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CORPS OF ENGINEERS, U. S. ARMY

**LABORATORY INVESTIGATION OF CERTAIN LIMESTONE
AGGREGATES FOR CONCRETE**



TECHNICAL MEMORANDUM NO. 6-371

CONDUCTED FOR

OFFICE, CHIEF OF ENGINEERS

BY

WATERWAYS EXPERIMENT STATION

VICKSBURG, MISSISSIPPI

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OCTOBER 1953

CORPS OF ENGINEERS, U. S. ARMY
OFFICE OF THE DIRECTOR
WATERWAYS EXPERIMENT STATION
VICKSBURG, MISSISSIPPI

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WESDR

SUBJECT: Transmittal of T. M. 6-371, "Laboratory Investigation of
Certain Limestone Aggregates for Concrete."

TO: Southwestern Division Laboratory

Two (2) copies of T. M. 6-371, "Laboratory Investigation of Certain
Limestone Aggregates for Concrete," are forwarded herewith for your
information and retention.

FOR THE DIRECTOR:

Incl (in dup)
T. M. 6-371

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D. 6-371

PREFACE

The comparison of limestones reported herein was authorized by the Chief of Engineers as a part of Civil Works Investigations, Item CW 602 "Research on Properties of Aggregates for Concrete." Samples of the limestones used as aggregate in the following projects were obtained and tested:

1. Lock and Dam No. 26, Alton, Illinois
2. Bluestone Dam, Hinton, W. Virginia
3. Wolf Creek Dam, Jamestown, Kentucky
4. Dale Hollow Dam, Celina, Tennessee
5. Center Hill Dam, Baxter, Tennessee
6. Allatoona Dam, Cartersville, Georgia
7. Bull Shoals Dam, Mountain Home, Arkansas
8. Chain of Rocks Lock, Granite City, Illinois

This investigation was accomplished by the Concrete Research Division under the supervision of Charles E. Wuerpel and Herbert K. Cook. The tests were performed by or under the direct supervision of E. J. Callan, Katharine Mather, and R. L. Curry. The report was prepared by Bryant Mather, E. J. Callan, Katharine Mather, and Nelson B. Dodge.

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LABORATORY INVESTIGATION OF CERTAIN LIMESTONE

AGGREGATES FOR CONCRETE

PART I: INTRODUCTION

Scope of Investigation

1. The intent and scope of this investigation are indicated by the following quotation from letter from the Chief of Engineers to the Division Engineer, Ohio River Division:

"This Department has under construction, or will have under construction in a short time, a good many concrete dams in which the aggregates in whole or in part are limestone. Some of these limestones are of excellent quality and some of them are open to serious doubt as to their ultimate durability in an hydraulic structure subject to heating and cooling through a wide range in temperature, to wetting and drying under adverse weather conditions, and to freezing and thawing. Borderline cases are too often accepted for use rather than to obtain materials of recognized quality at a somewhat higher price.

"In order to establish the relative merits of all the limestones being considered for use at this time, it is requested that representative samples of the aggregate from Wolf Creek, Center Hill, Dale Hollow, and Bluestone Dams be sent to ... (the Waterways Experiment Station) for test...."

2. The details of the tests to be made and the materials to be included were developed in cooperation with representatives of the Office, Chief of Engineers.

Distribution and Variation of Limestones

3. It has been estimated that sedimentary rocks make up approximately 75 per cent of all rocks exposed on the surface of the earth and that approximately 21 per cent of all sedimentary rocks are limestones. Approximately 75 per cent of all crushed stone aggregates used in the United States are limestones. The general term "limestones" includes those rocks composed principally of carbonate minerals, of which the most abundant are calcite (CaCO_3) and dolomite ($\text{CaCO}_3 \cdot \text{MgCO}_3$). "Carbonate rocks" is a more descriptive and accurate group name than "limestones."

4. A pure, high-lime, limestone consists almost exclusively of the mineral calcite. Limestones containing appreciable amounts of magnesium carbonate are called magnesian or dolomitic limestones; when the amount of magnesium carbonate becomes equal to the amount of calcium carbonate, the rock is properly a dolomite. A limestone containing appreciable amounts of sand is termed an arenaceous (sandy) limestone; when the sand becomes the predominant constituent, the rock is described as a calcareous sandstone. A limestone containing significant quantities of disseminated clay minerals is known as an argillaceous limestone. If a limestone rock is characterized by lenses and seams of shale it is called a shaly limestone; when the quantity of clay minerals or shaly material increases so as to become the predominant constituent, the rock is known as a calcareous shale. All of the types of material described above grade imperceptibly from one to another and are frequently found in close association with each other.

5. The rough subdivision of limestones given here is based on

composition and on average grain size of the mineral constituents, and particularly on the grain sizes, composition, and arrangement of the constituents that are not carbonates. The grain size, composition, and arrangement of both the noncarbonate constituents and the detrital part of the carbonate constituents are important and useful in the description and classification of limestones^{10*}. The same factors are useful in differentiating limestones which may be expected to perform satisfactorily as aggregates. The group name, limestone, is applied to rocks that have a very great range in chemical composition, physical properties, petrographic structure and texture, physical condition, and suitability for use as concrete aggregate. Rockwood¹⁷ has stated: "...no two limestones, in nature, are ever exactly alike...that is one factor that makes them so interesting."

6. Limestones vary not only in composition but in physical properties. The degree of consolidation and compaction controls the relative toughness of the rock and the ease with which the individual particles composing it may be separated from each other. The particle size of the individual grains composing the rock controls the ease with which the rock may be processed into graded manufactured sand. Composition and texture both play a part in controlling such properties as resistance to abrasion, porosity, and absorption. The mineral calcite -- and consequently most limestones -- has a thermal diffusivity of approximately 0.04 sq ft per hr; thus, limestone and concrete made with limestone aggregate will undergo temperature changes relatively more slowly

* Numbers inserted in this manner refer to literature cited in the references which follow the text of this report.

than concrete made with siliceous aggregate. The mineral calcite has an average linear coefficient of thermal expansion of 2.9×10^{-6} per degree F; consequently limestones generally have relatively low thermal coefficients. The average linear thermal coefficient of dolomite is 4.2×10^{-6} per degree F.

Previous Investigations

7. The problem of correlating the usefulness and serviceableness of limestone aggregates for concrete with their properties has been studied for many years. G. F. Loughlin¹² stated: "Limestone, including dolomite, is used for aggregate in greater quantity than any other kind of stone, and if it were not generally satisfactory poor concrete would be a commonplace." He then describes certain "inferior stones" characterized by either a soft, porous, chalky matrix; the presence of excessive amounts of shaly or clayey materials; or clay minerals that undergo large volume changes on wetting and drying. F. R. McMillan and G. W. Ward¹⁴ conclude: "Limestones that break with a smooth conchoidal fracture, particularly if the porosity is low, are usually good aggregates. Uneven fractures that tend to follow planes, the presence of many closely-spaced bedding lamellae and high insoluble matter, especially if clay minerals can be microscopically detected, are danger signs. If a high porosity accompanies any of the above the aggregate should be given close scrutiny....danger points, such as bedding planes, concentrations of clay minerals, mica seams, sulfides, etc., may occur and one should be on the watch for them."

8. Many properties of limestones have been studied to determine

whether they correlate with behavior and service. J. L. Young, J. H. Havens, and L. E. Gregg²⁰ wrote a progress report on an investigation in which they studied the following features of a number of Kentucky limestones which had been used as concrete aggregates:

Insoluble residue	Resistance to abrasion
Permeability	Toughness
Total porosity	Compressive strength
Effective porosity	Flexural strength
Bulk specific gravity	Hardness
Absolute specific gravity	Size, shape, and frequency of pores
Petrographic description	Thermal expansion
Clay mineral content and x-ray identification	Soundness in sodium and magnesium sulfate

The progress report states that the significance of these properties cannot be established until performance tests are completed.

9. H. S. Sweet¹⁹ investigated the following properties of certain limestones which have been used as concrete aggregates in Indiana:

- Natural moisture content
- Microscopic characteristics
- Void characteristics
- Resistance to sodium sulfate
- Resistance to unconfined freezing-and-thawing
- Resistance to freezing-and-thawing in concrete
- Apparent specific gravity
- Bulk specific gravity
- Absorption

Absolute specific gravity

Stratigraphic classification

10. Sweet concludes that for the purpose of differentiating limestones of good field performance from those with unsatisfactory performance as concrete aggregate

- a. Stratigraphic classification does not serve.
- b. The sodium sulfate test does not serve.
- c. Unconfined freezing-and-thawing of vacuum-saturated samples will serve, but a relatively low value for loss would have to be taken as the criterion.
- d. Apparent specific gravity, bulk specific gravity, and absorption do not serve.
- e. Total void volume and degree of saturation do not serve, but data from microscopic determination of volume of voids less than 0.005 mm in diameter indicate that limestones with good service records have a ratio of volume of such voids to solid volume of less than 0.06 while those with poor records have a ratio greater than 0.10.
- f. Freezing-and-thawing tests of concrete containing the limestone will serve to differentiate limestones of good and poor field performance.

11. Investigators at the Denver laboratories of the Bureau of Reclamation have reported interesting data on volume change and pore characteristics of limestones. R. F. Blanks¹ has described an apparatus for studying the size, continuity, and abundance of the pores in a rock by measuring the rate of evaporation from saturated specimens and the force associated with capillary movement of water into the material. This apparatus gives data in terms of rate of development of pressure deficiency in the closed system used. Poor durability of concrete is indicated when the limestone shows a rapid rise to high pressure deficiency. Results are given for three limestones: a clayey limestone, a

clayey dolomitic limestone, and a chalk, all of which showed a rapid rise to a high-pressure deficiency. These limestones were found to be non-durable when used in concrete tested by freezing-and-chewing. Roger Rhoades and Richard C. Mielenz¹⁶ report that argillaceous (clayey) limestones may expand more than 0.1 per cent linearly upon wetting and that an argillaceous limestone used in a major federal project in southeastern United States expanded 0.028 per cent linearly across the bedding and 0.016 per cent parallel to the bedding during immersion in water. They also note that when expansion results from the swelling upon wetting of montmorillonite clays, the volume change is accompanied by pressures greatly in excess of the tensile strength of concrete.

PART II: MATERIALS TESTED AND THEIR SOURCES

12. The limestones used in the eight projects considered in this report came from nine quarries. The materials are described in the following paragraphs.

Alton Lock and Dam Aggregates

13. Coarse aggregate for concrete for Lock and Dam No. 26 on the Mississippi River at Alton, Illinois, was obtained from the quarry of the Mississippi Lime and Stone Company. The site of the quarry is the Mississippi River bluff near Alton. Limestone of the St. Louis formation is worked along a face about a mile long and 60 to 80 ft high. The rock is mainly a hard, fine-grained, compact, gray limestone, having some beds of the extremely fine-grained lithographic type. It weathers to a chalky white color. Local thin shale partings occur but are not sufficiently numerous or thick to affect the general nature of the rock. The formation is medium bedded to massive, and joints are rare. It has been considered suitable for road material by the Illinois Division of Highways. Fine aggregate used in the concrete for Alton Lock and Dam was Mississippi River sand.

Bluestone Dam Aggregates

14. The Bluestone Dam project at Hinton, West Virginia, was started in 1942. The contractor, after investigating all possible sources of aggregate previously investigated by the government, decided to obtain stone from the quarry of the Acme Limestone Company located on the Greenbrier

River near Fort Spring, West Virginia. This quarry is 27 miles from the dam site and had been in operation for more than 40 years. The Acme Limestone Company produced approximately one-third of the processed aggregate, and the General Crushed Stone Company of Easton, Pa., which installed additional crushing facilities at the quarry, produced approximately two-thirds of the total requirements for the project. The quarry has a working face approximately 190 ft in height and 1400 ft in length in the Pickaway and Union members of the Greenbrier limestone formation. The exposed face consists of 19 beds ranging from 1 ft to 35 ft in thickness, including one 1-ft bed of shale, one 3-ft bed of argillaceous limestone, and two beds of siliceous limestone. There are between 2 to 5 ft of overburden and scattered crevices and vertical solution channels filled with mud. In addition to coarse aggregate, manufactured sand was produced and used to provide approximately 25 per cent of the total fine aggregate for the project. The remainder of the fine aggregate was natural sand from the Scioto River in south central Ohio, approximately 250 miles from the dam site, produced by the Miami Gravel Company and the Barnes Sand and Gravel Company.

Wolf Creek Dam Aggregates

15. Concrete aggregate for use in Wolf Creek Dam, Jamestown, Kentucky, was produced from the Maupin Quarry located on the left bank of the Cumberland River about 12 miles from the dam site. The quarry face is approximately 130 ft in height and contains beds representing the St. Louis and St. Genevieve formations. The lower 35 ft are assigned to the St. Louis formation and the upper 19 ft are assigned to the

St. Genevieve. An 8-ft to 14-ft bed of argillaceous limestone, located midway in the St. Genevieve formation, was removed and wasted. There was approximately 5 ft of overburden. A small amount of chert is present in this limestone.

Dale Hollow Dam Aggregates

16. The aggregate used in Dale Hollow Dam, Celina, Tennessee, was obtained from a limestone quarry known locally as the Pea Ridge Quarry, located in Clay County, Tennessee, near the Tennessee-Kentucky state line. A working face approximately 165 ft in height was developed. Numerous irregular mud-filled cavities were encountered near the top of the quarry. A considerable amount of chert was present and numerous thin layers of soft gray to green calcareous shale occurred between the limestone beds. The limestone probably represents portions of the St. Louis formation and consists predominantly of light gray oolitic and denser, darker gray material.

Center Hill Dam Aggregates

17. The aggregates for Center Hill Dam, Baxter, Tennessee, were obtained from a quarry located on the left bank of the Caney Fork about 1500 ft downstream from the axis of the dam, near Lancaster, Tennessee. The limestone in this quarry is a dark, compact, fine- to medium-grained crystalline rock representing the Cannon formation. The limestone beds average about 3 ft in thickness with thin shale beds. There is approximately 10 ft of overburden, and several deep solution fissures filled with clay were encountered.

Allatoona Dam Aggregates

18. The concrete aggregate for Allatoona Dam, Cartersville, Georgia, was produced from the Shinall Quarry at White, Georgia, located about 15 miles north of the dam site. The material produced from this quarry has been described as magnesian limestone containing approximately 75 per cent calcium carbonate, 20 per cent magnesium carbonate, and 3 per cent silica*. Chemical analysis of the original sample tested by the Waterways Experiment Station indicated that most of the rock was dolomite. A few segregations of shaly material were found to contain up to 18 per cent silica and aluminum. The shaly material was largely removed by scalping. The geologic map of Georgia indicates that the rock occurring at this locality is part of the Shady formation (Lower Cambrian); however, geologists of the South Atlantic Division who are familiar with the area are of the opinion that the rock developed at this quarry is a part of the Knox formation (Upper Cambrian and Lower Ordovician).

Bull Shoals Dam Aggregates

19. The concrete aggregates for Bull Shoals Dam, Mountain Home, Arkansas, were obtained from a quarry near Flippin, Arkansas, from beds of the Everton formation. The quarry is situated approximately 7 miles from the dam site and was located after extensive investigation of other formations and locations. The material exposed in this quarry consists

* C. E. Jackson in "Manufactured Aggregate Conference" report, p 7, 6 Nov 1947, Office, Chief of Engineers.

of crystalline magnesian limestone, sandy magnesian limestone, and calcareous to magnesian sandstone.

Chain of Rocks Lock Aggregates

20. Coarse aggregate for concrete for the Chain of Rocks project, Granite City, Illinois, was obtained from Columbia Quarries Company, Krause, Illinois. The quarry, the largest in southern Illinois, is located one and one-half miles north of Columbia in southwestern St. Clair County, in a hill not far from the Mississippi River bluff. The formation being quarried is the St. Louis limestone, which in this locality differs from the same formation at Alton by the presence here of more argillaceous beds and an appreciable amount of cherty and stylolitic limestone. However, the predominant material, as at Alton, is fine- to medium-grained, fresh, dense, light gray limestone. It was originally proposed to obtain crushed limestone fine aggregate for the Chain of Rocks project from the quarry of the East St. Louis Stone Company near Falling Spring, Illinois. However, the Falling Spring plant was destroyed by fire and until it could be rebuilt the crushed limestone fine aggregate was supplied from Prairie du Rocher, Illinois, by the Columbia Quarries Company, and from Thornton, Illinois, by the Materials Service Corporation. The new Falling Spring plant began to supply the fine aggregate early in 1949. The Prairie du Rocher and Thornton sources are not covered in this report. The Falling Spring quarry is located in the Mississippi River bluff about one-half mile northeast of Falling Spring. The rock formation being quarried is the St. Louis limestone. This material is in general similar to the same formation described above in the Columbia Quarries Company

operation at Krause. The principal material is fine- to medium-grained, fresh, dense, gray, thick-bedded limestone.

Geographic and Stratigraphic Distribution

21. The locations of these eight projects are shown in fig. 1 and the relative stratigraphic position of the formations from which these materials were obtained is indicated below:

Relative Position of the Various Limestones

in the Geologic Column

Paleozoic

Mississippian

Upper

Greenbrier

Union

Pickaway

)
) Bluestone project
)

Middle

Meramec

St. Genevieve

St. Louis

) Wolf Creek, Dale Hollow, Alton,
) and Chain of Rocks projects
)

Ordovician

Middle

Trenton

Cannon

) Center Hill project

Lower

Buffalo River

Everton

) Bull Shoals project

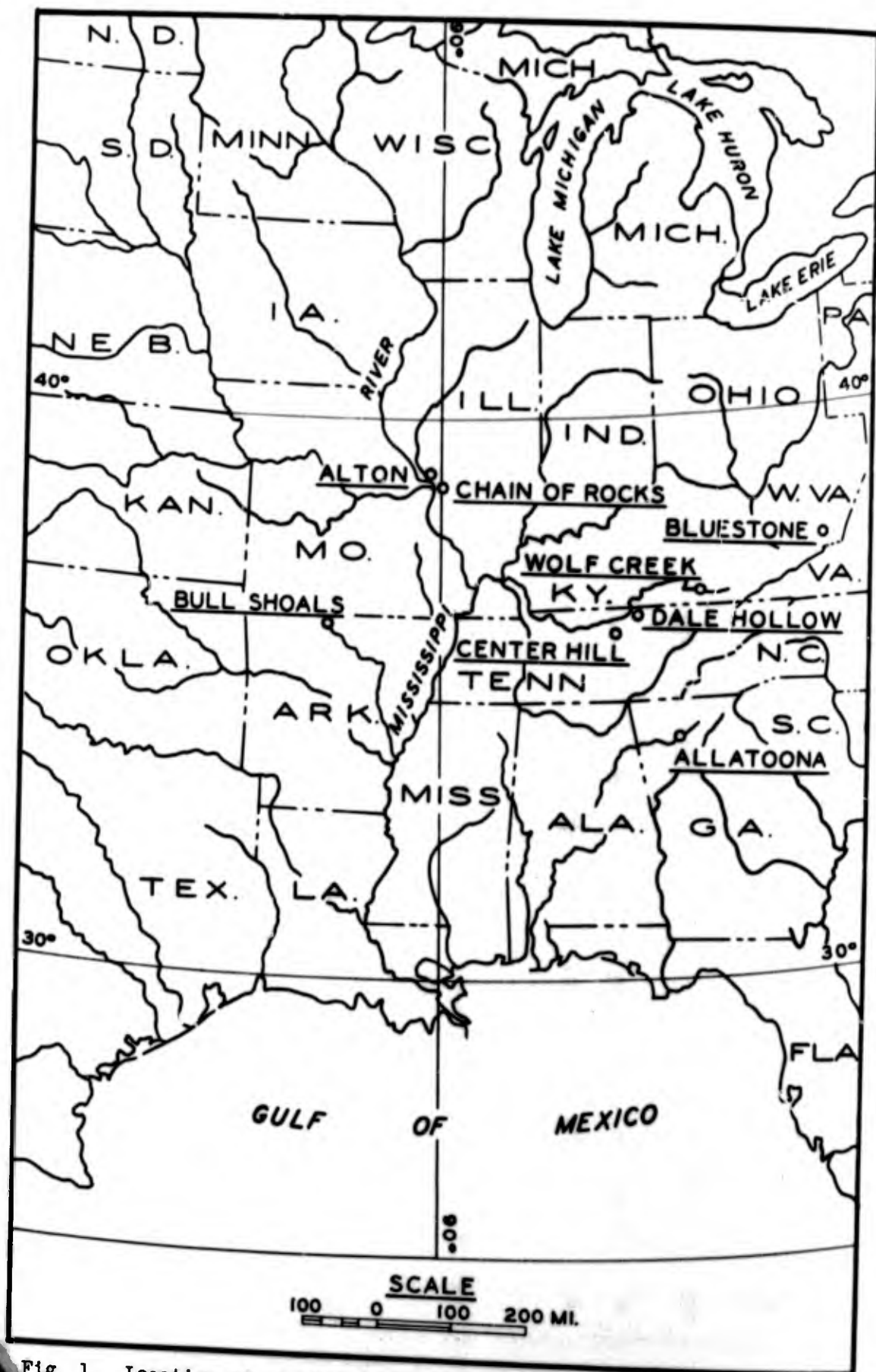


Fig. 1. Location of eight projects from which limestone was obtained

CambrianUpperKnox

) Allatoona

LowerShady

)

Summary of Data

22. Summaries of relevant data, including the results of routine tests, are given for all of the materials under consideration on data sheets 1-13. Available data on their use in field mass concrete are summarized in table 4.

PART III: LABORATORY INVESTIGATIONS

Petrographic Examination

23. A sample of limestone aggregate from each of the nine sources was examined in accordance with "Method of Petrographic Examination of Aggregate" (CRD-C 127-50) of Handbook for Concrete and Cement⁴. Various additional tests were made which are not ordinarily included in a routine examination. Representative portions of each sieve fraction of the coarse aggregate, and of the sieve fractions of the fine aggregate coarser than the No. 30 sieve, were examined megascopically and with the stereoscopic microscope. Sawed surfaces, and sawed surfaces etched with dilute hydrochloric acid, were examined using the stereoscopic microscope. Thin sections of each lithologic variety were prepared from selected pieces of coarse aggregate and examined using the petrographic microscope. Counts were made of the number of particles of each lithologic variety. Polished sections were prepared, and examined under the metallographic microscope for the detection of cracks and voids. Sieve fractions of fine aggregate passing the No. 30 sieve were examined using immersion mounts with the petrographic microscope. Pulverized samples of each lithologic variety in the coarse aggregate were digested in dilute hydrochloric acid and the amount of insoluble residue determined. Examination was then made to determine the mineral composition of each insoluble residue, using immersion mounts with the petrographic microscope.

24. Index of refraction and birefringence were determined for the clay minerals found as a portion of each insoluble residue; these properties were used to classify the clay minerals as members of the kaolinite

group, the montmorillonite group, or the illite group. The amount of insoluble residue was also determined in the fraction of fine aggregate retained on the No. 200 sieve. Schurecht's ratio was determined for each lithologic variety of each sample. Schurecht's ratio, in this report, is defined as the ratio of absorption after 24-hr soaking to absorption after 24-hr soaking and 5-hr boiling in water.

25. In the examination of these samples the greatest emphasis was placed on the coarse aggregate and the sizes of the fine aggregate retained on the No. 30 sieve, for the reason that various limestone types which may be of importance in the larger particle sizes tend to lose their identity in the finer sizes of the crushed limestone sand. These finer particles consist almost entirely of very fine-grained limestone or of cleavage fragments of single crystals. Chert, quartz grains, shale or clay partings, pyrite crystals, and other impurities except disseminated clay, if present in the larger particles of limestone, will be found as separate particles in the smaller sieve sizes of the fine aggregate. Oolites and fossils tend to be broken up.

Thermal Tests

26. Specimens of the limestone aggregates concerned in this report were tested for coefficient of linear thermal expansion in accordance with the procedures given in "Method of Test for Coefficient of Thermal Expansion of Coarse Aggregate (Strain-Gage Method)" (CRD-C 125-48). Sands manufactured from these limestones were tested according to "Method of Test for Coefficient of Thermal Expansion of Mortar" (CRD-C 126-49).

