# Prepared discussion

Objekttyp: **Group**

Zeitschrift: **IABSE congress report = Rapport du congrès AIPC = IVBH Kongressbericht**

Band (Jahr): **8 (1968)**

PDF erstellt am: **09.08.2024**

DISCUSSION PRÉPARÉE / VORBEREITETE DISKUSSION / PREPARED DISCUSSION

**Improvement of Structural Lightweight Aggregate Concrete by Synthesis of Gap Grading with Shrinkage-Compensating Matrix (Concrete Technology)**

Amélioration d'agrégats de béton légers par synthèse de la classification avec la matrice de compensation du retrait (technologie du béton)

Verbesserung von Leichtbetonaggregaten durch Synthese aus Klassierung mit Schwindausgleichformen (Betontechnologie)

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## 1. Introduction

Professor Adrian Pauw has ably and pertinently summarized the state-of-the-knowledge in structural lightweight aggregate concrete. As compared with normal-weight concrete, lightweight concrete is more affected by the moisture condition, has lower strength and modulus of elasticity, suffers more creep and shrinkage, requires slightly more cement, attains somewhat higher accelerated strengths and less creep and shrinkage by steam curing, can be improved in tensile splitting strength, bond strength, creep and shrinkage by partial sand replacement of the fines, and costs more because of more costly aggregate and more cement.

Lightweight aggregates, being mostly rotary-kiln manufactured, can be easily produced in rounded and smooth pebbles by presizing the feed and controlling the burning process. It is thus more adapted to gap grading than normal-weight aggregates. Inherently, gap-graded concrete has less specific surface, is less affected by the moisture condition, requires much less cement paste and hence much less cement and also water for the same water-cement ratio, attains higher strength and higher modulus of elasticity, suffers much less creep and shrinkage, and costs less than continuously-graded concrete. The much reduced cement requirement even permits the blending of the higher-premium shrinkage-compensating cement to produce shrinkage-compensating gap-graded concrete at less cost than conventional concrete.

It is, therefore, both technologically sound and economically feasible to synthesize gap-graded lightweight-aggregate shrinkage-compensating structural concrete by partial sand replacement of the fines and steam-cured. It can be competitive with normal-weight concrete of comparable strength.

## 2. Some Unique Properties of Structural Lightweight Aggregates That Can Be Improved by Gap Grading

To exploit the full potential of structural lightweight aggregates, the writer fully agrees with Professor Pauw in the understanding of their unique properties. Some of these unique properties can, however, be improved by gap grading. Gap grading is distinguished from continuous grading of aggregates by using only one size or a narrow range of size for both coarse and fine aggregates. A parallel exhibit is given below, using Professor Pauw's statements of some unique properties of structural lightweight aggregates as a basis, and the writer's observations that gap grading would improve such unique properties.

| Unique Properties of Structural Lightweight Aggregates | Feasible and Adaptable Improvements from Gap Grading |
|---|---|
| (1) More rounded aggregate can be produced by presizing or pelletizing the raw material feed and controlling burning to prevent or minimize agglomeration. | (1) Manufactured lightweight aggregates would realize advantages of gap grading without any alleged sacrifice of other sizes resulting from crushing natural aggregate material. |
| (2) Finer fractions generally have a somewhat greater unit weight due to the fact that they tend to include fractions of material which have bloated least. | (2) Gap grading generally results in less mortar requirement which would counterbalance the greater unit weight of finer fractions of lightweight aggregates and/or the increased weight of sand replacement. |
| (3) Difference in density between aggregate fractions results in somewhat greater tendency for segregation in stockpiles. | (3) Being only one size or within a narrow range of size in gap grading, the tendency for segregation in both coarse and fine-aggregate stockpiles would be eliminated. |
| (4) Consistent aggregate gradation is more critical for lightweight aggregate because changes in gradation can cause fluctuation in both the unit weight and other properties of the concrete. | (4) By virtue of only one size or within a narrow range of size, gap grading would ensure more uniform unit weight and other properties of the concrete. |
| (5) Maximum size (1-2.5 cm) of lightweight aggregates is generally smaller than most normal-weight concrete aggregates. | (5) Maximum size of gap grading is limited by the spacing of reinforcing steel or prestressing strands. The smaller maximum size of lightweight aggregates fits well with stress-carrying members of reinforced or prestressed concrete. |
| (6) Since the expanded particles contain voids or dead air spaces, the apparent speci- | (6) With gap grading, smaller particles in the coarse aggregate would be eliminated, |

fic gravity is difficult to determine (especially in the fine fraction because of variable absorption), and it has lower values with the larger pieces.

more uniform apparent specific gravity obtained, and more accurate unit weight of concrete predicted.

(7) Most lightweight aggregates can absorb 5 to 20% water by weight of dry material, and this does not normally occur during mixing and before placing. Hence allowance must be made for the aggregate's water demand to prevent stiffening of the mixture during the interval between mixing and placement. But it is difficult to account for this variable rate of absorption in maintaining uniform consistency in successive batches.

(7) The use of gap grading will confine to one maximum size or within a narrow range of the maximum size whose rate of absorption would be more uniform and whose water demand could be more easily determined for maintaining a uniform consistency in successive batches.

(8) The absorbed water is not available to the cement paste in the mix during the hydration process. The net effective water-cement ratio for lightweight concrete is, however, essentially the same, at comparable strengths, as that of normal-weight concrete.

(8) The less water requirement for gap-graded concrete of equal consistency and strength narrows down the gross difference between the greater water requirement for lightweight concrete and the smaller one for normal-weight concrete.

## 3. Some Physical Properties of Lightweight Aggregate Concrete That Can Be Improved by Gap Grading

As compared with normal-weight concrete, the properties of lightweight aggregate concrete are more affected by the moisture conditions. The lighter concretes require slightly more cement content, have a lower modulus of elasticity, and suffer more creep and shrinkage. The beneficial use of steam curing and sand replacement of the fines have been well covered by Professor Pauw. The following will confine to certain physical properties of lightweight concrete that can be improved by gap grading.

