POTENTIALLY REACTIVE CARBONATE ROCKS

Progress Report No. 8

A Strategy for Use and Control of Potentially Reactive Carbonate Rocks (Including an Annotated Bibliography of Virginia Research)

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(The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those of the sponsoring agencies.)

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PREFACE

The Council's research on potentially reactive carbonate rocks was formally initiated in 1961, as an outgrowth of observations made in the field and preliminary laboratory tests begun in 1957. The potential impact of research findings on construction, the national attention directed toward the problems associated with reactive rocks, and the length of time required for the observation of a destructive process that in some cases manifests itself only after years have passed, all have contributed to the time spanned by the project. Throughout the project, the goal has been to develop recommendations to guide the Virginia Department of Highways in its identification and acceptance of aggregate from quarries furnishing material for construction. This report contains those recommendations.

The numerous reports, publications, and presentations that have resulted from the project are listed in the Annonated Bibliography included in this report. As reflected in this bibliography, many individuals from the Council have contributed to the project, and their efforts are acknowledged with appreciation. Many other individuals and agencies outside the Council also contributed and appreciation for these contributions has been expressed in the various reports. This appreciation is here reiterated.

During the conduct of this work, Council personnel have held numerous discussions as a part of national technical committee activities with individuals from other governmental agencies, educational institutions, and industry. The contributions of these individuals, who know who they are, are gratefully acknowledged.

Because many of the ideas expressed in this report developed during some of the informal discussions mentioned above, some of the guidelines suggested closely parallel those being implemented by other agencies. In this category special mention should be made of the requirements stated in Appendix C of Standard Practice for Concrete, published by the Corps of Engineers in November 1971.

While this Progress Report No. 8 constitutes the conclusion of this project, measurements on some of the specimens and observations of concrete in service will continue with the goal of refining the understanding of this complex, interesting, and important problem of aggregate-cement paste interaction.

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INTRODUCTION

Previous reports based on this research* have established that carbonate rocks which undergo a detrimental reaction when exposed to cement alkalies occur in some quarries furnishing aggregates for highway construction in Virginia. Research has identified several manifestations of alkali-carbonate reactivity which may or may not be related. These are: (1) early expansion, (2) delayed expansion, and (3) formation of rims and/or modification of the paste-aggregate interface. Although all of these manifestations are important in developing an understanding of cement-aggregate interaction, the only distress in structures documented in Virginia was caused by early expanding aggregates. Thus, this report addresses itself only to this type of rock and recommendations for the control of delayed expanders and rim forming rocks are not made at this time. The petrographic and mineralogical characteristics of these early expanding rocks have been reasonably well established and testing methods for predicting reactivity have been developed and evaluated. The findings from the research in Virginia, in their essential features, have been confirmed by other agencies. Fortunately, studies in Virginia and elsewhere have shown that potentially reactive carbonate rocks are comparatively rare. But they can be sufficiently concentrated in a given area to cause detrimental expansion, cracking, and deterioration of concrete containing significant amounts of them as aggregates. Reactive materials have been shown to cohabit beds and to be interbedded with nonreactive rocks.

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*Note: Included in this report is an Annonated Bibliography of the reports and published papers resulting from the research project. These contain the detailed results of the research. The statements and conclusions of those reports form the bases of the guidelines and suggestions of this report. Specific references documenting the statements in this report will not be cited beyond this general reference to the Annonated Bibliography.

Research has also shown that concrete expansion and deterioration increases with increasing: (1) amounts of reactive material, (2) cement alkalies, (3) access to moisture, and (4) particle size.

Distress of concrete in the field has been documented and has been particularly evident when aggregate production was such as to concentrate the reactive materials in the quarry product for a significant length of time. Because of the occurrence of reactive aggregates in close proximity to innocuous ones within a quarry, there is great difficulty in characterizing production from a given quarry as either reactive or nonreactive, particularly over a long period of time. This situation causes uncertainty in using construction records to establish a completely unambiguous cause and effect relationship between the performance of concrete in service and materials characteristics. Similarity in occurrence and appearance of reactive and unreactive material also greatly complicates the sampling, testing, and control of such aggregates under procedures conventionally used for aggregate control.

Undoubtedly, some reactive aggregates have been used in concrete in Virginia without catastrophic failures. The relatively infrequent occurrence of reactive material, the comparatively low alkali contents of cements furnished in the past, and the natural dilution of the reactive rock by nonreactive material during quarrying all have combined to mitigate the detrimental effects of the reaction in most cases. The increasingly severe service conditions being imposed upon concrete in highways, however, demand that attention be given to all factors which might reduce service life. Thus, the recognition that potentially reactive rocks exist in some quarries furnishing aggregates to the Virginia Department of Highways and the documented cases of distress promoted by alkali-carbonate reaction impose upon the Department the burden of including an evaluation of reactivity in its program for aggregate acceptance.