27. In accordance with Method CRD-C 125, small slabs were sawed

from the aggregates oriented in three perpendicular directions, including the bedding plane if feasible. Strain gages were attached to the surfaces of the slabs which were then heated and cooled alternately between 135 F and 35 F. Strain readings were taken at the extreme temperatures. The coefficients of expansion were computed from these readings and averaged.

28. Following Method CRD-C 126, the test sands were made into standard mortars, molded into prisms containing inserts at the ends, and allowed to cure. Then they were brought to equilibrium alternately by immersion in water at 135 F and 35 F. Length readings were taken at the extreme temperatures. The coefficients of expansion were computed from these readings and averaged.

29. Some scattered data were obtained on other thermal properties of certain of the materials. These data were primarily thermal diffusivities and specific heats of aggregates or concretes; they were determined using Methods CRD-C 36 or 124. For diffusivity, regular-shaped specimens were heated to equilibrium at an elevated temperature and cooled in running water. The time-temperature cooling history was recorded using thermocouples, and the diffusivity calculated from the cooling curve. Specific heats were determined using the method of mixtures, in which specimens at a known temperature are placed in a bath of another known temperature. From the resultant temperature changes and a consideration of the masses of specimen and bath, the specific heat is calculated.

Freezing-and-thawing Tests

30. Thirty-three aggregate combinations (listed in table 6) were tested in accelerated freezing-and-thawing in general accordance with

"Method of Test for Soundness of Aggregates by Freezing and Thawing of Standard Concrete Specimens" (CRD-C 114-48). This method includes the design of a standardized concrete mixture containing the aggregates under test, either composed entirely of test fine and coarse aggregate, or composed of the fine or coarse test aggregate together with a standard aggregate. The standard mixture has a fixed water-cement ratio of 5.5 gal per bag, specified limits for grading and sand-to-total-aggregate ratio, consistency of 2.5 ± 0.5 in. slump, and plastic air content of 4.5 ± 0.5 per cent. The cement factor is permitted to vary as needed to secure the specified consistency.

31. After curing, the 3-1/2- by 4-1/2- by 16-in. test beams were tested for dynamic modulus of elasticity and installed in the automatic accelerated freezing-and-thawing apparatus. Twelve cycles of freezing-and-thawing between 0 F and 40 F were obtained per day, and dynamic modulus was determined at least every other day. Tests were continued for 300 cycles or until the specimens suffered a decrement in dynamic modulus of 50 per cent of the initial modulus.

32. Several departures were made from this test method for certain of the combinations tested. These are noted on table 6 and plates 6, 8, and 10. The principal departures included air contents outside the 4.5 ± 0.5 per cent limit, the use of a project grading in three of the six sets of beams containing Bull Shoals Dam aggregates, and the discontinuance of tests of several sets prior to completion. The sets were discontinued primarily for reasons of freezer space and schedules, and were limited to those combinations where a fairly reliable estimate of the durability factors could be made.

PART IV: RESULTS OF PETROGRAPHIC EXAMINATIONS

Composition

33. The lithologic compositions of the samples are summarized in table 1. The table indicates that oolitic limestone was an important constituent of six of the nine limestones (all except Center Hill, Bull Shoals, and Allatoona). The Center Hill sample contained more lithographic limestone than any of the others. The Bull Shoals sample contained more quartz, in sandy limestone and calcareous sandstone, than any other and was high in dolomitic limestone. The Allatoona sample was the only one classified as dolomite.

34. The rock in all of these samples was predominantly fresh and dense. Porous argillaceous limestone made up approximately 16 per cent of the Falling Spring and 21 per cent of the Columbia samples for the Chain of Rocks project. About 8 per cent of the Bull Shoals sample was weathered dolomitic limestone. Slightly weathered varieties or very small quantities of more thoroughly weathered varieties were found in other samples but were not believed to be significant in amount.

35. Calcite was the principal carbonate mineral in all of the samples except that from Allatoona and possibly that from Bull Shoals. The Allatoona rock was dolomite; more than half of the Bull Shoals sample was dolomitic limestone. The Center Hill limestone contained irregular dolomitic areas. Cherty limestone made up more than half of the Dale Hollow sample; a considerable part of the chert was chalcedonic. Minor amounts of chalcedonic chert were found in the samples from Wolf Creek, Falling Spring and Columbia Quarries, Center Hill, and Bull Shoals. No

other constituent known to be capable of deleterious reaction with the minor alkalies of portland cement was found.

36. Dense argillaceous limestone containing disseminated clay was the major constituent of the samples from Bluestone and Wolf Creek, and constituted about 10 per cent of the Center Hill material. The two Chain of Rocks samples from Columbia and Falling Spring Quarries contained important amounts of porous argillaceous limestone. Deleterious effects attributable to clay content are discussed in part VII of this report. The amounts and composition of the insoluble residue by lithologic varieties are shown in table 2.

37. Sand or silt was present in varying amounts in all of the samples. Silty limestone was a major constituent of the Bluestone aggregate; almost half of the Bull Shoals aggregate consisted of two intergrading varieties high in sand.

38. The sample from the Pea Ridge Quarry did not contain the soft green shale that can be seen in the quarry and at the bottom of popouts in the hand rail and curbing of the roadway across the Dale Hollow Dam. The sample from the Shinall Quarry contained some of the black shale that was present in the aggregate in varying amounts at different periods during the construction of Allatoona Dam. It should be remembered that the petrographic descriptions and the proportions of different types apply to the samples examined, but the samples may not have been representative of an average of the aggregate used in any of the structures.

39. The rocks of these samples comprised only a small segment of the possible range in composition, structure, and condition of limestone aggregates that have been considered for use in concrete. None of the

samples represented argillaceous limestones as undesirable as those described by G. F. Loughlin¹³. On the basis of routine petrographic examinations, all of these samples may be regarded as free from major undesirable physical features. However, the additional information obtained by determination of the amount and type of insoluble residue in each important lithologic variety raises a question as to the desirability of the porous argillaceous limestone in the two samples from the Chain of Rocks project.

Alton Lock and Dam aggregates

40. About 90 per cent of the coarse and fine manufactured limestone aggregate from Alton (samples designated CRD G-4, G-4(S)) consisted of two varieties of limestone. A medium-grained fossiliferous and often oolitic variety containing pellets of fine-grained limestone was about twice as abundant as an extremely fine-grained lithographic type. Both were fresh, dense, and tough. The remainder of the coarse aggregate was composed of shaly limestone, sandy limestone, limestone conglomerate, and about one per cent of other miscellaneous types. The remainder of the fine aggregate was composed of the following, in order of their relative abundance: sandy limestone, clear calcite, quartz, clay, and chert.

41. The predominant particle shape was pyramidal with angular corners. The surface texture was very smooth on the lithographic type and slightly irregular on the other types. Clay seams and stylolitic partings, both containing minerals of the kaolin group, were of common occurrence. The shaly limestone partially disintegrated during the boiling operation for determining Schurecht's ratio. Soft yellowish-green clay and red clay, amounting together to less than one per cent of the coarse

aggregate sample, completely disintegrated upon wetting. The green clay found on some of the particles in the two most abundant groups also disintegrated upon wetting.

42. Eleven chemical analyses of the St. Louis limestone in the vicinity of Alton, Illinois, gave the following results, in per cent by weight⁷:

	<u>Average</u>	<u>Range</u>
CaCO ₃	96.5	92.4 -98.1
SiO ₂	1.5	0.30- 6.52

The remainder was mainly Al₂O₃ with a little Fe₂O₃. The insoluble residue after digestion in dilute hydrochloric acid averaged between 3 and 4 per cent for the whole sample (see table 2). This agrees with the chemical analyses cited. The residues of the various limestone types were composed predominantly of clay minerals of the kaolin group; other constituents were quartz, feldspar, chert, and pyrite in varying amounts. A trace of chalcedony was found in the insoluble residue of the medium-grained limestone in the coarse aggregate, and also in the Nos. 100, 200, and -200 sieve sizes of the fine aggregate.

Bluestone Dam aggregates

43. The samples of manufactured coarse and fine limestone aggregates from Bluestone Dam (CRD G-6A, G-6B, and G-6(S)) were made up of generally equidimensional, angular particles of medium to dark gray limestone, usually with rounded corners and edges. Considerable amounts of limestone dust, probably crusher dust, adhered to the particle surfaces. The sample was composed of about equal portions of medium-grained, oolitic, fossiliferous limestone, fine-grained argillaceous limestone,

and fine-grained silty limestone. The medium-grained oolitic limestone and the silty limestone were essentially fresh and dense; the argillaceous limestone was fresh, but contained many tight clay partings that may be affected by moisture or freezing-and-thawing.

44. The insoluble residue after digestion in dilute hydrochloric acid averaged about 16 per cent for the whole sample (see table 2). This relatively high value was caused principally by the silty limestone, which contained about 31 per cent of insoluble material. The residues were composed essentially of very fine quartz grains with minor amounts of pyrite, mica, and montmorillonoid clay, which was present in very small quantities.

Wolf Creek Dam aggregates

45. The samples of manufactured coarse and fine limestone aggregates from Wolf Creek Dam (CRD G-7A, G-7B, and G-7(S)) were composed of approximately two-thirds medium-grained, fossiliferous, oolitic limestone, one-third fine-grained argillaceous limestone, and minor amounts of chert, calcite, and quartz. The particles were generally equidimensional, angular to subangular, and light to medium gray or light olive gray. Some crusher dust was noted on the particle surfaces, but this was easily removed by washing. A few of the particles contained fractures or fractured surfaces having a tight coating of limonite with recrystallized calcite and dolomite. The fracture of the rock was generally independent of the apparent bedding but was probably slightly influenced by the limonite-covered surfaces or tight clay seams. Approximately 90 per cent of the limestone was fresh and dense; the remainder was slightly weathered, but was dense and coherent. Microscopic traverses by reflected light of surfaces of several fragments of the two principal rock types indicated about

1 per cent of voids and open cracks, and about 6 per cent of narrow cracks in the medium-grained limestone. The argillaceous limestone contained only a trace of voids and open cracks and about 2 per cent of narrow cracks. Oolites from the medium-grained limestone appeared in the sand sizes as rounded grains. Dense, hard, banded, gray chert particles made up a small portion of the sample; these particles were associated with both of the limestones but were found more often with the argillaceous type. The 4 per cent of chert consisted essentially of chalcedony.

46. The insoluble residue remaining after digestion in dilute hydrochloric acid amounted to about 8 per cent for the No. 4- to 3/4-in. material, and about 4 per cent for the 3/4- to 1-1/2-in. material. The residues were composed of clay minerals of the kaolin group, quartz sand grains, pyrite, mica, zircon, and sphene.

Dale Hollow Dam aggregates

47. The samples of manufactured coarse and fine limestone aggregates from Dale Hollow Dam (CRD G-8A, G-8B, and G-8(S)) were examined. Over 90 per cent of the coarse aggregate consisted of cherty, lithographic, and medium-grained, fossiliferous, oolitic limestone, which was fresh, dense, and tough. The most abundant constituent was the cherty limestone, which amounted to a little over half of both the No. 4- to 3/4-in. and the 3/4- to 1-1/2-in. material; a considerable part of the chert was chalcedony. This variety was composed of fine-grained calcite with varying amounts of chert disseminated through the fragments; some pieces contained nodules of dense, light bluish-gray chert. Minor constituents were vuggy, dolomitic limestone and sandy, dolomitic limestone. The fine aggregate sample consisted of materials similar to the coarse

aggregate, plus calcite, quartz, and minor amounts of other minerals. The coarse aggregate particles were generally pyramidal in shape. The surface texture was smooth on the cherty and lithographic limestones and slightly irregular on the other types. All of the particles were angular to subangular.

48. The insoluble residue remaining after digestion in dilute hydrochloric acid averaged about 12 per cent for both the No. 4- to 3/4-in. and the 3/4- to 1-1/2-in. material. The residues were composed of chert, quartz, clay of the kaolin group, and small amounts of other minerals. Chalcedony occurred in most of the residues. Clay usually made up less than half of the residue.

49. Although soft green shale is present in the quarry, and was observed in popouts in the hand rails and curbs of the roadway at the top of the dam, it was not found in the coarse aggregate sample received for examination.

Center Hill Dam aggregates

50. The most abundant constituent of the samples of manufactured coarse and fine limestone aggregates from Center Hill Dam (CRD G-9A, G-9B, and G-9(S)) was lithographic limestone, which made up about two-thirds of both the No. 4- to 3/4-in. and the 3/4- to 1-1/2-in. material. The lithographic limestone was usually brown, but a gray variety was also common. The remainder of the coarse aggregate sample consisted of sandy limestone and less abundant argillaceous limestone. The fine aggregate sample consisted of the same materials as the coarse aggregate, plus calcite and minor amounts of other substances such as quartz, feldspar, chert, and pyrite. The particle shape was usually pyramidal, but the

number of tabular and elongated particles increased in the smaller sieve sizes of the coarse aggregate. All the particles were angular. The surface texture was smooth on the lithographic varieties and slightly irregular on the other types. Most of the particles of coarse aggregate contained irregular patches and layers of dolomitic limestone. The dolomite content was variable, ranging from 4 per cent for a particle of brown sandy limestone to 40 per cent for a particle of dark gray argillaceous limestone.

51. The insoluble residue remaining after digestion in dilute hydrochloric acid averaged about 6 per cent for both the No. 4- to 3/4-in. and the 3/4- to 1-1/2-in. material. More than half of the insoluble residue of each limestone type was composed of clay, mostly of the kaolin group, but with some illite. The remainder of the insoluble residue of each type consisted of grains of quartz, feldspar, pyrite, chert, and minor amounts of other materials. A portion of the chert was chalcedony.

Allatoona Dam aggregates

52. The samples of manufactured coarse and fine limestone aggregates from Allatoona Dam (MOB-2 G-3 and S-2) consisted of fresh, dense rock. The coarse aggregate sample consisted entirely of medium to dark gray, uniformly fine-grained dolomite with a sugary texture. There were numerous random light-gray calcite veins. The fracture was regular, with sharp corners and edges. There were some patches of white crystalline calcite. About 90 per cent of the fine aggregate sample consisted of particles of dolomite rock similar to that found in the coarse aggregate; about 10 per cent consisted of shaly particles. A major constituent of the sand finer than the No. 100 sieve was individual cleavage fragments

of single crystals of carbonate minerals; these are more easily broken down mechanically than are rock fragments.

53. The insoluble residue remaining after digestion in dilute hydrochloric acid was about 8 per cent of the dolomite rock of the coarse aggregate. A large part of this residue was montmorillonoid clay; other minerals found were quartz, mica, pyrite, feldspar, and garnet. Clay made up about 8 per cent of the sample tested.

Bull Shoals Dam aggregates

54. The most abundant constituent of the samples of manufactured coarse and fine limestone aggregates from Bull Shoals Dam (LR-1 G-69(2) and LR-1 G-69(2)S) was fresh, dense, dolomitic limestone, which amounted to nearly half of the coarse aggregate. Other major constituents were sandy limestone and highly calcareous, porous sandstone. A smaller amount of weathered and porous dolomite was present. The particles were angular to subangular; the particle surfaces varied from smooth to moderately rough, being influenced by the varying content of sand and clay.

55. The insoluble residue remaining after digestion in dilute hydrochloric acid averaged about 25 per cent of the sample. The principal substances found in the insoluble residues were quartz sand grains and clay. The clay was of the kaolin type except in the calcareous sandstone, in which a montmorillonoid clay was found in small quantities.

Chain of Rocks Lock aggregates

56. Falling Spring Quarry. The coarse aggregate sample from the quarry of the East St. Louis Stone Co. at Falling Spring, Illinois, (STL-2 G-1) consisted principally of relatively pure fine- to medium-grained limestone, including a large proportion of sublithographic to lithographic

limestone and medium-grained, fossiliferous, oolitic limestone. These varieties were fresh and dense. An appreciable quantity of argillaceous and porous limestone and minor amounts of argillaceous, stylolitic limestone and cherty limestone were present also. The particles were predominantly angular to subangular. The surface texture varied from very smooth in the lithographic type to moderately irregular in some of the other varieties.

57. The insoluble residue remaining after digestion in dilute hydrochloric acid averaged about 5 per cent. The predominant clay present was found to be the montmorillonoid type except in the residue from the argillaceous, stylolitic limestone, which contained clay of the kaolin group. Montmorillonoid clay amounted to about 4 per cent of the total.

58. Krause Quarry. The coarse aggregate sample from the quarry of the Columbia Quarries Company at Krause, Illinois, (STL-2 G-2) consisted principally of fine- to medium-grained, light gray limestone, which was fresh and dense. This material was essentially similar to the fine- to medium-grained varieties occurring at the Falling Spring Quarry. The remainder of the sample consisted of argillaceous and porous limestone, and a somewhat smaller amount of cherty, stylolitic limestone. This last variety probably corresponded to the argillaceous, stylolitic limestone and the cherty limestone which were differentiated as separate varieties in the sample from the Falling Spring Quarry. The particles were predominantly angular to subangular. The surface texture varied from very smooth in the finest grained rock to moderately irregular in some of the other varieties.

59. A chemical analysis of a rock sample from the quarry at Krause

gave the following results in per cent by weight⁷.

CaCO ₃	97.3
MgCO ₃	0.5
Al ₂ O ₃)	1.4
Fe ₂ O ₃)	
SiO ₂	<u>0.9</u>
	100.1

The variety of the limestone analyzed is not known; comparison of the analysis with the data on insoluble residues (table 2) suggests that the analyzed sample was one of the fine- to medium-grained varieties, free from chert, stylolites, and appreciable amounts of disseminated argillaceous or silty material.

60. The insoluble residue remaining after digestion in dilute hydrochloric acid averaged about 12 per cent. The residues were composed of chert, quartz, a montmorillonoid clay, and minor amounts of other materials. Montmorillonoid clay amounted to about 4 per cent of the total. The unusually high proportion of insoluble residue found for the cherty stylolitic variety was due largely to grains of quartz of silt size; this rock might more aptly be called a calcareous siltstone.

PART V: PHYSICAL AND THERMAL PROPERTIES

61. The physical and thermal properties of limestone aggregates are of considerable importance in their proper utilization in concrete. Statistical studies have been made of the relationship between results of those physical tests performed on limestone aggregate materials that yield specific numerical values and the resistance of concrete to accelerated freezing-and-thawing. These studies indicate that, of these results, the coefficients of thermal expansion and the absorption show greatest relation to resistance of concrete to freezing-and-thawing.

62. A summary of various physical properties of the coarse aggregates is given in table 3. A more detailed listing of the coefficients of thermal expansion is given in table 5, which shows the directional effects of the various specimen orientations on these coefficients. The results in the average column are given as simple averages for the three directions tested: in, across, and perpendicular to the bedding planes. A final weighted average based on percentage composition is also shown where indicated. In general, none of the aggregates had a very high degree of anisotropy; consequently, no great amount of care in their use is necessary in this respect. Some cases of deterioration due presumably to anisotropic thermal expansion have been reported. Coefficients of expansion are also given in table 5 for a number of standard mortars prepared with several of the fine aggregates used in these studies. The specimens tested in connection with Bull. Shoals Dam were taken from core hole No. 1 of the Flippin, Arkansas, quarry (LR-1 G-68) rather than from the actual quarry-run material (LR-1 G-69), but are considered to be

representative of this limestone.

63. A few miscellaneous tests were performed on certain of these limestones or on concretes composed from them. These included: (a) determinations of modulus of elasticity of LR-1 G-69, Bull Shoals Dam limestone and sandstone; (b) determination of thermal coefficient of expansion of concrete beams and cores prepared with LR-1 G-69; (c) determination of diffusivity and specific heat of concrete prepared with LR-1 G-69; and (d) determination of specific heat and diffusivity of limestone aggregates for Allatoona Dam (MOB-2 G-3). Results of these tests are given below:

<u>Aggregate</u>	<u>Type of Specimen</u>	<u>Test</u>	<u>Results</u>
LR-1 G-69	Aggregate (limestone)	Secant modulus of elasticity (1000 psi)	6.5×10^6 psi
LR-1 G-69	Aggregate (sandstone)	Secant modulus of elasticity (1000 psi)	5.3×10^6 psi
LR-1 G-69	Concrete beams	Thermal coefficient of expansion	3.5×10^{-6} deg ⁻¹ F
LR-1 G-69	Mass concrete cores	Thermal coefficient of expansion	4.6×10^{-6} deg ⁻¹ F
LR-1 G-69	Mass concrete cores	Thermal diffusivity	0.050 ft ² /hr
LR-1 G-69	Mass concrete (crushed)	Specific heat	0.24 B/lb-deg F
MOB-2 G-3	Aggregate	Thermal diffusivity	0.066 ft ² /hr
MOB-2 G-3	Aggregate	Specific heat	0.22 B/lb-deg F

These values may be considered as rather typical of limestone aggregates. No use is made of them in this report because of the limited number of tests and the scattered sources of the specimens.

PART VI: RESISTANCE TO FREEZING-AND-THAWING

Test Results

64. Thirty-three aggregate combinations tested for resistance to accelerated freezing-and-thawing are listed in table 6. They comprise a total of 186 concrete beams of three general classes: (a) limestone fine and coarse aggregates; (b) limestone fine aggregate with a standard diabase coarse aggregate; and (c) natural nonlimestone fine aggregate with a limestone coarse aggregate. All except 20 beams completed 300 cycles of freezing-and-thawing, or suffered at least 50 per cent loss in dynamic modulus of elasticity prior to 300 cycles. Two specimens were cracked or broken in the course of testing, and the remaining 18 beams were removed from the freezing-and-thawing apparatus between 200 and 300 cycles because of limitations of schedules and space for testing. In these 18 cases the durability factor at 300 cycles was estimated. All but 9 of the specimens were cured for either 9 or 21 days, with the 9 being cured for 365 days. Table 6 also lists the durability factor at 300 cycles for each group of 3 beams, the difference in coefficients of expansion of coarse aggregate and mortar, and the length of curing in days. The results of all tests are summarized on the following page.

65. The decrement in dynamic modulus with increasing number of freezing-and-thawing cycles is shown for each group of 3 beams on plates 1 through 16. The test results on the aggregate combinations listed on each plate, except plate 11, and in table 6 have been combined, where duplicate groups of specimens exist, so that only an average value and curve for each aggregate combination for each curing period are shown.

Summary of Freezing-and-thawing Results

(All values represent average DFE of three similar specimens tested simultaneously, except as noted. Where no values are shown, tests were not made because of insufficient supplies of aggregates.)

Curing Period, Days:	Alton	Bluestone			Wolf Creek		Dale Hollow		Center Hill		Allatoona	Bull Shoals		Chain of Rocks	Falling	Col-	
	9	9	21	365	9	21	9	21	9	21	9	9	9	9	9	9	
Ls and Ls	87(b)	92	96(a)	92	92	95(a)	92	96(a)	85	95(a)	77	81(a)	61(e)	61(b,f)	55(g)		
Ls and traprock	93(a)	93	91	93	94	90	86	87	83	90	--	----	----	-----	----		
Std qtz sand and Ls	63(c)	77	----	46	76(d)	87	70	86	44	71	--	----	----	25	23		
Other sand* and Ls	51(a)	--	----	--	74	75	42	80	53	70	--	----	----	28	31		

(a) Average of 2 sets, 6 specimens. (b) Average of 3 sets, 9 specimens. (c) Average of 4 sets, 12 specimens.
 (d) Avg of 1 set, 2 specimens, 1 cracked. (e) Avg of 3 sets, 8 specimens, 1 broke; sand graded to project specifications.
 (f) Includes two limestone sands. (g) Avg of 7 sets, 21 specimens. Includes two limestone sands.
 * "Other sand" indicates Pine Flat Dam sand for all but Chain of Rocks Lock specimens for which Mississippi River sand was used.

66. The two sets of curves shown with open and solid symbols on plate 11 for Bull Shoals Dam limestone aggregates are distinct only in that the grading of the fine aggregate was different. The curves marked with open symbols indicate that the fine aggregate was graded in accordance with the provisions of Method CRD-C 114; while the solid symbols indicate that the fine aggregate was graded to Bull Shoals project specifications. The curve on plate 11 marked "Tested in Falling Film Apparatus" shows the effects on this combination of testing in a different apparatus, but the results are not included in table 6, or otherwise used in this report.