(1) The lighter unit weight of lightweight structural concrete has made it an economical structural material in spite of the higher cost of the lightweight aggregate.

(1) The much less cement requirement of gap grading would make gap-graded lightweight concrete less costly than continuously-graded and still more competitive with normal-weight concrete.

(2) Compressive strengths of lightweight aggregate concrete up to a practical max-

(2) The much less cement requirement of gap grading could make gap-graded light-

imum of about 400 $kg/cm^2$ can be obtained with minor increases in cement content compared with normal-weight concrete of equivalent gradation and strength.

weight aggregate concrete having comparable strength as normal-weight concrete, without increase in cement content.

(3) The modulus of elasticity of both normal and lightweight concretes varies with the 1/2th power of $f'_c$ (compressive strength) and 3/2th power of w (unit weight), and hence it is lower for lightweight concrete.

(3) The generally higher compressive strength of gap-graded concrete would make the modulus of elasticity of gap-graded lightweight concrete higher than that of continuously-graded lightweight concrete. Tests have also shown that gap-graded concrete has higher modulus of elasticity.

(4) On the average, both creep and shrinkage are considerably greater for lightweight concrete than for normal-weight concrete.

(4) Both creep and shrinkage are much lower for gap-graded concrete. Thus, gap grading is especially beneficial to lightweight prestressed concrete.

(5) In general, the properties of lightweight aggregate concrete are more affected by the moisture condition because of its porosity and especially the variable porosities from the coarse to the fine fractions of its aggregates.

(5) Gap grading would limit the coarse aggregate to one size only or within a narrow range of size which would keep the porosity more uniform, moisture absorption less variable, and physical properties of the concrete less affected by the moisture condition.

## 4. Technological Synthesis of Gap-Graded Lightweight Aggregates and Shrinkage-Compensating Matrix

It is seen from the above comparisons that some of the major shortcomings of lightweight aggregate concrete are just counterbalanced or eliminated by the use of gap grading, and the drying shrinkage of concrete could be further nullified with shrinkage-compensating matrix using shrinkage-compensating cement. This concept has proven to be economically feasible because of the much less cement requirement in gap-graded concrete.

Technological developments of shrinkage-compensating expansive cements, their successful applications to producing shrinkage-compensating concrete, retrospect on gap grading, advantages and avoidable disadvantages of gap grading, size relation between coarse and fine aggregates, typical gap-graded aggregates in practice, technological synthesis of gap-graded aggregates, previous applications of gap-graded concrete, optimum matrix percentage, optimum slump and Vebe time, sample example of physical and mechanical properties of gap-graded concretes, gap-graded shrinkage-compensating concrete and its economics, have been treated in more detail with available authentic data in the writer's previous papers, namely:

1. "Expansive Cements and concretes," AREA Committee 25-Waterways and Harbors, Report on Assignment 7, AREA-Bulletin, Proc., Vol. 66, No. 588, November 1964, pp. 177-182.

2. Discussion of Paper by George W. Washa and Richard L. Fedell on "Carbonation and Shrinkage Studies of Non-plastic, Expanded Slag Concrete Containing Fly Ash," ACI Journal, Proc., Vol. 62, No. 3, March 1965, pp. 1767-1768.

3. "Expansive-Cement Concrete Construction," Concrete Construction, Vol. 10, No. 6, June 1965, pp. 207-209.

4. "Expansive-Cement Concretes--A Review," ACI Journal, Proc., Vol. 62, No. 6, June 1965, Title No. 62-43, pp. 689-706.

5. Closure of "Expansive Cement Concretes--A Review," ACI Journal, Proc., Vol. 62, No. 12, December 1965, Disc. 62-43, pp. 1683-1692.

6. "Proposed Synthesis of Gap-Graded Shrinkage-Compensating Concrete," ACI Journal, Proc., Vol. 64, No. 10, October 1967, Title No. 64-56, pp. 654-661.

7. Closure of "Proposed Synthesis of Gap-Graded Shrinkage Compensating Concrete," ACI Journal, Proc., Vol. 65, No. 4, April 1968, Disc, 64-56, pp. 343-345.

8. "Non-Shrinking Gap-Graded Concrete--Its Synthetic Technology," Paper presented to the Inter-American Conference on Materials Technology, 20-24 May 1968, San Antonio, Texas; ASME Transactions of Inter-American Conference on Materials Technology, 1968.

9. "Gap-Graded Shrinkage-Compensating Concrete Vs. Conventional Concrete," Paper presented to AREA Committee 25-Waterways and Harbors, Publication pending.

Additionally, in the above-said Paper No. 8, there are listed chronologically 61 references relevant to gap-graded aggregate concrete, shrinkage-compensating concrete, and gap-graded shrinkage-compensating concrete. Being restricted in space herein, the writer is obliged to refer those who are further interested in this discussion to the above cited publications.

The writer has initiated, since May 1968, a comprehensive series of investigations to determine the laws of variations of basic parameters to facilitate optimum job-mix proportioning, concreting, restraining, and curing of gap-graded shrinkage-compensating concretes of normal-weight and lightweight aggregates, with a view of translating the envisaged technological synthesis into actual engineering practice.

It is believed that gap-graded shrinkage-compensating structural concrete with partial sand replacement of the fines and steam cured should be more economically competitive with normal-weight concrete of comparable strengths than the heretofore continuously-graded lightweight concrete. This proposed synthetic lightweight concrete will be best suited for prestressed precast structural members by virtue of higher strength, higher modulus of elasticity, less shrinkage, less creep, and lower cost than conventional lightweight concrete.


## SUMMARY

Mostly rotary-kiln manufactured, lightweight aggregates can be easily produced in rounded pebbles by presizing the feed and controlling the burning process. They are more adapted to gap grading than normal-weight aggregates. When gap-graded, the advantages of reduction in specific surface, moisture variation, cement paste and water (for the same water-cement ratio), creep and shrinkage, and of increase in strength and modulus of elasticity, all contribute to eliminate corresponding shortcomings of conventional lightweight concrete. The lower cement requirement alone permits blending of higher-premium shrinkage-compensating cement to produce shrinkage-compensating gap-graded lightweight concrete at competitive cost.



