fine aggregate. The concrete was proportioned to produce a nominal compressive strength of 6000 psi (422 kg/cm²) at 28 days. Lightweight concrete of this strength and containing 100 percent normal weight sand fines has a nominal modulus of elasticity of 3.0 million psi (211,000 kg/cm²) at 28 days. The slump and air contents were maintained at approximately 3 in. (7.5 cm) and 4 percent, respectively. The laboratory mix data are presented in Table 1; accompanying measured physical properties of this concrete are presented in Table 2.

TABLE 1 -- LABORATORY CONCRETE MIX PROPORTIONS

Fine Aggregate, percent by vol.	Quantities per cu. yd. (m³) of concrete				Percent Air, Roll-A-Meter	Plastic Unit Weight, lb./ft.³ (kg/m³)	Slump, in. (cm)
	Water, lbs. (kg)	Cement, lbs. (kg)	Air-Dry Aggregates: Coarse,* lbs. (kg)	Air-Dry Aggregates: Sand,** lbs. (kg)			
44	315 (187)	623 (370)	900 (534)	1245 (739)	3.8	114.2 (1830)	2.8 (7)

* 3/4" maximum size lightweight aggregate
** Normal weight Elgin, Illinois sand

TABLE 2 -- PHYSICAL PROPERTIES OF CONCRETE *

Compressive Strength,** psi (kg/cm²)				Modulus of Elasticity,** 10^6 psi (10^5 kg/cm²)			
7 da.	28 da.	90 da.	1 yr.	7 da.	28 da.	90 da.	1 yr.
5220 (367)	6360 (447)	6990 (491)	7230 (508)	3.07 (2.16)	3.34 (2.35)	3.60 (2.53)	3.82 (2.69)

* All cylinders were continuously moist cured
** An average of four specimens.

The reinforced columns contained $^5/_8$-in. (16-mm) diameter high strength deformed bars, which conform to the ASTM A431 specification and have a nominal yield point of 75,000 psi (53 kg/mm^2).

Fabrication, Curing and Instrumentation of Specimens -- The study involved fabrication and long-time testing of eight 6-in. (15 cm) square by 36-in. (91 cm) long reinforced columns and 32 non-reinforced 6 by 12-in. (15 by 30-cm) cylinders.

The reinforcing was fabricated into tied column assemblies each containing four deformed bars. Lateral tie reinforcement consisted of $^1/_4$ -in. (6 mm) bars spaced at 6 in. (15 cm). The symmetrical longitudinal reinforcement was positioned to provide 1-in. (2.5 cm).concrete cover over the lateral tie reinforcement. The longitudinal bars were welded to 1-in. (2.5 cm) thick steel bearing plates.[1]

The columns were cast in a horizontal position and consolidation of concrete was by table vibration. The columns were moist cured for three days; they were then sealed in 0.003-in. (0.08 mm) thick copper foil to simulate idealized moisture conditions in the large prototype columns of the structure.

The elastic and time-dependent deformations were observed by a mechanical strain gage. At midheight of the columns, brass plugs were glued directly to the concrete on 10-in. (25-cm) centers on three of the four sides of the column. The deformation of the reinforcing steel and concrete have previously been measured to be equal[1], and measurements directly on steel were therefore not made during this study. More detailed description of fabrication and instrumentation procedures reported previously[1] are similar to those used in this study.