67. In a number of cases, aggregates from the same source are considered as distinct. This is because the samples of these aggregates were obtained at different times and the properties may not be considered as identical. The combinations show considerable differences in some cases, such as on plate 16 where Allatoona Dam limestone aggregate combinations yielded DFE's of 61 and 94 for two different samples from the same quarry. Much of this variation was caused by the amount of included shale. Smaller variations are found among the Chain of Rocks Lock

limestone samples. The degree to which aggregate variations are responsible for the observed differences in resistance to freezing-and-thawing is difficult to evaluate quantitatively since it is not possible to evaluate the effects of the concomitant variation in the concrete mixture designs.

68. The differences between coefficients of thermal expansion of coarse aggregate and mortar (indicated as Δc throughout this report) shown on table 6 correlate well with the observed DFE's except for those combinations involving the material designated by symbol SAC-1 S-1. The SAC-1 S-1 material contained considerable amounts of weathered granite and mica which contributed to lowered resistance to freezing-and-thawing of concrete in which it was present. Plate 17 shows the relation between resistance to freezing-and-thawing measured as DFE and these thermal coefficient differences. The two lines shown are the regression lines for the two groups of specimens: line 1, non-Chain of Rocks Lock aggregates; and line 2, Chain of Rocks Lock aggregates. Both lines show the decrement in DFE with increasing Δc . The combinations representing Allatocna Dam and Bull Shoals Dam aggregates were omitted from the statistical computation of these regression lines owing to sparsity of data.

69. The effects of duration of curing are shown on plate 18 for the 14 aggregate combinations tested after both 9- and 21-days curing. The DFE's are plotted against the Δc with the effects of length of curing period shown as the difference between DFE's for different curing periods.

70. The significance of these results will be discussed in more detail in a subsequent part of this report.

Results of Examination of Concrete Specimens after Test

71. An examination of the specimens after completion of the freezing-and-thawing test indicated that certain constituents were selectively affected by freezing-and-thawing, as discussed below.

- a. Alton. The minor constituents, green shale, weathered limestone, and shaly limestone split, crumbled, and flaked. Minor spalling of dense limestone was also found.
- b. Bluestone. There was a small amount of crumbling of oolitic limestone, especially when argillaceous or weathered. Also small amounts of shale and a few particles of the dense argillaceous limestone showed disintegration.
- c. Wolf Creek. The concrete showed a little splitting of shaly limestone and crumbling of oolitic limestone. Some porous chert in the limestone had been disrupted.
- d. Dale Hollow. A little disintegration of weathered limestone and splitting of shaly limestone were observed. Although not found in the sample received from Dale Hollow, soft green shale is present in small but significant quantities in the quarry and in the concrete of the dam. Numerous popouts have occurred in the handrail and curbing with green shale particles showing in the bottoms of the pits.
- e. Center Hill. A little splitting of shale and shaly limestone, especially weathered shale, was found. Some aggregate particles showed loss of oolites or fossils. A little flaking of limestone was apparent.
- f. Allatoona. Some pits resulting from disruption of shale particles were observed. A variable amount of shale was present in the quarry, and at different times in the aggregate. About 10 per cent of shaly particles was found in a small sample of the manufactured sand.
- g. Bull Shoals. The principal failures observed in the concrete were spalling of porous limestone, crumbling of weathered sandstone, scaling of dolomite, and splitting of thin-bedded dolomite.
- h. Chain of Rocks.
 - (1) Krause Quarry. Some pits were observed with disrupted shale at their bottoms; some crumbling of sandstone

was found, and there were a few disrupted chert particles. No sandstone had been found in the petrographic sample.

- (2) Falling Spring Quarry. A little disintegration of porous and weathered limestone was noted; occasional chert popouts were observed. There was also some failure of stylolitic limestone, splitting of shale, shaly limestone, and lamellar limestone, crumbling of sandstone and flaking of limestone. No sandstone had been found in the petrographic sample.

PART VII: DISCUSSION OF RESULTS

72. Some interrelations of the data set forth in parts IV, V, and VI are discussed in the following paragraphs.

Effects of Composition of Limestone Aggregates on
the Performance of Concrete

Type of clay

73. The association between type of clay and DFE is statistically significant for the 9 limestone aggregates tested. In five samples, those from Alton, Wolf Creek, Dale Hollow, Center Hill, and Bull Shoals, the clays were principally kaolin and the DFE's of beams containing limestone coarse and fine aggregates cured 9 days were above 80 (see table 3). Four samples, those from Allatoona, the two from Chain of Rocks, and Bluestone, contained montmorillonoid (swelling) clay; three of them had DFE's below 80. Use of the chi-square test* indicates that the probability is less than 2 in 100 of chance occurrence of the association between swelling clay and DFE below 80.

74. The Bluestone sample contained a very small amount of montmorillonoid clay and had a DFE of 92. Both Chain of Rocks aggregates contained about 4 per cent montmorillonoid clay; the Allatoona sample tested contained almost 8 per cent. If the type of clay were the only determining factor it would be expected that the Allatoona materials would yield lower DFE's than the two from Chain of Rocks, which was not the case. The interaction of several factors serves to explain the result. First,

* R. A. Fisher, "Statistical Methods for Research Workers" Tenth Edition, 1946, pp 85-92.

both the Chain of Rocks samples contained porous argillaceous limestone in which the insoluble material was all montmorillonoid clay, while the Allatoona rock was more uniform and of lower average absorption. Second, both Chain of Rocks samples contained more cracks and voids than the Allatoona sample. Third, the Allatoona rock was dolomite, with a higher coefficient of thermal expansion and consequently a smaller difference in thermal coefficient between coarse aggregate and mortar than that found for the calcitic limestones from Chain of Rocks.

75. The influence of arrangement of clay in limestone, regardless of type of clay, is discussed in paragraph 77.

Shaly limestone

76. When clay minerals in a limestone are concentrated in distinct layers, which are referred to as shale partings if they are thin, the rock will break easily along such layers; if the spacing of these partings is close, they may set a limit to the size of coarse aggregate which can be produced. They will also contribute weak, porous, shaly material to the finer sizes of the crushed stone or to manufactured fine aggregate prepared from it. Coarse aggregate pieces that include shale layers or partings will tend to fail along those layers in freezing-and-thawing, since the shale is usually less resistant than the limestone to that attack. Inspection of the quarry or outcrop is necessary in order to obtain adequate information regarding the presence of shale partings and their probable influence on suitability of the rock or on quarrying operations. As the rock tends to break along these shaly layers, samples other than complete cores received in the laboratory may not reveal their presence, or at best may indicate them only indirectly by the presence of

shale particles in the finer sizes.

Argillaceous limestone

77. Clay minerals in limestone that are not concentrated in distinct layers of shale or along stylolites are ordinarily not visible to the unaided eye. The clay may be distributed in several ways, which have different effects on the resistance of the rock to weathering. The least harmful condition is fine dissemination of the clay minerals at random throughout rock of low porosity¹⁰. The clay may occur as films around grains of calcite and quartz and around fossils or oolites; this lessens the cohesion of the rock, and puts the clay in a position where it may be easily reached by water if the clay films intersect the surface of the particle. A third mode of occurrence of clay in argillaceous limestones is in microscopic films parallel to the bedding; this may easily lead to splitting of the rock. Whatever the mode of occurrence of the clay, its effectiveness as a cause of weathering of the rock tends to vary directly with the permeability of the rock and the types of clay minerals present. The absorption (table 3) gives some measure of permeability. Clays are highly porous and absorptive but the swelling clays are virtually impermeable when saturated. The more readily water can penetrate to the clay, the greater is its opportunity to take up water. This may lead to disruption of the rock by alternate freezing-and-thawing. Even in mild climates limestone may tend to split or disintegrate as a result of weakening along wet clay films in bedding planes, along stylolites, or around crystals, fossils or oolites.

Sandy limestone

78. Scattered, well-separated quartz grains in a limestone may not

affect its suitability appreciably; they may show some tendency to concentrate in certain sizes of manufactured fine aggregate, giving these sieve fractions an unexpected composition and thermal behavior. Where sand grains are numerous and close together they may tend to cause crumbling in freezing-and-thawing. Smooth-surfaced, highly rounded quartz grains are not mechanically well-bonded in a calcite matrix; the thermal differences between the grains and the matrix will assist in weakening the mechanical bond. The Bull Shoals aggregate contained more sand than any of the others in the group, and failures of coarse aggregate by crumbling were noted in the freezing-and-thawing beams. This was observed, to a lesser extent, in samples from Falling Spring and Krause, both for the Chain of Rocks Project. By an increase in the proportion of sand, sandy limestone may pass into calcareous sandstone, as is the case with the Bull Shoals aggregate. Such material is likely to be porous with consequent weakness in freezing-and-thawing.

Oolites

79. Some oolitic limestones tend to disintegrate on weathering by failure of the bond between the oolites and the matrix. This is especially likely if a clay film surrounds each oolite. The oolitic limestones prominent in many of these samples appeared to be mostly fresh and dense, usually with low porosity and only a little tendency to disintegrate in freezing-and-thawing.

Cracks and voids

80. A rough but fairly definite correlation exists between DFE and the percentage of cracks and voids. In general, an appreciable amount of open spaces, as vugs and wide and narrow cracks, is associated with low

DFE and a tight compact rock is associated with high DFE (table 3). The Bull Shoals aggregate had the lowest DFE's of any samples in which the clay was kaolin, and also had the most cracks and voids.

Schurecht's Ratio

81. It is concluded that Schurecht's ratio is worthless for the evaluation of aggregates. It shows no correlation whatever with DFE, sulfate loss, or even absorption to which it is related (table 3).

Resistance to Freezing-and-thawing

82. The resistance to accelerated freezing-and-thawing as indicated by the DFE at 300 cycles is in general good for the concrete made with the manufactured coarse and fine limestone aggregates, although there are some discrepancies. The average DFE at 300 cycles falls between 81 and 92 for the aggregates from Alton, Bluestone, Wolf Creek, Dale Hollow, Center Hill, and Bull Shoals. For the Chain of Rocks project the Krause quarry material gave an average of 55, while the Falling Spring quarry material gave an average of 61. Ambiguous results were obtained for the Allatoona material; one set of six beams had an average DFE of 93 at 300 cycles (range 92-94), while another set of six beams had an average DFE of 61 at 300 cycles (range 58-63). The resistance of concrete to accelerated freezing-and-thawing is dependent upon many factors. In the tests discussed in this report, it is considered that the mixture designs are of uniformly high quality, and that the behavior observed is indicative of the quality of the aggregate combination tested.

83. Previous work has shown that concretes composed of limestone

aggregates are rather sensitive to variations in the amount of entrained air. Therefore, results on all combinations having plastic air contents outside the range 4.5 ± 0.5 per cent were discarded from this discussion with but two exceptions. The exceptions were both combinations of standard sand and Alton limestone, and were allowed since the DFE's did not significantly vary from those found in similar combinations where the air content was in the allowed range. One of these exceptions had a low air content, and the other a high air content. Since, except for these two groups, all specimens were within the tolerance for air content, no further consideration of the effects of air content upon the resistance to freezing-and-thawing was felt necessary. This is justified on the basis of previous statistical analyses for similar tests. Similarly, based on previous work, the effects on resistance to freezing-and-thawing of variations in cement factor and sand-aggregate ratio are considered negligible for these specimens. All were made with a constant water-cement ratio and specified consistency, and no effects are expected as a result of variation in these properties.

84. Thus, because of the standardized nature of the concretes, the principal reasons for variations in resistance to freezing-and-thawing of concretes cured for the same period are sought in the properties of the aggregates. The major quantitative factors have been found to be the absorption of the coarse aggregate, and the difference between coefficients of thermal expansion of the coarse aggregate and the mortar. Plate 17 shows two regression lines relating the DFE and Δc of two groups of concretes. The upper line, line 1, was obtained from the data for the following aggregates:

- CRD G-4 Alton limestone
- CRD G-6 Bluestone Dam limestone
- CRD G-7 Wolf Creek Dam limestone
- CRD G-8 Dale Hollow Dam limestone
- CRD G-9 Center Hill Dam limestone

It has the equation:

$$DFE = 99.97 - 7.32\Delta c$$

which indicates that as Δc increases, the resistance to freezing-and-thawing, measured as DFE, decreases. The lower line, line 2, was obtained from the data for the Chain of Rocks Lock aggregates. It has the equation:

$$DFE = 81.56 - 13.31\Delta c$$

This also shows the inverse DFE - Δc relationship. Additionally, the difference between the two lines at a zero value of Δc would appear to show the difference in quality of the two groups of aggregates. The Chain of Rocks limestones are the only two of the group of seven that contain more than a trace of montmorillonoid (swelling) clay; they also have higher absorption, as shown in table 3, and they show a greater rate of decreasing DFE with increasing Δc .

85. The effects of curing period are shown on plate 18 for fourteen combinations, all taken from the first group above. In general, those sets of specimens cured for 21 days average 9 per cent higher in DFE than those cured for 9 days. Of considerable interest is the increasing superiority of the 21-day curing period with increasing Δc . This indicates that the additional curing permits the added strength development in the pastes to withstand to a greater degree the stresses

imposed by the differential expansion of the coarse aggregates and mortars.

86. The stresses set up in concrete by the different coefficients of thermal expansion of coarse aggregate and mortar are given approximately by the formula $\sigma = TE \Delta c$, where σ is the stress at the interface, T is the temperature change from the equilibrium (no stress) condition, E is the modulus of elasticity, and Δc is the thermal coefficient difference between coarse aggregate and mortar. Since the probability of cracking increases with the stress, reduction of the stresses in concrete to the lowest value commensurate with other objectives is important. This may be done by reducing either T , E , or Δc individually or collectively. Limitations on cement factor and placing temperature will reduce the temperature change T for mass concrete, and have been successfully applied within recent years to an increasing degree. Lowering the cement factor, increasing the water content, replacing part of the cement -- all will tend to lower the modulus of elasticity to some extent. This, however, may conflict with structural, placement, or imperviousness requirements and the effectiveness of such procedures thus has limits. The Δc may be reduced by using fine aggregates manufactured from the coarse aggregates, rather than using sands with high thermal expansion.

87. Limestone aggregates are more susceptible to the effects of these thermal stresses than are many other types of aggregate. This is so principally because limestones as a group have quite low coefficients of thermal expansion, and high Δc values with siliceous sand mortars are common. Thus high stresses may be encountered. The Δc values should be kept as low as possible. Similarly, limestones with low

absorption and as little swelling clay as possible should be used if feasible. Curing should be continued as long as possible, particularly where high Δc values must be tolerated and the concrete is subject to exposure.

88. The effects of thermal diffusivity, specific heat, and modulus of elasticity on resistance to freezing-and-thawing of concretes containing limestone aggregates have not been quantitatively determined. The thermal effects other than those due to coefficient of expansion differences are believed to be of minor significance, and the elastic modulus effects are thought to be as described above.

Relations of Various Properties

Relations of absorption, insoluble residue, and resistance to freezing-and-thawing

89. As seen in table 3, the absorption was less than one per cent for the Bluestone, Wolf Creek, Dale Hollow, Center Hill, and Allatoona aggregates; for the other limestones the absorption was between one and two per cent. The Alton material, with an absorption of 1.1 per cent, contained only 3 per cent of insoluble materials. The Bull Shoals dolomitic aggregate, with an absorption of 1.4 per cent, contained 25 per cent of insoluble materials, but the greater part of this was quartz sand. The limestone from the Falling Spring Quarry, Chain of Rocks project, had an absorption of 1.2 to 1.6 per cent and contained 5 per cent of insoluble residue, mostly swelling clay. The limestone from the Krause Quarry, Chain of Rocks project, had an absorption of 1.6 to 1.8 per cent and contained 1² per cent of insoluble residue including considerable chert in

addition to swelling clay. It is worthy of note that the two Chain of Rocks aggregates, which showed the highest absorption, also gave the lowest values of DFE at 300 cycles of freezing-and-thawing (if the lower of the two disagreeing sets of results for the Allatoona material is disregarded). Similarly the other aggregates having absorptions greater than one per cent, Alton and Bull Shoals, have DFE's lower than the remainder of the aggregates for which the absorption was less than one per cent.

90. Apparently no correlation exists between DFE at 300 cycles and total insoluble residue, since high or low insoluble residue is associated with both high and low DFE; however, if the nature of the residue is taken into account, a good correlation emerges. Examination of cases in which a high amount of insoluble residue is associated with high DFE reveals that the high residue consists largely of chert, sand, or silt. When only the clay content of the residues is considered, it is found that high DFE accompanies a low clay content, and that the DFE decreases with increasing clay. In the case of the Falling Spring Quarry rock for the Chain of Rocks project, low insoluble residue is associated with low DFE; however, in this case, the absorption is one of the highest found, the residue is nearly all clay, and the most porous variety of limestone in the sample is an argillaceous type containing montmorillonoid clay. With a variety of more or less independent factors active, it should not be expected that perfect correlation of behavior with any single factor will be found.

PART VIII: SUMMARY AND CONCLUSIONS

91. The tests described in this report showed the resistance of freezing-and-thawing of concretes containing 7 of the 9 aggregates tested to be inversely proportional to the difference between coefficients of thermal expansion of the coarse aggregate and the mortar. This relation was shown to hold for two groups of aggregates of different quality although the actual values depended on the quality of the aggregates. Data for the other two aggregates were not sufficient to afford correlations.

92. The principal factor related to the difference in quality between the two groups was the type of clay mineral present. The two limestones giving the lowest DFE's were those in which a montmorillonoid (swelling) clay was present and amounted to about 4 per cent of the whole sample. When the results for all 9 aggregates were grouped by clay mineral present and DFE above and below 80, the association between swelling clay and DFE below 80 was statistically significant. All of the limestones in which the clay mineral belonged to the kaolin group had DFE's above 80.

93. The results also demonstrated the increased freezing-and-thawing resistance obtained by an increase in curing period, particularly for greater values of Δc .

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TABLES

Table 1

LITHOLOGIC COMPOSITION OF SAMPLES

Quarry and Project	Size Range	Lithologic Varieties - Weighted Averages as Per Cent of the Whole Size Range												
		Lithographic Limestone		Oolitic Fossiliferous Limestone		Argillaceous Limestone		Silty Limestone	Sandy Limestone	Calcareous Sandstone	Dolomitic Limestone	Dolomite	Miscellaneous	
		With Disseminated Chert		Dense	Weathered	Porous or Stylo-	Cherty							
Acme Limestone Co., Bluestone Dam	No. 4 - 3/4 3/4 - 1-1/2	--	--	26	34	--	--	40	--	--	--	--	--	
Maupin Quarry, Wolf Creek Dam	No. 4 - 3/4 3/4 - 1-1/2	--	--	64	30	--	--	--	1	--	--	--	5	
Pea Ridge Quarry, Dele Hollow Dam	No. 4 - 3/4 3/4 - 1-1/2	22	54	18	20	--	--	--	--	--	6	6	2	
Mississippi Lime Co., Alton Lock	31	--	--	60	--	1	--	--	3	--	--	--	5	
Columbia (Krause) Quarry, Chain of Rocks Lock	No. 4 - 1-1/2	--	--	65	--	21	--	14	--	--	--	--	--	
Falling Springs Quarry, Chain of Rocks Lock	No. 4-1	36	4	36	--	16	8	--	--	--	--	--	--	
Lancaster Quarry, Center Hill Dam	No. 4 - 3/4 3/4 - 1-1/2	66	67	--	13	--	--	--	21	--	--	--	--	
Flippin Quarry, Ball Shoals Dam	No. 4-6	--	--	--	--	--	--	--	25	22	53	--	--	
Shinall Quarry, Allatoona Dam	No. 4-1-1/2	--	--	--	--	--	--	--	--	--	100	--	--	

Table 2

AMOUNT AND COMPOSITION OF INSOLUBLE RESIDUES IN LIMESTONES

Quarry and Project	Name	Lithologic Variety		Per Cent Insoluble in Variety	Constituents of Insoluble Residue in Order of Abundance (a)
		Per Cent in Whole Sample	Sample		
Acme Limestone Co., Bluestone Dam	Oolitic fossiliferous Argillaceous dense Silty	26-32	7	Quartz sand, minor montmorillonoid Quartz sand and montmorillonoid Quartz, minor pyrite, mica, zircon, sphene, and montmorillonoid	
		34-37	8		
		40-31	31		
Maupin Quarry, Wolf Creek Dam	Oolitic fossiliferous Argillaceous dense	64	1	Quartz sand, minor pyrite, mica, zircon, sphene and kaolin Quartz, kaolin	
		30-34	7		
Rea Ridge Quarry, Dale Hollow Dam	Lithographic dense Lithographic cherty Oolitic fossiliferous Dolomitic Miscellaneous	22-19	2	Kaolin, quartz, chert, including chalcedony, etc. Chert including chalcedony dominant; quartz Quartz, minor chert, minor kaolin Quartz dominant; chert, feldspar, kaolin Quartz 50%; chert, feldspar, kaolin	
		52-54	20		
		18-20	1		
		6	1		
		1-2	6		
Mississippi Lime Co., Alton Lock	Lithographic dense Oolitic fossiliferous Argillaceous porous Sandy Miscellaneous	31	4	Quartz predominant; kaolin, pyrite, etc. Quartz, chert, including chalcedony, kaolin Quartz, chert, kaolin Quartz, feldspar, chert, kaolin, pyrite Quartz, feldspar, chert, kaolin	
		60	2		
		1	30		
		3	14		
		5	8		
Columbia (Krause) Quarry, Chain of Rocks Lock	Oolitic fossiliferous Argillaceous porous Argillaceous cherty	65	2	Montmorillonoid 75%; quartz, chert Montmorillonoid 100% Chert and quartz 90%; montmorillonoid 10%	
		21	9		
		14	58		
Falling Spring Quarry, Chain of Rocks Lock	Lithographic dense Lithographic cherty Oolitic fossiliferous Argillaceous porous Argillaceous stylonitic	36	4	Montmorillonoid 75%; chert 25% Chert 60%; montmorillonoid 40% Montmorillonoid 75%; chert 25% Montmorillonoid 100% Kaolin 75%; chert 25%	
		4	6		
		36	4		
		16	12		
		8	5		
Lancaster Quarry, Center Hill Dam	Lithographic dense Argillaceous dense Sandy	66-67	3	Kaolin and illite dominant; quartz, feldspar, pyrite, etc. Kaolin and illite over 50%; quartz, feldspar, pyrite, chalcidony Kaolin, quartz, feldspar, pyrite, chert	
		13-9	17		
		21-24	6		
Flippin Quarry, Bull Shoals Dam	Sandy limestone Calcareous sandstone Dolomitic limestone	25	2	Quartz 85%; kaolin 15% Quartz predominant; minor montmorillonoid Quartz 90%; kaolin 10%	
		22	66		
		53	21		
Shinnell Quarry, Allatoona Dam	Dolomite	100	8	Montmorillonoid 95%; carbonaceous material, quartz	

(a) Constituents identified by optical methods. The clay minerals were assigned to the kaolin, montmorillonoid, or illite groups on the basis of indices of refraction determined on aggregates, and on the basis of birefringence.

Table 3

SOME PHYSICAL AND CHEMICAL PROPERTIES OF VARIOUS LIMESTONE COARSE AGGREGATES

Source	Specific Gravity	Absorption Per Cent	Average Insoluble Residue, Per Cent	Type of Clay in Residue	Cracks and Voids, % of Volume	Schurecht's Ratio		Thermal Coefficient In./In./Deg F	DFE (a)
						Ratio	In./In./Deg F		
Alton Lock	2.66	1.1	3	Kaolin	Negligible	0.9	2.4	87	
Bluestone Dam	2.70	0.5	17	Montmorillonoid(b)	Negligible	0.9	2.3	92	
Wolf Creek Dam	2.68	0.8	8	Kaolin	Negligible	0.7	2.3	92	
Dale Hollow Dam	2.68	0.8	12	Kaolin	Negligible	0.9	2.9	92	
Center Hill Dam	2.70	0.7	6	Kaolin	Negligible	0.9	2.1	85	
Bull Shoals Dam	2.72	1.4	25	Kaolin	15	0.8	4.8	81	
Columbia (Krause) (Chain of Rocks)	2.62	1.8	12	Montmorillonoid(c)	8	1.0	2.9	55	
Falling Spring (Chain of Rocks)	2.63	1.6	5	Montmorillonoid(c)	6	0.9	2.6	61	
Allatoona Dam	2.83	0.5	8	Montmorillonoid(d)	3	1.0	4.9	77	

(a) Limestone + limestone sand combination average, after 9 days curing.