## RÉSUMÉ

Les agrégats légers, manufacturés le plus souvent dans le four rotatoire, peuvent être produits aisément dans des caillous ronds en classifiant les matériaux d'avance et en contrôlant le procédé de brûlage. Ils sont plus adaptés à la granulométrie discontinue que les agrégats à poids normal. Le béton léger à granulométrie discontinue a les avantages de la réduction de la surface spécifique, de la variation d'humidité, de la pâte de ciment et eau (pour le même rapport ciment-eau), du fluage et du retrait, de l'augmentation de la force de résistance et du module d'élasticité, éliminant ainsi les défauts du béton léger conventionnel. Le besoin en ciment diminué en lui seul permet d'utiliser un mélange de ciment à retrait diminué pour produire du béton léger à retrait compensé à un prix compétitif.



## ZUSAMMENFASSUNG

Meist können in Drehöfen hergestellte Leichtaggregate sehr einfach in abgerundeten Steinen produziert werden, wenn Brennmaterial und Brennprozess kontrolliert werden. Sie sind für die Klassierung besser geeignet denn normalgewichtige Aggregate. Der Vorteil in der geringeren spezifischen Oberfläche, in der Aenderung des Feuchtigkeitgehaltes, in Zementmischung und Wasser (bei derselben Zement-Wasser-Rate), in Kriechen und Schrumpfen (Schwinden) als auch in der Erhöhung der Druckfestigkeit und des Elastizitätsmoduls trägt dazu bei, die entsprechenden Nachteile des herkömmlichen Leichtbetons aufzuwiegen. Der geringere Zementverbrauch allein erlaubt das Beimischen teureren schrumpfausgleichenden Zementes, um schrumpfausgleichenden Leichtbeton zu vergleichbaren Kosten herzustellen.

# 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/mm²).

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.

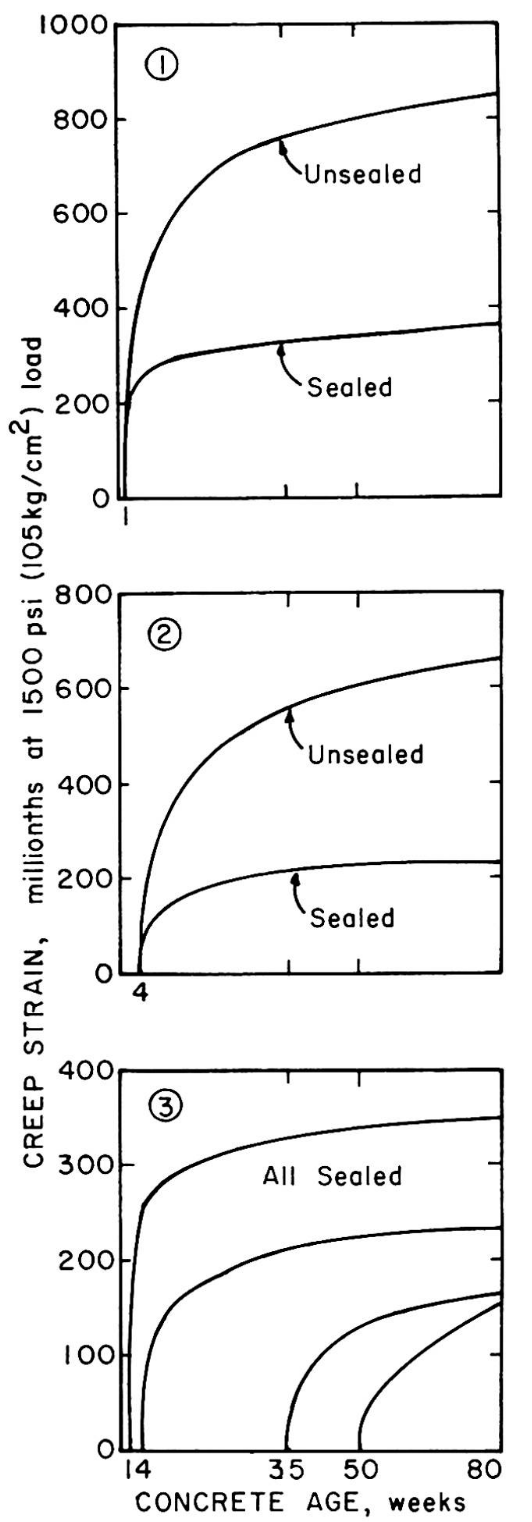
The 6x12-in. (15x30-cm) cylinders were cast in the vertical position and consolidation of concrete was by internal vibration. All cylinders including those wrapped in copper foil were continuously moist cured until time of test.

## 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/cm²) 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.

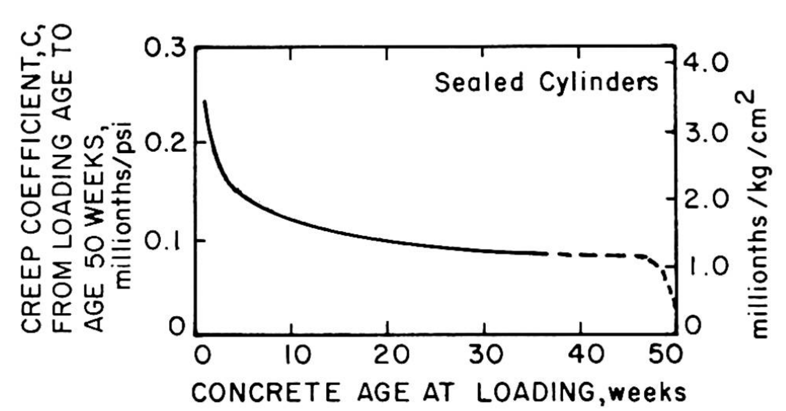



Fig.4—MEASURED CREEP COEFFICIENT OF PLAIN CONCRETE VERSUS CONCRETE AGE AT LOADING

Elastic and Creep Properties of Instantaneously Loaded Columns -- 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

