Deterioration zone petrology of selected highway concretes

James Halsey Elwell
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1969
DETERIORATION ZONE PETROLOGY OF SELECTED HIGHWAY CONCRETES

by

James Halsey Elwell

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of
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DOCTOR OF PHILOSOPHY

Major Subject: Geology

Approved:

Signature was redacted for privacy.

In Charge of Major Work

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Dean of Graduate College

Iowa State University
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1969
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Sloss says, "Actually geology is an integration of a great number of fields - chemistry, physics, biology, and mathematics, for example - and could easily be absorbed piecemeal into those disciplines. But if we didn't have geology as a distinct field, we would have to invent it. Geology gives the researcher a perspective the other sciences lack, and that is because he makes his scientific observations in a special context: the context of the Earth as a whole and in all its complexity." In addition other sciences are not equipped to deal with the time element, at least not on so grand a scale, as is the geologist. This background, he believes, gives geologists a definite advantage in dealing with major scientific studies and explorations, not only on our own oceans and continents, but on other planets as well.

Sam Hill (27)

Laurence L. Sloss - President A.G.I.
INTRODUCTION

This study is part of a series of related research projects sponsored by the Iowa State Highway Commission to investigate the behavior of certain carbonate aggregates in highways made from portland cement concrete. Although service records indicate that some highways have lasted for 30 to 40 years, other highways utilizing coarse aggregate from the Otis quarry developed characteristic deterioration 14 to 17 years after construction. Because coarse aggregate from this quarry source could pass current acceptance tests and did not show distress during the first few years of service, the cause of poor service performance is a subject for applied research. The most fruitful approach was determined to be the study of the concrete system as it changes with time under natural conditions of low temperature and pressure - this is better known as "weathering". Further knowledge of what happens to concrete as it changes with time seems essential to fully understand how such aggregates contribute to distress in highway pavements. This thesis deals with concrete weathering and is especially concerned with a study of the distressed portion of Otis aggregate concrete.

The study of changes during weathering in highway concrete was made possible by Iowa State Highway Commission Service Records which specified quantities and sources of materials, conditions of the concrete, and highway age by station number. This information permits highway concrete to be treated as a synthetic rock system composed of fine aggregate, coarse aggregate and hydrated cement which changes its physical and chemical
properties in service. Weathering of the synthetic rock system is a result of the adjustment to the new environment by interaction between component materials. The degree of interaction depends on the history of the materials as well as the present environment. The discontinuous changes in the properties of highway materials with time may be considered episodes in the history of the pavement. If materials have had a similar history prior to incorporation into the highway then they should adjust to the concrete environment at about the same rate. Thus highways of the same age constructed from the same source materials would be expected to behave the same. Previous aging studies on concrete made from Otis coarse aggregate established expected values for center-of-slab concrete which may be used to predict its service response for periods up to twenty five years.

Because distress starts at the edges of a concrete slab and progresses inward, the expected value or description valid for the central portion at a particular age does not apply to the slab margin of the same age. Consistent differences in the edge and center descriptions of similar source materials of various lengths of service provides a means for detecting which weathering changes already associated with the slab center are also related to the progressive deterioration found near the edges of Otis aggregate concrete.

Although this work deals with understanding how the weathering of Otis aggregate concrete contributes to its deterioration, the main value of this work lies in its application to other concrete systems with shortened service lives. The common symptoms of highway distress are as
follows:

1. The "blue" appearance of natural fracture surfaces.
2. The "brown" color of aged highway slab surfaces.
4. D-cracking of highway slabs at joints.
5. The progressive nature of concrete deterioration adjacent to patched areas.

An understanding of the conditions limiting the useful life of the Otis aggregate concrete system is gained through a systematic petrographic study of highway cores taken as a gradational sequence from sound to deteriorated areas across natural cracks and construction joints for different aged slabs. Such gradational sequences are called petrographic fences. Differences between materials sampled are used to explain: (1) which material changes associated with aging are also associated with the symptoms of highway distress; and (2) how the development of commonly reported descriptive features such as rim zones and "D" line cracking are related to highway performance.

Presentation

Since the subject of concrete deterioration is a broad field with many aspects, the approach used in this study attempts to place its many facets into an historical and spatial framework that facilitates understanding of material behavior. An historical approach is used because the same material responds to its environment differently at different ages. The spatial partition is used because similar materials located
at different positions in the slab show a sequence of deterioration from the edge toward the center for the same aged material, indeed for the same slab. The historical approach tries to fit the many interdisciplinary items of information about the concrete system into its proper sequential place so that discontinuities in material behavior may be treated as historical events. Differences in material behavior may then be understood in terms of its composition, environment or previous history.

Simplification of the complex nature of this study is begun by introducing the nature of sequences which serve as its historical framework. This is followed by a literature review introducing some concepts of highway distress, including traditional concepts taken from disciplines which may or may not be directly related to concrete technology. All, however, are related to material behavior. The review of interdisciplinary areas combining several types of knowledge provides the requisite vocabulary and the several types of information represent an important step necessary for understanding of changes within the concrete system. Following this section, a summary of the status of prior Otis aggregate studies on aging of the sound portion of the concrete is presented as a point of departure for the present effort.

The current study of deteriorated concrete is presented in the following sequence:

Petrographic fence study approach
Sampling program
Observational program
Results of case studies
Highway distress characteristics
The highway distress characteristics presented are an attempt to partition the symptoms of distress into sequences relative to the core samples of the highways studied.

The discussion of results shows how the observations of this study fit into the general history of the concrete and how this information and technique may be used to resolve conflicting concepts of highway deterioration. The conclusions attempt to place the entire work in the perspective of the historical framework.

Nature of the Study of Sequences

Material science deals with two types of information. The first concerns intensive properties defining the physical and chemical behavior of bulk material. Such information related to material property evaluation may be obtained by direct testing and observation of detectable differences in materials. The second type of information results from extensive changes occurring in material properties as the result of a process. Such change related data can not be obtained by determination of the properties of any one material; they can be determined only by the differences in extensive properties which describe the before and after condition or state of a material acted on by the process. In short, a minimum of two tests on samples containing the same amount of residual inert material are required to measure change.

In planned experiments designed to measure change, individual particles of complex samples may be indexed and identified before testing so that before and after measurements are taken on the same particle to cal-
culate change. This will provide better resolution than a calculation of the change in average values in the event that all particles do not act in the same way. In destructive testing experiments exemplified by concrete systems where highway core samples are considered to contain coarse aggregates representing an assortment of the quarry lithologies, some resolution is lost because before and after concrete core samples do not contain the same pieces of aggregate. However, comparison of the ranges of intensive properties for aggregate material identified as belonging to lithologies of individual ledges within the same quarry should permit detection but not the measurement of gross changes. Such a method which allows one to relate aggregates in concrete to individual ledges is the closest approximation that can be established for the before and after state of rock material changed by processes operating within the concrete system. This is a valid approach since repeated measurement and description of individual ledges in the Otis quarry from 1955 through 1965 have shown little lithologic change. This provides a suitable basis for describing the before condition of an individual piece of aggregate whose lithology can be related to a particular quarry ledge. The ability to do this has been successfully demonstrated in an earlier study (12). Thus in this study each lithology is considered a different starting material which undergoes a sequence of events starting with the pouring of the concrete.

In order to reconstruct the sequence of events (history of the pavement) from material changes, these changes must first be placed in a time sequence. Two special ways of forming sequences are recognized and
they create the system which is the framework of this study. The first applies to the hydrated cement, fine aggregates and coarse aggregates formed into concrete and considers a sequence to be the service life of the highway. Such a method assumes that all highways were made of the same materials, and samples taken of a five and a ten year old highway on the same day would duplicate the results of sampling one highway sequentially at five and ten years. This sequence would recognize all the material in one slab to be of the same age. The second way is related to the rate of deterioration and recognizes that the symptoms of distress start at a joint and progress toward the center of the slab. Material at the edge of the slab has been exposed to the local environment of distress longer than material in the center of the slab so distress features should be better developed at the slab edge. In terms of development of progressive deterioration, the gradational spatial sequence inward from the joint is also in one sense a separate distress sequence superimposed on whatever time dependent change the slab has reached during its service life. In mathematical terms the total change in any dependent variable, measured at any point, would represent the summation of the change determined for that variable in an equation which states its dependence on position within the slab, and an equation that states its dependence on the passage of time since the emplacement of the concrete. Measurements of the system necessary to calculate change may be then considered as revealing the simultaneous solution of these equations at the different sample points.

If concrete is a homogeneous system in which all of the materials
had the same behavior, then highway core samples that had reached the same sequential position would be expected to have a similar history. If the material behavior being studied was time dependent then the domain of each behavior could be specified in terms of sequential position. Discontinuous changes in behavior of a material location with the passage of time would constitute the events of its history. In real concrete systems, materials representing different quarry lithologies have identical sequence positions. Material behavior is therefore complicated by differences in response to the concrete environment characteristic of the quarry ledge rather than of the quarry. Because Iowa State Highway Commission records only identify the source materials as to the concrete ledges within a quarry, differential lithologically controlled responses will be used to identify the ledge material associated with poor highway performance.

Discontinuous changes in behavior which are not sensitive to the kind of lithology present but are characteristic of its length of service will be interpreted as a general response to aging. The establishment of a history based on this type of change will permit meaningful evaluations of the extrapolations of short time test results.
SOME CONCEPTS OF HIGHWAY DISTRESS

This part of the study is presented under several topics to bring together the applicable concepts developed by others. This section is not intended to be a chronicle of major contributions leading to the present state of the art: its purpose is to serve as a guide to subject areas which relate to the problems of highway distress.

There are many specialties that are related to the interdisciplinary problem of highway distress. Contributions to the central problems of these disciplines may bear indirectly on the problems of highway distress. Some of these specialties include:

1. **Engineering**
   - Design
   - Maintenance
   - Civil
   - Traffic
   - Soil

2. **Chemistry**
   - Cement
   - Physical
   - Analytical
   - Geochemistry

3. **Geology**
   - Economic
   - Engineering
   - Mineralogy
Each specialty generates a vocabulary within its own literature, which is indexed in terms of key words for the initiated. In the present computer oriented society, subject areas and key words unlock vast domains of stored interdisciplinary knowledge, and the present problem can be considered one of keeping up with the ever expanding list of key words on the fringe of a research specialty. Introduction of the following concepts provides a means of presenting a vocabulary related not only to concepts commonly applied to highway distress, but also to those developed in other areas for different purposes. By showing the interdependence of these concepts within the context of highway distress, the reader may be made aware of the nature of the relationship between (1) the different specialties, (2) the wording of report titles and (3) the explanation or prevention of highway distress.