(b) Total amount negligible.

(c) Montmorillonoid amounted to 4 per cent of the total.

(d) Montmorillonoid amounted to 8 per cent of the total.

Table 4

USE OF LIMESTONE AGGREGATES IN FIELD MASS CONCRETE (1)

	Bull Shoals		Allatoona		Center Hill		Wolf Creek	
	Interior	Exterior	Interior	Exterior	Interior	Exterior	Interior	Exterior
Cement factor, bags/cu yd	3.0	4.0	3	4	3	4.5	3	4.5
Slump, in.	1-1/4 - 4	2-1/4 - 4	1 - 2-1/2	1/2 - 2	1/2 - 2	1/2 - 2	1-1/2 - 2-1/2	2-3
Water cement ratio by wt	.61-.66	.50-.55	.64-.74	.52-.58	.64-.71	.51-.58	.65-.69	.47-.51
Air % (a)	5.2-6.5	3.8-5.5	5-7	5-7	3-6	3-6	4.5 - 6	4.5-5.8
Sand, % of total aggregate	0.22-0.26	0.22-0.26	.27	.27	.29	.265	.24	.21
No. 4 - 3/4 lb/yd	537	521	573	555	465	675	606	607
3/4 - 1-1/2 lb/yd	396	384	604	585	530	695	588	590
1-1/2 - 3 lb/yd	960	932	635	615	862	1280	680	677
3 - 6 lb/yd	932	905	1010	980	1015	----	918	867
Sand Grading (b), %								
+ No. 4	As Batched	Mixed						
No. 4 - 8	3.0	3.0	0	0	0	0	0	0
No. 8 - 16	13.8	11.2	10	10	11	11	15.6	15.6
No. 16 - 30	19.2	13.5	28	38	30.4	41	27.5	27.5
No. 30 - 50	18.1	15.0	25	25	20.2	20.2	20.2	20.2
No. 50 - 100	20.0	19.7	17	53	16.3	50	15.6	15.6
No. 100 - 200	16.9	18.5	11	11	13.6	13.6	9.2	9.2
Finer than No. 200	5.5	7.9	4	9	3.4	9	5.5	5.5
	3.3	11.2	5	9	5.1	9	6.4	6.4
FM	2.75	2.36	2.82	2.83	2.83	2.89		

(a) In that portion of the concrete finer than the 1-1/2-in. sieve.
 (b) Sand manufactured by hammer mill.

(1) Data taken from a paper by Byram W. Steele "Cracking and Water-Tightness in Concrete as Affected by Content and Type of Cement and Grading and Proportion of Fine Aggregate with and without Air-Entrainment"

Table 5

COEFFICIENTS OF THERMAL EXPANSION OF LIMESTONE AGGREGATES

Serial No.	Source	Description	Coefficient of Thermal Expansion x 10 ⁶ /Deg F			
			In Bedding Plane	Across Bedding Plane	Perpendicular To Bedding Plane	Average
			(a)	(a)	(a)	(a)
CRD G-4	Alton, Ill.	Limestone	(a)	(a)	(a)	2.4(c)
CRD G-4(s)	Alton, Ill.	Limestone sand mortar	(b)	(b)	(b)	4.7
CRD G-6	Bluestone Dam	Limestone	(a)	(a)	(a)	2.3(d)
CRD G-6(s)	Bluestone Dam	Limestone sand mortar	(b)	(b)	(b)	4.7
CRD G-7	Wolf Creek Dam	Limestone	(a)	(a)	(a)	2.3(e)
CRD G-7(s)	Wolf Creek Dam	Limestone sand mortar	(b)	(b)	(b)	4.7
CRD G-8	Dale Hollow Dam	Limestone	(a)	(a)	(a)	2.9(c)
CRD G-8(s)	Dale Hollow Dam	Limestone sand mortar	(b)	(b)	(b)	5.0
CRD G-9	Center Hill Dam	Limestone	(a)	(a)	(a)	2.1(c)
CRD G-9(s)	Center Hill Dam	Limestone sand mortar	(b)	(b)	(b)	4.8
Standard fine	Georgetown, Miss.	Natural sand mortar	(b)	(b)	(b)	6.9
Standard coarse	New Haven, Conn.	Diabase	(a)	(a)	(a)	3.9
SAC-1 B-1	Pine Flat Dam	Natural sand mortar	(b)	(b)	(b)	5.8
LR-1 G-68(B,D)	Flippin, Ark.	Dolomite - rich limestone (70%)	4.8	4.8	4.8	4.8
LR-1 G-68(A)	Flippin, Ark.	Sandstone (22%)	5.9	5.7	5.7	5.8)4.8(f)
LR-1 G-68(C)	Flippin, Ark.	Calcite - rich limestone (8%)	1.9	1.9	1.9	1.9)
StL-2 G-1	Falling Spring, Ill.	Lithographic Ls (no orientation)	1.6	1.4	2.4	1.8)
	Falling Spring, Ill.	Med gr fossil. Ls w/chert bands	2.4	3.0	3.0	2.7)2.2
	Falling Spring, Ill.	Ls w/stylo. partings and chert incl.	1.8	2.1	2.8	2.2)
StL-2 G-1(4)s	Falling Spring, Ill.	Limestone sand mortar	(b)	(b)	(b)	4.8
StL-2 G-1(5)	Falling Spring, Ill.	Coarse gr stylo. Ls	2.1	2.1	2.8	2.3)
	Falling Spring, Ill.	Fine gr dark gray Ls	3.0	1.3	2.7	2.3)2.5
	Falling Spring, Ill.	Med gr light gray Ls	2.4	3.2	3.0	2.9)
StL-2 G-1(5)s	Falling Spring, Ill.	Limestone sand mortar	(b)	(b)	(b)	4.6
StL-2 G-2	Krause, Ill.	Dense mottled limestone	2.1	1.9	1.8	1.9)
	Krause, Ill.	Dense limestone	2.4	2.3	1.8	2.2)
	Krause, Ill.	Dense stylo, cherty limestone	2.0	1.9	1.6	1.8)2.9
	Krause, Ill.	Arg. Ls w/lamellar structures	5.4	5.2	5.0	5.2)
	Krause, Ill.	Arg. Ls w/globular structures	3.7	4.1	2.7	3.5)
StL-2 G-2(s)	Krause, Ill.	Limestone sand mortar	(b)	(b)	(b)	4.4
StL-2 S-1 and 2	Krause, Ill.	River sand mortar	(b)	(b)	(b)	6.2
Mob-2 G-3B	Allatoona Dam	Shaly limestone	4.8	5.5	5.1	5.1)
Mob-2 G-3B	Allatoona Dam	Veined nonshaly limestone	4.4	4.7	4.7	4.6)4.9
Mob-2 G-3B	Allatoona Dam	Ls w/little shale	4.8	5.0	4.6	4.8)
Mob-2 G-3	Allatoona Dam	Nonshaly limestone	5.1	4.4	4.8	4.7)
Mob-2 G-3(4)s	Allatoona Dam	Limestone sand mortar	(b)	(b)	(b)	6.2

- (a) Data not available on individual orientations.
 (b) Orientation not applicable to tests on mortar.
 (c) Average of 7 specimens.
 (d) Average of 8 specimens.
 (e) Average of 6 specimens.
 (f) Weighted.

Bull Shoals Dam limestone taken from Flippin, Ark. Quarry.
 Chain of Rocks Locks limestone taken from Falling Spring, Ill., and Columbia (Krause) Ill. Quarries.
 Allatoona Dam limestone taken from Shinall Quarry.

Table 6

RESULTS OF FREEZING-AND-THAWING TESTS ON LIMESTONE AGGREGATES

Fine Aggregate (a)	Coarse Aggregate (a)	Source	Durability Factor at 300 Cycles	Ac	No. Beams	Days Curing
CRD G-4(s)	CRD G-4	Alton, Ill.	87	2.3	9	9
Standard	CRD G-4	Alton, Ill.	63	4.6	12	9
SAC-1 S-1	CRD G-4	Alton, Ill.	51	3.4	6	9
CRD G-4(s)	Standard	Alton, Ill.	93	0.8	6	9
CRD G-6(s)	CRD G-6	Bluestone Dam	92	2.4	3	9
Standard	CRD G-6	Bluestone Dam	77	4.7	3	9
CRD G-6(s)	Standard	Bluestone Dam	93	0.8	3	9
CRD G-6(s)	CRD G-6	Bluestone Dam	96	2.4	6	21
CRD G-6(s)	Standard	Bluestone Dam	91	0.8	3	21
CRD G-6(s)	CRD G-6	Bluestone Dam	92	2.4	3	365
Standard	CRD G-6	Bluestone Dam	46	4.7	3	365
CRD G-6(s)	Standard	Bluestone Dam	93	0.8	3	365
CRD G-7(s)	CRD G-7	Wolf Creek Dam	92	2.4	3	9
Standard	CRD G-7	Wolf Creek Dam	76	4.7	3	9
SAC-1 S-1	CRD G-7	Wolf Creek Dam	74	3.5	3	9
CRD G-7(s)	Standard	Wolf Creek Dam	94	0.8	3	9
CRD G-7(s)	CRD G-7	Wolf Creek Dam	95	2.4	6	21
Standard	CRD G-7	Wolf Creek Dam	87	4.7	3	21
SAC-1 S-1	CRD G-7	Wolf Creek Dam	75(b)	3.5	3	21
CRD G-7(s)	Standard	Wolf Creek Dam	90(b)	0.8	3	21
CRD G-8(s)	CRD G-8	Dale Hollow Dam	92	2.1	3	9
Standard	CRD G-8	Dale Hollow Dam	70	4.1	3	9
SAC-1 S-1	CRD G-8	Dale Hollow Dam	42	2.9	3	9
CRD G-8(s)	Standard	Dale Hollow Dam	86	1.1	3	9
CRD G-8(s)	CRD G-8	Dale Hollow Dam	96	2.1	6	21
Standard	CRD G-8	Dale Hollow Dam	86	4.1	3	21
SAC-1 S-1	CRD G-8	Dale Hollow Dam	80	2.9	3	21
CRD G-8(s)	Standard	Dale Hollow Dam	87(b)	1.1	3	21
CRD G-9(s)	CRD G-9	Center Hill Dam	90	2.7	3	9
Standard	CRD G-9	Center Hill Dam	44	4.9	3	9
SAC-1 S-1	CRD G-9	Center Hill Dam	53	3.7	3	9
CRD G-9(s)	Standard	Center Hill Dam	83	0.9	3	9
CRD G-9(s)	CRD G-9	Center Hill Dam	95	2.7	6	21
Standard	CRD G-9	Center Hill Dam	71(b)	4.9	3	21
SAC-1 S-1	CRD G-9	Center Hill Dam	70(b)	3.7	3	21
CRD G-9(s)	Standard	Center Hill Dam	90(b)	0.9	3	21
IR-1 G-69(2)s	IR-1 G-69(2)	Bull Shoals Dam	81(c)		6	9
IR-1 G-69(2)s	IR-1 G-69(2)	Bull Shoals Dam	61(d)		9	9
StL-2 G-2(s)	StL-2 G-1	Falling Spring, Ill.	64	2.2	3	9
Standard	StL-2 G-1	Falling Spring, Ill.	25	4.8	3	9
StL-2 S-1 and 2	StL-2 G-1	Falling Spring, Ill.	28	4.0	9	9
StL-2 G-1(5)s	StL-2 G-1(5)	Falling Spring, Ill.	60	2.1	6	9
StL-2 G-2(s)	StL-2 G-2	Columbia Quarry	75	1.5	3	9
Standard	StL-2 G-2	Columbia Quarry	23	4.1	3	9
StL-2 S-1 and 2	StL-2 G-2	Columbia Quarry	31	3.3	3	9
StL-2 G-1(4)s	StL-2 G-2(4)	Columbia Quarry	42	1.9	9	9
StL-2 G-1(6)s	StL-2 G-2(5)	Columbia Quarry	62	1.7	9	9
Mob-2 G-3(s)	Mob-2 G-3(A and B)	Allatoona Dam	61	1.3	6	9
Mob-2 G-3(4)s	Mob-2 G-3(4)	Allatoona Dam	92	1.5	3	9
Mob-2 G-3(s)2	Mob-2 G-3(3)	Allatoona Dam	94	1.5	3	9

- (a) "Standard" refers to materials used in test method CRD-C 114 as coarse or fine aggregate with fine or coarse aggregate samples tested as such rather than as part of a test fine and coarse aggregate combination.
- (b) Specimens removed from freezing-and-thawing apparatus between 200 and 300 cycles, because of schedule and space limitations. DFE's listed are estimated DFE's at 300 cycles.
- (c) DFE's of 3 beams tested in another type of freezing-and-thawing apparatus are excluded from this table.
- (d) These specimens were cast using project grading of fine aggregate rather than CRD-C 114 grading specified for freezing-and-thawing tests.

DATA SHEETS

STATE: Ky.	INDEX NO.:	AGGREGATE DATA SHEET	TESTED BY: CRD
LAT: 36 N	LONG.: 85 W		DATE: May 1947
LAB SYMBOL NO.: CRD G-7	TYPE OF MATERIAL: Limestone		
LOCATION: Quarry near Wolf Creek Dam located in Russell County, Ky., approximately 3 mi west of Rowena, Ky.			
PRODUCER:			
SAMPLED BY: Resident Engineer, Jamestown, Ky.			
TESTED FOR: Comparison of limestones (Wolf Creek Dam)			
PROCESSING BEFORE TESTING: Manufactured sand received from field			

GEOLOGICAL FORMATION AND AGE:

GRADING (CRD-C 103)(CUM. % PASSING):						TEST RESULTS				
SIEVE	3-6"	1 1/2-3"	3/4-1 1/2"	3/8-3/4"	FINE AGG.	3-6"	1 1/2-3"	3/4-1 1/2" (c)	3/8-3/4" (c)	FINE AGG.
BULK SP. GR., SAT SURF DRY (CRD-C 107,108):								2.68	2.68	2.67
ABSORPTION, PER CENT (CRD-C 107,108):								0.8	0.8	0.8
ORGANIC IMPURITIES, FIG. NO. (CRD-C 121):										
SOFT PARTICLES, PER CENT (CRD-C 130): *								1.3	0.2	
PER CENT LIGHTER THAN SP. GR. (CRD-C 129):										
PER CENT FLAT AND ELONGATED (CRD-C 119,120):								12.9	13.6	
WEIGHTED AV. % LOSS, 5 CYC. MgSO ₄ (c) 1/2-1", 3/4-1 1/2" (CRD-C 115)		100						8.4	16.5	3.7
ABRASION LOSS (L. A.), % (CRD-C 117):		100						29.4	26.7	
UNIT WT., LB/CU FT (CRD-C 106):		66	100					90.6	91.0	
CLAY LUMPS, % (CRD-C 118)		23	99							
COAL AND LIGNITE, % (CRD-C 122):		1	70							
SPECIFIC HEAT, BTU/LB/DEG. F. (CRD-C 124):		1	47							
NO. 4			8	100						
NO. 8				79						
NO. 16				59						
NO. 30				34						
NO. 50				30						
NO. 100				21						
NO. 200										
- 200 ^(a)				12.5						
F.M. ^(b)				2.68						

(a) CRD-C 105 (b) CRD-C 104

MORTAR-MAKING PROPERTIES (CRD-C 116)											
TYPE III CEMENT, RATIO 3 DAYS, 128 % 7 DAYS, 105 %											
LINEAR THERMAL EXPANSION X10 ⁴ DEG. F. (CRD-C 125,126):											
ROCK TYPE		PARALLEL		ACROSS		ON		AVERAGE			
								2.3			
MORTAR:											
MORTAR-BAR EXPANSION AT 100F, % (CRD-C 123):				FINE AGGREGATE				COARSE AGGREGATE			
				3 MO.		6 MO.		3 MO.		6 MO.	
LOW-ALK. CEMENT: % Na ₂ O EQUIVALENT:											
HIGH-ALK. CEMENT: % Na ₂ O EQUIVALENT:											
SOUNDNESS IN CONCRETE (CRD-C 40, 114):								F & T		HW-C D	
FINE AGG.				COARSE AGG:				DFE 300			
FINE AGG.				COARSE AGG:				DFE 300			

PETROGRAPHIC DATA (CRD-C 127):

REMARKS: * Tested by a hammer blow

STATE: Tenn. INDEX NO.: _____ AGGREGATE TESTED BY: CRD
 LAT.: 36 N LONG.: 85 W DATA SHEET DATE: May 1947

LAB. SYMBOL NO.: CRD G-8 TYPE OF MATERIAL: Limestone
 LOCATION: Pea Ridge Quarry, Clay County, Tenn. 6 3/8 mi. NE of Celina,
on secondary road 2 mi NE of Pea Ridge Store
 PRODUCER: _____

SAMPLED BY: Resident Engineer, Celina, Tenn.
 TESTED FOR: Comparison of limestones (Dale Hollow Dam)
 PROCESSING BEFORE TESTING: Manufactured sand received from field

GEOLOGICAL FORMATION AND AGE: _____

GRADING (CRD-G 103)(CUM. % PASSING):						TEST RESULTS																												
SIEVE	3-6"	1 1/2-3"	3/4-1 1/2"	3/8-3/4"	FINE AGG.	3-6"	1 1/2-3"	3/4-1 1/2" (c)	3/8-3/4" (c)	FINE AGG.																								
8 IN.						BULK SP. GR., SAT SURF DRY (CRD-C 107,108):																												
5 IN.								2.66	2.66	2.64																								
4 IN.						ABSORPTION, PER CENT (CRD-C 107,108):																												
3 IN.								0.7	0.8	1.3																								
2 1/2 IN.						ORGANIC IMPURITIES, FIG. NO. (CRD-C 121):																												
2 IN.								0	0																									
1 1/2 IN.						SOFT PARTICLES, PER CENT (CRD-C 130):*																												
1 IN.						PER CENT LIGHTER THAN SP. GR. (CRD-C 129):																												
3/4 IN.								4.4	8.2																									
3/8 IN.						PER CENT FLAT AND ELONGATED (CRD-C 119,120):																												
1/2 IN.								0.4	1.1	2.5																								
1/4 IN.						WEIGHTED AV. % LOSS, 5 CYC. MgSO ₄ ((c) 1/2-1", *4-1/4") (CRD-C 115)																												
NO. 4					100	ABRASION LOSS (L. A.), % (CRD-C 117):																												
NO. 8					93	UNIT WT., LB/CU FT (CRD-C 106):																												
NO. 16					44	CLAY LUMPS, % (CRD-C 118)																												
NO. 30					5	COAL AND LIGNITE, % (CRD-C 122):																												
NO. 50					1	SPECIFIC HEAT, BTU/LB/DEG. F. (CRD-C 124):																												
NO. 100					32	REACTIVITY WITH NaOH (CRD-C 126):																												
NO. 200					1	Sc, mm/L:																												
- 200 ^(a)					81	Rc, mm/L:																												
F.M. ^(b)					56	MORTAR-MAKING PROPERTIES (CRD-C 116)																												
					41	TYPE <u>III</u> CEMENT, RATIO <u>3</u> DAYS, <u>105</u> %, <u>7</u> DAYS, <u>110</u> %																												
					31	LINEAR THERMAL EXPANSION X10 ⁴ /DEG. F. (CRD-C 125,126):																												
					24	<table border="1"> <thead> <tr> <th>ROCK TYPE</th> <th>PARALLEL</th> <th>ACROSS</th> <th>ON</th> <th>AVERAGE</th> </tr> </thead> <tbody> <tr> <td></td> <td></td> <td></td> <td></td> <td>2.9</td> </tr> </tbody> </table>					ROCK TYPE	PARALLEL	ACROSS	ON	AVERAGE					2.9														
ROCK TYPE	PARALLEL	ACROSS	ON	AVERAGE																														
				2.9																														
					18	MORTAR:																												
					2.68	<table border="1"> <thead> <tr> <th colspan="4">FINE AGGREGATE</th> <th colspan="4">COARSE AGGREGATE</th> </tr> <tr> <th>3 MO.</th> <th>6 MO.</th> <th>9 MO.</th> <th>12 MO.</th> <th>3 MO.</th> <th>6 MO.</th> <th>9 MO.</th> <th>12 MO.</th> </tr> </thead> <tbody> <tr> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> </tr> </tbody> </table>					FINE AGGREGATE				COARSE AGGREGATE				3 MO.	6 MO.	9 MO.	12 MO.	3 MO.	6 MO.	9 MO.	12 MO.								
FINE AGGREGATE				COARSE AGGREGATE																														
3 MO.	6 MO.	9 MO.	12 MO.	3 MO.	6 MO.	9 MO.	12 MO.																											

(a) CRD-C 105 (b) CRD-C 104

MORTAR - BAR EXPANSION AT 100F, % (CRD-C 123):

LOW-ALK. CEMENT: % Na₂O EQUIVALENT:

HIGH-ALK. CEMENT: % Na₂O EQUIVALENT:

SOUNDNESS IN CONCRETE (CRD-C 40, 114):

FINE AGG. COARSE AGG: F & T HW-CD HD-CW

FINE AGG. COARSE AGG: DFE₃₀₀

FINE AGG. COARSE AGG: DFE₃₀₀

PETROGRAPHIC DATA (CRD-C 127):

MARKS: * Tested by a hammer blow

STATE: Tenn. INDEX NO.: _____ AGGREGATE TESTED BY: CRD
 LAT.: 36 N LONG.: 85 W DATA SHEET DATE: April 1947

LAB. SYMBOL NO.: LR-1 G-55 TYPE OF MATERIAL: Limestone
 LOCATION: Quarry near Center Hill Dam Site located on the Caney Fork River
in Putnam County, Tenn., about 3 mi SW of Buffalo Valley, Tenn.