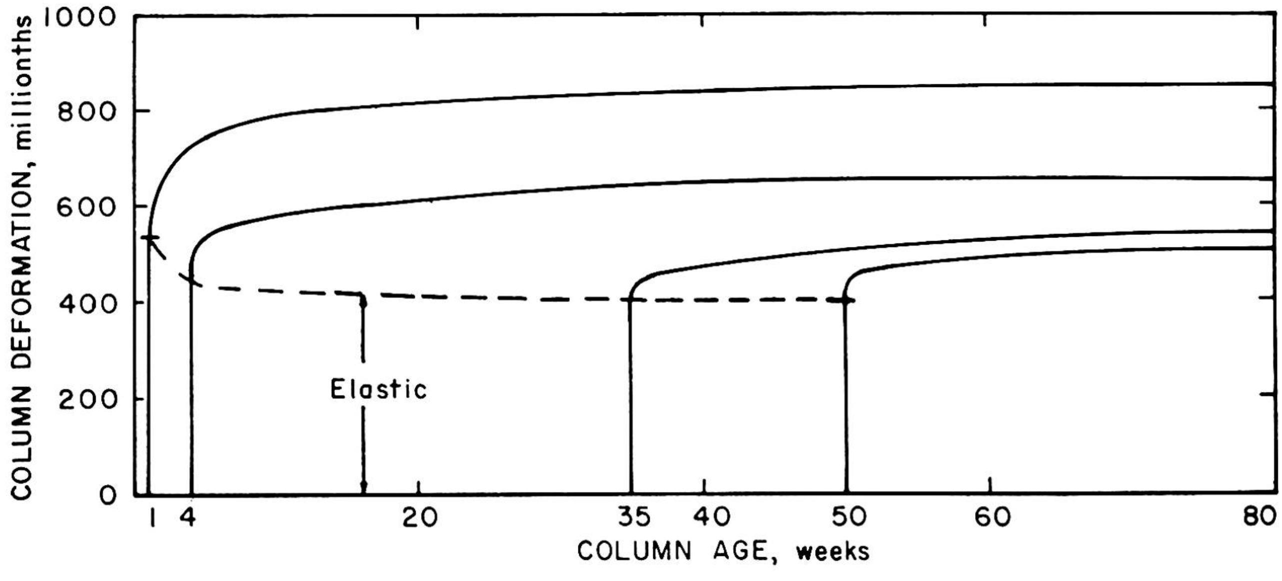



Fig. 5 — ELASTIC AND TIME-DEPENDENT CREEP DEFORMATION OF INSTANTANEOUSLY LOADED REINFORCED COLUMNS

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

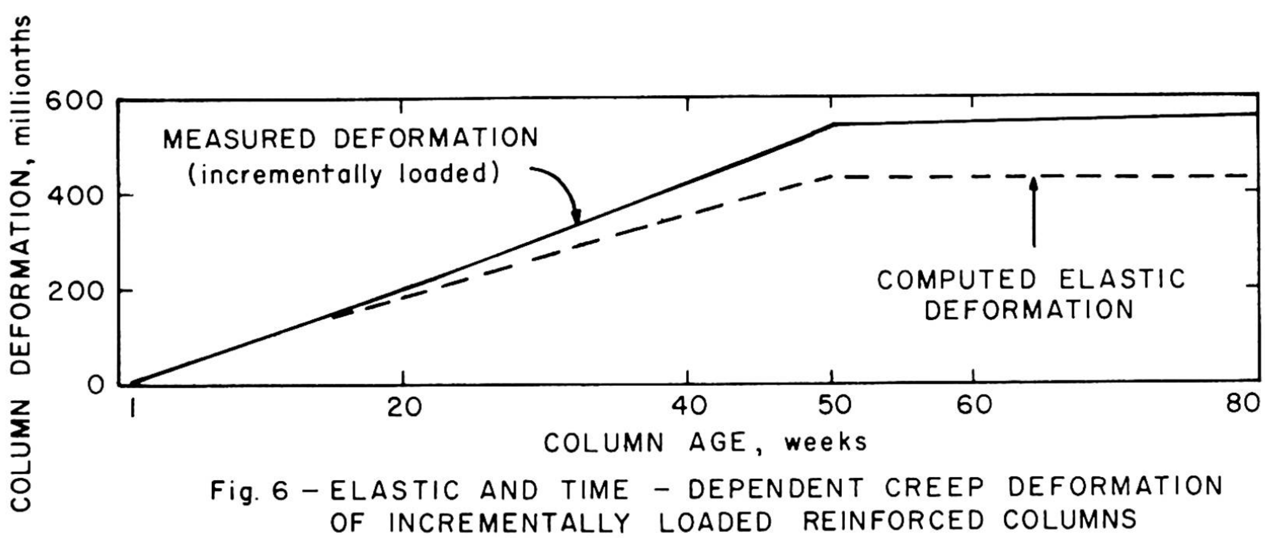



Fig. 6 – ELASTIC AND TIME – DEPENDENT CREEP DEFORMATION OF INCREMENTALLY LOADED REINFORCED COLUMNS

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 multistep solution, which takes account of changing concrete properties results in a ratio of $\Delta f_s$(meas.)/ $\Delta f_s$(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 $A_s/A_g$

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

$\Delta f_s$ = 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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# Experiment on Lightweight-Concrete Composite Girder Bridges

Expériences sur des poutres métalliques composées avec du béton léger

Versuch über Leichtbeton-Verbundbrücken

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## 1. Introduction

Recently in Japan, due to the shortage of natural aggregate and to growing requirement of lightweight structure, inquiry and application of lightweight concrete have greatly been promoted. In case of a steel bridge with lightweight-concrete slab, a composite girder is found to be a reasonable and economical construction.