PHILOSOPHY FOR CONTROL

Based upon research in Virginia and that published by other agencies, the ideas outlined in this section form a logical and defensible framework on which to construct a program for the control of reactive carbonate rocks. They hopefully represent a reasonable compromise among the responsibility of the consumer to assure the use of materials that will not detrimentally affect the performance of the concrete in service, the right of the producer to operate under only those requirements essential and applicable to his production of quality materials, and the important economic consequences of imposing requirements which are either so restrictive as to curtail production or so lax as to result in a shortened service life of the concrete in which the aggregates are used.

The bases of the strategy for the control of reactive carbonate rocks are as follows:

1. The evaluation should be made using:
   a. Thin section examination in accordance with the requirements of ASTM Designation C 295, "Petrographic Examination of Aggregates for Concrete".
   b. Length changes of rock cylinders tested in accordance with ASTM Designation C 586, "Potential Alkali-Reactivity of Carbonate Rocks for Concrete Aggregates (Rock Cylinder Method)", and
   c. In exceptional cases by length change measurements of concrete made with the aggregates and tested in accordance with ASTM Designation C 157, "Length Change of Cement Mortar and Concrete".

2. An aggregate should be considered reactive if it exhibits any one of the following characteristics or properties:
   a. Reactive texture as seen in thin section or compostion corresponding to those identified in ASTM Designation C 33, "Standard Specification for Concrete Aggregates", which states: "The characteristic texture is that in which large crystals* of dolomite are scattered in a fine-grained matrix of calcite and clay. The characteristic composition is that in which the carbonate portion consists of substantial amounts of both dolomite and calcite, and the acid-insoluble residue contains a significant amount of clay".
   b. Expansion of rock cylinders in excess of 0.2 percent at 16 weeks when tested in accordance with ASTM C 586.
   c. Expansion of concrete greater than .03 percent when tested in accordance with ASTM Designation C 157 and made with cement having an alkali content equal to or greater than that of the cement likely to be used with the aggregate and stored continuously moist for a period of one year.

3. The goal of the control program should be to utilize to the maximum extent consistent with satisfactory performance the production from quarries containing reactive material.

4. Because of the time required for the test and because the rapid changes accompanying the turnover of material in stockpiles, the evaluation should be made on material sampled

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*As used here the term "large crystals" is intended to identify dolomite crystals which are large when compared with the size of the calcite and clay rather than in any absolute sense. Research has shown that in reactive rocks the dolomite crystals are typically smaller than 100μ and often smaller than 50μ.

from the quarry face. Supplementary testing of stockpiles may also be helpful. However, by establishing the locations and distribution within the quarry of materials with varying reactivities and the limits of expansion of the rocks, information necessary for utilizing the rock, using selective quarrying or natural dilution, can be obtained whereas stockpiled aggregate merely represents material from a specific location or a restricted time period.

5. The end result of the program in every case would be to reduce the amount of reactive rock below 20 percent of the total aggregate content in concrete.

6. The sampling plan should have two stages. The first, or preliminary, screening (Stage I) would furnish sufficient information to establish either the absence or presence of reactive rock within a quarry. A second, more detailed sampling procedure (Stage II) would be used where warranted for quarries shown in the Stage I sampling to contain significant amounts of reactive rocks.

7. The service conditions under which the concrete is to be used should be considered in the implementation of the controls.

8. Where available, valid performance data should be utilized to supplement or replace sampling and testing.

SERVICE CONDITIONS AND INTENSITY OF SAMPLING

Recognition of the fact that the Virginia Department of Highways utilizes concrete in a variety of locations and situations using aggregates from a multitude of sources suggests the need for some flexibility in the control and inspection program. This flexibility can be achieved by utilizing two stages of sampling and exercising engineering judgment within a general framework embodying the principles outlined in the previous section.

Service Conditions

Theoretically, it should be possible to identify situations in which the service conditions would permit the use of greater amounts or require the use of lesser amounts of potentially reactive aggregates than those established in this report. Concretes which would not attain a high degree of saturation or be exposed to deicing chemicals and those made with cements having very low alkali contents might be expected to accommodate larger amounts of reactive aggregates than 20 percent. Concretes made with aggregate with a low expansive reactivity would be expected to show less expansion than concretes containing aggregate with a higher reactivity, so that more of the lower expanding aggregate might be accommodated. By the same token, in the reverse of these situations or for structural elements particularly sensitive to the effects of unanticipated expansion, a smaller amount of reactive aggregate would be warranted.

