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Shu-tien Li

V. Ramakrishnan

LOW COST HIGH QUALITY AND HIGH STRENGTH GAP-GRADED CONCRETE FOR URBAN RENEWAL HOUSING CONSTRUCTION

by

Shu-t'ien Li, Ph.D., P.E., F.ASCE* and V. Ramakrishnan, Ph.D., M.ASCE**

INTRODUCTION

Reduction in the cost of design and construction of structures has been and is the primary motivation of the bulk of the research in civil engineering all over the world. Research activity has been concerned with several areas such as materials, design philosophies, structural forms, construction techniques, quality control, construction management, precasting, standardization, mass manufacture and so on. The quick dissemination of research developments to enable their beneficial inplementation in practice is the responsibility of the researchers. Of the various factors which contribute to the total cost of the urban renewal construction, the choice of materials exert the greatest influence. Therefore, a vigorous search is on to find new materials and to improve the performance of existing materials by improved manufacturing techniques. The authors are presenting in this paper, a summary of the findings from an extensive investigation undertaken (1-11) to ascertain merits and performance characteristics of gap-graded concrete in comparison with the conventionally used continuously-graded concrete.

Concrete is now being used in greater quantities in urban renewal housing construction than any other man-made building material. It has become indispensable in practically all types of buildings and many of their supporting components. The demands for housing and other building programs will continue to increase. It is estimated, for example, that even if the population increases only 50 percent in the United States of America in the next 30 years, a new living unit will be needed every 20 seconds, requiring very large quantities of concrete. Additionally, concrete has the unique advantage that the engineer can formulate the mixture, within limits, to meet specific requirements for durability, strength, finishability, etc. Important as are the merits of conventional continuously-graded concrete used hitherto, a number of performance improvements and the behavioral efficiency of building components could be much enhanced by using concrete which is gap-graded.

WHAT IS GAP-GRADED CONCRETE?

The traditional continuous aggregate-grading curves of Fuller-Thompson have not always proven to give concrete the optimum physical and mechanical properties because of the wedging action of intermediate sizes of aggregate. This approach of using all sizes of aggregates intensifies the problem of segregation. Under the present stage of almost universal depletion of naturally occurring continuously-graded aggregates in practically every region of the world after more than a century's exploitation of such suitable aggregates for making concrete, continuous grading has become a labor-consuming, time-consuming, and uneconomical process.

Nor has the customary idea of throwing more bags of portland cement into the concrete mix always guaranteed a better concrete. It simply ensues more cement paste, requires more water to keep a target water-cement ratio, invites more drying shrinkage, aggravates shrinkage cracks, causes more creep under sustained loading, and entails less creep recovery upon load removal. All these drawbacks are minimized with "gap-graded concrete."

"Gap-grading" is defined as "the grading of both coarse and fine aggregates by using only a narrow range of the permissible maximum sizes of coarse aggregate, not using any intermediate sizes, and a moderate range of admissible maximum sizes of fine aggregate, deleting all the extreme fines." In principle, the aggregates are considered in two parts, -1- the main body, which constitutes 65 to 75% of the combined aggregates and is composed of single sized 1 1/2", 3/4" or 1/2" material, and -2- a fine aggregate or filler representing 35 to 25% of the combined aggregates. The sizes of the coarse and fine aggregates are so related as to allow the whole of the filler to pass freely into and through all the voids in the compacted coarse aggregate. Thus, one cubic yard of coarse aggregate will produce approximately one cubic yard of concrete, the filler (sand), cement and water filling the interstices of the particles of coarse material. From this it is clear that to design a gap-graded concrete the bulk density of the coarse aggregate must be determined in relation to the general placing conditions. From this data and the relevant specific gravity, the voids in percent can be calculated and hence the volumes or weights of filler, cement, and water can be found to meet the requirements of strength and workability specified.

RESEARCH RESULTS

The inportant conclusions for the investigation (1-11) involving 375 mixes of gap-graded and continuously-graded mixes are summarized herein. The mixes used were in the strength range of 3000 psi to 7500 psi, with four different maximum sizes of coarse aggregates. The water-cement ratios (by weight) varied from 0.35 to 0.65 and the aggregate-cement ratios (by weight) varied from 2.0 to 10.0. The tests were conducted, whenever applicable, according to ASTM Standard Methods.