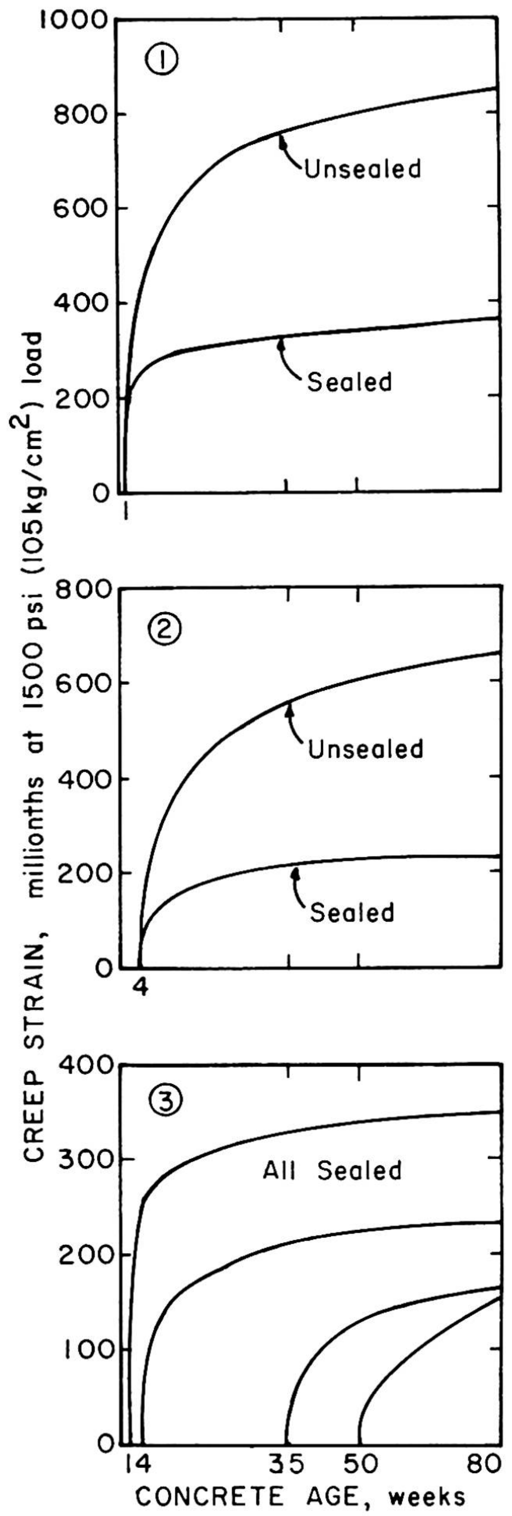
The 6x12-in. (15x30-cm) cylinders were cast in the vertical position and consolidation of concrete was by internal vibration. All cylinders including those wrapped in copper foil were continuously moist cured until time of test.

TEST PROGRAM

All eight reinforced columns were eventually loaded to 70,000 lbs. (31,780 kg). Two were loaded in 50 increments of 1400 lbs. (636 kg) over a 50-week period, starting when concrete was one week old. The remaining six were loaded instantaneously to 70,000 lbs. (31,780 kg), two at a concrete age of 1 week, two at 4 weeks, one at 35 weeks, and one at 50 weeks.

The 6x12-in. (15x30 cm) plain concrete cylinders were subjected to strength and modulus of elasticity testing at ages 7, 28, 90, and 365 days. Creep and drying shrinkage tests on unsealed cylinders began at ages 1 and

4 weeks and those specimens were then stored at 73°F (23 C) and 50 percent relative humidity. Creep tests on copper-foil wrapped cylinders began at ages 1, 4, 35, and 50 weeks. All creep specimens were loaded to 1500 psi (105 kg/cm²). The later-age sealed creep specimens (plain and reinforced) were initially observed to verify the lack of drying shrinkage in the copper-wrapped specimens.



Figs. 1,2,3 – Creep of Plain Concrete–Effect of Age of Concrete at Loading and Drying Shrinkage.

TEST RESULTS

Strength and Elastic Properties -- The properties of the plain concrete presented in Table 2 indicate that substantial increases in strength and stiffness of the concrete occurred as a function of curing time.

Creep Properties of Plain Concrete -- The measured creep of these sealed and unsealed concretes are shown in Figs. 1 to 3.

Fig. 1 shows the creep of concretes loaded at an age of 1 week. After 79 weeks of loading, the measured creep of the sealed and unsealed cylinders was 370 and 850 millionths, respectively. The drying shrinkage of the companion unsealed concrete was 570 millionths at that same time. It is noted that the presence of drying shrinkage has the significant effect of approximately doubling the measured creep at age 50 weeks.

Fig. 2 shows the creep of concretes loaded at 4 weeks. After 76 weeks of loading, the measured creep of the sealed and unsealed cylinders was 230 and 650 millionths, respectively. The drying shrinkage of the companion unsealed concrete was 510 millionths at that same time. With this loading age the creep at age 50 weeks is almost tripled when drying shrinkage is allowed.

Fig. 3 shows the measured creep of the sealed cylinders which were loaded at ages 1, 4, 35 and 50 weeks. These data show the well-known influence of age of concrete at loading, and illustrate low creep characteristics of these sealed lightweight concretes.