Although theory and logic would support the desirability of considering service conditions in determining the effects of reactive aggregates, practical considerations make this very difficult. On any given job, a contractor normally obtains his concrete from one source because of several factors, and this source, because of other factors, utilizes the same aggregate at all times. The additional storage facilities for several aggregates or cements as well as problems associated with the administration of differing material requirements on the same project would be practical only on projects of extraordinary size as compared with the usual highway structure. However, where practical, service conditions may be considered in implementing the recommendations outlined in this report.

Thus, judgment would be needed, particularly in cases of extraordinary structures such as tunnels, major river crossings, and long paving projects which would normally require special attention.

Intensity of Sampling

Stage I sampling for preliminary screening should be conducted periodically (perhaps at 5 to 10 year intervals) and would require comparatively few samples as described later.

Stage II sampling, which would require more intensive sampling and testing, would be necessary only when Stage I sampling indicated the presence of reactive material or as required for extraordinary structures.

SAMPLING

Sampling is the most complex aspect of the evaluation of prospective quarry sites or producing quarries for potential reactivity. This complexity results from the cohabitation and interbedding of reactive and nonreactive rocks in what are designated as single lithologic units by conventional geologic criteria.

Producing quarries must be sampled in sufficient detail to permit comparisons of the results with the maximum allowable content of reactive aggregate of 20 percent of the total aggregate. Experience in Virginia and the work of the Corps of Engineers have shown that a minimum of 5 samples and an average of approximately 10 samples per quarry will give a sufficiently indicative preliminary indication of the amount of reactive materials present. Because the occurrence of reactive rock is relatively rare, such a preliminary screening (Stage I sampling) is satisfactory to permit acceptance of material from quarries indicated to be free from reactive rock. These would constitute the vast majority of the commercial operations.

Several strategies for sampling are possible. The overall level of reactivity of the quarry production could perhaps be established by testing samples from randomly selected areas. Logic and the scientific method suggest that lithology should play a part in locating the sample areas. At the same time, research has shown that expansion can vary widely within a given lithology. Some lithologies are quite uniform, such as Lithology 1-8*, which has been intensively studied in Virginia and can be readily identified on a macroscopic scale. Other lithologies, such as Lithology 5-1, which appears to be quite uniform on a macroscopic scale, exhibited a widely varying reactivity related to structure at the microscopic level. Engineering and geologic judgment therefore must be used in designating the sample locations.

Both lithology and structure should be considered in selecting the sample locations because of their relationship to quarry production. If random samples are used, the amount of reactive material can be determined, but the locations may not be readily relatable to the quarrying operation. In any event, the basis for selecting a sampling plan should be such as to permit application of the results to production volumes and to furnish guidelines for utilizing natural or artificially induced dilution.

Because of the nature of the phenomenon being studied, the provisions for sampling contained in ASTM Designation C 295, "Petrographic Examination of Aggregates for Concrete", more closely describe the requirements than do those contained in ASTM Designation D 75, "Sampling Stone, Slag, Gravel, Sand, and Stone Block for Use as Highway Materials", because the latter anticipates the conducting of a variety of tests, most of which require comparatively large amounts of crushed or naturally graded materials of relatively small particle size. The rock prism test and thin section examination are normally applied to fewer but larger pieces of rock.

Where the test for potentially reactive carbonate rocks is made in conjunction with other tests, the sampling could be in accordance with ASTM D 75. Where the intent of the sampling is specifically for the assessment of potential reactivity, the applicable requirements of ASTM C 295 would be sufficient. In either case, the sample presented for test by ASTM Designation C 586 and C 295 should approximate the requirements of ASTM C 295, which calls for at least 4 lb. (1.8 kg) of rock with no piece weighing less than 1 lb. (0.45 kg).

Stage I - Sampling

For developed quarries, the following guidelines should apply:

1. A minimum of 5 and an average of approximately 10 samples should be taken per quarry. Even though a quarry might appear to contain

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*Throughout the Virginia studies a two-number designation has been used to identify sources. The first number indicates a specific quarry and the second a specific lithology. Thus "1-8" indicates a sample from Quarry 1 and Lithology 8.

only one lithology, multiple samples are necessary because of the variability of reactivity within a given lithology.