Plastic Concrete

A comparison of the results for gap-graded versus continuously-graded concretes on the basis of equal maximum size of coarse aggregate, water-cement ratio, and aggregate-cement ratio has shown the relative ease of placing gap-graded concrete to attain uniform compaction. A comparative study of the efficacy of slump test versus vebe time as a measure of workability has revealed that slump test is not fully indicative of the workability for stiffer mixes with slump less than one inch. Hence vebe test is recommended for stiffer mixes and a relationship is obtained showing the correlation between slump and vebe time.

For the convenience of field engineers who are equipped to do the slump test only, the following equation relating the slump in inches (S) and the vebe time in seconds (T_V), was derived based on the test data:

$$T_V = \frac{4.79}{S^{0.215}}$$

Observations of the physical appearance of the plastic concrete, the recorded vibration time, the number of strike-offs needed to obtain a good surface finish, and the pictorial records of the final appearance, have clearly indicated that, for equal compressive strength and maximum size of coarse aggregate, the gap-graded concrete is equally placeable, workable, and finishable as its continuously-graded counterpart.

Hardened Concrete

For equal compressive strength, maximum size of coarse aggregate, and approximately equal workability, gap-graded concrete has higher unit weight, higher modulus of elasticity, less shrinkage, less creep and less permeability than continuously-graded concrete. The study has also shown that for equal maximum size of coarse aggregate, gap-graded concrete can be produced with 20 to 30% less cement than continuously-graded concrete to give the same compressive strength. Based on test data, the following dimensionally consistent empirical relations are proposed to relate modulus of elasticity with compressive strength and unit weight, and for the prediction of creep strains for both gap-graded and continuously-graded concretes:

*Professor Emeritus and Consulting Engineer, P. O. Box 1810, Rapid City, South Dakota 57701, U.S.A.

**Professor of Civil Engineering, South Dakota School of Mines and Technology, Rapid City, South Dakota 57701, U.S.A.

Modulus of elasticity

(a) for gap-graded concrete,

$$E_{cg} = 0.109 \times 10^6 w + 185 f'_c - 12.14 \times 10^6 \quad 2$$

and (b) for continuously-graded concrete,

$$E_c = 0.0670 \times 10^6 w + 185 f'_c - 6.223 \times 10^6 \quad 3$$

where E_{cg} = Young's modulus for gap-graded concrete in psi
E_c = Young's modulus for continuously-graded concrete in psi
w = Unit weight of 6 x 12-in. cylinder specimen in lb per cu ft
f'_c = Compressive strength of 6 x 12-in. cylinder in psi

Creep

(a) for gap-graded concrete,

$$C_g = \frac{0.668t}{45.2+t}$$

(b) for continuously-graded concrete,

$$C = \frac{0.893t}{46.4+t}$$

where C_g = Creep for gap-graded concrete in in/in/psi
C = Creep for continuously-graded concrete in in/in/psi
t = time under sustained load in days

The above creep equations are applicable for a stress strength ratio of 18 percent. Creep at other stress-strength ratios, or at other loads on the same concrete, could be estimated from the above equations by proportionality.

Shrinkage-Compensated Concrete

Some preliminary studies were made of shrinkage-compensated concretes using Type-K cement in the final part of the investigation. The comparison of expansion-shrinkage characteristics of gap-graded and continuously-graded shrinkage-compensating concretes has shown that unrestrained continuously-graded shrinkage-compensating concrete requires 37.7 percent more Type-K cement, while with lateral reinforcement (1.16 percent), it requires 39.2 percent more Type-K cement, than the equivalent gap-graded shrinkage-compensating having same compressive strength and workability. Thus, this investigation has shown that a significant economy can be achieved for shrinkage-compensating concretes by adopting gap grading instead of the conventional continuous grading of aggregates.