Concepts of Highway Pavement Failure

Highway maintenance

Lichtefeld (39) in 1958 discussed the warning signs of pavement distress in terms of direct and indirect evidence of the onset of airport pavement failure. Under direct evidence he listed random cracks and
"bird bath" or water pumping at joints. Such features are usually followed by progressive deterioration. Additional evidence is listed as follows:

1. Extrusion of joint material
2. Displaced joint material permitting entrance of water
3. Crazing or map cracking
4. Loss of surface texture (skid resistance)
5. Build up of turf or soil resulting in entrapment of moisture.

Indirect evidence was gained from past performance of (a) design and materials, (b) traffic, and (c) people and personalities.

**Highway design**

Livingston (40) in 1958 presented a basis on which the direct evidences of failure could be rated. The interdependency of items listed are as follows:

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<td>Overstressing due to inadequate strength in pavement structure.</td>
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</tbody>
</table>

Livingston concluded that most rating is done at a time when the highway structure has been destroyed as a usable facility, rather than at
a time when ratings could initiate necessary steps to stop destruction occurring from either loads or natural forces.

**Highway traffic engineering**

Mellinger (44) in 1958 presented the evaluation of pavements from the standpoint that relates traffic loading and its frequency to the physical properties of pavement. He stresses that construction defects and overloading should be the cause of most pavement failure. Mellinger explains that over-loading can occur over a period of several years as a function of fatigue strength of the concrete and supporting media, and that, until distress becomes evident by excessive spalling at the joints and structural breaks in the pavement, over-loading is seldom detected.

**Highway distress features**

Hveem (28) in 1958 added depth to the description of highway failure by means of a series of picture definitions for terminology of distress features in bituminous and portland cement pavements. Among the terms defined were:

1. **Pumping** - water ejected through a joint under traffic load.
2. **Faulted joint** - removal of subgrade material due to pumping results in vertical displacement of slabs.
3. **Curling of slab** - due to expansion of the underside from moisture, or expansive soil.
4. **Longitudinal cracks** - parallel to traffic direction.
5. **Transverse cracks** - perpendicular to traffic direction.
6. Diagonal cracks - directions other than those defined.
7. Corner breaks - cracks developed in shoulder near slab.

Hveem classified failure in portland cement pavements as follows:

1. Inadequacies in concrete properties
   a. Disintegration
      (1) Alkali aggregate reaction
      (2) Freezing
      (3) Sulphate attack
   b. Cracking
      (1) Volume change
      (2) Heavy loads
      (3) Alkali aggregate reaction
   c. Warping, curling of slab
      (1) Moisture
      (2) Temperature
      (3) Lack of restraint

2. Lack of "Team Work" between pavement and base
   a. Faulting
      (1) Curling slabs
      (2) Erodable subgrade soil
      (3) Heavy traffic
   b. Cracking
      (1) Resilient foundation
      (2) Heavy loads
      (3) Low friction between slab and subgrade

3. Weakness in base, subbase or underlying soils
   a. Cracking
      (1) Yielding foundation
      (2) Heavy loads
   b. Break through
      (1) Weak foundation
      (2) Heavy loads
   c. Marked elevation of joints
      (1) Expansive soils
      (2) Non-uniform infiltration of water
Highway deterioration symptoms

Idorn (30) in 1967 considered the following symptoms of deterioration to be meaningful in the evaluation of field survey inspection data.

1. Crazing - Pattern cracking extending through only the surface layer; a result of more drying shrinkage in the surface than the interior of the plastic concrete.

2. 'D' Lines - A form of disintegration characterized by the successive formation of a series of fine cracks at rather close intervals paralleling edges, joints and cracks, and usually curving across corners, the initial cracks forming very close to the edge and additional cracks progressively developing, each a little farther from the edge than the preceding one. Ordinarily the cracks are filled with a calcareous deposit.

3. Hair-checking - Small cracks not conforming to a regular pattern which extend to an appreciable depth but not to the full depth of the structural member, occurring before the concrete takes its final set.

4. Map-cracking - A form of disintegration in which cracking of the concrete surface develops in random pattern resembling the political subdivisions on a map. The condition may develop over the entire surface or appear only in localized areas. It may or may not be associated with abnormal growth of the concrete.

5. Surface scaling - The peeling away of the surface mortar of portland cement concrete, exposing sound concrete even though the scale extends into the mortar surrounding the coarse aggregate.

6. Progressive scaling - A condition of concrete disintegration which in its initial stages appears as surface scaling, but which gradually progresses deeper and deeper below the surface stratum.

7. Pitting - The displacement of individual particles of aggregates from the concrete surface, due to the action of traffic or disintegration of the particles, without major displacement of the cementing material or mortar.

8. Flecking - The dislodgment of the thin mortar film from the outermost portions of occasional particles of coarse aggregate on a concrete surface resulting in their exposure, generally attributable to lack of bond between the mortar and aggregate.
9. Pop-outs - Crater-like depressions caused by the breaking away or forcing off of a portion of the concrete surface by the expansion of a piece of underlying coarse aggregate. Pop-outs often appear in an incipient form with the cone-shaped fragment still in place but surrounded by a fine crack.

10. Raveling - The progressive disintegration from the surface downward or edges inward by the dislodgment of aggregate particles.

Additional symptoms of deterioration are found in surface deposits as follows:

1. Incrustation
2. Stalactites
3. Resinous gel
4. Flakes of dry gel
5. Efflorescence
6. Rust staining

Sequential highway deterioration

Welp and De Young (57) in 1964 described the type of highway failure associated with the Otis coarse aggregate materials of the present study. They suspected that the coarse aggregate known as Otis stone, from the Otis member of the Devonian Wapsipinicon formation, was directly related to early pavement deterioration. They summarized the problem as follows:

The unit ranges from 20 to 25 feet in thickness and consists of alternating beds of fine and medium to coarse-grained rock that varies from dolomite limestone to calcitic dolomite and contains more than 95 percent total carbonate. Each ledge in the quarry face used for concrete meets the test requirements of the specifications.

Deterioration was first noticed in 1958 on pavements ranging from 14 to 20 years of age. Joints showed evidence of spalling near the quarter point and one to two joints per mile had been patched. Some discoloration was noted but no "D" cracks were seen. During the next few years periodic observations were made on many sections of Otis pavement ranging from 5 to 23 years of age. Deterioration of varying severity was noted in all pavements exceeding 14 years of age. In general, deterioration was more severe on pavements more than 16 years of age.
General Pattern of Deterioration

The general pattern, at whatever age it begins, is similar for aggregates meeting and for those failing to meet specifications. Significant variations are noted in the age at which deterioration is first observed, the rate at which it progresses, and the area of slab affected. Deterioration in all cases is progressive. The first noticeable sign is a general discoloration in the vicinity of the joints and cracks, and sometimes along the edges of the slab. The border of the discolored area is generally slightly concave toward the long axis of the crack or joint.

"D" line cracking, the next sign of deterioration, is a network of fine, parallel, hairline cracks which generally develop on both sides of a joint or fracture before progressive scaling is observed. These fine cracks parallel the joints, fractures or edges, usually curve across slab corners and are interconnected by random transverse cracks. Sometimes these cracks accumulate a small, light blue-gray, ridge-like deposit and are referred to as "blue-line" cracks. Within the cracked area, the surface layer of concrete from 1/8 to 1/4 in. thick is loosened and is easily peeled from the slab. Discoloration generally continues to spread ahead of the "D" line cracking.

The deteriorated area is deepened by progressive scaling. The concrete in these areas is easily disintegrated by a light hammer blow. The matrix is generally chalky, and cavity walls may be coated with a white powder.

In extreme cases the entire slab may be affected. In the final stage the concrete deteriorates to a condition resembling loosely compacted gravel. Any one pavement will generally show all degrees of deterioration. Variations in the severity of deterioration are greater in a horizontal direction away from the joints and cracks than from top to bottom in the vicinity of joints or cracks.

On pavement with transverse joints, deterioration appears to start adjacent to the expansion joints, then the contraction joints and finally develop adjacent to the cracks. With time, progressively more area of the pavement is affected. In most instances there does not appear to be any obvious displacement of the pavement in the deteriorated areas.

Discussion From this brief sampling of highway pavement failure concepts it is evident that the words used to describe failure have at least three different meanings. The first meaning of the word is entirely
descriptive: for example a "D" line crack is a deposit filled crack. A second implies a genetic origin such as crazing. A third implies that the observed features fit into a sequence of events. Progressive scaling is a term that is commonly used in this sense. Since all the words may be used to convey one, two or all three meanings, problems in communication are the inevitable result. Words used purely descriptively may appear misleading if they are interpreted genetically or sequentially. For this reason the words used in this study will be restricted to their descriptive meanings. Thus attention will be centered on distress characterized by "D" line features since it is this kind of deterioration occurring at an early age that constitutes the problem at hand.

Genetic implications of "D" line cracks

The sequential nature of progressive "D" line cracks fit the description of Mellinger (44) already presented as evidence for over-loading that exceeded the fatigue strength of the concrete and supporting media.

Cordon (6) in 1966 presents in his review article the presently prevailing interpretation of such cracks as follows:

D-line cracking (short for deterioration line) consists of relatively fine cracks which run approximately parallel to the joints or edges of concrete surfaces. Presumably these cracks are caused by freezing of water in the voids of paste and aggregates. As disintegration develops, more water travels through cracks to feed capillaries farther from the edge of the slab.

Discussion Although these two concepts of failure stress the genetic driving force responsible for this particular highway distress, an explanation for the accelerated rate of failure in the Otis stone
highways is sought in this study. Because the problem of highway distress is one of rate rather than one of kind of behavior, the resistance of a highway to this cracking and the mechanism by which the resistance is altered are extremely important.

Freezing and Thawing Concepts

Hydraulic pressure

T. C. Powers, in 1945, published a hydraulic pressure hypothesis that would explain the frost resistance of concrete. In 1949, he (48) reported the air requirement for frost resistant concrete in terms of void spacings to prevent failure of saturated paste. According to theory spacing factors from 0.01 to 0.026 in. were required for pastes cooled at 20 F degrees per hour. Experimental results indicated a maximum spacing factor of about 0.01.

Volume changes

Powers, T. C. and Helmuth (50) in 1953 presented two mechanisms to explain volume changes during freezing.

1. The generation of hydraulic pressure as water freezes in capillary cavities.

2. The growth of the bodies of ice in capillary cavities or air voids by diffusion of water from the gel. Air voids limit the hydraulic pressure and shorten the period during which the ice cavities can increase. The closer the air voids are to each other the more effective they are in controlling either mechanism.