2. Every lithology representing more than 10 percent of the production should be sampled. Multiple samples should be taken from lithologies likely to constitute a sizeable percentage of any given production run.

3. Lithologies representing less than 10 percent should be combined on the basis of structure and location to represent 10 percent of the anticipated production and should be sampled from a random location within the combined lithologies.

4. Where the quarry consists of many small volume lithologies; i.e., thin beds of varying character, the quarry face should be sampled at a minimum of 10 systematically selected locations.

For undeveloped quarry sites, the same procedures may be used except that the sampling areas would be selected from material recovered during core drilling or other important samples representing the anticipated production. The assessment of properties from such cores is normally required under current practice.

Stage II - Sampling

Stage II sampling would follow the guidelines established for Stage I sampling but would include a larger number of samples. Experience in Virginia indicates that from 50 to 100 samples may be required. Obviously this amount of testing would be costly; however, the extensive testing would be concentrated on the quarries previously shown to contain significant amounts of reactive material. The alternative to more extensive testing is not to allow the use of any stone from the quarry. This, obviously, is a more expensive alternative. Experience to date suggests that results from the more extensive and refined sampling delineate the presence of a lesser volume of reactive aggregate than may be indicated from the results of the Stage I sampling.

Stage II sampling could be applied to core samples from undeveloped quarries, if necessary.

TESTING

Research has shown that measurements of length changes of rock prisms and characterization of the texture by petrographic examination of thin or polished sections both give valid indications of potential reactivity. Each technique has particular advantages. The main advantage of length change measurements is that they provide numerical values that can be readily compared with a quantitative standard. The major disadvantage of these measurements is the time required for conducting them. Petrographic examinations usually provide quicker results, but the results are qualitative. The variability of rock within a given lithology suggests that at least three independent measurements would be desirable in order to classify a sample as either reactive or nonreactive. For these reasons testing by both methods is desirable.

Consequently, it is recommended that from each sample the length changes of two cylinders drilled side by side should be determined as outlined in ASTM Designation C 586. One thin or polished section should be examined in accordance with the procedures described in ASTM Designation C 295.

Any thin or polished section that shows even a minor area of characteristic reactive texture should be considered as suspect, and the field sampling unit which it has been taken to represent should be classified as potentially reactive.

Under unusual circumstances, the testing of aggregate in concrete by the procedures of ASTM Designation C 157, "Length Change of Cement Mortar and Concrete may be warranted. Such testing usually would be in conjunction with Stage II sampling and testing when the volume of reactive rock is so large that sufficient dilution during production will prove difficult. Cement representative of that likely to be used with the aggregate in actual construction should be used.

APPLICATION OF TEST RESULTS

Once a rock has been classified as potentially reactive, the following actions are indicated:

1 By selective quarrying avoid using rock classified as potentially reactive in the production of concrete. It should be emphasized that aggregate classified as reactive in portland cement concrete is normally acceptable for other uses such as base material, bituminous concrete, etc.

2. If it is not feasible to avoid the use of rock classified as potentially reactive, then the minimum aggregate size that is economically feasible should be used. Also, the amount of potentially reactive rock should be diluted until it does not exceed 20 percent of the coarse aggregate, 20 percent of the fine aggregate, or 15 percent of the total aggregate in the concrete, if both fractions contain reactive materials.

3. When using any reactive aggregate it is desirable to use low alkali cement as designated in AASHO Designation M 85, "Standard Specification for Portland Cement" (equivalent to ASTM Designation C 150). This practice should be considered particularly if the amount of reactive material approaches the limits set forth in 2. Experience in Virginia has shown that in the past, cements supplied for highway construction have for the most part met this requirement. However, the changing patterns of cement supply brought about by emerging marketing practices within the industry and the possibility of increased alkali

contents accompanying plant alterations to meet pollution abatement measures may change this situation. Thus, the necessity to use low alkali cement will have to be determined with consideration of the specific circumstances.

4. If it is not practical to invoke the conditions above, then material from the quarry should not be used for portland cement concrete.

Quarries shown to contain potentially reactive rocks in the Stage I survey should be given interim approval for use depending upon the amount of material indicated by the survey, its location in the quarry, the anticipated degree of natural dilution, and the magnitude and nature of the work in which the material would be used pending the more thorough Stage II survey. Final action would be based upon the results from the Stage II survey.

The evaluation of both Stage I and Stage II samples could be made by district geologists after modest additional training. A small amount of equipment would be needed; notably a petrographic microscope.