The measured creep coefficients (creep strain per unit load) at age 50 weeks range from 0.08 to 0.25 millionths/psi (1 to 4 millionths/kg/cm^2) for the sealed concretes. The data shown in Fig. 4 relate this measured creep coefficient occurring from the time of loading to the 50-week age versus the concrete age at loading. These data will be used later in the application of the theoretical prediction equation to the incrementally loaded sealed reinforced columns.

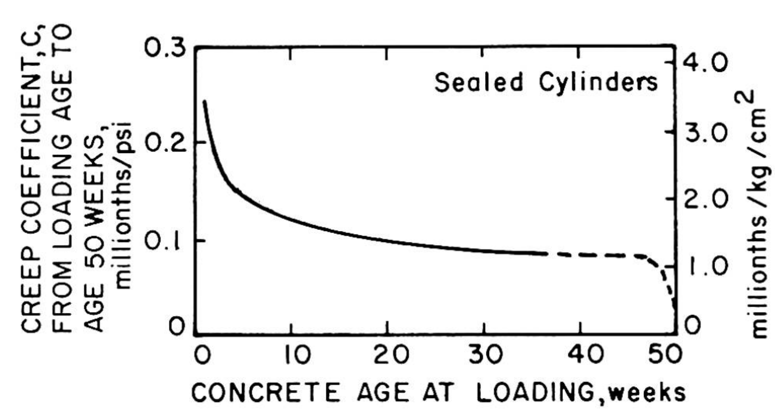


Fig.4—MEASURED CREEP COEFFICIENT OF PLAIN CONCRETE VERSUS CONCRETE AGE AT LOADING

<u>Elastic and Creep Properties of Instantaneously Loaded Columns</u> -- The measured data from the instantaneously loaded columns are shown in Fig. 5. The elastic response to load is in accord with elastic theory, and the significant increase in modulus of elasticity of concrete as a function of curing time is quite evident in the measured elastic response of these reinforced columns. The measured

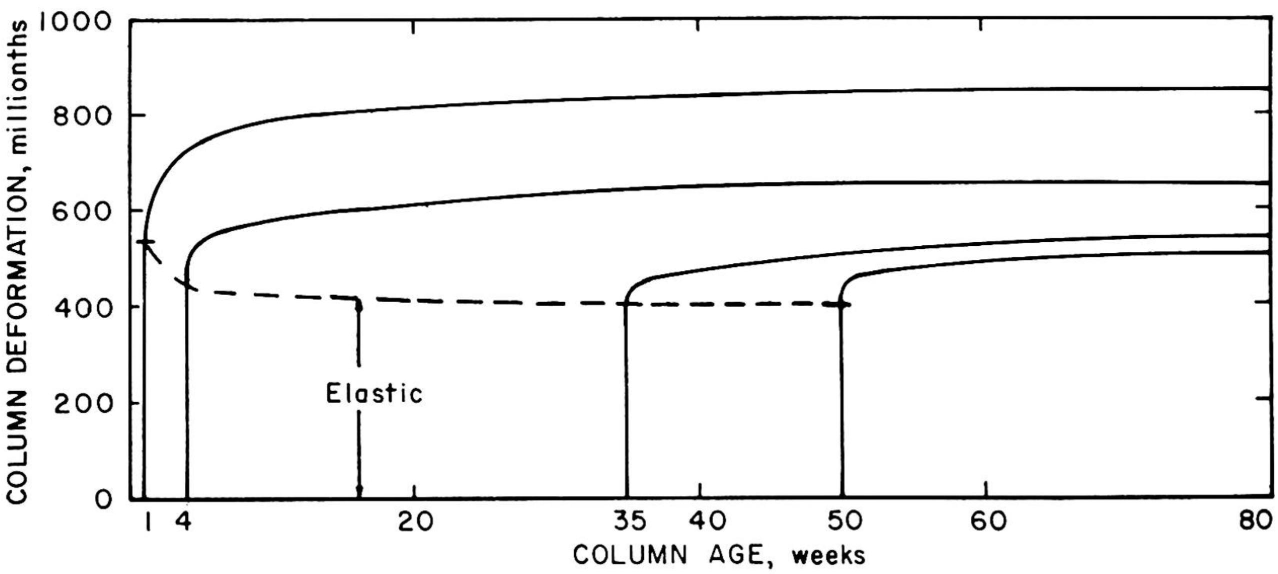


Fig. 5 — ELASTIC AND TIME - DEPENDENT CREEP DEFORMATION OF INSTANTANEOUSLY LOADED REINFORCED COLUMNS

time-dependent creep characteristics also reflect the influence of age of concrete at loading on the time-dependent behavior of reinforced columns. At age 50 weeks the ratio of creep strain to elastic strain ranges from 0. 57 with the 1-week loading to 0. 25 with the 35-week loading.