Coarse aggregate failure

Larson et al. (35) in 1964 presented a general review of frost damage which stressed the role of the coarse aggregate susceptibility to failure.
This was followed in 1965 (36) by an interim report on experimental test conditions to detect frost susceptibility in coarse aggregates. They examined pore characteristics, aggregate particle expansion, petrographic examination and the Powers freeze-thaw test. They found that capillarity data are inconclusive, that petrographic analysis explained and predicted behavior of test aggregates in freeze-thaw testing, and that dilation of specimens during the cooling cycles is the most sensitive indicator of frost damage.

Discussion Since highways constructed with Otis coarse aggregate develop D-line failures at an early age it would be easy to conclude that frost susceptible coarse aggregates were used in this highway construction. However, although this is possible it would indicate that present tests are insensitive since this material passed specifications at the time it was paved. Another possibility would be that the properties of the material have changed in service so that the altered material which fails after being subjected to freezing cycles over a 14 to 16 year period is not the same as that which survived the first few winters without distress.

Recommendations for increased durability

Cordon (6) in 1966 concluded his monograph with ten recommendations for establishing freezing and thawing durability for concrete.

1. Entrain 4 to 6 percent air in all exposed concrete that may be saturated in freezing weather.

2. Avoid concrete aggregates having high absorption.

3. Use the minimum amount of mixing water possible, commensurate with good construction practices.
4. Avoid saturation of exposed concrete in freezing weather.

5. Be sure that hydration of portland cement is well advanced before concrete is subjected to freezing and thawing.

6. Prevent rapid drying of the exposed concrete surface before bleeding is complete.

7. Do not finish the surface of exposed concrete until bleeding water has disappeared.

8. Avoid the use of salts for ice or snow removal.

9. After curing, allow exposed concrete to dry as much as possible then seal the surface.

10. Provide adequate drainage for all exposed concrete surfaces.

Concrete Material Properties

Causes of failure

Slate (54) in 1949 distinguished between physico-chemical and mechanical causes of failure. Processes involving changes in chemical composition (chemical reactions), freezing of water and crystallizing of salts in voids, capillary forces, and temperature stresses are considered to be physico-chemical; processes involving uneven swelling of the supporting medium or traffic loads are considered to be mechanical. In discussion of the action of salts he pointed out that sodium and magnesium sulfate cause disintegration of concrete by crystal growth with resulting pressure within the pores and by converting calcium aluminate to calcium sulfo-aluminate. Sodium chloride and calcium chloride which are used as ice control chemicals cause deterioration presumably by conversion of calcium aluminate to calcium chloroaluminate. The various salts can be leached from the soil and deposited above the water level within the pavement
or rise by capillary action to be deposited in the surface pores of concrete.

Environmental testing

Kennedy and Mather (33) in 1953 compared laboratory freezing and thawing behavior with natural sea water freezing and thawing at Treat Island, Maine. They formed the following hypotheses to explain differences in the behavior of limestone aggregate in concrete:

Limestone fine aggregate ranked fairly high in the laboratory because minute particles of limestone finer than No. 200 produced characteristic entrained air voids of small mean and maximum size, which gave the beams superior frost resistance compared to beams made with siliceous fine aggregates containing similar air content in larger voids. Limestone fine aggregate ranked low at Treat Island because it swelled in sea water, adding another kind of volume change to that of freezing and thawing.

Limestone was a relatively poor coarse aggregate in the laboratory because it had fairly high absorption and finer pore structure than the others which had significant absorption, so that some pieces drew water from the mortar and achieved an undesirable state of saturation. Limestone was a relatively good coarse aggregate in the field because increased swelling of the clay and time (and additional sodium ion) to develop alkali reaction outweighed differences in thermal expansion and fine pore structure. Both additional swelling and alkali reaction improved bond. Development of internal cracking in some of the coarse aggregate -- cracking of a type common in concretes known to have been damaged by alkali-aggregate reaction suggests that after longer exposure at Treat Island the limestone coarse aggregate might not rank as high as it does now.

Deleterious characteristics

Swenson and Chaly (55) in 1956 suggested a classification of the deleterious characteristics of concrete aggregate materials as follows:

1. Physical
   a. External encrustations
      highly weathered surfaces
      highly polished surfaces
undesirable shape
extreme fineness

b. Internal
undesirable pore characteristics
high volume change with wetting-drying
lamination and cleavage
soft and weak particles
unfavorable thermal expansion

2. Chemical
a. Reaction with cement
alkali reactivity
organic impurities
salt impurities
base exchange

b. Independent of cement
oxidation
hydration
carbonation
air-entraining impurities
solubility

This arrangement is based on a recognition of harmful properties rather than on types of materials, thus providing the testing engineer with a more systematic basis for laboratory evaluation of aggregates.

Joint failures

Colley and Humphrey (4) in 1967 have investigated the role of coarse aggregate interlock across joints in concrete pavements. They find that the aggregate plays a significant part in load transference and establishing the point at which a pavement is overloaded.

Strain relaxation

Emery (16) in 1966 reported a strain measurement on rocks in relationship to highway design. He has used bonded photoelastic plastic strips to measure the relaxation strain-time relationships in quarry or road sur-
faces. Emery considers the behavior of road surfaces as follows:

Surfacing materials are usually rock fragments bonded or otherwise. The fragments are characteristic of the rock mass from which they originated. All contain some strain energy.

If the aggregate is crushed rock the act of crushing will have relieved the particles of some of their elastic energy because of rebound. If the rock is piled before use the time-dependent strain energy will be restrained and will not completely relieve. Relief will continue in the road surface.

In some rocks such relief serves to crack up the fragments further and so cause deterioration of the aggregate. If relief is considerable a form of "growth concrete" results. This is not necessarily chemical although chemical reaction may accompany the relaxation. Strains transferred to the enclosing cement from the expanding aggregate can cause surface spalling and attendant deterioration of the concrete.

Limestones are often sufficiently varied in their inherent strain retention that one layer will be strongly reactive while an overlying or underlying one will not be. This is particularly so in the Paleozoic limestones in the area about Kingston, Ontario, for example.

Alkali-carbonate rock expansion

Swenson and Gillott (56) in 1964 presented a review of eight years of work on the alkali-carbonate rock reaction initiated by the study of the alkali-carbonate reactive rock at Kingston, Ontario. They commented on the mechanisms of coarse aggregate expansion as follows:

Mineralogical studies show that the clay minerals were of the non-swelling type. The simple hypothesis that expansion was due to the presence or formation of swelling clay minerals had therefore to be abandoned.

An interesting approach is provided by the work of A. A. deGast (Department of Mining Engineering 1962, Queen's University, M.S. thesis, unpublished). He postulated that expansion of the rock resulted from release of residual elastic strain due to the removal of restraint. The stored energy was inherited from earlier epochs and resulted from geological processes acting on the calcite and dolomite which have different rheological properties. Hanlin (24) and Griggs (23). Handin showed that dolomite is ten times more resistant to deformation than calcite and Griggs demonstrated that, unlike calcite, dolomite is not susceptible to recrystallization. It is concluded that elastic strain, if present is stored in the composite grains of the material. The supposition of stored elastic energy within the rocks of the Kingston area is supported by several field examples.
A laboratory investigation was made in which strain was measured by the photoelastic technique. This is of high sensitivity and permits the detection of integrated strain. Measurements were made on limestone wafers and cubes and an evaluation was made of the strain distribution in concrete. It was shown that shear strains were present around aggregate of defective concrete. Studies of limestone prisms confirmed the results obtained by other workers that the alkaline solution is the major factor contributing to deterioration. Expansion due to elastic readjustment of inherent elastic energy was concluded to be of minor importance.

There is additional evidence to show that release of residual elastic strain is not the underlying cause for expansion of the Kingston rock in alkali. In particular, little or no residual intergranular strain is likely to remain in rock which has been powdered to a crystallite size of the same order as the component minerals. Large expansions have, however, been registered by Kingston material in the powder-cell test. There is also evidence to show that the clay fraction is involved in the expansive mechanism. It is very unlikely that clay minerals would play a special role in retaining elastic energy in the manner postulated.

Expansion is explained by the steps of a hypothesis as follows:

1. Dedolomitization exposes "active" clay materials.
2. Exchange sites on the clay absorb some sodium ions.
3. Water uptake by this "new" clay results in swelling.

**Mechanism of the alkali-carbonate reaction**

Gillott (21) in 1964 further clarified the mechanism and kinetics of the alkali-carbonate reaction.

His conclusions are summarized below.

1. Strong alkali reacts with dolomite to cause an overall increase in the volume of the system. In general, there is no accompanying increase in solid volume and the expansion registered in the dilatometer probably occurs in the liquid phase.
2. Mixtures of the same composition as Kingston rock show no increase in solid volume when attacked by strong alkali.
3. The action of alkali upon reactive Kingston rock causes an increase of solid volume owing to water uptake.
4. Fine grinding causes textural damage to reactive rock that decreases its capacity for water uptake when attacked by strong alkali.
5. Textural damage is caused by release and exposure of clay minerals formerly enclosed within dolomite crystals.

6. The dedolomitization reaction is closely related to, but is probably not the direct cause of, expansion of the reactive rock.

7. Thermograms of alkali-treated Kingston rock display an enhanced 900°C endotherm. This implies participation in the reaction by the clay minerals that is not shown by compositionally similar mixtures.

8. When destruction of dolomite by strong alkali (dedolomitization) results in release of clay the latter has an unwetted surface and therefore is in an "active" state; it is quite different from the acid-separated clay in a mechanical mixture.

9. An equilibrium is established in which Na⁺, Ca⁺, and Mg²⁺ ions are adsorbed onto exchange sites on the newly exposed clay mineral surfaces, and a double layer develops.

10. Cracks open and allow water and alkali to gain access to clay minerals enclosed in the matrix. This clay responds similarly to that released from dolomite.

11. Expansion on dedolomitization of Kingston rocks results from water uptake by the newly exposed clay minerals owing to formation of the hydrous double layer.

Iron influenced silica reactions

Fridland and Tsyurupa (18) in 1966 presented a study on the influence of iron films on the exchange capacity of amorphous and crystalline silica. They found that Fe₂O₃ in sand coats the quartz grains as an uneven intermittent layer, the concentration of iron being maximal in cracks and depressions on grains. The results of measurement of the cation exchange capacity before and after impregnation with iron are as follows:

1. Calcination of samples (both original and iron-impregnated) leads to marked reduction of the exchange capacity. This appears to step from dehydration, the loss of OH⁻ or crystallization of iron film in the process of heat treatment of the objects investigated.