Once the procedures have been established for selective quarrying to avoid or dilute the potentially reactive rock, the effectiveness of these procedures can be estimated by visual inspection. The offending material is usually identifiable by color and texture or in thin or polished sections. When it is, periodic sampling and particle counts from stockpiled material can be used to evaluate the effectiveness of the dilution procedures. Keys to identification such as color, texture, etc. might vary from quarry to quarry but with training from the district geologists, aggregate inspectors would be able to monitor the production.

IMPLEMENTATION

Of the 135 sources approved to supply coarse aggregates for portland cement concrete in Virginia, 66 contain limestone and/or dolomite. A Stage I survey of these quarries would necessitate the collecting of approximately 660 samples, and the evaluation of about 660 thin or polished sections and about 1320 rock prisms.

Based upon past experience, from 9 to 11 quarries will require Stage II sampling and testing. This could require testing of from 300 to 400 samples.

The last Stage I survey was conducted for 42 quarries in 1962. This was followed by a Stage II survey of 7 quarries in 1964.

Since it has been 10 years since the last Stage I survey, another should be initiated. Stage I surveys should then be conducted periodically. Whether the Stage I surveys should be conducted at 5 or 10 year intervals can be determined after considering the degree of agreement between the results from the two Stage I surveys.

ANNONATED BIBLIOGRAPHY OF VIRGINIA REPORTS, PUBLICATIONS, AND PRESENTATIONS

The first indication that carbonate aggregates being quarried in Virginia were alkali reactive resulted from measurements obtained in 1957 from an instrumented bridge in Rockingham County. Abnormal expansions from both the bridge deck and a companion beam were indicated. Subsequent lab and field investigations led to initiation of a research project designed to locate and study reactive carbonate rocks. This project was begun in 1961. When it became evident that there was a potentially significant problem and that the project would require a major effort, a format was adopted for reporting the results in eight installments, each treating a specific facet of the total project. The sequence of reports proposed reflected logical organization and progression rather than chronology.

As the project developed, the eight-report format was maintained, but a number of collateral studies and studies of limited scope were reported. Presentations before national and international audiences reflected the interest in the topic and served to aid implementation of the findings.

Because of the time period spanned by the research, the complexity of the subject and the interrelationships among the numerous reports, publications, and presentations, the annonated bibliography which follows has been prepared for the reader interested in pursuing the study in detail.

I. Working Plans and Progress Reports

1. Newlon, H. H., Jr., A Study of Potentially Reactive Carbonate Rocks, Proposal (Feb. 1961)
   This preliminary proposal outlined the field and laboratory work suggested by the expansion measured in a bridge deck and reference beams.

2. Newlon, H. H., Jr., A Study of Potentially Reactive Carbonate Rocks, Working Plan (Apr. 1961)
   This work plan refined the work to be done as suggested in the Proposal. It was the basis for approval of the work for HPR financing.

3. Newlon, H. H., Jr. and W. C. Sherwood, Progress Report No. 1 -- Potentially Reactive Carbonate Rocks -- Initial Investigations (May 1962)
   This report presents the findings of the investigations made on the Rockingham County Bridge and the aggregate that went into the suspected concrete. It includes descriptions of the expansion and cracking of the concrete bridge, the laboratory study of alkali induced rock expansions, studies of laboratory concrete, and the characteristics of reactive rock. From these investigations it was

concluded that a significant portion of the aggregate used in the bridge was alkali reactive, that the alkali reactive aggregate can cause expansion and cracking in concrete, and that reactivity can be detected in the laboratory by a simple prism test.

4. Sherwood, W. C. and H. H. Newlon, Jr., Progress Report No. 2 -- Potentially Reactive Carbonate Rocks -- Statewide Survey for Reactive Carbonate Aggregates (Feb. 1964)
Two hundred and twenty-four rock samples were taken from 42 of the principal limestone and dolomite producing quarries throughout the state. These samples were tested for absorption and specific gravity and analyzed for mineral composition by thin section and X-ray methods. Also, prisms were made from each sample and tested for alkali reactivity in an NaOH solution. Compositions of the samples were plotted in binary and ternary diagrams and expansive samples were shown on the same diagrams. Rocks with near equal amounts of calcite and dolomite and high insol contents were found to be most reactive. Rim formation in aggregates in concrete was briefly discussed.