PRODUCER: _____
 SAMPLED BY: _____
 TESTED FOR: Comparison with Bull Shoals (Center Hill Dam)
 PROCESSING BEFORE TESTING: Manufactured sand received from field

GEOLOGICAL FORMATION AND AGE: _____

GRADING (CRD-C 103)(CUM. % PASSING):						TEST RESULTS				
SIEVE	3-6"	1 1/2-3"	3/4-1 1/2"	3/8-3/4"	FINE AGG.	3-6"	1 1/2-3"	3/4-1 1/2" (c)	3/8-3/4" (c)	FINE AGG.
6 IN.						BULK SP. GR., SAT SURF DRY (CRD-C 107,108):	2.70	2.70	2.60	2.68
5 IN.						ABSORPTION, PER CENT (CRD-C 107,108):	0.4	0.4	0.6	0.6
4 IN.						ORGANIC IMPURITIES, FIG. NO. (CRD-C 121):	—	—	—	2
3 IN.	100					SOFT PARTICLES, PER CENT (CRD-C 130):*	0	0	5	—
2 1/2 IN.						PER CENT LIGHTER THAN SP. GR. (CRD-C 120):				—
2 IN.		63	100			PER CENT FLAT AND ELONGATED (CRD-C 119,120):	1.4	3.0	5.5	
1 1/2 IN.		21	90			WEIGHTED AV. % LOSS, 5 CYC. MgSO ₄ ((c) 1/2-1", 3/4-1 1/2") (CRD-C 115)		0.8	11.9	9.2
1 IN.		8	39	100		ABRASION LOSS (L. A.), %, (CRD-C 117):				23.2
3/4 IN.		6	7	94		UNIT WT., LB/CU FT (CRD-C 106):	91.7	90.1	92.8	116.4
1/2 IN.		5	2	61		CLAY LUMPS, % (CRD-C 118)				
3/8 IN.		4	1	38		COAL AND LIGNITE, % (CRD-C 122):	—	—	—	—
NO. 4		3	1	7	98	SPECIFIC HEAT, BTU/LB/DEG. F. (CRD-C 124):				
NO. 8					77	REACTIVITY WITH NaOH (CRD-C 128) Sc, mm/L:				
NO. 16					48	Rc, mm/L:				
NO. 30					30	MORTAR-MAKING PROPERTIES (CRD-C 116)				
NO. 50					21	TYPE <u>III</u> CEMENT, RATIO <u>3</u> DAYS, <u>127</u> %, <u>7</u> DAYS, <u>118</u> %				
NO. 100					16	LINEAR THERMAL EXPANSION X10 9 DEG. F. (CRD-C 125,126):				
NO. 200										
- 200 ^(a)					12					
F.M. ^(f)										

(a) CRD-C 105 (b) CRD-C 104 MORTAR:

MORTAR-BAR EXPANSION AT 100F, % (CRD-C 123):	FINE AGGREGATE				COARSE AGGREGATE			
	3 MO.	6 MO.	9 MO.	12 MO.	3 MO.	6 MO.	9 MO.	12 MO.
LOW-ALK. CEMENT: % Na ₂ O EQUIVALENT:								
HIGH-ALK. CEMENT: % Na ₂ O EQUIVALENT:								

SOUNDNESS IN CONCRETE (CRD-C 40, 114):		
FINE AGG.	COARSE AGG:	F & T HW-CO HD-CW
		DFE 300
		DFE 300

PETROGRAPHIC DATA (CRD-C 127):

* Tested by a hammer blow

STATE: Ga.	INDEX NO.:	AGGREGATE	TESTED BY: CRD
LAT 34 N	LONG. 84 W	DATA SHEET	DATE: Feb. 1948
LAB SYMBOL NO. MOB-2G-3(3) & MOB-2G-3(s)(2)		TYPE OF MATERIAL: Limestone	
LOCATION: Shinnell Quarry at White, Ga., 10 miles north of Allatoona Dam Site on the L & N Railroad and U. S. Highway No. 411			
PRODUCER: Lambert Brothers Inc., Knoxville, Tenn.			
SAMPLED BY:			
TESTED FOR: Allatoona Dam			
PROCESSING BEFORE TESTING:			
GEOLOGICAL FORMATION AND AGE:			

GRADING (CRD-G 103)(CUM. % PASSING):						TEST RESULTS				
SIEVE	3-6"	1 1/2-3"	3/4-1 1/2"	3/8-3/4"	FINE AGG.	3-6"	1 1/2-3"	3/4-1 1/2" (c)	3/8-3/4" (c)	FINE AGG.
						BULK SP. GR., SAT SURF DRY (CRD-C 107,108):				
8 IN.								2.80	2.88	2.83
5 IN.						ABSORPTION, PER CENT (CRD-C 107,108):				
4 IN.								0.3	0.6	0.7
3 IN.						ORGANIC IMPURITIES, FIG. NO. (CRD-C 121):				
2 1/2 IN.						SOFT PARTICLES, PER CENT (CRD-C 130):*				
2 IN.								0.0	0.0	—
1 1/2 IN.						PER CENT LIGHTER THAN SP. GR. (CRD-C 129):				
1 IN.								23.2	29.5	—
3/4 IN.						PER CENT FLAT AND ELONGATED (CRD-C 119,120):				
3/8 IN.								0.2	0.7	3.5
1/2 IN.			100			WEIGHTED AV. % LOSS, 5 CYC. MgSO ₄ (1/2-1", 3/4-1 1/2") (CRD-C 115)				
1/4 IN.			97							17.3
NO. 4			47	100		ABRASION LOSS (L. A.), % (CRD-C 117):				
NO. 8			12	99		UNIT WT., LB./CU FT (CRD-C 106):				
NO. 16			4	78		CLAY LUMPS, % (CRD-C 118)				
NO. 30			2	49		COAL AND LIGNITE, % (CRD-C 122):				
NO. 50			1	2	100	SPECIFIC HEAT, BTU/LB./DEG. F. (CRD-C 124):				
NO. 100					86	REACTIVITY WITH NaOH (CRD-C 128):				
NO. 200					59	S _c , mM/L:				
-200 ^(a)					33	R _c , mM/L:				
F.M. ^(b)					19	MORTAR-MAKING PROPERTIES (CRD-C 116)				
					11	TYPE III CEMENT, RATIO 3 DAYS, 150 % 7 DAYS, 138 %				
					5.2	LINEAR THERMAL EXPANSION X10 ⁶ DEG. F. (CRD-C 125,126):				
					5.8	ROCK TYPE				
					2.92	PARALLEL				
						ACROSS				
						ON				
						AVERAGE				

(a) CRD-C 105	(b) CRD-C 104	MORTAR:				FINE AGGREGATE				COARSE AGGREGATE			
MORTAR - BAR EXPANSION AT 100F, % (CRD-C 123):		3 MO.	6 MO.	9 MO.	12 MO.	3 MO.	6 MO.	9 MO.	12 MO.	3 MO.	6 MO.	9 MO.	12 MO.
LOW-ALK. CEMENT: % Na ₂ O EQUIVALENT:													
HIGH-ALK. CEMENT: % Na ₂ O EQUIVALENT:													
SOUNDNESS IN CONCRETE (CRD-C 40, 114):										F & T	HW-C D	HD-CW	
FINE AGG.					COARSE AGG:					DFE 300			
FINE AGG.					COARSE AGG:					DFE 300			

PETROGRAPHIC DATA (CRD-C 127):

REMARKS:

* Tested by a hammer blow

STATE: Ill.	INDEX NO.:	AGGREGATE DATA SHEET	TESTED BY: CRD
LAT 38 N	LONG: 90 W		DATE: Oct. 1947
LAB SYMBOL NO.: STL-2G-2, STL-2G-2(S)	TYPE OF MATERIAL: Limestone		
LOCATION: Columbia Quarry located near Krause, Ill.			
PRODUCER: Columbia Quarry Co., St. Louis, Mo.			
SAMPLED BY: F. Schneider			
TESTED FOR: Chain of Rocks Lock			
PROCESSING BEFORE TESTING:			
GEOLOGICAL FORMATION AND AGE:			

GRADING (CRD-C 103)(CUM. % PASSING):						TEST RESULTS				3-6"	1 1/2-3"	3/4-1 1/2" (C)	3/8-3/4" (C)	FINE AGG.							
SIEVE	3-6"	1 1/2-3"	3/4-1 1/2"	3/8-3/4"	FINE AGG.	BULK SP. GR, SAT SURF DRY (CRD-C 107,108):	ABSORPTION, PER CENT (CRD-C 107,108):	ORGANIC IMPURITIES, FIG. NO. (CRD-C 121):	SOFT PARTICLES, PER CENT (CRD-C 130): *	PER CENT LIGHTER THAN SP. GR. (CRD-C 129):	PER CENT FLAT AND ELONGATED (CRD-C 119,120):	WEIGHTED AV. % LOSS, 5 CYC. MgSO ₄ ((C) 1/2-1", *4-1/2") (CRD-C 115)	ABRASION LOSS (L. A.), % (CRD-C 117):	UNIT WT., LB/CU FT (CRD-C 106):	CLAY LUMPS, % (CRD-C 118)	COAL AND LIGNITE, % (CRD-C 122):	SPECIFIC HEAT, BTU/LB/DEG. F. (CRD-C 124):	REACTIVITY WITH NaOH (CRD-C 128): Sc, mM/L: Rc, mM/L:			
8 IN																			2.63	2.63	
5 IN																				1.5	1.8
4 IN																					
3 IN																					
2 1/2 IN																					
2 IN																					
1 1/2 IN																					
1 IN					100																
3/4 IN					76																
3/8 IN					51																
3/16 IN					31																
NO. 4					3	100															
NO. 8						94															
NO. 16						76															
NO. 30						44															
NO. 50						20															
NO. 100						5															
NO. 200																					
- 200 ^(a)						0.9															
F.M. ^(b)						2.61															

(a) CRD-C 105 (b) CRD-C 104

MORTAR-MAKING PROPERTIES (CRD-C 118)
 TYPE III CEMENT, RATIO 3 DAYS, 115 %, 7 DAYS, 121 %

LINEAR THERMAL EXPANSION X10⁶ DEG. F. (CRD-C 125,126):

ROCK TYPE	PARALLEL	ACROSS	ON	AVERAGE

MORTAR:

MORTAR - BAR EXPANSION AT 100F, % (CRD-C 123):	FINE AGGREGATE				COARSE AGGREGATE			
	3 MO.	6 MO.	9 MO.	12 MO.	3 MO.	6 MO.	9 MO.	12 MO.
LOW-ALK. CEMENT: % Na ₂ O EQUIVALENT:								
HIGH-ALK. CEMENT: % Na ₂ O EQUIVALENT:								

SOUNDNESS IN CONCRETE (CRD-C 40, 114):

FINE AGG.	COARSE AGG:	DFE 300

PETROGRAPHIC DATA (CRD-C 127):

REMARKS:

* Tested by a hammer blow

STATE: Ill.	INDEX NO.:	AGGREGATE DATA SHEET	TESTED BY: CRD
LAT: 38 N	LONG: 90 W	DATE: Oct. 1947	
LAB. SYMBOL NO.: STL-2 G-1	TYPE OF MATERIAL: Limestone		
LOCATION: Falling Spring Quarry located in St. Clair County near Falling Spring, Ill.			
PRODUCER: East St. Louis Limestone Co., East St. Louis, Ill.			
SAMPLED BY: F. Schneider			
TESTED FOR: Chain of Rocks Lock			
PROCESSING BEFORE TESTING: Crushed and graded at CRD			

GEOLOGICAL FORMATION AND AGE:

GRADING (CRD-C 103)(CUM. % PASSING):					TEST RESULTS				FINE AGG.	
SIEVE	3-6"	1 1/2-3"	3/4-1 1/2"	3/8-3/4"	FINE AGG.	3-6"	1 1/2-3"	3/4-1 1/2" (c)	3/8-3/4" (c)	FINE AGG.
6 IN.					BULK SP. GR., SAT SURF DRY (CRD-C 107,108):					2.64
5 IN.					ABSORPTION, PER CENT (CRD-C 107,108):					1.6
4 IN.					ORGANIC IMPURITIES, FIG. NO. (CRD-C 121):	---	---	---	---	
3 IN.					SOFT PARTICLES, PER CENT (CRD-C 130): *					0.3
2 1/2 IN.					PER CENT LIGHTER THAN SP. GR. (CRD-C 129):					
2 IN.					PER CENT FLAT AND ELONGATED (CRD-C 119,120):					10.4
1 1/2 IN.					WEIGHTED AV. % LOSS, 5 CYC. MgSO ₄ (c) 1/2-1", 3/4-1 1/2" (CRD-C 115)					10.1
1 IN.					ABRASION LOSS (L. A.), %, (CRD-C 117):					26.1
3/4 IN.				100	UNIT WT., LB/CU FT (CRD-C 108):					
1/2 IN.				76	CLAY LUMPS, % (CRD-C 118)					
3/8 IN.				52	COAL AND LIGNITE, % (CRD-C 122):	---	---	---	---	
3/16 IN.				30	SPECIFIC HEAT, BTU/LB/DEG. F. (CRD-C 124):					
NO. 4				3	REACTIVITY WITH NaOH (CRD-C 128):	Sc, mM/L:				
NO. 8						Re, mM/L:				
NO. 16					MORTAR-MAKING PROPERTIES (CRD-C 116)					
NO. 30					TYPE _____ CEMENT, RATIO _____ DAYS, _____ % _____ DAYS, _____ %					
NO. 50					LINEAR THERMAL EXPANSION X10 9/DEG. F. (CRD-C 125,126):					
NO. 100					ROCK TYPE					AVERAGE
NO. 200					PARALLEL	ACROSS	ON			
- 200 ^(a)										
F.M. ^(b)										

(a) CRD-C 105 (b) CRD-C 104

MORTAR:

MORTAR-BAR EXPANSION AT 100F, % (CRD-C 123):	FINE AGGREGATE				COARSE AGGREGATE			
	3 MO.	6 MO.	9 MO.	12 MO.	3 MO.	6 MO.	9 MO.	12 MO.
LOW-ALK. CEMENT: % Na ₂ O EQUIVALENT:								
HIGH-ALK. CEMENT: % Na ₂ O EQUIVALENT:								

SOUNDNESS IN CONCRETE (CRD-C 40, 114):			
FINE AGG.	COARSE AGG:	F & T	HW-C D
		DFE ₃₀₀	
		DFE ₃₀₀	

PETROGRAPHIC DATA (CRD-C 127):

REMARKS:
* Tested by a hammer blow

STATE: Miss.	INDEX NO.:	AGGREGATE DATA SHEET	TESTED BY: CRD
LAT 31 N	LONG.: 90 W		DATE: 1947
LAB. SYMBOL NO.: CRD S-4		TYPE OF MATERIAL: Siliceous sand	
LOCATION: Georgetown, Miss.			
PRODUCER: Greene Brothers, Georgetown, Miss.			
SAMPLED BY:			
TESTED FOR: Comparison of limestones			
PROCESSING BEFORE TESTING:			
GEOLOGICAL FORMATION AND AGE:			

GRADING (CRD-C 103)(CUM. % PASSING):					TEST RESULTS					3-6"	1 1/2-3"	3/4-1 1/2" (c)	3/8-3/4" (c)	FINE AGG.																					
SIEVE	3-6"	1 1/2-3"	3/4-1 1/2"	3/8-3/4"	FINE AGG.																														
						BULK SP. GR., SAT SURF DRY (CRD-C 107,108):									2.60																				
6 IN.						ABSORPTION, PER CENT (CRD-C 107,108):									0.9																				
5 IN.						ORGANIC IMPURITIES, FIG. NO. (CRD-C 121):					---	---	---	---	2																				
4 IN.						SOFT PARTICLES, PER CENT (CRD-C 130):																													
3 IN.						PER CENT LIGHTER THAN SP. GR. (CRD-C 129):																													
2 1/2 IN.						PER CENT FLAT AND ELONGATED (CRD-C 119,120):																													
2 IN.						WEIGHTED AV. % LOSS, 3 CYC. MgSO ₄ ((c) 1/2-1", 3/4-1 1/2") (CRD-C 115)									2.8																				
1 1/2 IN.						ABRASION LOSS (L. A.), % (CRD-C 117):																													
1 IN.						UNIT WT., LB/CU FT (CRD-C 106):									112																				
3/4 IN.						CLAY LUMPS, % (CRD-C 118):																													
3/8 IN.						COAL AND LIGNITE, % (CRD-C 122):					---	---	---	---																					
3/16 IN.						SPECIFIC HEAT, BTU/LB/DEG. F. (CRD-C 124):																													
NO. 4					97	REACTIVITY WITH NaOH (CRD-C 128):					S _c , mM/L:																								
NO. 8					87						R _c , mM/L:																								
NO. 16					74	MORTAR-MAKING PROPERTIES (CRD-C 116)																													
NO. 30					48	TYPE _____ CEMENT, RATIO _____ DAYS, _____ % _____ DAYS, _____ %																													
NO. 50					9	LINEAR THERMAL EXPANSION X10 1/DEG. F. (CRD-C 125,126):																													
NO. 100					1	<table border="1"> <thead> <tr> <th>ROCK TYPE</th> <th>PARALLEL</th> <th>ACROSS</th> <th>ON</th> <th>AVERAGE</th> </tr> </thead> <tbody> <tr><td> </td><td> </td><td> </td><td> </td><td> </td></tr> <tr><td> </td><td> </td><td> </td><td> </td><td> </td></tr> <tr><td> </td><td> </td><td> </td><td> </td><td> </td></tr> </tbody> </table>					ROCK TYPE	PARALLEL	ACROSS	ON	AVERAGE																				
ROCK TYPE	PARALLEL	ACROSS	ON	AVERAGE																															
NO. 200					1																														
- 200 ^(a)					1																														
F.M. ^(b)					2.81																														

(a) CRD-C 105 (b) CRD-C 104		MORTAR:				FINE AGGREGATE				COARSE AGGREGATE			
MORTAR-BAR EXPANSION AT 100F, % (CRD-C 123):		3 MO.	6 MO.	9 MO.	12 MO.	3 MO.	6 MO.	9 MO.	12 MO.				
LOW-ALK. CEMENT:	% Na ₂ O EQUIVALENT:												
HIGH-ALK. CEMENT:	% Na ₂ O EQUIVALENT:												
SOUNDNESS IN CONCRETE (CRD-C 40, 114):										F & T	HW-C D	HD-CW	
FINE AGG.					COARSE AGG:					DFE ₃₀₀			
FINE AGG.					COARSE AGG:					DFE ₃₀₀			

PETROGRAPHIC DATA (CRD-C 127):

REMARKS:

STATE: **Miss.** INDEX NO.: _____ AGGREGATE TESTED BY: **CRD**
 LAT.: _____ LONG.: _____ DATA SHEET DATE: **1948**

LAB. SYMBOL NO.: **CRD S-4 (3)** TYPE OF MATERIAL: **Siliceous sand**
 LOCATION: **Georgetown, Miss.**

PRODUCER: **Greene Brothers, Georgetown, Miss.**

SAMPLED BY: _____
 TESTED FOR: **Comparison of limestones**

PROCESSING BEFORE TESTING: _____

GEOLOGICAL FORMATION AND AGE: _____

GRADING (CRD-C 103)(CUM. % PASSING):						TEST RESULTS				3-6"	1 1/2-3"	3/4-1 1/2" (c)	3/8-3/4" (c)	FINE AGG.
SIEVE	3-6"	1 1/2-3"	3/4-1 1/2"	3/8-3/4"	FINE AGG.	BULK SP. GR., SAT SURF DRY (CRD-C 107,108):								
6 IN.						ABSORPTION, PER CENT (CRD-C 107,108):								2.63
5 IN.						ORGANIC IMPURITIES, FIG. NO. (CRD-C 121):	---	---	---	---				0.5
4 IN.						SOFT PARTICLES, PER CENT (CRD-C 130):								1
3 IN.						PER CENT LIGHTER THAN SP. GR. _____ (CRD-C 129):								---
2 1/2 IN.						PER CENT FLAT AND ELONGATED (CRD-C 119,120):								---
2 IN.						WEIGHTED AV. % LOSS, 5 CYC. MgSO ₄ (c) 1/2-1", 3/4-1/2" (CRD-C 115)								2.9
1 1/2 IN.						ABRASION LOSS (L. A.), %, (CRD-C 117):								---
1 IN.						UNIT WT., LB/CU FT (CRD-C 106):								---
3/4 IN.						CLAY LUMPS, % (CRD-C 118)								---
1/2 IN.						COAL AND LIGNITE, % (CRD-C 122):	---	---	---	---				---
3/8 IN.						SPECIFIC HEAT, BTU/LB/DEG. F. (CRD-C 124):								---
NO. 4					98	REACTIVITY WITH NaOH (CRD-C 128):	Sc, mM/L							
NO. 8					89		Rc, mM/L							
NO. 16					76	MORTAR-MAKING PROPERTIES (CRD-C 116)								
NO. 30					52	TYPE III CEMENT, RATIO 3 DAYS, 101 %, 7 DAYS, 104 %								
NO. 50					11	LINEAR THERMAL EXPANSION X10 9/DEG. F. (CRD-C 125,126):								
NO. 100					1									
NO. 200														
- 200 ^(a)														
F.M. ^(b)					2.72									

(a) CRD-C 105 (b) CRD-C 104 MORTAR:

MORTAR-BAR EXPANSION AT 100F, % (CRD-C 123):	FINE AGGREGATE				COARSE AGGREGATE			
	3 MO.	6 MO.	9 MO.	12 MO.	3 MO.	6 MO.	9 MO.	12 MO.
LOW-ALK. CEMENT: % Na ₂ O EQUIVALENT:								
HIGH-ALK. CEMENT: % Na ₂ O EQUIVALENT:								

SOUNDNESS IN CONCRETE (CRD-C 40, 114):			F & T	HW-C&D	HD-CW
FINE AGG.	COARSE AGG:		DFE ₃₀₀		
FINE AGG.	COARSE AGG:		DFE ₃₀₀		

PETROGRAPHIC DATA (CRD-C 127):

REMARKS:

STATE Conn.	INDEX NO.:	AGGREGATE DATA SHEET	TESTED BY: CRD
LAT. 39 N	LONG.: 72 W		DATE: Sept. 1946

LAB SYMBOL NO.: _____ TYPE OF MATERIAL: **Trap rock**

LOCATION **North Branford, Conn.**

PRODUCER **New Haven Trap Rock Co., New Haven, Conn.**

SAMPLED BY _____

TESTED FOR: **Comparison of limestones**

PROCESSING BEFORE TESTING: _____

GEOLOGICAL FORMATION AND AGE: _____

GRADING (CRD-C 103)(CUM. % PASSING):						TEST RESULTS				2"	1-1/2"	3/4"	1/2"	FINE AGG.
SEIVE	2"	1-1/2"	1"	3/4"	FINE AGG.	BULK SP. GR., SAT SURF DRY (CRD-C 107,108):	2.90	2.95	2.90	2.92				
6 IN						ABSORPTION, PER CENT (CRD-C 107,108):	0.3	0.7	0.8	1.3				
5 IN						ORGANIC IMPURITIES, FIG. NO. (CRD-C 121):	—	—	—	—				
4 IN						SOFT PARTICLES, PER CENT (CRD-C 130):*	0	0	0	0				
3 IN	100					PER CENT LIGHTER THAN SP. GR. (CRD-C 129):								
2 1/2 IN						PER CENT FLAT AND ELONGATED (CRD-C 119,120):	9	18	12	1				
2 IN	96					WEIGHTED AV. % LOSS, 5 CYC. MgSO ₄ ((C) 1/2-1", (A) 4-1/2") (CRD-C 105):	0.5	0.7	1.0					
1 1/2 IN	45	100				ABRASION LOSS (L. A.), % (CRD-C 117):		11.9	11.9	11.9				
1 IN	5	52				UNIT WT., LB/CU FT (CRD-C 108):	101.9	97.1	100.6	99.8				
3/4 IN	2	13	100	100		CLAY LUMPS, % (CRD-C 118)								
1/2 IN	1	2	41	100		COAL AND LIGNITE, % (CRD-C 122):								
3/8 IN		1	3	57		SPECIFIC HEAT, BTU/LB/DEG. F. (CRD-C 124):								
NO. 4		0	1	8		REACTIVITY WITH NaOH (CRD-C 128):	Sc, mM/L:							
NO. 8						Rc, mM/L:								
NO. 16						MORTAR-MAKING PROPERTIES (CRD-C 116)								
NO. 30						TYPE _____ CEMENT, RATIO _____ DAYS, _____ % _____ DAYS, _____ %								
NO. 50						LINEAR THERMAL EXPANSION X10 9/DEG. F. (CRD-C 125,126):								
NO. 100														
NO. 200														
- 200 ^(a)														
F M (b)														

(a) CRD-C 105 (b) CRD-C 104

MORTAR-BAR EXPANSION AT 100F, % (CRD-C 123):	FINE AGGREGATE				COARSE AGGREGATE			
	3 MO.	6 MO.	9 MO.	12 MO.	3 MO.	6 MO.	9 MO.	12 MO.
LOW-ALK. CEMENT: % Na ₂ O EQUIVALENT:								
HIGH-ALK. CEMENT: % Na ₂ O EQUIVALENT:								
SOUNDNESS IN CONCRETE (CRD-C 40, 114):						F & T	HW-CO	HD-CW
FINE AGG. COARSE AGG:					DFE 300			
FINE AGG. COARSE AGG:					DFE 300			