2. Treating original and iron impregnated samples with a 10% solution of HCl and heating them on a water bath led to a marked de-
crease in the exchange capacity (in the case of iron compounds, to lower values as compared with the parent substance). Only for montmorillonite clay is this effect implicit or completely absent. The sizable reduction of the exchange capacity of the silicates investigated resulting from treatment with acid may stem from variation in the surface properties of mineral (loss of $\text{OH}^-$ groups, exchangeable ions, etc.) or from dissolution of the iron films coating particles. It is difficult to attribute this effect to lattice disintegration for on the data of chemical analyses heat and acid treatments cause no substantial change in the mineral mass (as is confirmed especially clearly by the constancy of $\text{SiO}_2/\text{R}_2\text{O}_3$ molecular ratios).

3. The role of iron films in the exchange capacity of different silicates is due to the physicochemical surface properties of a mineral. Thus for substances with an inert surface (quartz, kaolinite) and for minerals with an active surface (montmorillonite and to a lesser extent muscovite) iron films promote an increase and a decrease respectively, in absorption capacity.

**Sorbed water effects on mechanical properties**

Sereda et al. (52) in 1966 reported the effect of sorbed water on the mechanical properties of hydrated cement pastes and compacts. They found that Young's modulus remains fairly constant for either kind of sample from 0 to 50 percent relative humidity. In these tests porosity is the basic parameter determining the strength and Young's modulus. The re-entry of water into the lattice of tobermorite is the suggested explanation of the observed increase in Young's modulus in the region of 50 to 100 percent relative humidity. These results were obtained under conditions that avoided carbonation and gradients within samples.

**Factors influencing aggregate-cement bonds**

Alexander et al. (1) in 1965 reviewed the nature of the aggregate-cement bond, cement paste strength and the strength of concrete. Among other effects they reported the effect of age and temperature on bond and
paste strength as follows:

Temperatures reported were 40, 70, and 110 F.

At low temperatures, bond strength equals or nearly equals paste strength at all ages studied (9h to 56 days). If the curing temperature is raised, the rate of strength gain in the paste increases, and the paste strength greatly exceeds the bond strength at early ages. However, the ultimate strength for paste does not rise with curing temperature and, after a few weeks, bond strength reaches this same value. This point is better demonstrated by (a test covering a) longer interval of 30h to 4½ years. Insofar as paste and bond are concerned after an equivalent modulus of rupture is reached (about 6 months), the mode of tensile fracture changes from preferential bond rupture to preferential failure in the paste.

They concluded the review article as follows:

The modulus of rupture of the aggregate-cement bond for different portland cements is linearly related to paste strength and, in the case of extrusive rocks, is directly proportional to the silica content of the aggregate. At early ages, the bond strengths of the most effective normal aggregates are approximately twice those of the least effective. In contrast to paste strength, which is extremely sensitive to curing temperature, bond strength may be independent of curing temperature under certain circumstances. Bond strength is affected by vibration and by surface texture and porosity of aggregate, whilst both bond and paste strength are influenced by admixtures.

The familiar relationship between concrete strength and water-cement ratio reflects the dependence of shear bond, tensile bond and paste strength on water/cement ratio. Large aggregate disrupts the usual pattern of compressive strength relationships for concrete because shear bond is affected by aggregate size at low water contents. The modulus of rupture of the aggregate-cement bond does not depend on aggregate size but large pebbles are more vulnerable to differential loss of bond strength by bleeding.

In concrete under compression, discontinuities attributable to shear bond microcracking initiate at 45 to 80% of ultimate strength. Although hard rocks tend to cause premature initiation of microcracking, the adverse effect can be more than offset by other properties of the aggregate.

There is a linear multiple regression of concrete strength on paste and bond strength in which the coefficient for paste strength is approximately twice that for bond. An analogous regression applies to the proportion of coarse aggregate broken during the transverse testing of concrete.
The bond between "inert" siliceous aggregates and portland cement is pozzolanic in origin, and mechanical interlocking is unnecessary for the development of tensile bond strength.

**Time independent parameters of 28 day concrete strength**

Scholer (51) in 1967 reviewed the role of the mortar aggregate bond of concrete and stressed the time independent parameters governing the strength of 28 day concrete.

**Changes in Concrete Materials**

**Diagenesis of silica sediments**

Dapples (8) in 1967 outlined the role of silica in diagenesis of sediments. He cited the incompatability of quartz and carbonate rocks as follows:

Certain thin beds of quartz sandstone interbedded with carbonate rocks contain quartz grains of exceptional roundness. Some of the grains show additions of quartz as well-terminated overgrowths, but rarely such grains are completely surrounded by chert deposited as a rind around the grain (Dietrich et al., 10). Generally the time of precipitation of such silica is difficult to date, but Dietrich and his associates have been able to show rhombs of dolomite included within the quartz overgrowths.

The order of paragenesis is not always the same as shown by examples in which secondarily enlarged grains of quartz are engulfed and partially replaced by calcite. Such calcite was precipitated as a cement, but has by replacement of quartz grains virtually destroyed the original sandstone texture (Chanda 3, 1963).

The influence of pH on solubility of silica is such that between pH limits of 2 and 8.5 the solubility is approximately constant in the range of 10 to 20 ppm. At higher pH the solubility rises abruptly attaining values of 5,000 ppm at pH 11 (Krauskopf 34, 1959).
Alkali-silica reaction

Idorn (30) in 1967 reviewed the properties of the alkali-aggregate reaction (commonly expressed as alkali-silica reaction) as follows:

1. Crack formations and chemical alterations in reacted particles, classified according to type of rock (porous flint, dense flint, composite rocks).

2. Formation and precipitation of gel.—(In most cases, gel is alkali-silica gel originating from alkali-aggregate reaction.)


Discussion The alkali-silica reaction is considered separately from alkali-carbonate and freezing and thawing distress.

Tobermorite gel reactions

Copeland et al. (5) in 1967 discussed the reactions of tobermorite gel with aluminates, ferrites and sulfates. The significance of the work was thought to involve the effect that substitution reactions may have on the mechanical properties of hardened paste and concrete such as strength, elastic and thermal properties, and shrinkage characteristics. They made the following summary and conclusions:

The reactions of tobermorite gel with aluminates, ferrites, and sulfates are consistent with the requirements for substitution reactions.

1. Aluminum, iron and sulfur of sulfate ions will substitute for silicon in tobermorite gel; aluminum, and iron will also substitute for calcium. The maximum amount of substitution that occurs corresponds to approximately one atom of substituent to 6 atoms of silicon.

2. Substitution will occur directly into tobermorite gel, and also during the formation of the gel if the substituent is present. It occurs in hardened pastes as well as slurries.
3. In the case of sulfate ion, charge balance is maintained by replacement of 2 hydroxyl ions by oxygen ion. When aluminum substitutes for silicon, charge balance is maintained by introduction of a Proton to change one of the unshared oxygens of the tetrahedron to hydroxyl. Two Fe$^{3+}$ substitute for 1 Ca$^{2+}$ and 1 Si$^{4+}$ simultaneously, thus maintaining charge balance. Aluminum substitutes for calcium in the ratio 2 Al$^{3+}$:3Ca$^{2+}$ to balance the charge.

4. Changes in morphology of the gel, and apparent structure of hardened pastes accompany the substitution reactions.

5. That one substituent in a gel can be displaced by another is shown by the reaction of sulfate ion with aluminum-substituted gel to form calcium sulfoaluminate and sulfate-substituted gel; the converse reaction also occurs.

**Reactive iron sulfides in concrete**

Mielenz (46) in 1963 reviewed reactions involving solubility or oxidation of aggregates while they are enclosed in concrete. He defined a reactive sulfide as follows:

Oxidation phenomena of significance to the performance of aggregates in concrete appear to be restricted to metallic iron and compounds containing ferrous iron. By far the greatest effect to oxidation in this context relates to the decomposition of the ferrous sulfides, pyrite ($\text{FeS}_2$), marcasite ($\text{FeS}_2$), and pyrrhotite ($\text{Fe}_{x-1}\text{S}_x$); that is, ferrous sulfides in which sulfur is stoichiometrically in excess of the iron.

Mielenz concluded as follows:

Reactions of aggregates involving solubility, oxidation, sulfates, or sulfides are indicated by published information and the experience of the author to be of minor significance generally. Aggregates containing sulfides or sulfates may create local problems that are primarily the development of unsightly conditions on concrete construction, such as efflorescence, staining, or sporadic spalling and pop-out formation.

At this time, it appears that reliable methods of testing for detection of reactive forms of ferrous sulfides would be a worthwhile addition to testing procedures in localities where these minerals have been shown to be of significance in the performance of concrete.
Petrographic examination should be of value in identification of aggregates suspected of susceptibility to solubility, oxidation, or reactions of sulfides or sulfates while enclosed in concrete.

**Sulfate attack of concrete**

Idorn (29) in 1957 presented a case study of the petrographic description of concrete suffering sulfate attack. He starts with the macroscopic description as follows:

The disintegrated concrete below the original groundwater level was a dark grey-blue mouldered mass of sticky mortar and loose aggregate pebbles. The concrete aggregates consist of fine-grained, "sharp" sand mainly quartz and rounded compact pebbles of about 12 to 50 mm size, the rock types being flint, limestone, granite etc. After driving in the laboratory the dark mouldered mass turns to sand grains covered by a greyish film, in which white, needle-shaped crystallites occur spotwise. Some parts of the faces show a white appearance obviously due to progressed alteration of the paste; other parts have an unusual grey-blue, dim color like dried ink, indicating staining of the paste by a bluish substance or precipitation of some secondary materials of this color. The front between the white and bluish paste appears as marked rounded lines, here and there of a dense bluish color. Secondary deposits occur frequently as exceptionally well developed crystalline formations over broken faces, in voids, and on uncovered faces of aggregate pebbles. The following three substances were especially remarkable:

1. Calcium sulfoaluminate
2. Calcite
3. Calcium aluminum hydrate (?).

**Discussion**

This case study is helpful as a collection of the petrographic and optical properties of the secondary compounds associated with the distress of sulfate attack.

**Discoloration of concrete**

Greening and Landgren (22) in 1966 presented laboratory studies on mottling discoloration of horizontal concrete slabs. In their studies the following was noted.
The dark spot discoloration appears to be caused by alkali salts that migrate to the drying concrete surface and concentrate in the more porous or checked areas of the surface. These deposits of salt are relatively transparent and continuous. Their optical behavior is apparently similar to that of water or clear oil, which will darken paste when absorbed. Microscopic examination indicated that the materials causing dark spots on slabs without calcium chloride were alkali carbonates - reaction products of cement alkalies and carbon dioxide from the air. Dark spots on slabs containing calcium chloride are primarily crystalline potassium and sodium chloride-reaction products of cement alkalies and calcium chloride.

In high alkali cements with calcium chloride the ... extreme discoloration is characterized by light spots directly over coarse aggregate particles near the concrete surface.