5. Newlon, H. H., Jr. and W. C. Sherwood, Progress Report No. 3 -- Potentially Reactive Rocks -- Alkali Contents of Cements Used in Virginia Highway Construction (May 1964)
A total of 317 cement samples representing 76 shipments from 12 mills were taken throughout the state. Seven mills were found to predominate as suppliers in Virginia. The predominant alkalies, with the exception of that in the cement produced at one plant, were found to be potassium compounds. Also, with the exception of this one plant, equivalent Na_2O averaged less than 0.70 percent in all cases with most plants being between 0.50 percent and 0.60 percent. It would appear then that if alkali contents of less than 0.40 percent were ever required, some adjustment in procedures would be required of all plants.

6. Newlon, H. H., Jr. and W. C. Sherwood, Progress Report No. 4 -- Potentially Reactive Rocks -- A Study of Remedial Methods for Reducing Alkali-Carbonate Reaction (May 1963)
This report describes the results of laboratory work investigating remedial measures which might be employed where alkali reactive aggregates must be used. The measures investigated were: (1) reduction of cement alkalies and (2) dilution of reactive aggregate with nonreactive aggregate. It was concluded that both measures were effective in reducing concrete expansion, but that dilution of reactive aggregate with nonreactive aggregate appears to be a more practical and efficient remedial procedure. Freeze-thaw studies indicated that durability is also significantly affected by the combination of amount of reactive aggregate and cement alkali level.

7. Newlon, Howard H., Jr., Michael Ozol, and W. Cullen Sherwood, Progress Report No. 5 -- Potentially Reactive Carbonate Rocks -- An Evaluation of Several Methods for Detecting Alkali-Carbonate Reaction (May 1972)
This report covers the evaluation of 4 test methods using a suite of 22 rocks exhibiting a wide range of potential expansion and mineralogical compositions. Testing methods included measurement of the expansion of concrete moist cured for 5 years, expansion of mortar bars, and length changes of rock prisms stored in NaOH solutions. The concretes were made with cements of 3 alkali contents. The results were compared with each other and with the results from testing of quarries conducted in cooperation with the operating personnel of the Virginia Department of Highways.

8. Ozol, M. A. and H. H. Newlon, Jr., Progress Report No. 6 (Partial) -- Potentially Reactive Carbonate Rocks -- An Example of Bridge Deterioration Promoted by Alkali-Carbonate Reaction (May 1971)
Detailed petrographic examinations were made on concrete samples removed from bridge decks on 2 adjacent interstate projects. Performance surveys were also made of the decks, which were approximately 10 years old. The location and timing of construction were such that the only identifiable difference between the concrete on the 2 projects was the source of coarse aggregate. Performance on 1 project, which contained a reactive carbonate aggregate that had been extensively researched, was very poor; whereas the other project, where the concrete contained an aggregate that was not reactive, performed well. The examination confirmed beyond reasonable doubt the contribution of alkali-carbonate reaction to the poor performance.

9. Sherwood, W. C. and H. H. Newlon, Jr., Progress Report No. 7 -- Potentially Reactive Carbonate Rocks -- Studies on the Mechanisms of Alkali-Carbonate Reaction: Part I. Chemical Reactions (Feb. 1964)
An understanding of the mechanisms of alkali-carbonate rock reaction which result in expansion of concrete is of primary importance in dealing with the resultant problems on a practical level. Each of the 3 major constituents of carbonate rocks -- silica, clay minerals, and the carbonate minerals -- were exposed to alkali solutions. The silica and clays gave no apparent expansive reaction. The carbonates, particularly dolomite, reacted and increased in volume in the presence of alkali solutions. The reaction products developed in alkali solutions of different concentrations were identified. Evidences of some of these products were found in aggregate from distressed field concrete.

10. Hilton, Marvin H., Progress Report No. 7b -- Potentially Reactive Carbonate Rocks -- The Effects of Textural and External Restraints on the Expansion of Reactive Carbonate Aggregates (Sept. 1968)
The length changes of cylinders of reactive carbonate rock with different internal structures as indicated by their appearance in thin sections were measured while the cylinders were submerged in an NaOH solution. Part of the cylinders were unrestrained and the remainder restrained by a special frame against which they were forced to expand. The expansions were quite different and the portion of unrestrained expansion which was manifested under restraint reflected the differences in structure. To predict the behavior, theoretical relationships were derived using a model of an expanding sphere surround by a nonexpanding matrix. Variables in the model included proportions and deformation characteristics of the 2 components. The analyses correlated with the behavior of the aggregate in concrete or dolomite in the calcite-clay matrix.

