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Autor: Li, Shu-T'ien

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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)

SHU-T'IEN LI
FASCE, Professor of Civil Engineering
South Dakota School of Mines and Technology
Rapid City, S. Dak.

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.

(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.

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

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

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

(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.