In summary, type of discoloration produced is influenced by both the alkali content of the cement and the calcium chloride content. For example, air cured slabs made with low-alkali cement A and 0.2 percent calcium chloride have dark spot discoloration, and ones made with 2 percent calcium chloride have light spot discoloration. At the other extreme, air-cured slabs made with high-alkali cement E and very high percentages of calcium chloride (about 5 percent or greater) show light spot discoloration in contrast to the dark spot discoloration with lower amounts of calcium chloride. The factor mainly determining the type of discoloration in the slab is the ratio of the alkalies to the calcium chloride present in the concrete. High and low ratios produce dark spot and light spot discoloration, respectively.

Diagenetic features of sandstone

Dapples (7) in 1967 reviewed the diagenetic features of sandstones. He considered diagenetic modification as occurring in the following stages.

1. Redoxomorphic - oxidation-reduction reactions involving iron in particular characterize early burial.

2. Locomorphic - cementation and mineral replacement involving primarily silica and carbonates are typical of lithification.

3. Phyllomorphic - authigenesis of micas and feldspars is a late burial feature.

Chemical reactions which occur during each of the three stages of diagenesis result in equilibrium mineral assemblages which are considered to identify the pH and Eh of the interstitial fluids.
Redoxomorphic changes

Oxidation and reduction reactions can be demonstrated to dominate modification of the sediment during and immediately after burial. During this time, compaction is in progress and fluids are being ejected with concentration gradients towards the depositional interface. Principal reactants involved are iron, oxygen, sulfur and carbon. Deposits consisting of a significant fraction of organic matter tend to contain sulfur as well as carbon. Of these, carbon compounds appear to be most rapidly oxidized and may be regarded as contributing electrons to drive the iron into the ferrous state and thus permitting fixation of the sulfur as pyrite. As long as the organic fraction remains important, the gray color will prevail and pyrite will be scattered throughout the rock often in considerable amounts.

Inasmuch as the precipitation of iron hydroxide is indirectly controlled by pH, a slightly acid condition of many streams would tend to keep the iron primarily in the reduced form during transportation and red color would develop only after deposition in an environment of higher pH, such as a sea or playa lake.

A more common situation is believed to prevail during which the equilibrium between Fe$^2+$ and Fe$^3+$ is shifted toward oxidation sometime after burial. In its most obvious form this can be seen in strata in which the red color transects bedding, and coloration follows fractures or permeable positions related to introduction of water carrying dissolved oxygen. Conversely bleaching of the red color can be demonstrated for masses of irregular outline or for concentric zones about some center. Paragenetic relations between minerals from such zones show rather persistent association between iron oxides, biotite, chlorite, siderite and calcite in bleached zones (i.e., where iron is in the reduced state), and decomposed condition or absence of such minerals where the iron is oxidized, is interpreted to illustrate the following reactions:

\[
\text{biotite} \xrightarrow{\text{oxidation}} \text{iron oxides} + \text{clay minerals (illite + kaolinite)} \xleftarrow{\text{reduction}} \text{biotite} \rightarrow \text{chlorite}
\]

(in presence of calcite and in slightly reducing environment)

---calcite which is present in the bleached portion extends a short distance into the red rock. Here it tends to split detrital grains of strongly oxidized and decomposed biotite along cleavage laminae.

Generalized stability realms of sandstones indicate the following minerals are unstable above a pH of 8.
1. Biotite
2. Muscovite
3. Glaucorite
4. Montmorillonite
5. Illite
6. Chlorite

Locomorphic changes

In many sediments modification identified as locomorphic involve changes in the pore cement only. ... The progressive nature of change is unidirectional from opal to quartz within the physical conditions of stability of sandstone.

opal → chalcedony → quartz

Chert replacement of clay matrix

This process is of common occurrence. Chert tends to become converted to quartz in time. However, concentrations of calcite tend to inhibit recrystallization of chert to quartz.

Calcite replacement of clay

In some sandstones the calcite has replaced the clay fraction in the sense that the clay no longer is present as an insoluble residue in the carbonate. In other examples, at least some of the clay remains as a residue within the calcite and can be recovered on solution of the carbonate. The mechanism of such replacement is not understood but it appears that certain clay minerals, known to be primarily illite and kaolinite in the case of some graywacke are flocculated by Ca-ion and occupy less interstitial space allowing the remainder to be filled by the precipitated carbonate. On the basis of what is known of solute precipitation, replacement of clay minerals by calcite is favored by a pH > 8 and a high concentration of Ca-ion under which conditions certain clay minerals become unstable.

Calcite-dolomite replacement

Replacement of calcite by dolomite is noted in -- the quartzose group which passes by lateral facies change into limestone, which at some later time is subjected to whole-sale dolomitization. In such rocks quartz grains may be completely engulfed in carbonate, dolomitization may be limited to the replacement of calcite and the quartz is unaffected. --Replacement is also unidirectional and any later addition of calcite appears to be limited to joint or cavity fillings and not to the reversal of the reaction calcite-dolomite.

A second type is recognized among sub-graywacke sandstones in which the primary calcite cement contains isolated rhombs of dolomite.
and siderite. The presence of Fe$^2+$ ions seems to favor precipitation of siderite rather than an iron-rich dolomite, although later investigation may show greater abundance of dolomite than currently recognized. This occurrence suggests that the dolomite may possibly represent some exsolution phenomenon rather than the result of introduction of magnesium from some outside source.

Phyllomorph changes

Feldspar-calcite replacement

In certain arkoses which are known to have attained the phyllomorphic stage it is not uncommon to note significant replacement of potash feldspar by calcite precipitated as a cement. In these, both quartz and feldspar are partially replaced. --The typical alteration represented is interpreted as resulting from a process by which solutions rich in Ca$^2+$ and CO$_3^{2-}$ ions are capable of destroying the potash feldspar lattice, possibly by causing the silica tetrahedral units to go into solution under high pH —. Since calcite replaces plagioclase beds of Eocene age, -- the replacement reaction is not restricted to potash feldspar.

In less oxidizing conditions albite may be an equilibrium mineral of this stage in basic solutions. In oxidizing, neutral environments the orthoclase form becomes stable. Acid solutions favor stability of micas rather than feldspars.

Concepts of Highway Pavement Observation

Concrete petrography

Mielenz (45) in 1946 presented the observation of concrete aggregates as a petrographic problem. He recognized opal, chalcedony, tridymite, intermediate to acidic volcanic glasses and probably the hydromicas of some phyllites as deleterious constituents of concrete aggregates.

Mather (41) in 1948 suggested that the techniques of petrography be used to determine the presence of known reactive materials, whenever aggregate samples are subjected to chemical tests or performance tests for
alkali-reactivity.

Mather (42) in 1952 reviewed the use of the microscope in concrete research as extensions of its use in petrology, mineralogy and chemistry. She stressed the quantitative applications of mineral composition and air content by linear traverse and point count techniques. In 1955 (43) she recognized the problem of communication between the highway engineer and the highway petrographer. She introduced in table form an outline for examination of concrete (a) with eye and hand lens and (b) with a stereomicroscope.

Levels of concrete investigations

Idorn (30) in 1967 outlined the framework for concrete investigations as follows:

1. Visual examination of the field behavior of concrete.
2. Compilation and evaluation of data on initial concrete quality.
3. Detailed examinations of concrete specimens and of concrete materials (cement, aggregates, etc.)
4. Exploration of exposure conditions of the structure, i.e. the physio-chemical influence from surrounding air, water and soil.
5. Supplementary experiments on concrete in the field.
6. Supplementary laboratory experiments.

He further subdivided the detailed examination of concrete specimens into (a) macroscopic examinations and (b) thin section examinations.

Idorn stressed that macroscopic observations formed a link between the field inspection of a structure and the thin section investigation of concrete microstructures. Commonly macroscopic observations of cores added the third and fourth dimensions to the original surface descriptions.
Details of his concept of macroscopic investigation were given in Idorn (31) 1964.

Components of phases identified in thin section investigations include the following:

1. Calcium hydroxide
2. Beta-dicalcium silicate
3. Calcite
4. Aragonite
5. Gypsum
6. Brucite
7. Calcium aluminate sulfate hydrates
8. Calcium aluminate hydrates
9. Gel - (Optically isotropic, transparent to translucent, colorless. Refractive index very much lower than impregnating medium. Often shows cracking due to drying shrinkage.)

Limestone failure surfaces

Harvey (26) in 1966 presented the microtexture and grain surfaces of limestones which failed in tension or shear as observed from electron micrographs of direct carbon replicas. The following differences were noted at magnifications of 5400 to 23,500 times.

Tensile failure:
1. Small, roughly hemispherical nodes are commonly observed on certain crystallographic surfaces. The diameter of the nodes averages 0.1 micron. Similar nodes were not seen on smoothed and etched surfaces, but larger nodes up to 2 microns in diameter were noted on secondary calcite grains.
2. Tensile fractures in limestones (particularly in grains larger than 10 microns) are characterized by cleavage steps.
3. Breakage of limestone in tension produces fractures that follow grain contacts in some places and cross grain contacts in others.

Shear failure:
1. Shear fracture surfaces are characterized by slip and/or twin lamellae, partial grain cracks, surface grooves on large grains, and a fine dust
on some grain surfaces.

2. Some cleavage fracturing also occurs on shear surfaces.

**Identification by staining carbonate minerals**

Friedman (19) in 1959 recommended several procedures for the identification of carbonate minerals. He included a stain based on potassium ferricyanide for the detection of ferrous iron in dolomites.

**Peels of stained carbonate surfaces**

Davies and Till (9) in 1968 presented a method of impregnating and sectioning recent carbonate sediments, and a dry ethyl cellulose-trichlor-ethylene sheet technique to obtain peels of stained carbonate surfaces. By obtaining serial sections of polished and stained surfaces, calcite, ferroan calcite, high magnesium calcite, aragonite, dolomite and ferroan dolomite may be identified. They considered stained peels better than thin sections for the study of carbonate sediments.

**Measurement of concrete air content**

Hanna et al. (25) in 1966 presented the problem of interpreting differences in the plastic air content of highway samples. They used statistical quality control procedures to establish significant differences based on the reproducibility of construction practice.

**Concepts of Weathering**

**Durability of weathered rock for concrete**

Dolar-Mantuani (11) in 1964 discussed the problem of acceptance of fresh and weathered Beekmantown dolomitic rock for coarse aggregate in
Portland cement concrete. In this study weathering was restricted to processes occurring at the quarry face so the product of the quarry was either fresh or weathered material from the same quarry ledge. Several ledges were considered. She described the materials as follows:

The weathering of this material varied, as megascopically revealed by the gradation from slightly discolored relatively dark grey normally shaly and/or sandy dolomitic rocks to a dull, highly porous brownish dolomite, poor in argillaceous impurities.

Pyrite in single crystals is often finely divided in the Beekmantown dolomite....In weathered layers it is transformed into limonite. Sulphates although present in traces, have been detected only in the filtrates of the insoluble residues.