11. Newlon, Howard, Jr., W. C. Sherwood, and M. A. Ozol, Progress Report No. 8 -- Potentially Reactive Rocks -- A Strategy for the Control and Use of Potentially Reactive Carbonate Aggregates (July 1972)
Based upon the results from the field and laboratory research, guidelines for the use and control of potentially reactive carbonate aggregates were developed. The first stage would be a preliminary screening program using petrographic examination and the measurement of length changes of rock cylinders. Guidelines for sampling were recommended along with suggestions for the application of the criteria. The goal of the program is to keep the amount of reactive material below 20 percent of the total aggregate in a given concrete.

II. Reports from Collateral Studies

12. Newlon, Howard H., Jr., "Summary of Cooperative Testing of Carbonate Aggregates by Subcommittee II-b of ASTM Committee C-9" (n.d. Nov. 1967)
In order to establish the suitability of the Mortar Bar Method (ASTM Designation C 227) for detecting alkali-carbonate reactions 4 laboratories cooperatively tested 7 aggregates in mortar bars using a high alkali cement. Five of the aggregates were from the Virginia study, as was the cement. Two aggregates were furnished by the Corps of Engineers. The expansions measured by the cooperating labs were indicative of the potential reactivity indicated by other methods but varied among the labs and were less than or of the same order as those of concrete made with the aggregates.
These results are discussed in Progress Report No. 5 (Item 7).*

*Item numbers in parentheses refer to the number designations in this report.

13. Walker, Hollis N., "Alkali-Carbonate Reaction Products Found in Mortar Bars and Prisms" (Dec. 1967)
Detailed petrographic examinations were made on mortar bars used in the ASTM cooperative tests. Rock prisms and untreated rock specimens representative of those included in the testing program were also examined using X-ray diffractrometry. These examinations indicated that the minerals of the hydrotalcite-sjogrenite mineral groups (complex magnesium carbonate hydroxides) can be the chief products of the alkali-dedolomitization near the surface of the test prisms and that brucite can be the major de-dolomitization product in the interior of the aggregate.

14. Hilton, M. H., "An Investigation of the Effects of Restraining Pressures on the Expansion of Reactive Carbonate Aggregate" -- Thesis Proposal (n.d. 1964)
The proposal outlined studies of restrained and unrestrained length changes for rock specimens stored in alkali solutions.

15. Hilton, M. H., "The Effects of Textural and External Restraints on the Expansion of Reactive Carbonate Aggregate", Thesis M.C.E. (Aug. 1966)
This thesis describes in detail the studies more briefly outlined in Progress Report No. 7b (Item 10).

III. Interim Reports

16. Sherwood, W. C., "Interim Report -- Statewide Survey for Reactive Carbonate Aggregates" (May 1962)
This is merely introductory to Progress Report No. 2 (Item 4) and should not be used as a substitute.

17. Hilton, M. H., "Progress Report No. 5 -- An Evaluation of Several Methods for Detecting Alkali-Carbonate Reaction (Mortar Bar Studies) Partial Rough Draft (May 1964)
This report treats in detail the mortar bar studies which were a part of the evaluation of test methods reported in Progress Report No. 5 (Item 7). More details are given in this report than in P.R. No. 5, but the later report summarizes the mortar bar results and their relationship to the remaining test methods studied.

18. Liu, Y. N., "Reactivity of Carbonate Aggregates -- Expansive Effects of Different Kinds of Solutions (June 1962)
The length changes of prisms made from rocks showing 2 levels of expansive reactivity were determined after storage in solutions containing a variety of soluble salts individually or in combination. Twenty solutions were used. Length change results to an age of 14 weeks were reported. These length changes varied greatly depending upon the particular solution in which the prisms were stored.

19. Newlon, H. H., Jr. and W. C. Sherwood, "Durability of Concrete in Service", Discussion of a report by ACI Committee 201. Journal of American Concrete Institute (Dec. 1962)
Using results from Progress Reports 1, 2, and 4 (Items 3, 4, and 6) this discussion questioned certain statements made in the Committee report.

IV. Published Papers
(Papers marked by an asterisk (*) were orally presented at the meeting reflected by the publishing agency.)

20. *Newlon, H. H., Jr. and W. C. Sherwood, "An Occurrence of Alkali-Reactive Carbonate Rock in Virginia", Bulletin 355, Highway Research Board (Oct. 1963) also VHRC Reprint No. 51.
This paper is based upon Progress Report No. 1 (Item 3).

21. *Sherwood, W. C. and H. H. Newlon, Jr., "A Survey for Reactive Carbonate Aggregates in Virginia", Highway Research Record 45, HRB (1964), also VHRC Reprint No. 59.
This paper is based upon Progress Report No. 2 (Item 4).