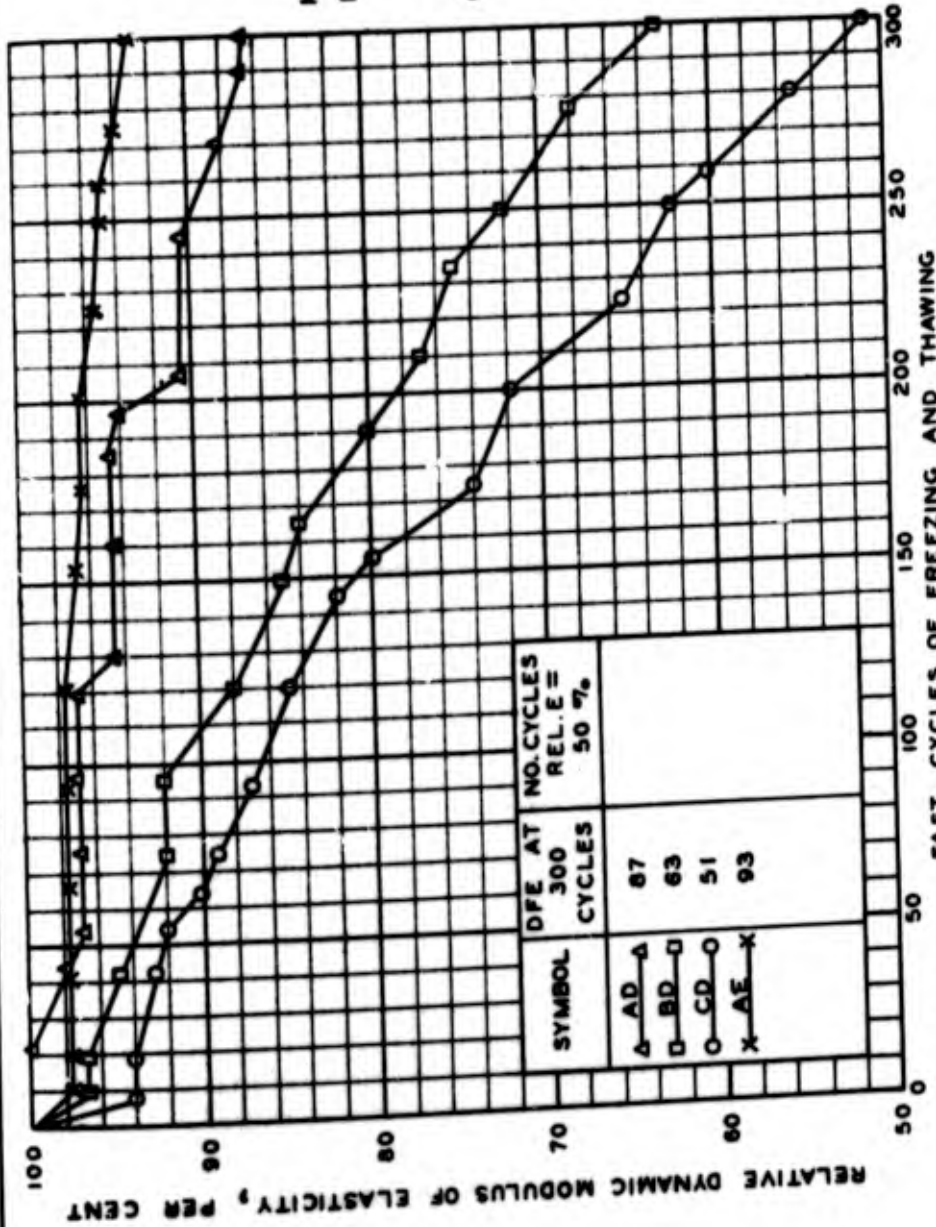
PETROGRAPHIC DATA (CRD-C 127):

REMARKS:
* Tested by a hammer blow

PLATES

METHOD: CRD-C-114-48

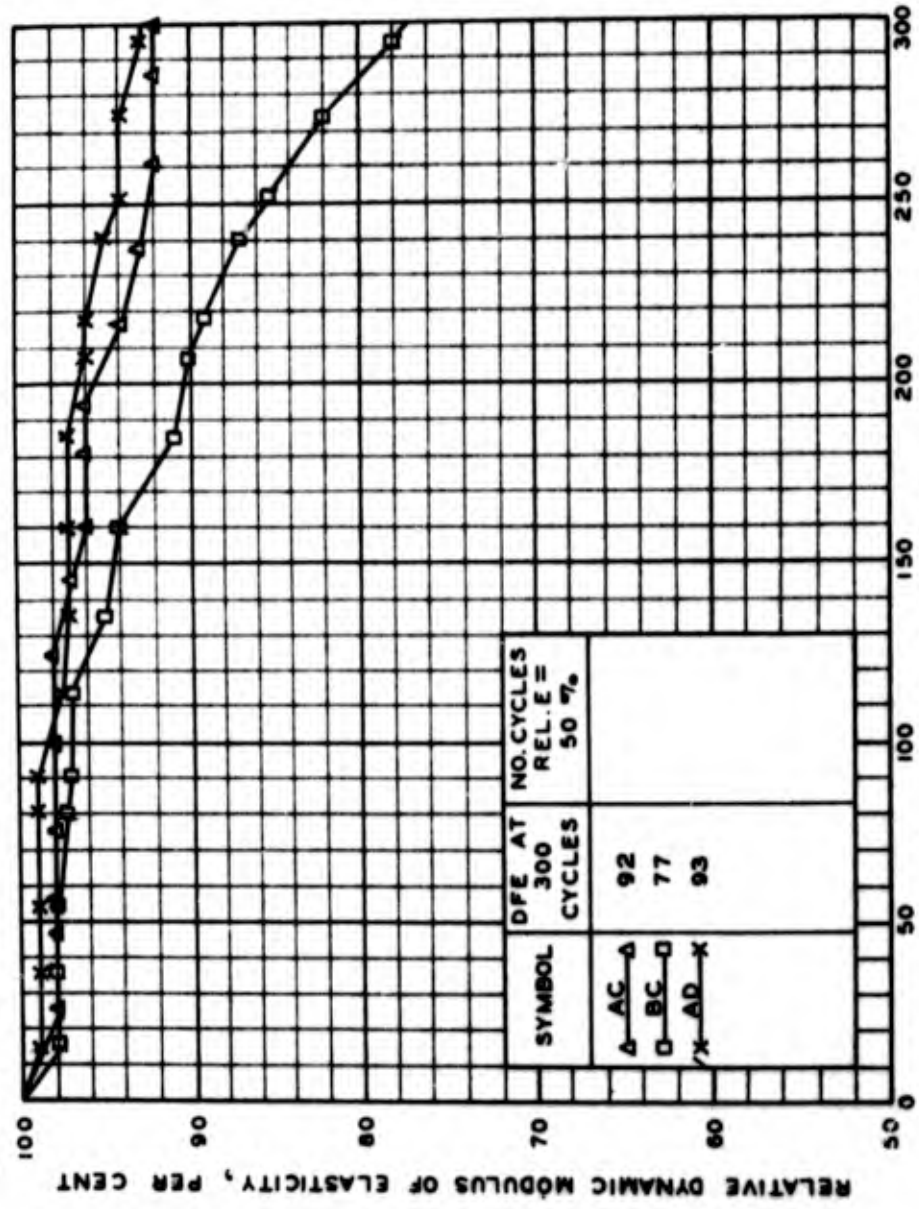
- FINE AGG:
 A. CRD G-4 (S)
 B. STANDARD
 C. SAC-1 S-1
- COARSE AGG:
 D. CRD G-4
 E. STANDARD



SYMBOL	DPE AT 300 CYCLES	NO. CYCLES REL. E = 50 %
△ AD	87	
□ BD	63	
○ CD	51	
× AE	93	

RESISTANCE OF CONCRETE BEAMS TO ACCELERATED FREEZING AND THAWING
 ALTON LOCK AND DAM AGGREGATES (9 DAYS CURING)

METHOD: CRD-C-114-48
 FINE AGG:
 A. CRD G-6 (S)
 B. STANDARD
 COARSE AGG:
 C. CRD G-6
 D. STANDARD



RESISTANCE OF CONCRETE BEAMS TO ACCELERATED FREEZING AND THAWING
 BLUESTONE DAM AGGREGATE (9 DAYS CURING)

METHOD: CRD-C-114-48

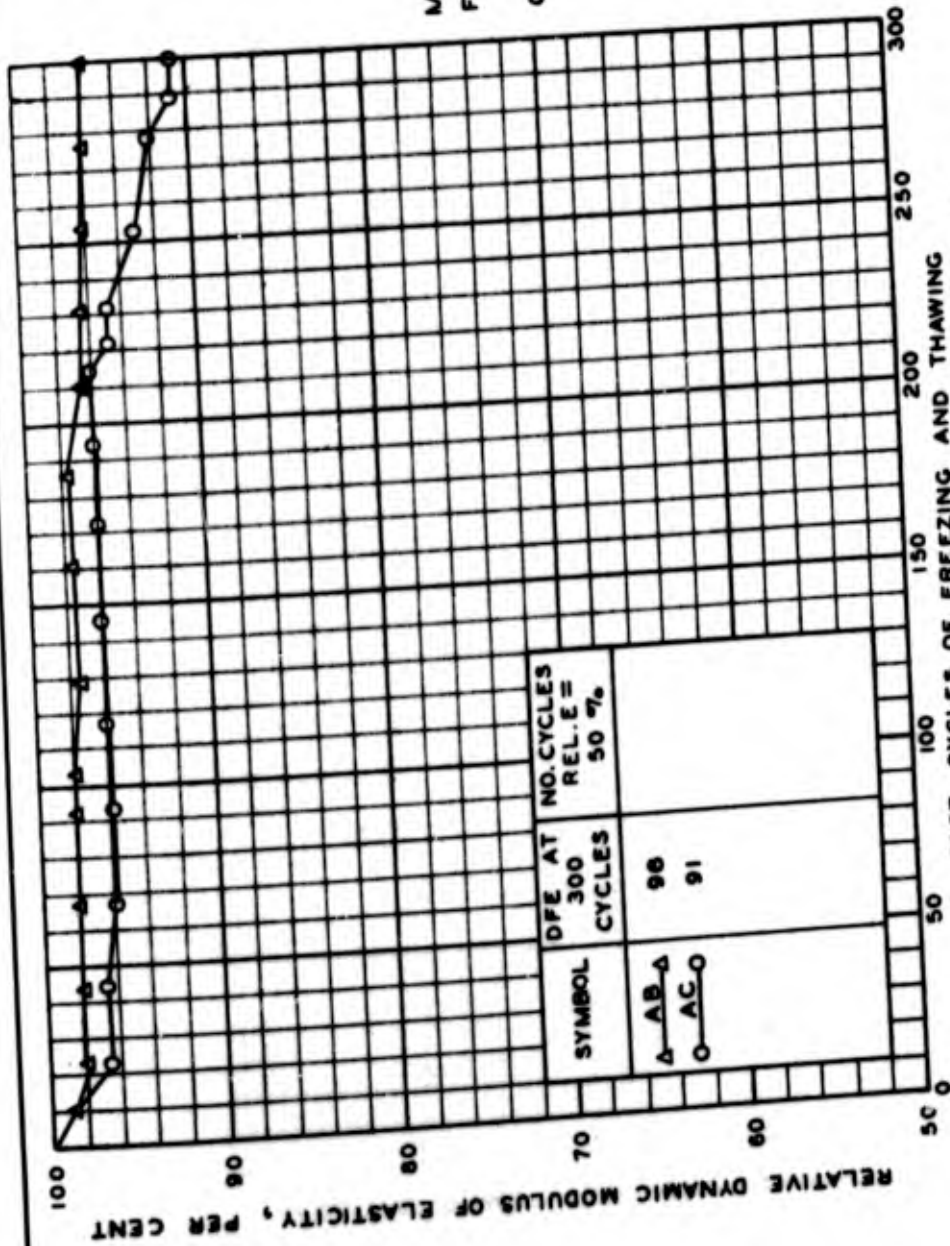
FINE AGG:

A. CRD G-6 (S)

COARSE AGG:

B. CRD G-6

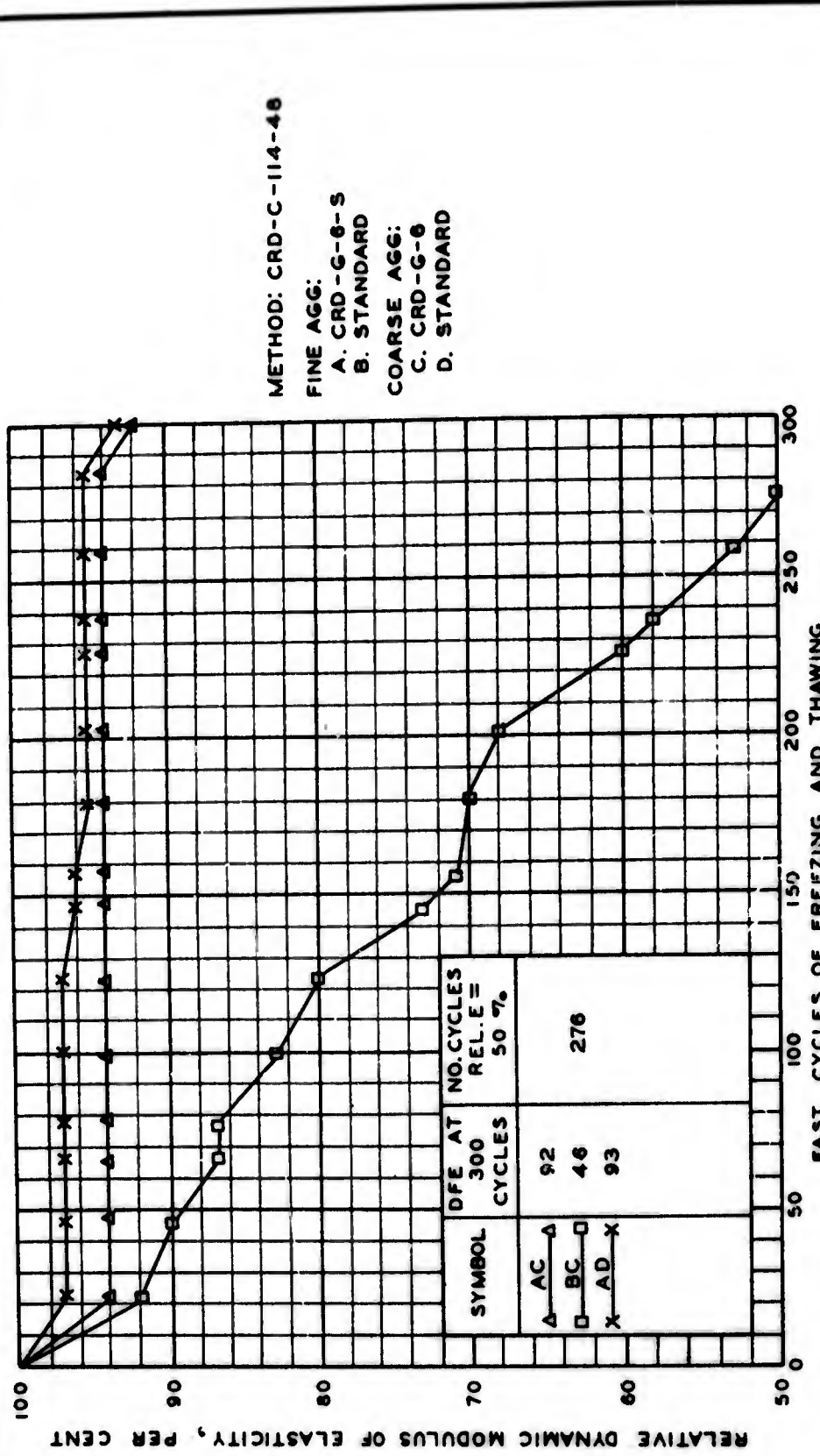
C. STANDARD



FAST CYCLES OF FREEZING AND THAWING

RESISTANCE OF CONCRETE BEAMS TO ACCELERATED FREEZING AND THAWING

BLUESTONE DAM AGGREGATE (21 DAYS CURING)



METHOD: CRD-C-114-48

FINE AGG:
 A. CRD-G-6-S
 B. STANDARD

COARSE AGG:
 C. CRD-G-6
 D. STANDARD

RESISTANCE OF CONCRETE BEAMS TO ACCELERATED FREEZING AND THAWING
 BLUESTONE DAM AGGREGATE (1 YEAR CURING)

SYMBOL	DFE AT 300 CYCLES	NO. CYCLES REL.E = 50 %
△ AC	92	276
□ BC	46	
X AD	93	

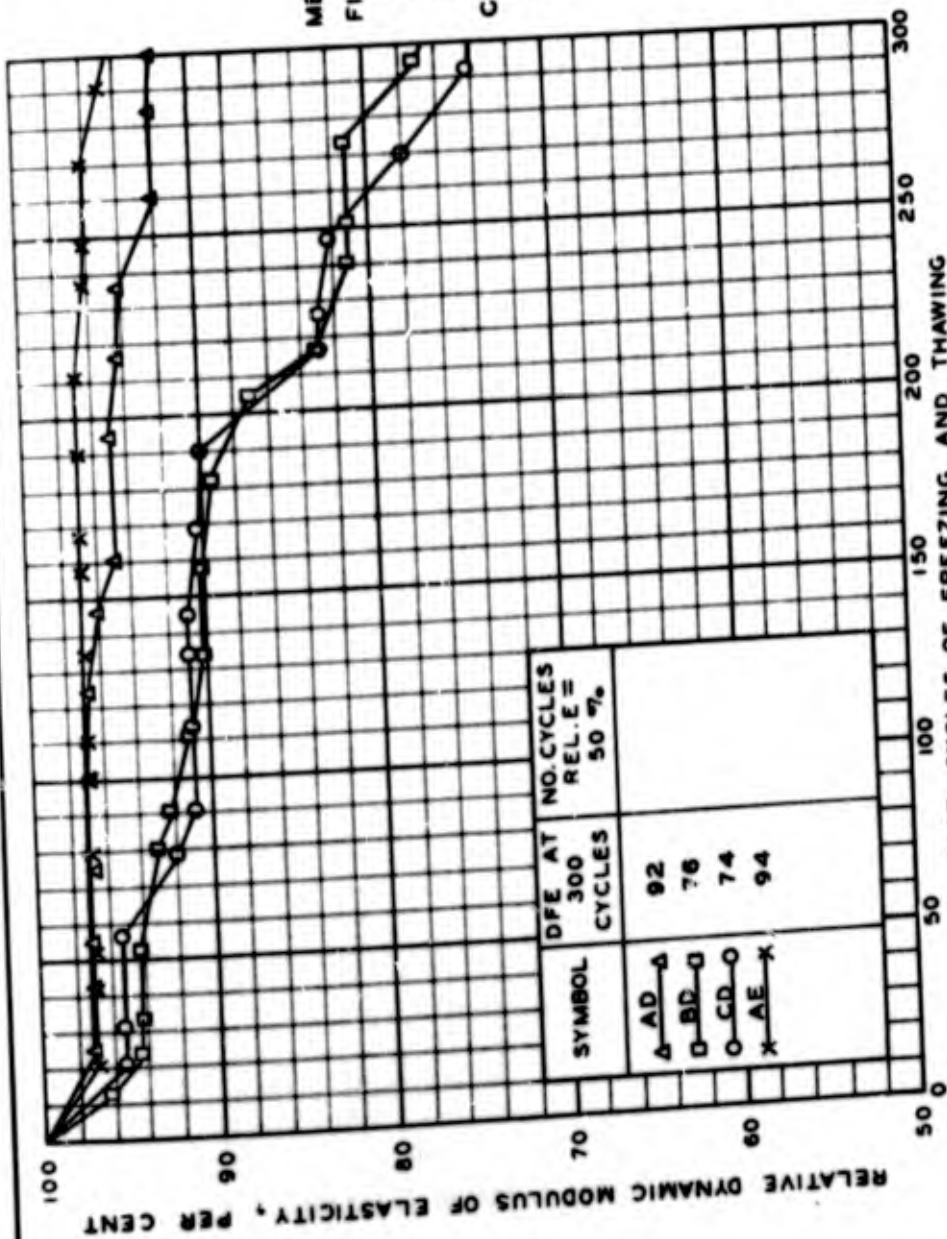
METHOD: CRD-C-114-48

FINE AGG:

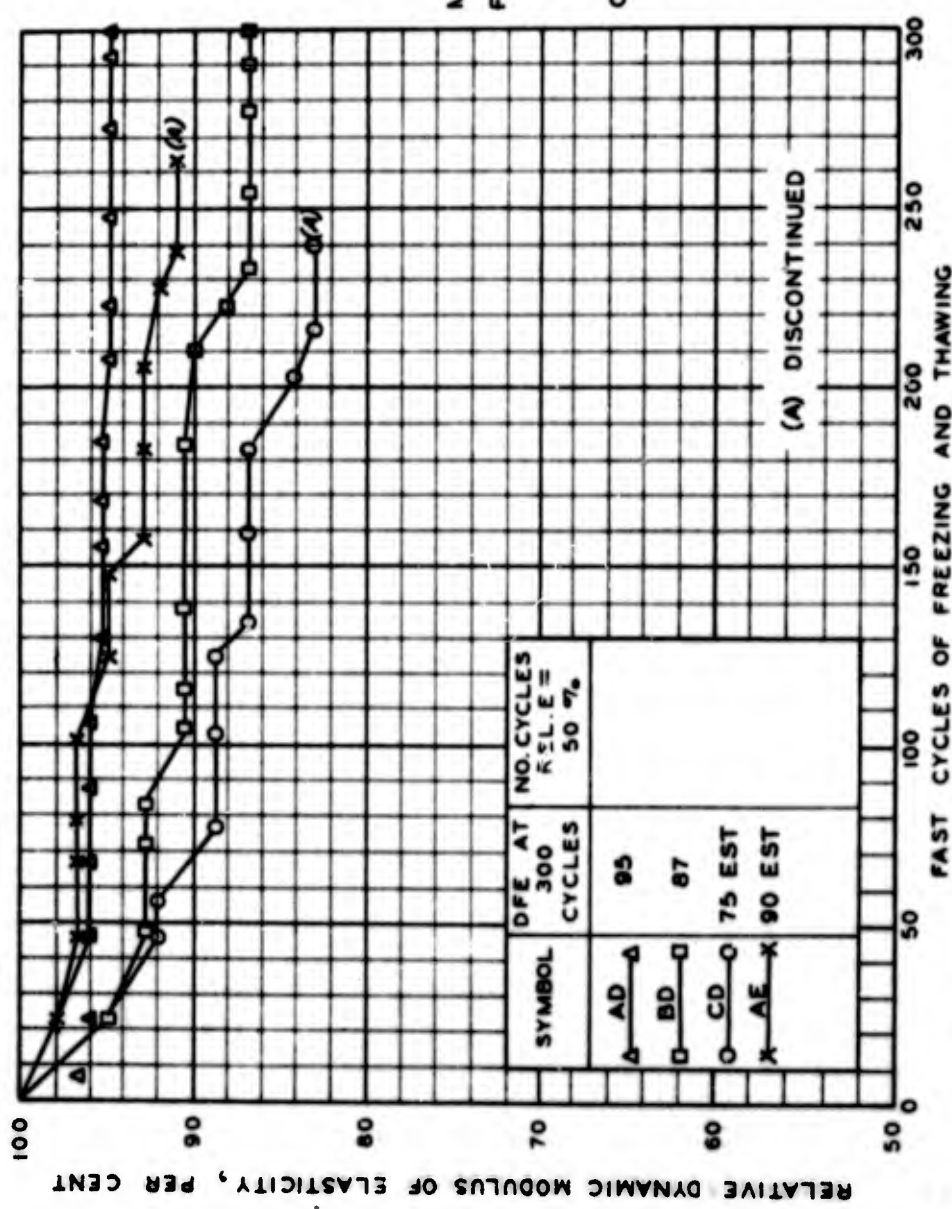
- A. CRD G-7 (S)
- B. STANDARD
- C. SAC-1 S-1

COARSE AGG:

- D. CRD G-7
- E. STANDARD



RESISTANCE OF CONCRETE BEAMS TO ACCELERATED FREEZING AND THAWING
WOLF CREEK DAM AGGREGATE (9 DAYS CURING)