The clay minerals were commonly illite, ... and chlorite.

A comparison with...test results obtained on fresh dolomite aggregates and concretes made of such material, demonstrates that the weathered material and even more so the weathered gravel have a low apparent specific gravity, a high percentage of absorption and a high percentage of loss after the Los Angeles abrasion test. Also concrete made with coarse aggregate that consisted entirely of partially weathered dolomite reflected lower durability in the freezing and thawing test.

Dolar-Mantuani concluded the following:

As a result of the extensive studies briefly outlined in this paper, it was recommended that the near-surface layers of dolomite should be carefully stripped off in the quarries should Beekmantown dolomite be considered as concrete aggregate. Furthermore, the requirement of a maximum of 1 percent limit of intensely weathered dolomitic rocks was introduced into the specifications for concrete aggregate.

In the meantime concrete in which from 5 to 60 percent of the 3/4-inch fraction of a sound aggregate were replaced by intensely weathered dolomitic gravel, in appropriate percentages was included in the outdoor testing programs...This concrete showed popouts developed at the spots where weathered dolomites occurred at or close to the surface. Although the outdoor test proved that a concrete containing weathered Beekmantown dolomite will not disintegrate because of the undesirable aggregate used, popouts as well as initial cracks developed over such harmful aggregate particles. These popouts and cracks are not only unsightly but also promote damage to a concrete subjected to severe weathering conditions.
STATUS OF OTIS AGGREGATE CONCRETE STUDIES

Approach

Lemish and Moore (38) in 1964 presented a systematic approach to the study of highway concretes. They studied the physical and chemical changes that take place in concrete as it ages. Using concretes made from the same aggregate but of different ages, a chronological sequence of concrete highways was established. Cores taken from the selected highways at one time are used to estimate the weathering of a single highway over time intervals studied. Since the systematic approach of coring one highway over a 20 to 40 year period was not feasible, the composite picture obtained from selected highway core samples is the best estimate of the modifications of highway materials in service. The cores were stored in a CO₂ free environment, and in addition to the standard compressive strength test a chemical analysis, reported in the form of principal oxides for the 1, 3, and 5 inch depths, was required for the matrix and coarse aggregate.

In 1963 several Otis aggregate concrete highways were sampled using this approach. The study was termed weathering research since the cores were taken from the central portion of highway slabs of different aged highways constructed from the Otis aggregate concrete.

Progress Reported: 1963 Program

Elwell, Moore and Lemish (13) in 1966 reported the chemical and compressive strength data for the 1963 Otis aggregate concrete core samples. Data reported included SiO₂, CaO, MgO, Al₂O₃, Fe₂O₃, Na₂O, K₂O, SO₃, CO₂
and weight loss between 300-950°C for the matrix. (Simon, 1968 (53) reported FeO and free CaO for these samples.) Based on the 1, 3, and 5 inch depth samples the alkali content decreases to an equilibrium value. Slight changes are noticed for the Al₂O₃, Fe₂O₃, and SO₃ values reported for the concrete matrix samples but the greatest change is the increase in CO₂ with time for the Otis coarse aggregate. The chemical analysis of the matrix reflects the brand of cement, the mix proportions and the source of coarse aggregate.

**Bulk chemical results**

Investigations conducted by Simon and reported by Lemish (37) in the 1967 Final Report suggested that the major change in the chemical compositions for the 1963 cores was an increase in CaCO₃ and corresponding loss of Ca(OH)₂ and CSH compounds with time.

**Silicate structural results**

These bulk chemical results were further supported by structural analysis of cement compounds performed by Dr. C. W. Lentz on the same 1963 core samples for which the oxide data were reported. His raw data were reorganized, plotted by the author, and reported by Lemish (37) in 1967. The Lentz data indicate that hydrated cement silicates changed from monomer to dimer to polysilicate forms with increasing service life. The formation of polysilicates is equated with loss of "glue" or destruction of the tobermorite structure. Different cement brands were found not only to have different amounts of "glue" initially but also to lose their "glue" at different average rates.
Compressive strength results

Compressive strength tests on the highway concrete cores taken in 1963 were made by the Materials Laboratory of the Iowa State Highway Commission and reported as preliminary data by Welp and De Young (57). These data were reorganized and plotted by the author. Classification by coarse aggregate and cement brand indicated two kinds of behavior. Test results for recently constructed highways indicated an increasing compressive strength vs age relationship that was characteristic of the brand of cement employed in construction and independent of the coarse aggregate used. The older more weathered samples displayed a different behavior: namely, all highways constructed of the same coarse aggregate had nearly the same strength even though they were constructed with different brands of cement. Because of this dual behavior, breaking studies were undertaken to investigate the nature of the compressive strength.

Identification of Otis coarse aggregate ledge materials

A petrographic study of the cores sampled in 1963 was undertaken as further information on a concrete system that was already defined in terms of chemical composition and compressive strength. The objective of the behavior study on various lithologies of Otis coarse aggregate in highway concretes of various ages, reported by the author, Elwell (12) in 1966, showed differences of response in the same environment. The unique aspect of this research was to relate individual pieces of coarse aggregate to the exact ledges in the quarry from which they came. Once the particles were identified as belonging to a certain ledge, the behavior of this material can be compared not only with the material from other ledges with-
in one core sample but also between different aged cores containing the same ledge material.

**Breaking study of Otis coarse aggregates**

Breaking behavior studies were undertaken by Kemp and Elwell (32) on the identified ledge material in slices of 1963 Otis aggregate concrete cores. The locations of failure were distinguished on the basis of the relative bending strength of the aggregate, inner rim, bond zone, outer rim, and matrix of the concrete slice. It was reported by the author, Elwell (12), that during the initial 5 year period of service the coarse aggregate-matrix bond was most easily broken regardless of the lithology tested. This time period correlated well with the early compressive strength dependence on the brand of cement employed. (Limited observation of the fracture surfaces of cores which had failed under compressive tests confirmed bond zone fractures.) After the initial period, the bending behavior observed was dependent on the ledge material tested since the aggregate-matrix bond became relatively stronger with time and did not remain the weakest link in the concrete system. Ledge materials may be classified into those which eventually become stronger than the matrix (strong) and those which fail more easily than the matrix (weak). It was assumed that the weak ledge material would be undesirable. Under this assumption all parameters obtained from short time tests explain only bond zone failure; such tests fail to predict or explain aggregate failure which is the mode of failure (weakest link) at an age when highway deterioration is evident.
Progress Reported: 1966 Program

In 1966 some of the same slabs that were sampled in 1963 were re-sampled to act as a control for the present study. Some new slabs were added to the program to test changes estimated from the 1963 core data. A compressive strength test on the highway concrete cores was made as before by the Materials Laboratory of the Iowa State Highway Commission and these data were organized by the author and reported by Lemish (37) in 1967. The results obtained by resampling the same slabs are shown together with the original and 1963 data points in Figure 1. The point by point comparison of these data supported the trends reported for 1963 data and the use of different highways to form a composite history.

Compressive strength

The composite history indicated that compressive strength of an Otis aggregate concrete core increases up to about 10,000 psi and then decreases in older concretes. The maximum strength is reached after 12 to 14 years of service when the first signs of rapid highway distress are observed. Older highways constructed with the same cement but containing coarse aggregate from a different geologic source have not reached a strength maximum and do not show deterioration in the field after as much as 30 years of service.

The compressive strength reported in 1966 for highways constructed with a single brand of cement and the same source of coarse aggregate material is shown in Figure 2A. By reducing the variation in compressive
Figure 1. Comparison of the compressive strength of cores from selected highway slab samples in 1963 and 1966 with initial strength characteristics of Otis aggregate concrete.
• SAMPLED 1963
• SAMPLED 1966
○ I.S.H.C. LAB TESTS
-- CEMENT "A"
-- CEMENT "B"
--- SAME SLAB RESAMPLED
Figure 2A. Compressive strength of cores constructed of Otis coarse aggregate and brand A cement sampled from different aged highway slabs.

Figure 2B. Percent saturation of air entrainment size voids in cores representing slabs constructed of brand A cement when the highways were sampled for compressive strength.
strength associated with different source materials these data have sufficient resolution to distinguish the increased compressive strength associated with the use of non-air entrained concrete. These data suggest that air entrained concrete may reach a strength maximum at an earlier age than non-air entrained concrete.

**Air entrainment size void water content**

The water content of the air entrainment size voids determined for selected 1966 core samples is shown in Figure 2B. Data from determinations made by the Materials Laboratory of the Iowa State Highway Commission were organized by the author and reported by Lemish (37). For Otis aggregate concrete high percent saturations of the air entrainment size voids are associated with the high compressive strength non-air entrained concrete. Both air entrained and non-air entrained concrete appear to decrease in percent saturation with increasing elapsed time.

A special test was used to measure the water or hydrated minerals which were present in the highway but not detected in standard laboratory determinations of the amount of air entrainment size voids. Percentage of air entrainment size voids determined by standard test methods for concrete slabs used in this study is shown in Figure 3A. This plot indicates an appreciably higher void content for air entrained concrete samples. Figure 3B contrasts these air entrained percentages obtained from all slabs in 1966 with the plastic air test results that were recorded for these concretes during construction. These sets of values are considered to be in good agreement as to the total percentage of voids in this size range.
Figure 3A. Percentage of total sample that consists of air entrainment size voids as determined by standard test methods for 1966 samples of various aged Otis aggregate concrete highways.

Figure 3B. Percentage data for the 1966 air entrained concrete samples of Figure 3A is presented as a percentage versus age profile of five to fourteen year old concrete. A similar profile is shown for the initial percentages calculated from plastic air determinations recorded during construction of these highways.
Figure 3C is another plot of the total void percentage which is arranged to show differences between air entrained and non-air entrained concrete studied. Special tests permitted measurement of air entrainment size voids which were filled in the highway slab under service conditions at the time of sampling. Percentage of these filled voids is shown in Figure 3D and available air filled space is shown in Figure 3E. Because water filling these size voids will require additional space during freezing it would appear that a significant portion of air entrainment size void volume measured in standard tests is not available to meet design requirements of air entrained concrete.

The explanation of the path of concrete failure consistent with all observed data is as follows:

1. A gradual loss of water with time.
2. A gain in solids leached from the coarse aggregate.
3. Air entrainment size voids are filled increasingly with leached solids and secondary minerals.
4. The filling voids reach a critical percent saturation.
5. Failure of concrete by freeze and thaw action in the critical zone.
6. Core samples of damaged concrete have less than the maximum compressive strength.
7. Accumulated damage results in the decreasing strength - age relationship determined for the older Otis aggregate concrete.