22. *Newlon, H. H., Jr. and W. C. Sherwood, "Methods for Reducing Expansion of Concrete Caused by Alkali-Carbonate Rock Reactions", Highway Research Record 45, HRB (1964)
This paper is based on Progress Report No. 4 (Item 6).

23. *Sherwood, W. C. and H. H. Newlon, Jr., "Studies on the Mechanisms of Alkali-Carbonate Reactions, Part I. Chemical Reactions", Highway Research Record 45, HRB (1964), also VHRC Reprint No. 60.
This paper is based upon Progress Report No. 7 (Item 9).

24. *Newlon, Howard H., Jr., "Chemical and Physical Reactions of Carbonate Aggregates in Concrete", Proceedings of the 17th Annual Highway Geology Symposium, Department of Earth Science Publication No. 1, Iowa State University, July 1968 (Presented on April 23, 1966).

25. *Newlon, Howard H., Jr., "Alkali-Carbonate Rock Reactions in Concrete", Concrete Journal, Japanese National Council on Concrete (JANACC) Vol. 6, No. 8 (Aug. 1968) (published in Japanese). Also published in "Abstracts of papers from U.S.-Japan Seminar on Research on Basic Properties of Concrete, Jan. 1968.

V Presentations
(Presentations marked by an asterick (*) have been offered or will be offered for publication by the organization sponsoring the presentation.) In addition to the 6 presentations reflected by the published papers indicated in Section IV, other presentations of research have been made.

26. Newlon, Howard, "Alkali-Carbonate Rock Reactions", Second Conference on Fundamental Research in Plain Concrete, University of Illinois, September 5, 1961.
This presentation was based primarily upon Progress Report No. 1 (Item 3).

27. Newlon, H. H. and W. C. Sherwood, "Potentially Reactive Rocks", presented to the Committee on Materials of the Southeastern Association of State Highway Officials, Louisville, Kentucky, October 30, 1962.
This presentation was based on Progress Report No. 1 (Item 3).

28. Newlon, H. H., "Alkali-Carbonate Reaction", 9th Engineering Conference on Crushed Stone, sponsored by the National Crushed Stone Association, Washington, D. C., March 21, 1966.
The presentation was based upon the work in Progress Reports 1, 2, 4, and 5 (Items 3, 4, 6, and 7). Emphasis was placed upon the methods being used in Virginia to control the use of potentially reactive aggregates.

29. Newlon, Howard, Jr., "Concrete Durability Related to Coarse Aggregate", Panel Discussion along with six others. 17th Annual Highway Geology Symposium, Iowa State University, Ames, Iowa, April 23, 1966.

30. *Ozol, Michael A. and Howard H. Newlon, Jr., "An Example of Bridge Deck Deterioration Influenced by Alkali-Carbonate Reaction", presented at Session 1 of the 48th Annual Meeting of the Highway Research Board, January 13, 1969.
This presentation was based upon Progress Report No. 6 (Item 8).

31. *Hilton, Marvin H., "Effects of Textural and External Restraints on Expansion of Reactive Carbonate Rocks", presented at Session 1 of the 48th Annual Meeting of the Highway Research Board, Jan. 1969.
This presentation was based upon Progress Report No. 7b.

32. *Ozol, M. A. and H. H. Newlon, Jr., "Bridge Deck Deterioration Promoted by Reaction of a Dolomitic Limestone Coarse Aggregate with Cement Alkalies" (Abstract), Geological Society of American Abstracts with Programs, Vol. 2, No. 7, October 1970 (Presented at the 83rd Annual Meeting of the Geological Society of America at Milwaukee, Wisconsin, November 12, 1970).
This presentation was based on Progress Report No. 6 (Item 8).

33. *Newlon, Howard, Jr., M. A. Ozol, and W. Cullen Sherwood, "An Evaluation of Several Methods for Detecting Alkali-Carbonate Reaction", presented to the 74th Annual Meeting of the American Society for Testing and Materials, Atlantic City, N. J., July 1, 1972.
This presentation was based on Progress Report No. 5 (Item 7).

34. Newlon, Howard, Jr., "The Expansive Behavior of Reactive Carbonate Aggregates in a Variety of Chemical Solutions", presentation at Session 52 of the 51st Annual Meeting of the Highway Research Board, Washington, D. C., January 20, 1972. A report of the results of the study initiated by Y. N. Liu (Item 18) but reflecting length change measurements after 1 year of testing. The wide variations in length changes were interpreted and correlated with the pH and soluble ions in solution.