From such standpoint, after model tests were carried out, the first lightweight-concrete composite girder bridge in Japan was successfully constructed by the Hanshin Expressway Public Corporation.

Following experiments are conducted always in comparison with a lightweight concrete composite girder and a normal-weight-concrete composite girder.

## 2. Model test of shear connector and composite beam

### 2.1. Specimens

As shown in Figs.1 and 2, push-out test specimens, and composite beams with reinforced concrete slab and shear connectors were prepared.

Push-out test specimens contain various types with different pitches of shear connectors. Back surface of H-beam is oiled, and concrete placing

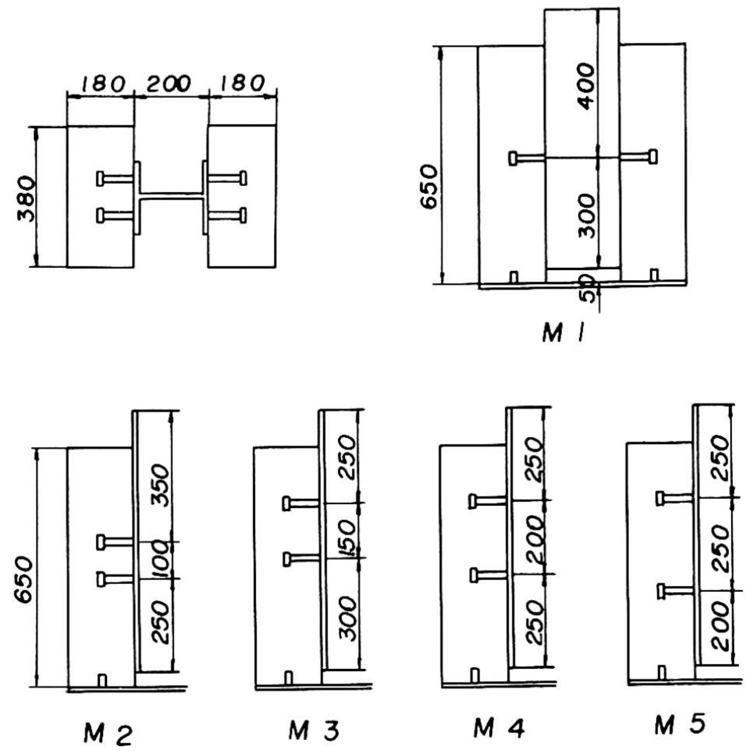



Fig. 1. Push-out specimens

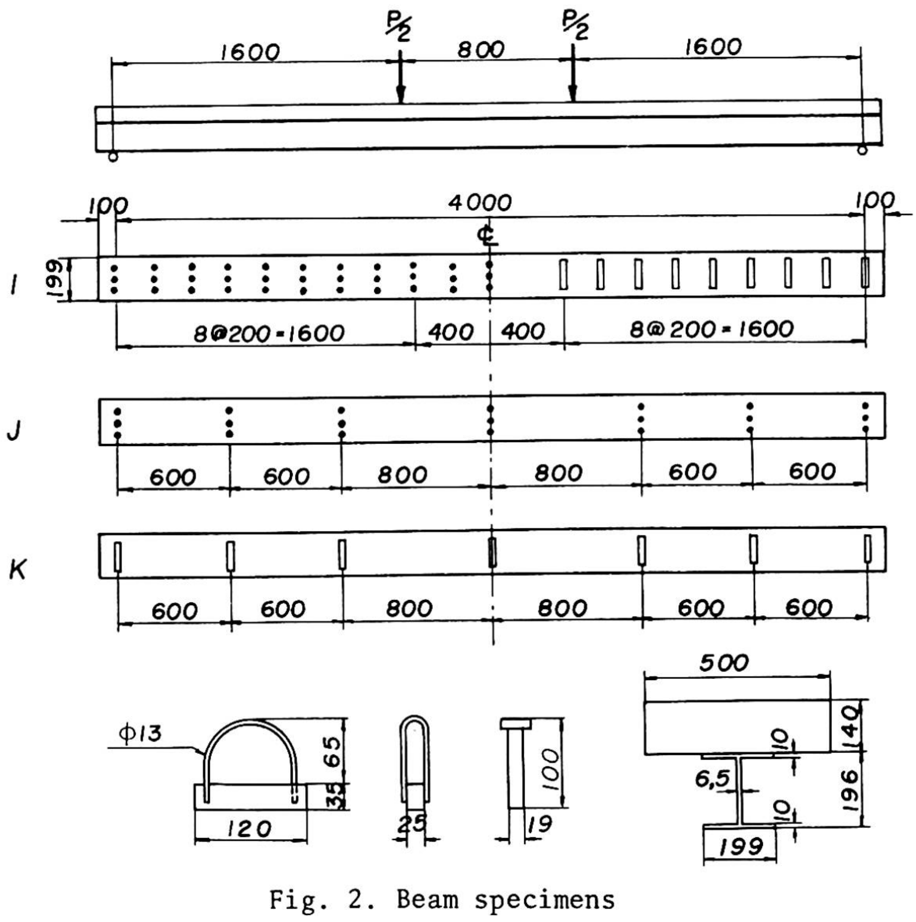



Fig. 2. Beam specimens

is executed from the lateral side, so that the bearing strength of shear connectors may not be influenced by bleeding of the concrete at the lower surface of the reinforcing bars.

Beam I has stud shear connectors and block shear connectors whose strength are quite equal as the preliminary test shows. Beams J and K are made to only few shear connectors, so that breaking strength of shear connectors as well as ultimate strength of beams may also be examined.

Table 1 shows the number of specimens, and Table 2 strength and Young's modulus of concrete on the 28th day in contrast with normal-weight concrete beam and lightweight-concrete beam. Mean value of yielding stress of steel is about 2700 $kg/cm^2$.