Bulk chemical results

Preliminary chemical aspects of the 1966 cores investigated by Simon and reported by Lemish (37) show considerable refinement of the chemical
Figure 3C. Percentage of total sample consisting of air entrainment size voids is presented as two profiles. Classification of 1966 samples to form profiles is on the basis of being air entrained or non-air entrained concrete.

Figure 3D. Percentage of total sample consisting of liquid or solid filled air entrainment size voids is presented as two profiles for these classified samples.

Figure 3E. Percentage of total sample consisting of air filled air entrainment size voids is presented as two profiles for these classified samples. These results represent the available space for expansion during freezing in the highway slabs when sampled.
data. Although the phase ratios provided by the Lentz data show the relative abundance of the silica present they do not show how the amount of silica contributed by the hydrated cement matrix changes with time. To accomplish this it was necessary to separate the contribution of the fine aggregate from the hydrated cement. Methods developed by the author to separate silica by size and solubility were employed by Simon to follow the breakdown of the fine aggregate and hydrated cement in service. Simon interpreted the data as follows:

The coarse fraction represents the sand-sized residue of hydrochloric acid soluble material and is interpreted to contain the quartz and feldspar particles originally added to the highway as sand when the concrete was mixed. The fine fraction, separated on the basis of size, represents HCl and by the fine aggregate as minor amounts of fine quartz and feldspar material. Soluble silica represents primarily cement material which is soluble in HCl and should correspond to the sum of the polysilicate, dimer and monomer forms of Lentz.

Simon (53) in 1968 reports the results of his study on the partition of calcium using normative calculations to apportion his oxide data into phase data. On the basis of his study of Otis aggregate concrete samples in 1966 he draws the following conclusions.

1. A major chemical process of aging is carbonation of the calcium-bearing phases contained in hydrated cement of concretes. The main phases which carbonate readily are Ca(OH)$_2$ and CSH. These phases have high negative correlation with increasing CO$_2$.

2. The primary source of CO$_2$ is considered to be the atmosphere and is experimentally demonstrated by the large increase of CO$_2$ at the surface.

3. C$_3$ACSH$_{12}$, which is petrographically associated with CaCO$_3$ in deteriorated concrete, is considered to be the most stable phase present. The lack of correlation with CO$_2$ substantiates this conclusion.
4. C₆AFH₁₂ is considered slowly attacked by CO₂ because of its low correlation to the CO₂ content. Also, the decrease in aluminum with age is considered equivalent to the amount released by carbonation of C₆AFH₁₂.

5. The alkalis which have high mobilities were shown to be concentrated at the highway surface. This concentration is largely due to the evaporation of pore water moving upward by capillary action.

6. The relationship of coarse and fine insoluble residues at the surface substantiates petrographic evidence that quartz grains of the fine aggregate are being fractured and broken by carbonation of hydrated cement material at the highway surface.

7. The use of a material balance for the calcium bearing phases demonstrates that it is possible to establish a calcium balance for the phases in hydrated cement. Also, the calcium balance provided a means to show the path of changes occurring in the hydrated portion of the concrete.

   The major change is carbonation of the calcium-bearing phases, which with time alters the composition of these phases binding the concrete together. A common assumption prevalent in the literature is that carbonation of the cement portion of concrete has little or no effect on its performance. This investigation demonstrates that carbonation and other changes of hydrated cement which occur must be considered in any study of the behavior of concretes.

A unique feature of this study was the new basis which permitted comparison of the relative abundance of oxides in different core samples as additions or deletions to an original composition. Equations necessary to transform the non-additive weight percent data to the new additive basis were originated by the author, Elwell (14), and employed by Simon (53) so that large numerical changes would not bias the amounts of minor constituents necessary for quantitative calculations.

Highway Concrete Aging

In 1966, Elwell et al. (12), reported on the petrographic aspects of center of the slab Otis concrete cores. Of all the changes detected
by comparison of different aged material identified as coming from the same quarry ledge none was so striking as loss of color with time. Removal of the iron-rich coloring material was accelerated by availability of moisture and recrystallization of carbonate grains. Coarse aggregate pieces with lighter colored edges (inner rims) were considered the result of differential leaching of iron material from the aggregate: some of the leached iron was found as a dark outer rim in the surrounding matrix. The leached iron appears as a brown gel in the matrix.

At the highway surface, aging is correlated with loss of fine aggregate and smoothing of the surface. Loss of fine aggregate may be explained in terms of loss of bonding forces between fine aggregate and hydrated cement. Loosening of bonds is associated with the presence of brown gel. Extreme disruption of the matrix by loosening of the hydrated cement particles and their carbonation changes the matrix color from brown to blue gray and then to white for the liberated grains.

In summary progressive changes in chemical, strength, and petrographic aspects serve to characterize these general aging changes for Otis aggregate concrete. Aggregates assumed to come from different quarry ledges have dissimilar consistent behavior patterns. Since all highway core samples were taken from the center of the slab they represent the least damaged portion. These changes represent a history that is least associated with "D" line cracked highway concrete.
PETROGRAPHIC FENCE STUDY APPROACH

The present study deals with the separation of changes which are associated with the early deterioration of highway pavement from the general time dependent changes established for the Otis aggregate concrete system. The following assumptions are necessary to separate these changes through a petrographic fence study.

1. Because the concrete system changes with time, the material which fails does not represent the initial condition of the material.

2. Because deterioration starts at the slab edge and progresses inward toward the sounder center, destructive changes would proceed more rapidly at the slab edge. By comparison this assumption permits separation of possible destructive changes from the general changes which occur during aging.

3. Samples taken across the highway slab at right angles to edges will form a gradational sample sequence which will reflect the changes present in the slab.

4. The chemical and physical changes associated with destructive changes will be observable by comparison of optical descriptions.

Under these assumptions it was necessary to set up a sampling program which would provide information as follows:

1. Concrete deterioration of the Otis type must be described in sufficient detail so that it may be associated with changes within the concrete system.

2. Materials and practices must be controlled through service records so changes are not due to different starting mixtures.
SAMPLING PROGRAM

The service records for Iowa Highways are identified by coarse aggregate source, fine aggregate source and cement brand. Study of the records enabled the selection of highway sites which were paved with similar materials and represent various service lives from 5 to 28 years. Center-of-slab cores from these selected highways serve as a control or estimate of the minimum expected change due to weathering of these materials. The 4-inch diameter cores are obtained by a water cooled diamond drill and are identified by code numbers as follows: (CD-66-61-150-A-1).

1. Letters represent the coarse aggregate source; thus CD identifies Otis coarse aggregate.
2. First set of digits stands for year cored.
3. The next pair represents the year paved.
4. The third set of digits identifies the highway number.
5. The next letter or number identifies the particular core taken from the designated sample site.
6. The last set of digits represents a core depth of a subsample of the primary core sample.

The identification of cores used in this study for control purposes are shown in Table 1.

As part of the highway selection process it was necessary to field check and mark the sample locations. At this time sample sites that appeared to show typical expressions of deterioration around joints were selected for the petrographic fence study. Such locations were chosen to show development of the distress feature rather than to estimate the
Table 1. Otis aggregate concrete control cores program HR-116

<table>
<thead>
<tr>
<th>Code</th>
<th>Cores</th>
<th>Station</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD-66-61-150</td>
<td>A-G</td>
<td>213</td>
<td>HW 150 from HW 151 to old HW 30</td>
</tr>
<tr>
<td>CD-66-58-150</td>
<td>A-G</td>
<td>59</td>
<td>Relocation HW 150 to HW 151</td>
</tr>
<tr>
<td>CD-66-57-W</td>
<td>A-G</td>
<td>16</td>
<td>HW W east of Williamsburg</td>
</tr>
<tr>
<td>CD-66-56-218</td>
<td>A-G</td>
<td>250 and 75</td>
<td>HW 218 from Sec 21-8-7 to HW 84</td>
</tr>
<tr>
<td>CD-66-52-1</td>
<td>A-G</td>
<td>227 and 80</td>
<td>HW 1 north of Mt. Vernon</td>
</tr>
<tr>
<td>CD-66-51-W</td>
<td>A-G</td>
<td>--</td>
<td>HW W east of Williamsburg</td>
</tr>
<tr>
<td>CD-66-50-64</td>
<td>A-G</td>
<td>43</td>
<td>HW 64 and HW 151 in Cedar Rapids</td>
</tr>
<tr>
<td>CD-66-48-84</td>
<td>A-G</td>
<td>161 and 10</td>
<td>Airport road near HW 218</td>
</tr>
<tr>
<td>CD-66-48-151</td>
<td>A-G</td>
<td>43</td>
<td>Inside lane on HW 151 in Cedar Rapids</td>
</tr>
<tr>
<td>CD-66-48-3</td>
<td>A-G</td>
<td>--</td>
<td>HW 3 south east of Edgewood</td>
</tr>
<tr>
<td>CD-66-48--</td>
<td>A-G</td>
<td>--</td>
<td>Old HW 30 near Marshalltown</td>
</tr>
<tr>
<td>CD-66-46-1</td>
<td>A-G</td>
<td>840</td>
<td>HW 1 near Mt. Vernon</td>
</tr>
<tr>
<td>CD-66-41-1</td>
<td>A-G</td>
<td>666</td>
<td>HW 1 north at Solon</td>
</tr>
<tr>
<td>CD-66-38-38</td>
<td>A-G</td>
<td>208 and 20</td>
<td>HW 38 near Monticello</td>
</tr>
</tbody>
</table>
average condition of the highway. These samples were set up as case studies for which the distress zones were classified as follows:

1. Design features
   a. Expansion joints
   b. Contraction joints

2. Natural fractures
   a. Joints (fractures between slabs)
   b. Cracks (fractures within slabs)

Prior to sampling, photographs were taken so that the core locations could be spatially related to the condition of the highway slab and traffic direction. The surfaces of the cores were marked with arrows showing the traffic direction which also indexed the core orientation. The case study included one or more cores at each location depending on the scale of the feature investigated. An attempt was made to obtain undamaged materials from each slab investigated. The sample locations are listed in Table 2.