Optimum Mix-Design Method for Gap-Graded Concrete

An optimum mix-design method for proportioning gap-graded concrete and a step-by-step procedure for using this method and an illustrative numerical example are given in reference (8). A comparison of the proposed method with that of ACI 613-54 (Revised 1969) has shown a saving of 34 percent in cement content for gap-graded concrete versus the conventional concrete for equal maximum size of coarse aggregate, compressive strength and approximately equal workability.

FIELD OBSERVATIONS

To the practical engineer in the structural and construction fields, it must be evident that concrete cannot be thought of in isolation from the formwork in which it is to be placed or the steel with which it shares the induced stresses. It is also true that it is unwise to consider concrete mix design on the basis of merely compressive strength alone because, with a high performance cement, the water-cement ratio at which the required strength can be attained is unnecessarily high and hence a potential for excessive shrinkage, creep, or both, exists. In spite of this the majority of concrete specifications are determined on the compressive strength after a particular lapse of time, together with some reference to workability, and such physical properties of the combined materials as shrinkage and creep are seldom, if ever, mentioned.

It is not that these phenomena are not recognized or understood, for research has established that they are intimately associated with the proportioning of the constituent materials of the concrete, but that the usual basis of mix design is empirical and hence is divorced from the science of this subject. It is also associated, one fears, with a lack of site experience in placing and compacting concrete by the bulk of designers and detailers of reinforced concrete structures and aggravated by a lack of training of the labor force actually manipulating the concrete.

Vibration is now virtually universally applied in placing concrete whether in the field or in the precast factory. Where internal vibrators are employed, consideration must be given to the distribution of the steel in the various members to be formed so that not only the concrete but also the vibrators can easily be introduced into the forms. There is also an association between the diameter of the internal vibrator and the volume of concrete to be dealt with per insertion as well as the relationship of the maximum aggregate size to this diameter. For example, no one would really consider using a 1 1/2" vibrator in dam construction where the concrete contained 6" aggregate. In reinforced concrete structures with heavy reinforcement, it should be remembered that the steel itself absorbs energy from the vibrator by virtue of transmission through the concrete. Consequently, as the effectiveness of a poker is proportional to the square of its diameter (centrifugal force times surface area), a poker of less than 2 1/2" may prove rather inefficient in terms of the ultimate quality of the concrete. This is particularly true of continuously-graded concretes where the use of high mortar contents are common.

ADVANTAGES OF GAP-GRADED CONCRETE

Based on the research and field experience of the authors, the following are the realistically achievable advantages through the use of gap-graded concrete for whatever purpose conventional concrete is being used:

1. Any sound coarse and fine aggregates will make good gap-grading provided that the size ratio of the coarse aggregate to the fine is such that the latter can be admitted to the side interstices of the former during compaction.
2. Gap-grading can best use all available sizes. For example, in a building project, the largest sizes of gravel or crushed stone can be used in footings and retaining walls, the medium sizes in heavy girders and columns, and the smaller sizes in beams and slabs.
3. Gap-grading provides a unique solution to the depletion of naturally occurring continuously-graded aggregates.
4. Gap-grading reduces segregation to a minimum and provides greater uniformity of quality. Hence, quality control of the concrete is much easier and better for a given control effort. A smaller value of standard deviation may thus be used for a required probability of failure.
5. Once compacted, the concrete has a higher resistance to deformation in the fresh state as compared with traditional concrete. This allows appreciably lower pressures to be used in the design of formwork, the value being about 600 lb/ft^2 for continuous pouring up to 30' at a rate of 10 to 15 yds^2/hr.
6. Because of 5. above, vertical forms can be stripped within two hours or less of completion of the pour. This allows exposed aggregate finishes to be produced in situ and avoids the concrete at stop-ends having to be hacked. No retarders or accelerators are necessary.
7. Any structural floor slab can be walked on immediately after placing without the surface being deformed. Hence, any type of finish, such as grano, can be placed and trowelled off immediately after the section has been placed and compacted.
8. Because both shrinkage and creep are less in gap-graded concrete, larger areas of floor slab or pavement can be laid at one time, making crack control cheaper.
9. The advantages to be gained in pre- and post-stressed units due to reduced shrinkage, creep and increased Young's Modulus are obvious.
10. Gap-grading can improve concrete blocks by virtue of less shrinkage and reduce their cost as a result of lower