Elastic and Creep Properties of Incrementally Loaded Columns -- The measured data from the incrementally loaded columns are shown in Fig. 6. It is quite evident that the non-linear creep behavior was small as observed by the measured linear response during the incremental loading period. Creep is being further observed after the 50th and last load was applied. Since this last load application, the columns have shortened only about 20 millionths during the 30-week period following the last loading.

The computed elastic shortening, taking into account the increased modulus of elasticity of the concrete, is also shown in Fig. 6. It is seen

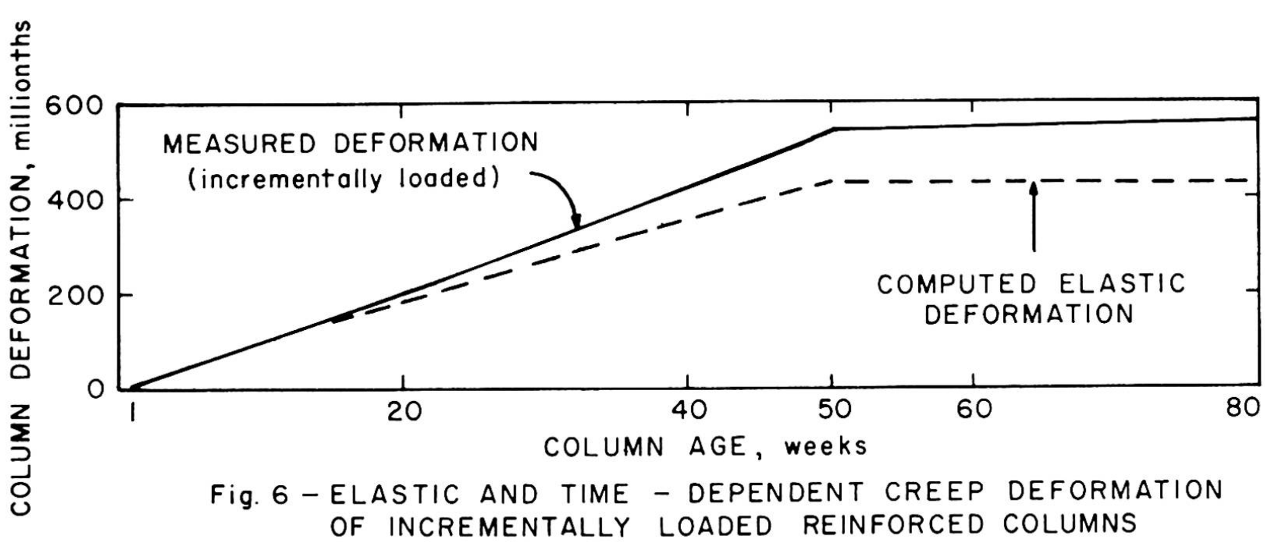


Fig. 6 – ELASTIC AND TIME – DEPENDENT CREEP DEFORMATION OF INCREMENTALLY LOADED REINFORCED COLUMNS

that the influence of creep is small when sealed reinforced columns are incrementally loaded during a long-time period. At an age of 50 weeks the ratio of measured creep strain to computed cumulative elastic strain was 0.25.

ANALYSES OF DATA

The analyses of data are presented in a condensed form due to the IABSE manuscript length limitation. More significant details and data analyses will be provided in future extensions of this investigation.

Elastic Analysis -- The elastic response of these reinforced lightweight concrete columns was found to be in accord with elastic theory. The measured elastic shortenings for the 5 conditions of loading were as follows:

Instantaneous Load at	1 week	=	540	millionths elastic shortening
" "	4 weeks	=	434	" " "
" "	35 weeks	=	400	" " "
" "	50 weeks	=	400	" " "
Incrementally Loaded during	50 weeks	=	433	" " "

Creep Analysis -- Theoretical analyses as discussed by Leonhardt[2,3] have been shown[1] to adequately predict the time-dependent strain in reinforced columns caused by creep and drying shrinkage. The following equation[1] was used to predict the time-dependent steel stresses in the reinforced columns of this study caused by creep:

$$\Delta f_s = \frac{f_o}{p_g}\left[1 - e^{-\alpha C E_c}\right] \qquad \ldots\ldots (1)$$

Eq. (1) can be converted to time-dependent reinforced column strain by applying the measured creep values (C) obtained from the unreinforced copper-wrapped cylinders and then by calculating the resulting change of steel strain which also equals change of column strain.