METHOD: CRD-C-114-48

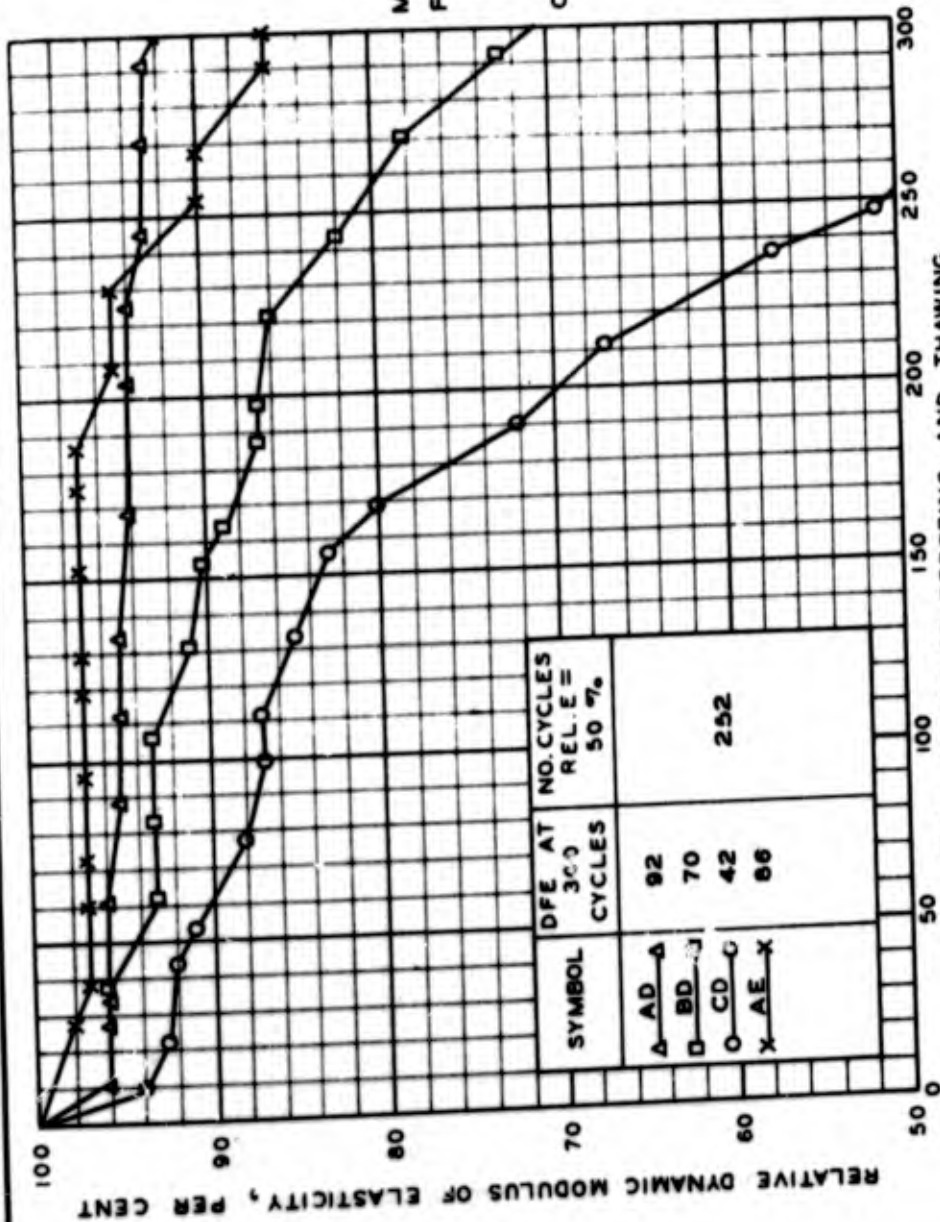
FINE AGG:

- A. CRD G-7 (S)
- B. STANDARD
- C. SAC-1 S-1

COARSE AGG:

- D. CRD G-7
- E. STANDARD

RESISTANCE OF CONCRETE BEAMS TO ACCELERATED FREEZING AND THAWING
WOLF CREEK DAM AGGREGATE (21 DAYS CURING)



METHOD: CRD-C-114-48

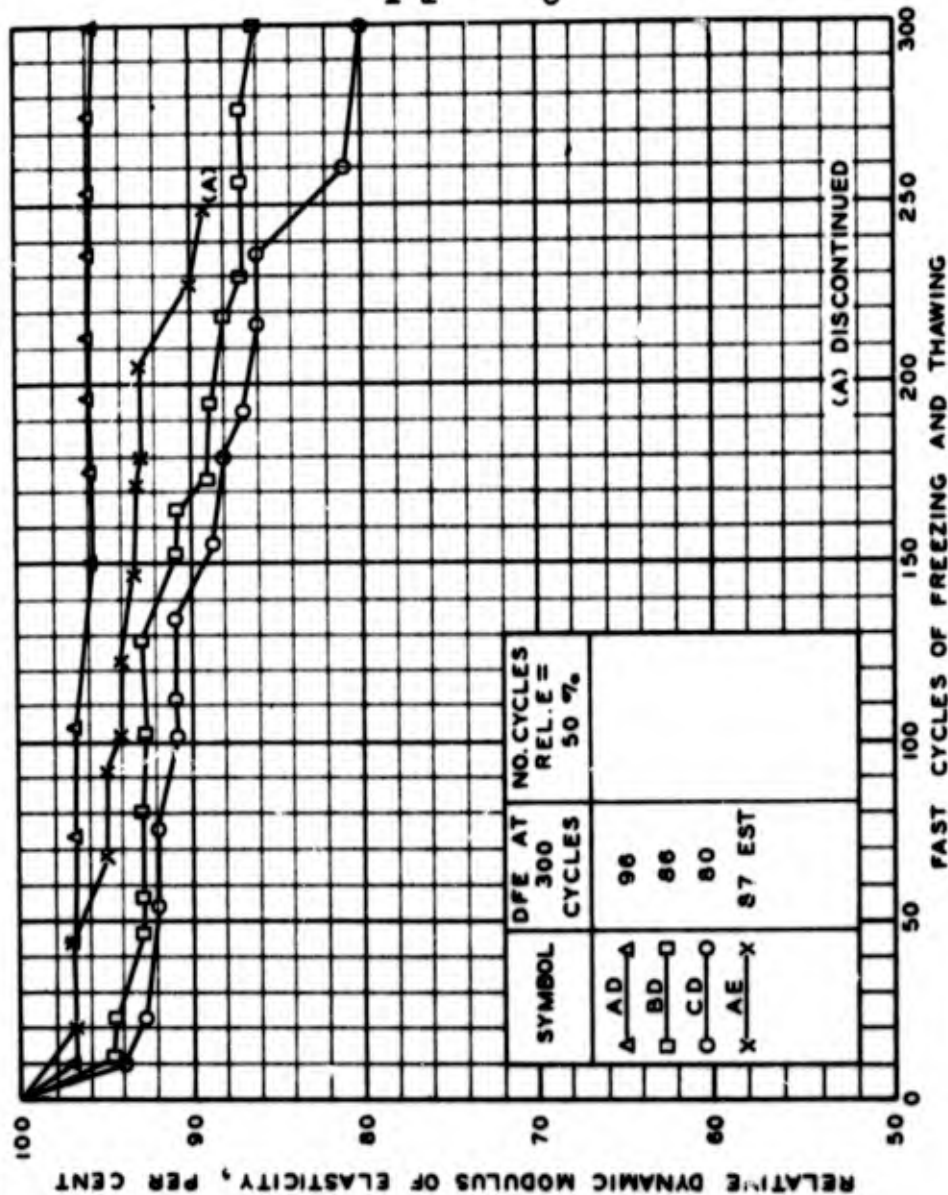
FINE AGG:

- A. CRD-G-8 (S)
- B. STANDARD
- C. SAC-1-S-1

COARSE AGG:

- D. CRD-G-8
- E. STANDARD

RESISTANCE OF CONCRETE BEAMS TO ACCELERATED FREEZING AND THAWING
DALE HOLLOW DAM AGGREGATE (9 DAYS CURING)



METHOD: CRD - C-114 - 48

FINE AGG:

A. CRD - G - 8 (S)

B. STANDARD

C. SAC - IS - 1

COARSE AGG:

D. CRD G - 8

E. STANDARD

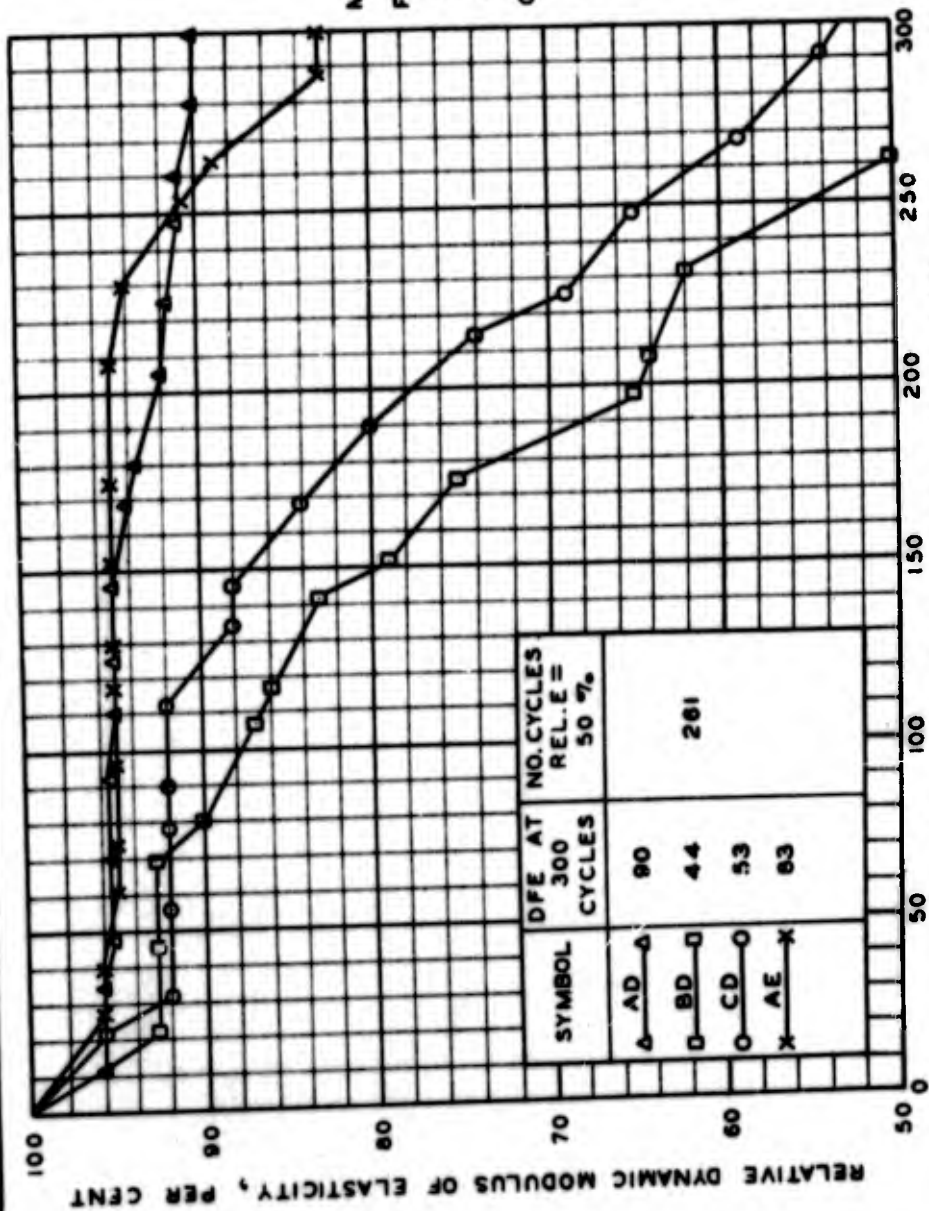
RESISTANCE OF CONCRETE BEAMS TO ACCELERATED FREEZING AND THAWING
DALE HOLLOW DAM AGGREGATE (21 DAYS CURING)

METHOD: CRD-C-114-48

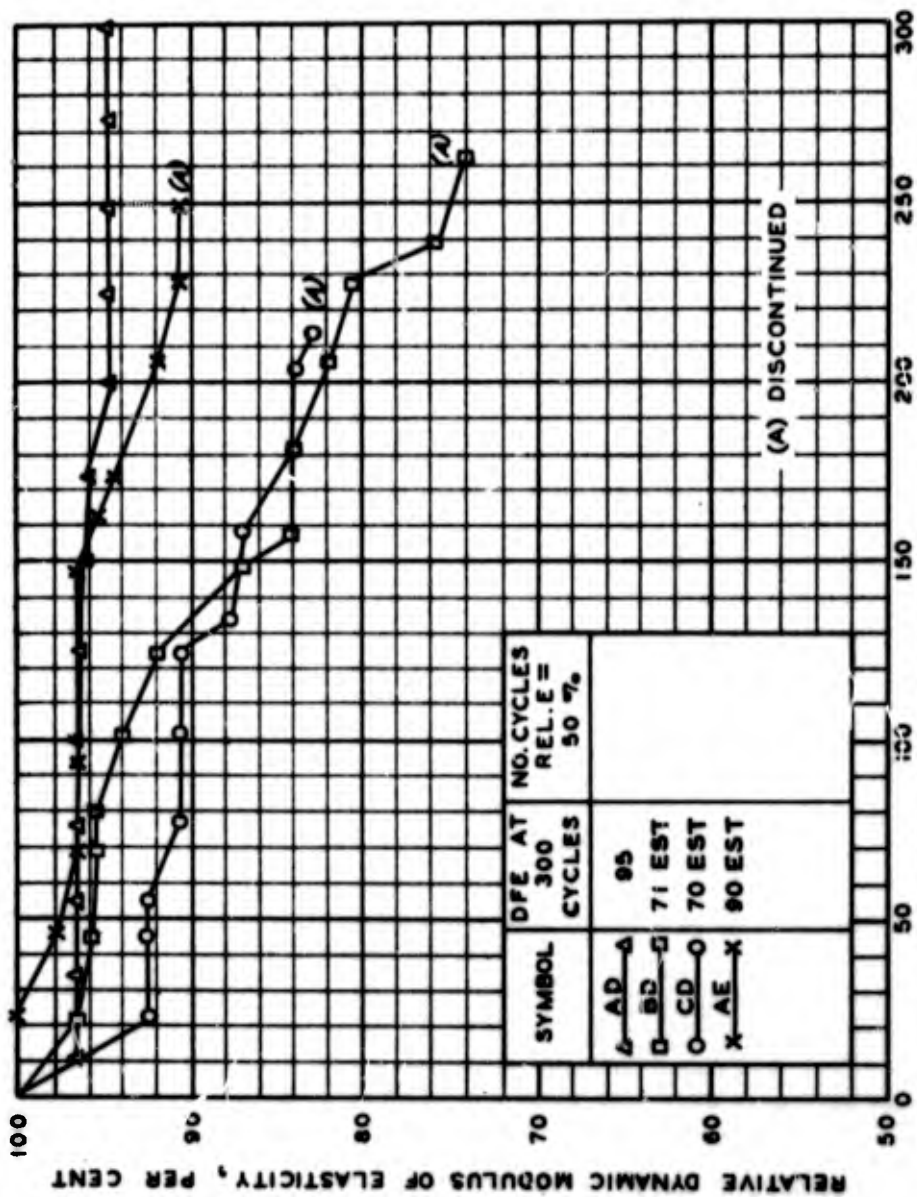
FINE AGG:

- A. CRD-G-9(S)
- B. STANDARD
- C. S.A.C-1-S-1

COARSE AGG:
D. CRD-G-9
E. STANDARD



FAST CYCLES OF FREEZING AND THAWING
RESISTANCE OF CONCRETE BEAMS TO ACCELERATED
FREEZING AND THAWING
CENTER HILL DAM AGGREGATE (9 DAYS CURING)



METHOD: CRD - C - 114-48

FINE AGG:

- A. CRD G-9 (S)
- B. STANDARD
- C. SAC-15 -1

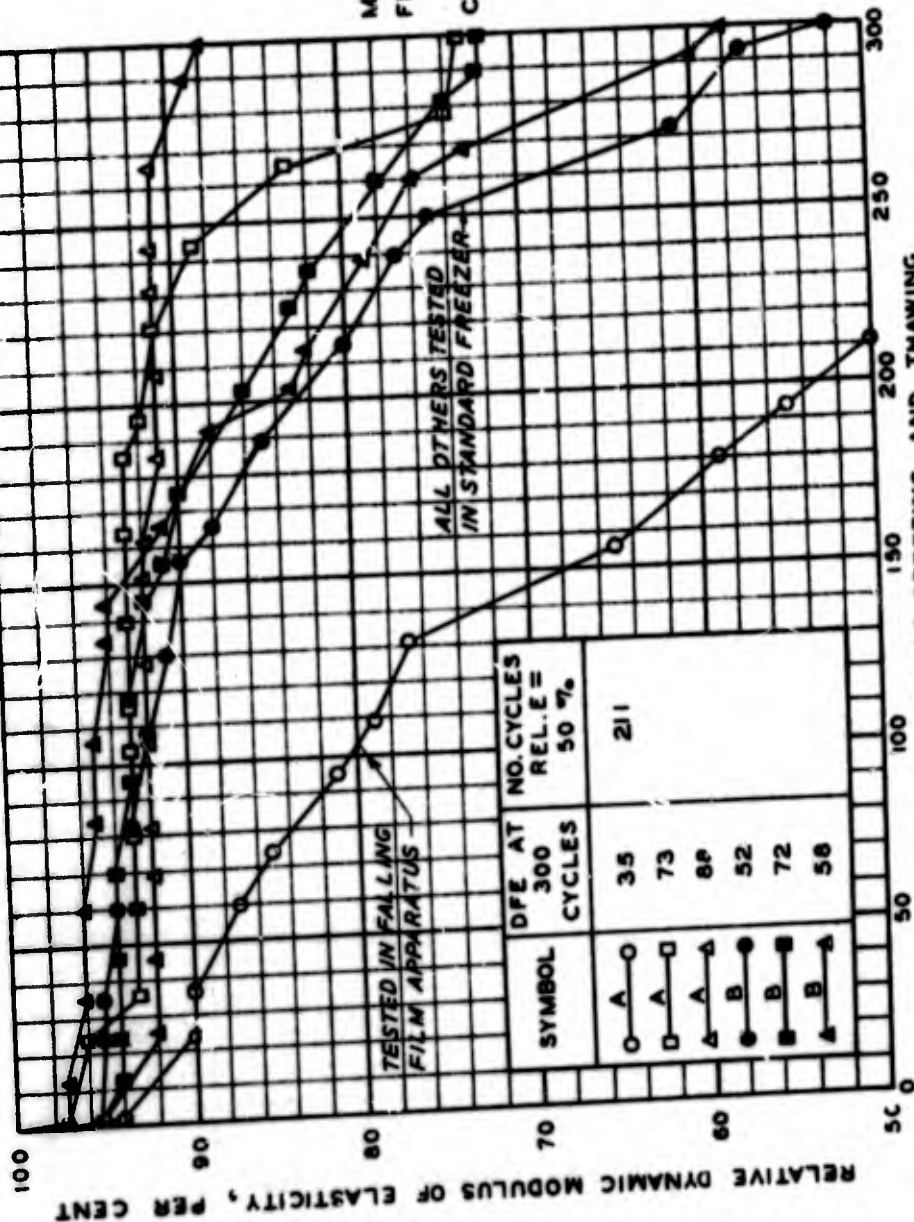
COARSE AGG:

- D. CRD G-9
- E. STANDARD

FAST CYCLES OF FREEZING AND THAWING

**RESISTANCE OF CONCRETE BEAMS TO ACCELERATED
FREEZING AND THAWING**

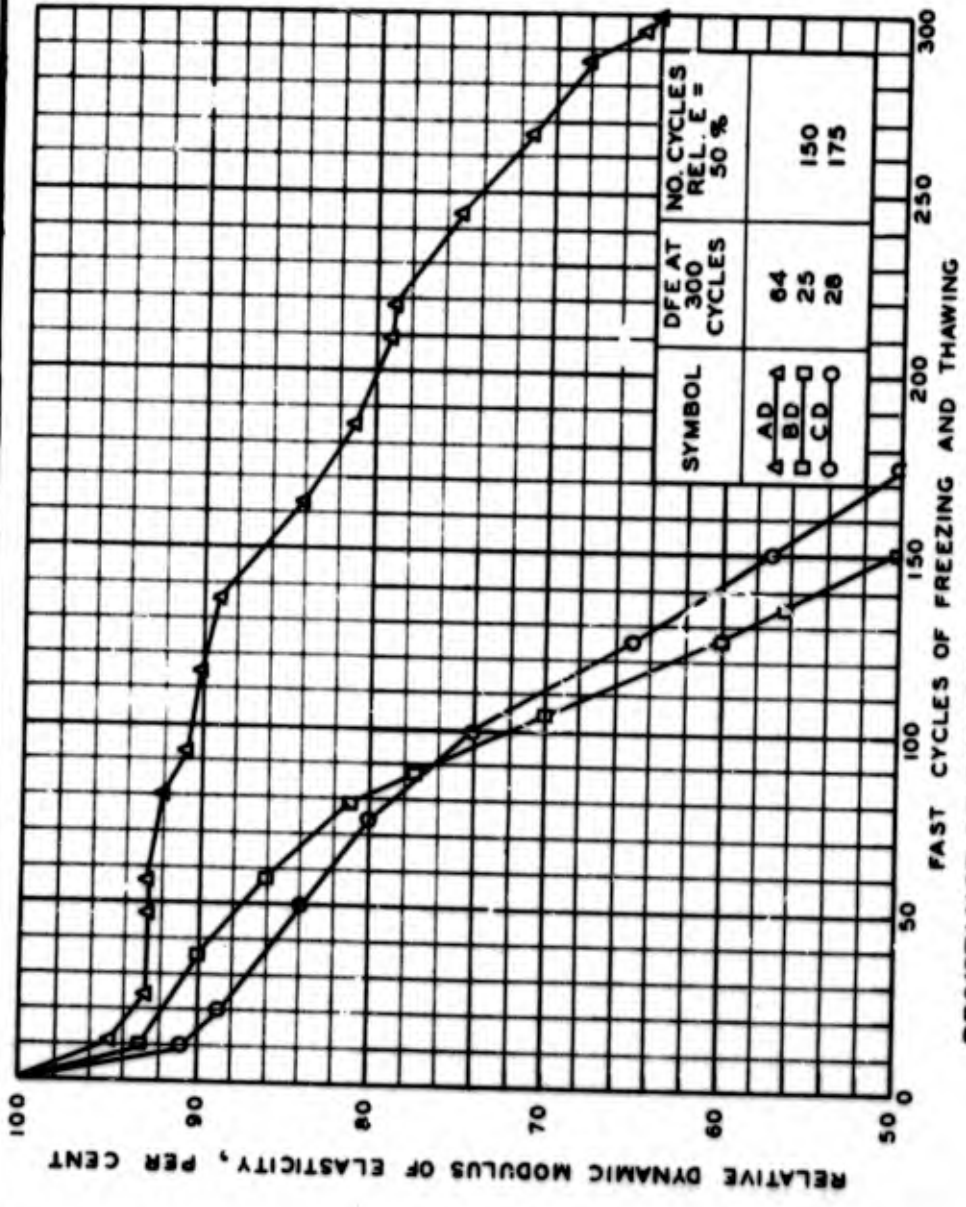
CENTER HILL DAM AGGREGATE (21 DAYS CURING)



METHOD: CRD-C-114-48
 FINE AGG: LR-1G-69(2)S
 COARSE AGG: LR-1G-69(2)
 A-CRD C-114 GRADING
 B-PROJECT GRADING

FAST CYCLES OF FREEZING AND THAWING
 RESISTANCE OF CONCRETE BEAMS TO ACCELERATED
 FREEZING AND THAWING
 BULL SHOALS DAM AGGREGATE