cement requirement.
11. Gap-grading is imperative for precasting exposed aggregate wall panels, as has been done for more than three decades, to show the exposed aggregate more uniformly and more prominently.
12. Gap-grading is the only logical grading for manufactured lightweight aggregate which can be most expediently produced in equal size. Uniform size of coarse aggregate is the mathematically ideal size for gap grading to save the maximum amount of cement.
13. Gap-grading can reduce the cost of shrinkage-compensating concrete.
14. Gap-grading can considerably improve the physical and mechanical performances of building components by virtue of lower shrinkage, lower creep, higher compressive strength, and higher moduli of elasticity and rigidity for the same cement content and the same maximum size of coarse aggregate.

CONCLUSIONS

To stretch the dollar for urban renewal and development at a time of so much needed physical urban improvement under so limited availability of public and private funds, the saving of material costs can be under complete control of the engineer.

Because every type of urban renewal housing project needs concrete retaining walls, basements, floors, roofs, wall panels, staircases, sidewalks, and even structural frames, the reduction in concrete cost constitutes a major factor in saving material costs.

The extensive research results (1-11) and field observations made by the authors have proved that gap-graded concrete, even though with a relatively stiffer and drier mix, could be placed and finished without undue effort for all constructions wherein continuously-graded concrete has been used heretofore.

A considerable saving in cement requirement and significant improvements in physical and mechanical properties are the realistic advantages achievable through the use of gap-graded concrete for urban renewal housing construction.

REFERENCES

1. Li, Shu-t'ien and Ramakrishnan, V., "Relation of Modulus of Elasticity with Compressive Strength--Gap-Graded Versus Continuously-Graded Concrete," September 1969, Available from NTIS, Springfield, Va.
2. Li, Shu-t'ien and Ramakrishnan, V., "Workability of Gap-Graded Versus Continuously-Graded Concrete and the Correlation between Slump and Vebe Time," October 1969, Available from NTIS, Springfield, Va.
3. Li, Shu-t'ien and Ramakrishnan, V., "Optimum Proportioning of Gap-Graded Versus Continuously-Graded Concrete," January 1970, Available from NTIS, Springfield, Va.
4. Li, Shu-t'ien and Ramakrishnan, V., "Shrinkage, Creep and Creep Recovery of Gap-Graded Versus Continuously-Graded Concrete," March 1970, Available from NTIS, Springfield, Va.
5. Li, Shu-t'ien, and Ramakrishnan, V., "Gap-Graded Versus Continuously-Graded Shrinkage-Compensating Concrete," May 1970, Available from NTIS, Springfield, Va.
6. Li, Shu-t'ien and Ramakrishnan, V., "Permeability of Gap-Graded Versus Continuously-Graded Concrete," May 1970, Available from NTIS, Springfield, Va.
7. Li, Shu-t'ien and Ramakrishnan, V., "Finishability of Gap-Graded Versus Continuously-Graded Concrete," May 1970, Available from NTIS, Springfield, Va.
8. Li, Shu-t'ien and Ramakrishnan, V., "Optimum Mix Design for Gap-Graded Concrete," May 1970, Available from NTIS, Springfield, Va.
9. Li, Shu-t'ien and Ramakrishnan, V., "Gap-Graded Vs. Continuously-Graded Concrete--Summary of Findings," August 1970, Available from NTIS, Springfield, Va.
10. Li, Shu-t'ien and Ramakrishnan, V., "Young's Modulus, Creep, and Shrinkage of Gap-Graded Vs. Continuously-Graded Concrete," HRB Highway Research Record No. 324, 1970, pp. 77-88.
11. Li, Shu-t'ien and Ramakrishnan, V., "Workability of Gap-Graded Vs. Continuously-Graded Concrete and the Correlation of Slump with Vebe Time," (Condensed version), Cement and Concrete Research--An International Journal, Vol. 1, No. 4, July 1971, pp. 403-412.