Table 1. Number of specimens

| Specimen | Name | Number | | Kind of shear connector |
|---|---|---|---|---|
| | | NC | LC | |
| Push out | L | 4 | 4 | Block |
| | M | 12 | 12 | Stud |
| Composite beam | I | 1 | 1 | Block and stud |
| | J | 1 | 1 | Stud |
| | K | 1 | 1 | Block |
| Sum | | 19 | 19 | |

Table 2. Strength and Young's modulus of concrete ( $kg/cm^2$ )

| Concrete | Compressive strength | Tensile strength | Bending strength | Young's modulus, $E_{0.3}$ | n at $E_{0.3}$ |
|---|---|---|---|---|---|
| NC | 285 | 25.5 | 41.3 | 276,000 | 7.6 |
| LC | 313 | 24.1 | 30.6 | 194,000 | 10.8 |
| NC/LC | 0.91 | 1.05 | 1.35 | 1.42 | |

2.2. Push-out test

The load corresponding to useful capacity ( residual slip = 0.08mm ) [1] per one shear connector are shown in Table 3. Capacity of LC is larger than NC, even if in consideration of the difference of their compressive strength in Table 2.

Table 3. Useful capacity of shear connector

| Concrete | M1 | M2 | M3 | M4 | M5 |
|---|---|---|---|---|---|
| NC | 4.1 ton | 3.4 | 4.3 | 3.8 | 3.5 |
| LC | 5.5 ton | 4.5 | 4.5 | 4.8 | 5.0 |
| NC / LC | 0.75 | 0.75 | 0.96 | 0.79 | 0.70 |

The pitch of stud shear connector has a slight influence upon its capacity, and ultimate strength of LC is a little lower than NC.

2.3. Beam test

Deflection and stress of LC beam are somewhat larger than those of NC beam. The deflection of beams are shown in Fig.3. where the calculated values are described as n = 7 for NC beam, and n = 10 for LC beam. As compared with these results, the theoretical values coincide well with the measured ones.

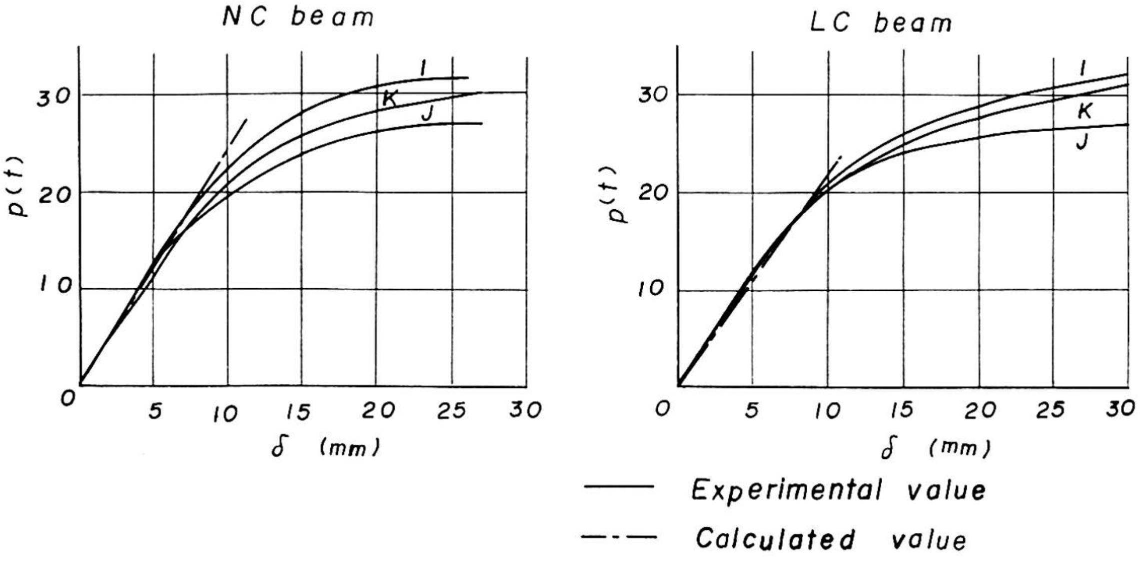



Fig.3. Deflection of beamsat center

Breaking state of NC beams as in LC beams are due to bending. The calculation method of breaking moment can be classified into 3 cases (Fig. 4), according to the strength of concrete and shear connector [2].

In both NC and LC beams, beam I corresponds to case II , beams J and K correspond to case III . By comparing the calculated breaking load with the experimental one in Table 4, we can see that they agree quite well.