Application of Eq. (1) to the sealed reinforced columns which were instantaneously loaded at 1, 4, and 35 weeks results in single-step solutions which underestimate the measured time-dependent shortenings at 50 weeks of age by 13 to 27 percent. This underestimate may result because the use of the singular creep coefficient determined at a particular loading age does not take into account the change in creep characteristics as a function of time.

However, when Eq. (1) is applied to the incrementally-loaded columns in a 50-step solution, using the data in Fig. 4 to account for changing creep coefficients and the assumptions of superposition, much better results are obtained. The cumulative creep of the incrementally loaded columns was predicted to be 113 millionths and the measured creep was 106 millionths. The multi-step solution, which takes account of changing concrete properties results in a ratio of Δf_s(meas.)/ Δf_s(calc.) of 0.94.

CONCLUDING REMARKS

Data obtained from the incrementally loaded reinforced columns show that little creep takes place when the load is applied at a realistic rate and when the drying shrinkage influence on creep is eliminated. The creep that was measured during this 50-week loading period was only 25 percent of the elastic response, and the time-dependent creep phenomena essentially stopped after the 50th and final load was applied.

Theoretical time-dependent strains[2] compared well with the test data, so that theoretical analyses may be used to estimate such time-dependent movements.

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NOTATION

A_s = cross-sectional area of longitudinal reinforcement

A_g = gross cross-sectional area of concrete column

C = unit creep coefficient of plain concrete

e = base of natural logarithms

E_c = modulus of elasticity of concrete

E_s = modulus of elasticity of reinforcement

f_o = initial elastic stress in concrete

n = modular ratio E_s/E_c

p_g = percentage of reinforcement A_s/A_g

$\alpha = \dfrac{p_g n}{1 + p_g n}$

Δf_s = change in steel stress due to creep

SUMMARY

Tests were made at the Portland Cement Association Laboratories regarding the elastic and time-dependent shortening of reinforced lightweight concrete columns which were fabricated and loaded to simulate construction conditions encountered in a 50-story concrete building 714 ft. (218 m) tall. The measured data from these incrementally loaded columns show low creep when the load is applied at a realistic rate. A 3-year field investigation of the actual structure will be undertaken and comparison between laboratory and field data will be made. Such comparison will provide data toward developing improved design concepts for ultra-highrise concrete buildings.

RÉSUMÉ

Aux laboratoires de l'association du Portland Cement on a fait des tests concernant le raccourcissement élastique et celui en fonction du temps sur des colonnes en béton armé léger, fabriquées et chargées de façon à simuler les conditions rencontrées dans une construction en béton de 50 étages et de 218 m de haut. Les valeurs mesurées sur ces colonnes chargées différentiellement montrent peu de fluage tant que les charges appliquées restent dans une limite raisonnable. Il sera procédé à des essais sur nature pendant 3 années, et des comparaisons seront faites entre les résultats de laboratoire et ceux obtenus sur le bâtiment. On profitera de ces comparaisons pour améliorer la projection de constructions en béton d'extrême hauteur.

ZUSAMMENFASSUNG

Die Portland Cement Association hatte Versuche zwecks Bestimmung der elastischen und zeitabhängigen Verkürzung an Leicht-Stahlbetonsäulen durchgeführt, die unter den Bedingungen eines fünfzigstöckigen und 218 m hohen Betongebäudes hergestellt und belastet wurden. Die Messergebnisse zeigen, dass die mit differentiellem Lastzuwachs belasteten Säulen geringes Kriechen zeigen, wenn die Lasten mit einer vernünftigen Geschwindigkeit aufgebracht werden. Eine Dreijahresuntersuchung dieses Gebäudes wird unternommen und Vergleiche zwischen Laboratoriums- und Felddaten werden angestellt. Solche Vergleiche sollen Angaben zur Entwicklung derartig hoher Massivbauten liefern.

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