METHOD: CRD-C-114-48
 FINE AGG:
 A. STL 2 G-2 (S)
 B. STANDARD
 C. STL-2 S-1 & 2
 COARSE AGG:
 D. STL-2 G-1



RESISTANCE OF CONCRETE BEAMS TO ACCELERATED FREEZING AND THAWING
 CHAIN OF ROCKS LOCK-FALLING SPRING COARSE AGGREGATE

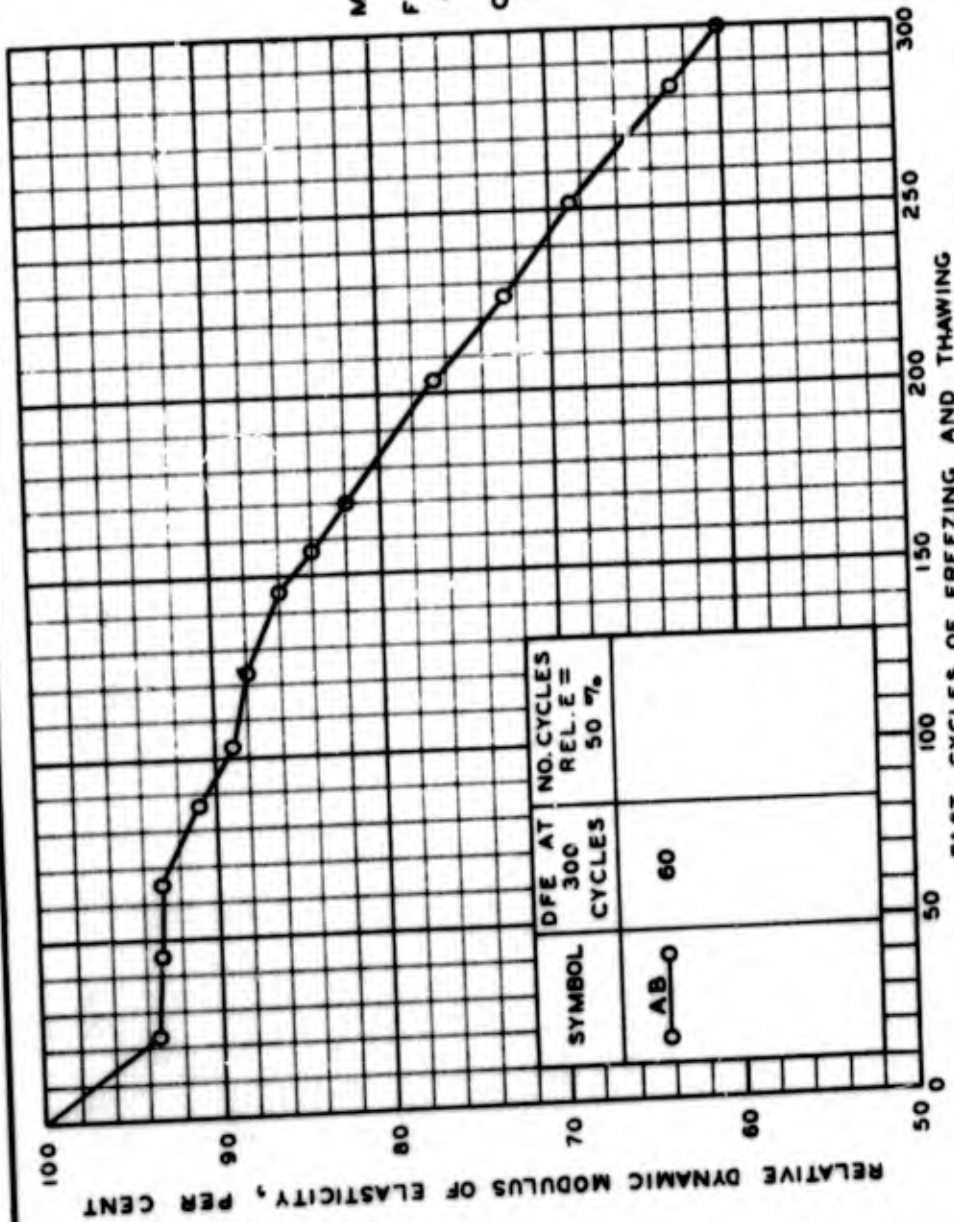
METHOD: CRD-C-114-48

FINE AGG:

A. STL-2-G-1(5)S

COARSE AGG:

B. STL-2-G-1(5)



RESISTANCE OF CONCRETE BEAMS TO ACCELERATED
FREEZING AND THAWING

CHAIN OF ROCKS LOCK-FALLING SPRING COARSE AND FINE AGGREGATE

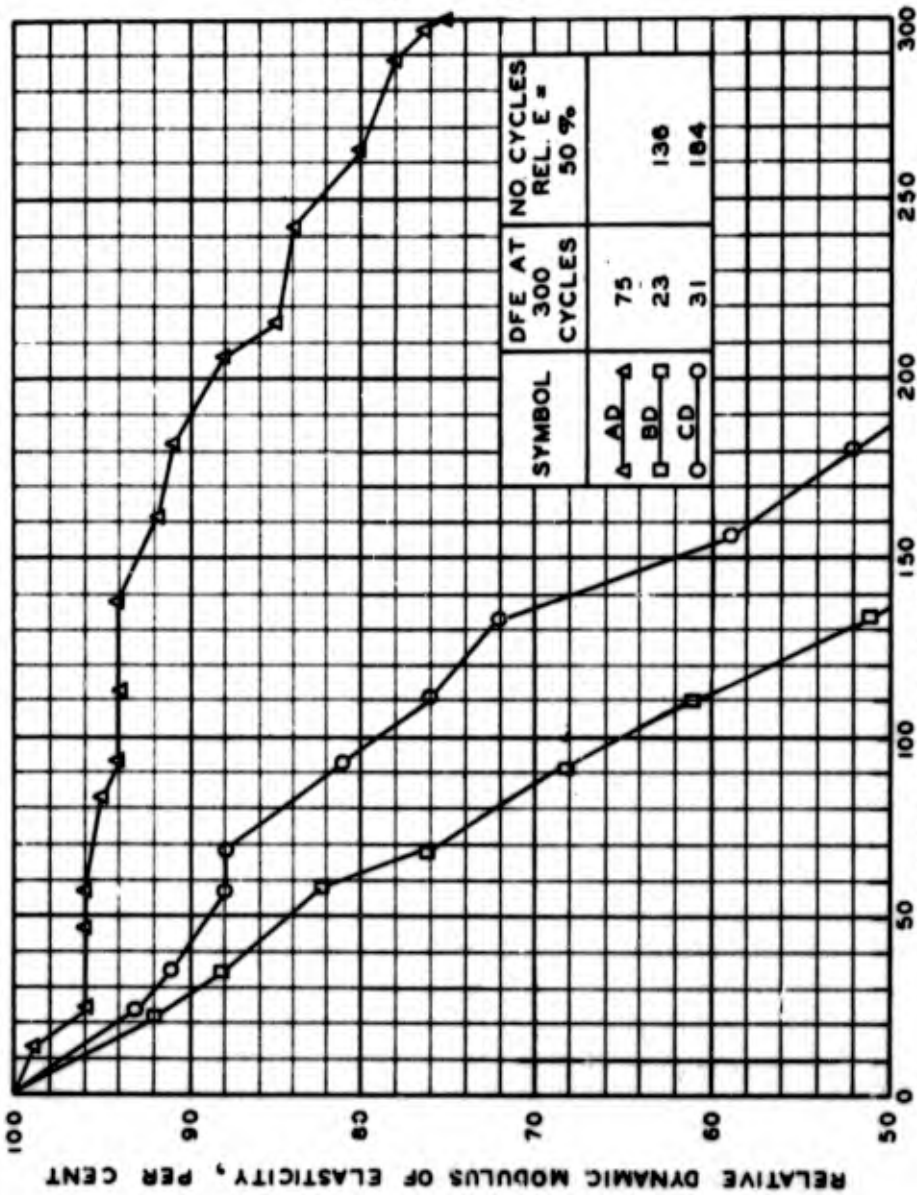
METHOD: CRD-C-114-48

FINE AGG:

- A. STL-2 G-2 (S)
- B. STANDARD
- C. STL-2-S-1 & 2

COARSE AGG:

- D. STL-2 G-2



RESISTANCE OF CONCRETE BEAMS TO ACCELERATED FREEZING AND THAWING
CHAIN OF ROCKS LOCK - KRAUSE AGGREGATE

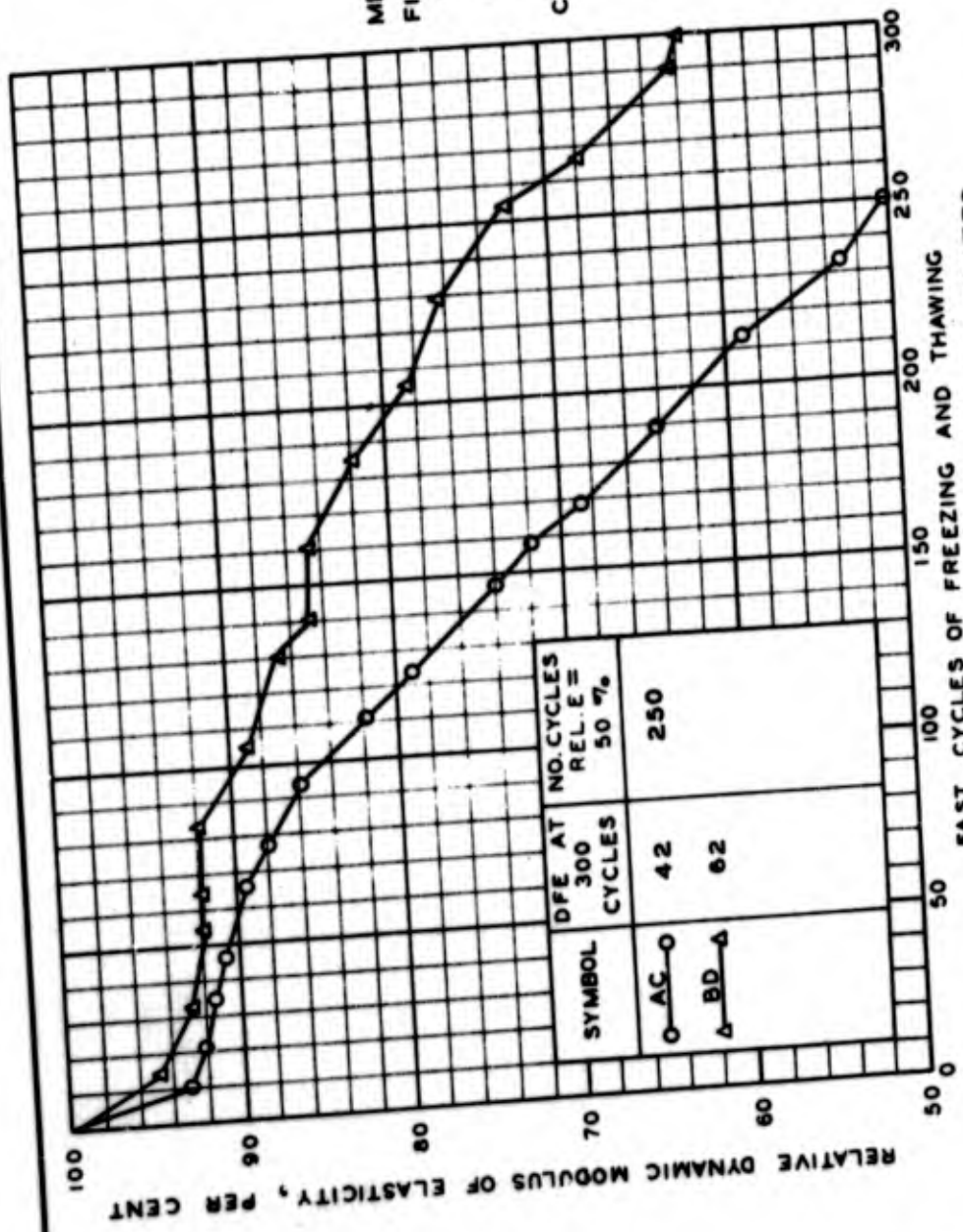
METHOD: CRD-C-114-48

FINE AGG:

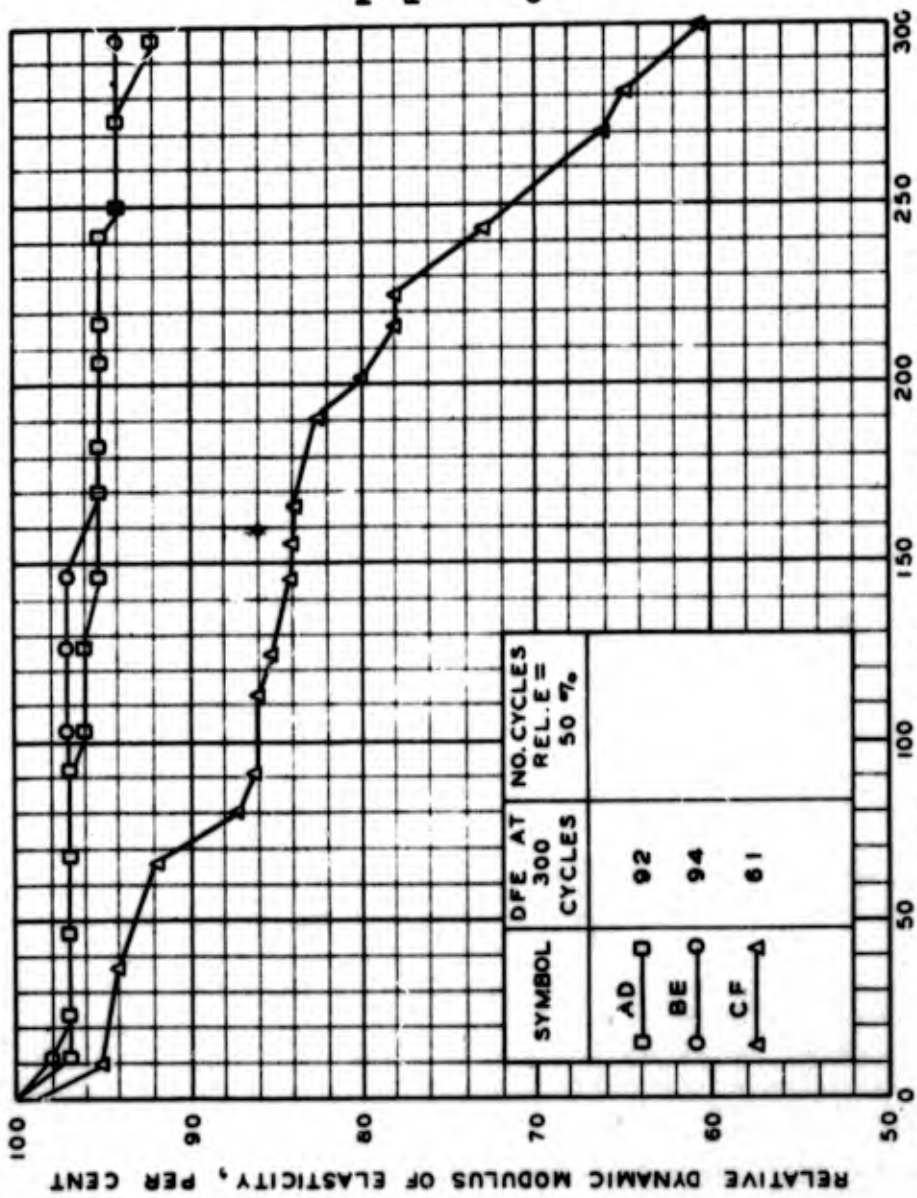
- A. STL-2 G-1 (4) S (FALLING SPRING)
- B. STL-2 G-1 (8) S (FALLING SPRING)

COARSE AGG:

- C. STL-2 G-2 (4) (KRAUSE)
- D. STL-2 G-2 (5) (KRAUSE)



RESISTANCE OF CONCRETE BEAMS TO ACCELERATED FREEZING AND THAWING
 CHAIN OF ROCKS LOCK-FALLING SPRING AND KRAUSE AGGREGATES



RESISTANCE OF CONCRETE BEAMS TO ACCELERATED FREEZING AND THAWING
ALLATOONA DAM AGGREGATE

METHOD: CRD-C-114-48

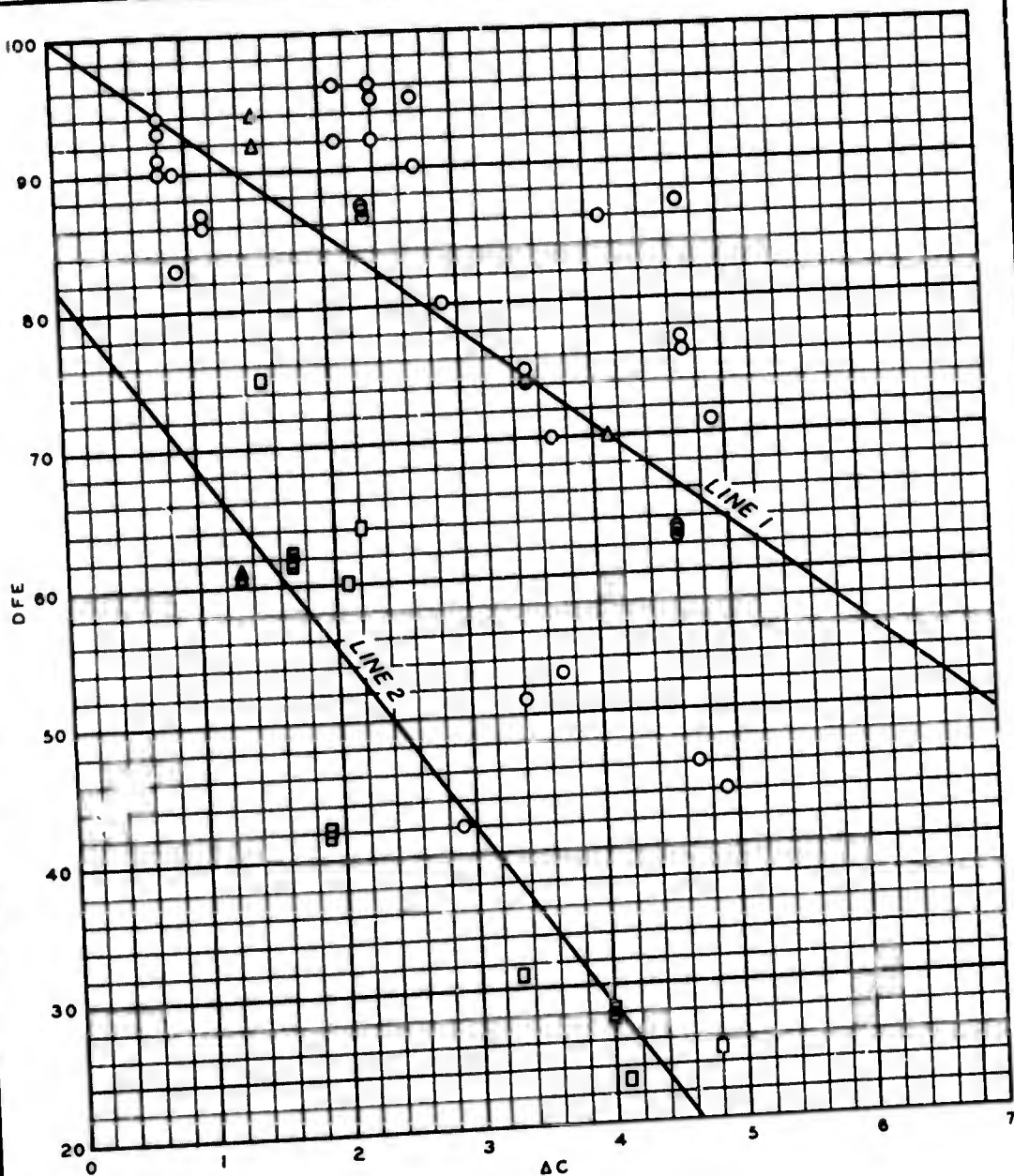
FINE AGG:

- A. MOB-2-G-3 (4) (S)
- B. MOB-2-G-3 (S) 2
- C. MOB-2-G-3 (S)

COARSE AGG:

- D. MOB-2-G-3 (4)
- E. MOB-2-G-3 (3)
- F. MOB-2-G-3 (A&B)

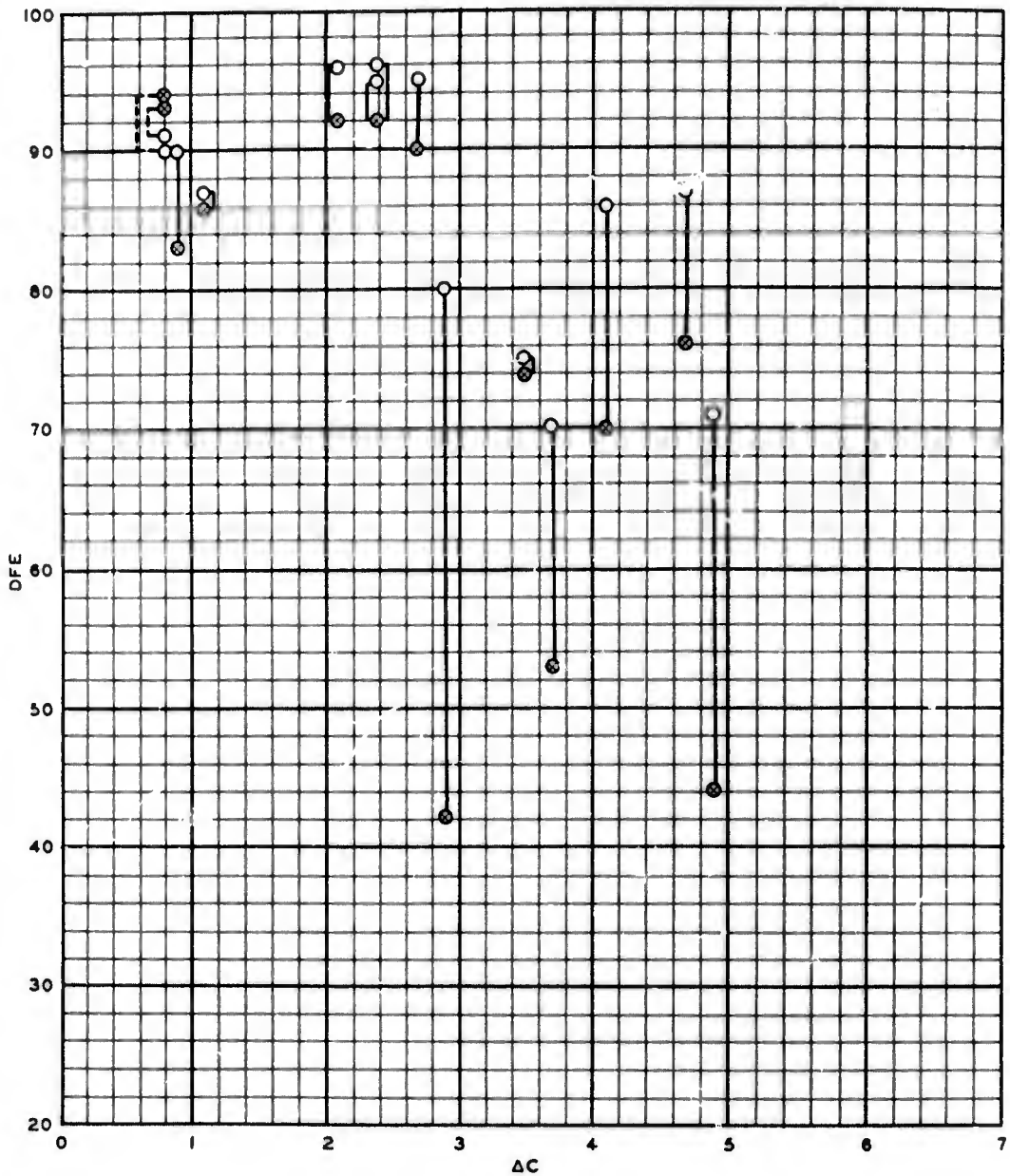
SYMBOL	DPE AT 300 CYCLES	NO. CYCLES REL. E = 50 %
AD	92	
BE	94	
CF	61	



LEGEND

- ALTON, BLUESTONE, WOLF CREEK, DALE HOLLOW AND CENTER HILL LS
- CHAIN OF ROCKS LS
- △ ALLATOONA DAM LS
- LINE 1: NON-CHAIN OF ROCKS AGGREGATE
- LINE 2: CHAIN OF ROCKS AGGREGATE

RELATION BETWEEN RESISTANCE TO ACCELERATED LABORATORY FREEZING-AND-THAWING AND DIFFERENCE IN COEFFICIENTS OF THERMAL EXPANSION OF COARSE AGGREGATE AND MORTAR, FOR LIMESTONE AGGREGATE CONCRETES



LEGEND

LENGTH OF CURING

○ 21 DAYS

● 9 DAYS



DFE₂₁ > DFE₉

DFE₉ > DFE₂₁

NUMBER

12

2

14

TOTAL DIFFERENCE

134

6

128

21-DAY CURING AVERAGES 9% DFE HIGHER

EFFECTS OF CURING PERIOD UPON RESISTANCE TO
ACCELERATED LABORATORY FREEZING-AND-THAWING (DFE) FOR
VARIOUS THERMAL COEFFICIENT DIFFERENCES (ΔC)

2072