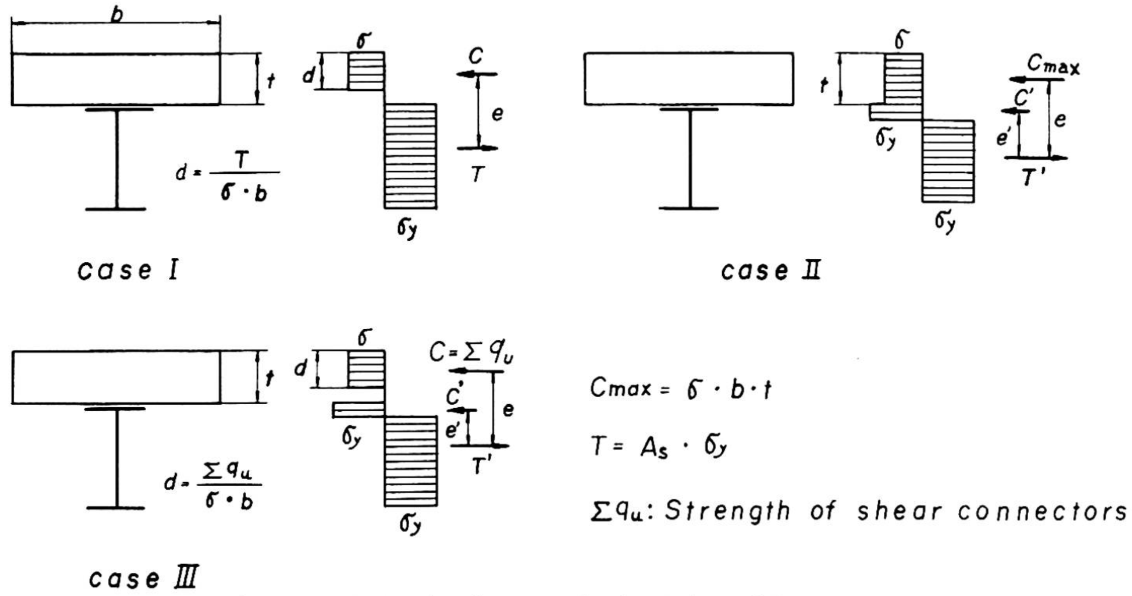



Fig. 4. Calculation method of breaking moment

Table 4. Breaking load of beams

| Beam | NC | | | LC | | |
|---|---|---|---|---|---|---|
| | I | J | K | I | J | K |
| Experimental value (ton) | 33.8 | 29.4 | 31.0 | 35.2 | 30.2 | 33.0 |
| Calculated value (ton) | 33.3 | 29.3 | 31.0 | 34.2 | 29.1 | 30.6 |
| Ex./ Cal. | 1.02 | 1.00 | 1.00 | 1.03 | 1.04 | 1.08 |

## 3. Field experiment of two test bridges

### 3.1. Test bridges

Statical and dynamical tests were conducted in two multiple plate girder bridges in the Hanshin Expressway. One is a composite girder bridge built of the normal concrete ( NC girder ) and the other a bridge of the lightweight concrete ( LC girder ).

Table 5. Value of concrete

| Concrete | Measured value | | Value used in calculation | |
|---|---|---|---|---|
| | $\sigma_c$ (kg/cm²) | $E_c$ (kg/cm²) | $E_c$ (kg/cm²) | $\gamma_c$ (kg/cm³) |
| NC | 302 | $2.47 \times 10^5$ (n=8.5) | $3.00 \times 10^5$ (n=7) | $2.5 \times 10^{-3}$ |
| LC | 331 | $1.71 \times 10^5$ (n=12.3) | $1.75 \times 10^5$ (n=12) | $1.8 \times 10^{-3}$ |

Table 5 shows 28th-day compressive strength $\sigma_c$, Young's modulus $E_c$ and density $\gamma_c$ for two concrete materials used in these bridges.

Besides, the shape and dimension of the two bridges are designed in the same way as shown in Fig. 5. Total steel weight of NC girder is 41.5 ton, that of LC girder being 39.6ton. In this case, weight of steel material is slightly saved. If the span length is longer, however, we shall be able to expect more economical design of a girder and substructure.

By the way, the pavement, hand-rail and curbs were not equipped during the tests to avoid the errors involved in the experimental results owing to their uncertain stiffness.

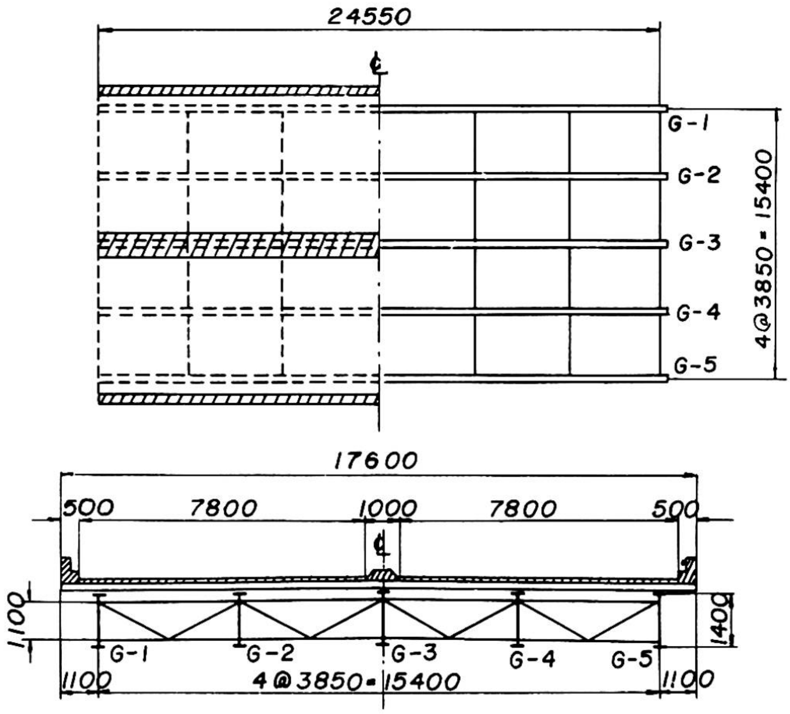



Fig. 5. General view of test bridges

3.2. Theoretical study

As the width of these bridges is greater compared with their span length, the vibration should be analyzed by regarding these bridges as two dimensional structures. Accordingly, the dynamical response of the multiple plate girder bridge has been developed in reference to the literatures [4] and [5].

The outline of analysis is as follows; First, the bridge is idealized in an orthotropic plate as is seen in the theory of Guyon and Massonnet[6]. Next, by assuming the mode of vibration in the transverse direction and by applying the Lagrange's equation, the fundamental differential equation of motion can be obtained. From this equation, simple and practical formula for determining the natural frequency, and a method of analyzing the response due to dynamical forces are derived. Finally, an approximate method to estimate deflection and stress-resultants under statical forces has also been proposed by the above theory.

### 3.3. Statical loading test

The statical loading tests were made by loading four 12tons vehicles with tire rollers. These vehicles were loaded upon the bridge, back to back, symmetrical with respect to the middle point of span under three loading conditions. Values of deflection for two typical loading conditions are plotted in Fig. 6.

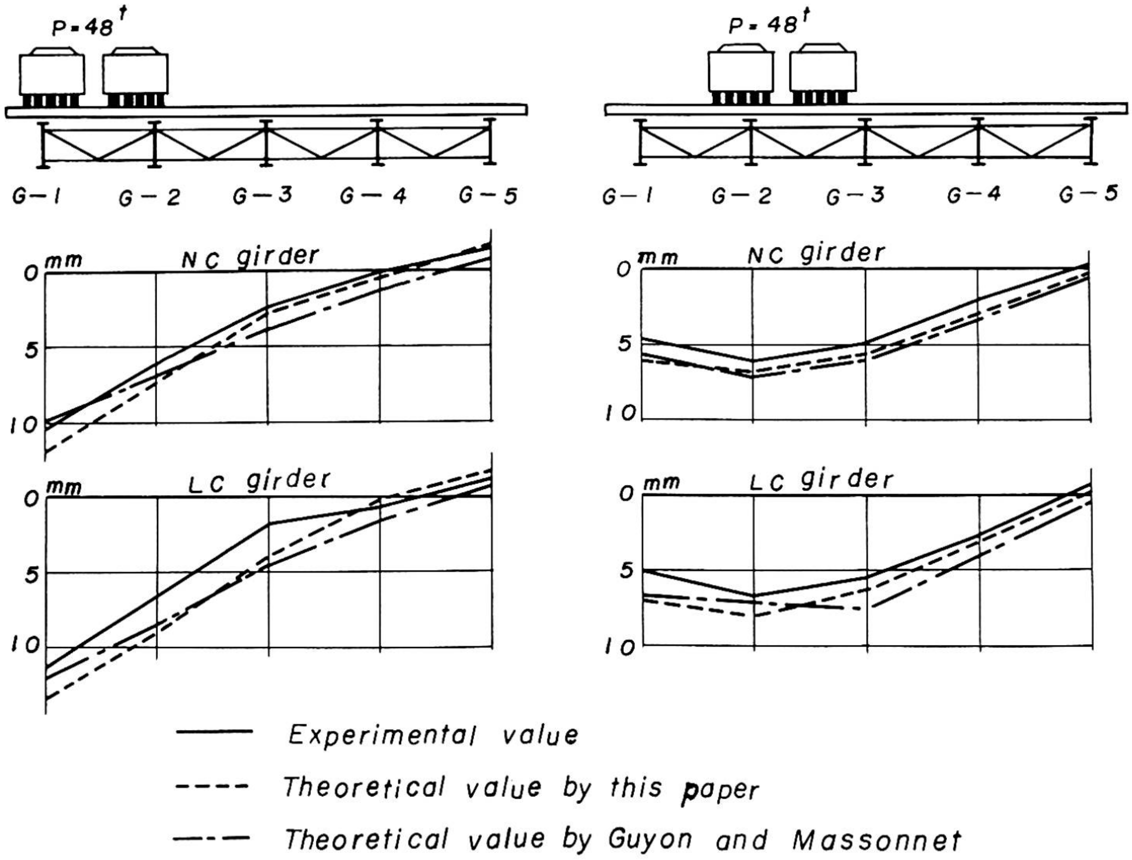



Fig.6. Deflection of girder

By comparing these results, the theoretical values are found to coincide well with the measured ones.

Thus we can see that the weakness of low Young's modulus of lightweight concrete can be made up for by making use of a composite girder.

### 3.4. Dynamical loading test

The dynamical tests were conducted by pulsating the bridges with an oscillator and by recording the dynamical deflection and stress with the oscillograph. From these data, resonance curves are drawn and three resonant frequencies are clearly obtained.

The vibration patterns are shown in Fig. 7 and experimental values together with the theoretical ones are summarized in Table 6, and we can see quite complete agreement between them.

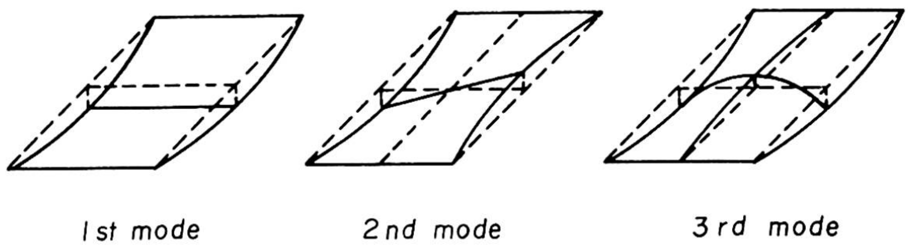
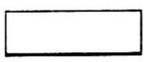
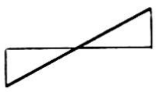



Fig. 7. Vibration pattern

Table 6. Natural frequencies ( cycle/sec. )

| Girder | Vibration mode | 1st mode  | 2nd mode  | 3rd mode  |
|---|---|---|---|---|
| NC | Experimental value | 4.55 | 5.03 | 8.77 |
| | Theoretical value | 4.59 | 5.35 | 8.66 |
| | Th./Ex. | 1.01 | 1.06 | 0.99 |
| LC | Experimental value | 4.71 | 5.66 | 9.77 |
| | Theoretical value | 4.82 | 5.67 | 9.49 |
| | Th./Ex. | 1.02 | 1.00 | 0.97 |

Then, by the drop test of wheel of tire roller, we obtained logarithmic damping coefficient, $\Delta$=0.33 for LC girder, $\Delta$=0.20 for NC girder.

## References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## SUMMARY

In consequence of (1) the push-out test and the beam test, and of (2) the experiment of two test bridges equivalently designed, we can recognize that the lightweight-concrete composite girder brige is a quite useful type, as compared with a normal-weight-concrete composite girder bridge.



## RÉSUMÉ

Suite au test des goujons (1) et au test de la poutre, ainsi qu'aux expériences (2) sur deux ponts dimensionnés identiquement, nous concluons que le pont en action combinée acier-béton léger constitue un type tout-à-fait acceptable, comparé au pont acier-béton normal.



## ZUSAMMENFASSUNG

In Folgerung des Dübel- und Balkenversuchs (1) sowie der Untersuchung zweier gleichwertiger Brücken (2), können wir erkennen, dass die Leichtbetonverbundbrücke, verglichen mit der Normalbeton-Verbundbrücke, durchaus brauchbar ist.

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