Sub-samples were obtained by cutting into a series of depth slices with an oil-bathed saw. The cutting oil was removed in benzene prior to microscopic observation of the sub-sample. Sections cut perpendicular and parallel to the highway surface were indexed as to depth and geometric relationship to crack or joint being tested. Vertical slices \( \frac{1}{4} \) to \( \frac{1}{2} \) inch thick were obtained to observe how main fracture patterns pass through coarse aggregates. These thin slices were very important to the study since they exposed two or three perpendicular surfaces of the same coarse aggregate. By observing one side of a slice, the coarse aggregate
Table 2. Otis aggregate concrete petrographic fence program HR-116

<table>
<thead>
<tr>
<th>Code</th>
<th>Station</th>
<th>Feature</th>
<th>Cores</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD-66-58-150</td>
<td>43 and 80</td>
<td>Joint</td>
<td>-1,-2,-3</td>
</tr>
<tr>
<td>CD-66-52-1</td>
<td>110 and 50</td>
<td>Joint</td>
<td>-1,-2,-3,-4</td>
</tr>
<tr>
<td>CD-66-51-W</td>
<td></td>
<td>Joint</td>
<td>-1</td>
</tr>
<tr>
<td>CD-66-48-old 30</td>
<td></td>
<td>Crack</td>
<td>-1,-2</td>
</tr>
<tr>
<td>CD-66-46-1</td>
<td>840 and 65</td>
<td>Contraction Joint</td>
<td>-1,-2</td>
</tr>
<tr>
<td>CD-66-46-1</td>
<td>840 and 30</td>
<td>Expansion Joint</td>
<td>-3A,-4</td>
</tr>
<tr>
<td>CD-66-41-1</td>
<td>665 and 4</td>
<td>Expansion Joint</td>
<td>-2,-3,-4</td>
</tr>
<tr>
<td>CD-66-38-38</td>
<td>208 and 20</td>
<td>Contraction Joint</td>
<td>-1,-2</td>
</tr>
</tbody>
</table>

may be evaluated by considering the length of a fracture trace which is transgranular, intragranular or bordering within the coarse aggregate. The results may show all three types with the majority of the fracture traces being transgranular across different aggregates.

Observation on both sides of the thin slices permits the estimation of the mode of fracture failure with greater certainty than only one side because each coarse aggregate particle acts as an independent sample. Commonly if observations are made on the other side of the slice the entire length of fracture trace may exist as a bordering fracture of a single coarse aggregate cross-section. The explanation preferred by
the author is that the external shape of the coarse aggregate may change much faster than the shape of the fracture surface. For this reason the thin slice technique, which exposes a volume of material, is considered superior to traditional block samples that expose, on the average, only a single plane of polish for any one coarse aggregate particle.
The overall purpose of the petrographic fence study is the identification of the weathering changes that are associated with highway distress. In this context, the definition of change must be redefined to a more restricted usage than that commonly now accepted. Change is frequently considered as the difference in before and after descriptions of a sample. However, in natural systems exact descriptions of material before and after reaction are commonly not available nor are they available in this study. Thus change must be estimated from descriptions of a sequential set of samples rather than repeated descriptions of the same sample. For these experiments the differences in descriptions may be due to changes which take place during reaction or to initial differences which existed before the reaction occurred. For the purposes of this study the definition of change will be restricted to include only the differences between the before and after descriptions of the system that cannot be attributed to using different initial samples.

Statistical parameters of size, shape and distribution commonly used to characterize a particular sample are not useful in this study since they define precisely that which was excluded from the restricted definition of change. However, if samples are considered as a different assortment of the same materials, the intensive properties of such samples may be compared feature by feature to detect change. Because intensive properties vary from point to point, differences in magnitude and dis-
Problems involving classification and identification of materials must be solved before changes within any one material may be detected. Classification was accomplished as follows:

1. Highway station numbers identified the concrete ledges of a particular quarry as the coarse aggregate material source.

2. The ledge by ledge description of the Otis quarry serves as an estimate of the initial material employed in the highway construction (Elwell (12) 1966).

3. The prior Otis weathering study and center of the slab cores taken in 1966 are used as a standard of general change that is not necessarily related to highway distress (Elwell (12) 1966).

Identification techniques included field checking of highway surfaces, hand specimen identification, use of binocular and petrographic microscopes and acetate peel studies. Except for the acetate peel techniques which were developed for this study, the observational techniques employed are sufficiently well known to need no further explanation.

**Acetate peel studies**

Sawed surfaces of concrete cores are the primary samples of this study. Such surfaces are sufficiently smooth to accept acetate peels without grinding or polishing. Clear Aquabees Acetate Paper 0.003 inch thick is bonded to the concrete surface by softening the film with a liquid coating of acetone and permitting the film to dry in contact with
the sample surface. Theoretically any size surface is suitable for the peel technique, however air bubbles caught between the peel and sample surface provide a non-replicating zone that in practice limits the useful size of the peel. A convenient size for this study is about 3 by 4 inches.

If the acetate peel is left on the concrete sample it provides a "wet" surface color. This aids in identification of the coarse aggregate lithologies as wet colors are much more characteristic than dry colors, washing core being the traditional preparation for logging core. Such permanent color was formerly possible only by grinding and polishing the specimen with the finest grits which would not only be more time consuming but also would destroy the curved fracture surfaces of interest in this study. Attached peels also serve as dust covers for binocular microscope studies of sawed surface morphology.

If the peels are removed from the sample, 3\(\frac{3}{4}\) by 4 inch slide mounts provide not only a means of projecting peels but also a plane surface for viewing the peel under the petrographic microscope. In this mount the peel is suitable for study at magnifications up to about 500 X. For higher magnifications or use of oil immersion techniques, mounting of selected areas on glass slides is recommended. The preserved surface replica may be studied under transmitted, reflected or polarized light. The film has a biaxial negative character and the normal birefringence of the film resembles quartz in thin section. Birefringence of trapped mineral fragments modify the normal film birefringence and in this manner indicate their mineral composition.
After the initial peel has been removed, the sawed surface may be polished mechanically and etched in HCl prior to bonding of a second acetate peel. Peeling of the etched surface will reveal grain boundaries and mineral compositions by differential solution. Such peels may be treated as serial sections. Thus comparisons of peel morphology before and after etching is useful in distinguishing minor cracks from calcite veins. Even though the etched specimen peeling removes a layer of carbonate aggregate and hydrated cement material, polishing of the surface restores the surface to almost the unpeeled condition. Unlike thin sections which destroy the setting of the feature sampled, acetate peels are the next best thing to non destructive testing. In studies of changes in mineral structure the peel technique may be used to locate sensitive areas for which thin sections are desired, and after each thin section is obtained, peels may serve as a map record of the surface sampled.

Detailed investigation of the sawed sections of the core was facilitated by the use of acetate peels. Attachment of the peel provides a dust proof wet surface for recognition of coarse aggregate lithologies. Light may be reflected from an attached acetate peel surface so that surface voids and cracks are easily observed.

Figure 4A presents a sawed slice of concrete from highway CD-66-52-150. The upper surface of the slice is the highway surface. A peel taken of this surface is shown as Figure 4B. Note that the photograph of the peel has much of the detail present in the photograph of the sawed surface. A peel taken after the surface was etched in HCl is shown as Figure 4C. Note the darker area near the highway surface revealed by
Figure 4a. Sawed vertical slice of concrete. Top of the figure contains the highway surface.

Figure 4b. Acetate peel surface of slice shown in preceding figure.

Figure 4c. Acetate peel of HCl etched surface of slice shown in preceding figures.
etching. This denotes the carbonated zone of surface scale. Through acetate peel studies such zones may be followed along fractures and particle boundaries microscopically.

Staining procedures necessary to identify carbonate minerals have already been discussed. Peeling stained surfaces and comparison of areas stained in successive peels eliminate the possibility of interference usually associated with repeated staining of the "same" surface. Dyes formed from laboratory solutions of potassium ferrocyanide and potassium ferricyanide and 10 percent HCl solutions may be used to detect ferric and ferrous iron by means of similar blue stains. Differences in color between peels which show ferrous iron and those which show ferric iron using their stains should not be sensitive to factors such as grain size and porosity. Both stains should have approximately the same concentration vs time response, because the same colored complex is formed in the same pH solution.

Although acetate peel techniques were developed for the study of carbonate rocks, adaptation of the technique and staining procedures to the acid soluble fraction of the concrete matrix was a contribution of this study. Iron stained peel sequences were particularly useful in detecting the role of iron in the formation of inner rim zones in Otis coarse aggregate (Elwell et al. [15] 1967).

Highway Distress Observation

The expected sequence for highway distress was obtained from the composite description of all distressed areas used in this study. The
description will consist of several feature topics applied at several core levels. Topics will be classified as follows:

1. General aspects
2. Color changes
3. Coarse aggregate inner rims
4. Voids and Coatings
5. Fractures

The core levels which will be considered separately will be defined as needed.

The observational program consists of the following:

1. Description of the distressed concrete at each sample location.
2. Association of the description with features necessary to describe the general system.
3. Selection of changes detected in aging that are associated with the sequential steps that lead to the features of D-line cracking and the ultimate failure of highway concrete.
results of case studies

Introduction

The petrographic fence studies are presented in sequence ranging from the youngest to the oldest highways. Although direct observations on any individual fence pertain only to that particular highway sampled at some specific age, the sequential arrangement of fence observations for different highways from youngest to oldest makes it possible to consider the observed data as a composite series of descriptions representing changes occurring in a single highway over a given length of time rather than a series of unrelated special problems. The materials used were brand A cement, Otis coarse aggregate, and, for the most part, Cedar Rapids sand as fine aggregate. Highways constructed in 1941 and 1958 which were used in this study employed brand B cement. This study attempts to describe the interaction of these materials with their environment over the service life of the highway. The petrographic fence samples are taken from the highway in the vicinity of joints where moisture may enter the concrete. Such areas commonly show distress in the form of D-line cracking prior to disintegration of the highway slab. Comments will follow the presentation of each petrographic fence description.

CD-66-58-150

This petrographic fence consisting of three cores from a highway slab represents the earliest stage of distress studied. These cores were obtained in 1966 from highway 150 which was constructed in 1958. The cores are located on highway station numbers. This fence is found at
station 43 plus 80 feet. The highway surface before coring is shown in Figure 5. Core samples about 4 inches in diameter were obtained from the approximate center of the highway slab containing identification marks. Shown crossing the highway is a joint, bordered by dark zones roughly paralleling the surface trace of the joint; such dark zones are characteristic of the early stages of D-line cracking. A few discontinuous cracks may be noted particularly at the interior corner of the slab. The black specks that cover the slab are minor pop-outs.

The core arrangement for both the top and side views of the petrographic fence are shown in Figure 6. The centers of the cores are laterally located approximately 7 inches, 1 foot 7 inches, and 2 feet 8 inches from the highway joint. Each of the cores was removed from the highway in at least two pieces. Such short cores were due to a lower fracture zone which is represented in the figure as a dashed line between cores. An upper fracture zone was observed in the first core, CD-66-58-150-1. These three cores form the primary samples of this fence study.

The highway surface trace of the upper fracture zone is the feature usually identified in highway condition survey reports as D-line cracking. This three dimensional feature will be identified in this study as a D-line fracture zone which contains individual D-line fractures. In keeping with the accepted definitions already presented, only traces of the fracture on the highway surface will be identified as D-line cracking. Traces on other planes or surfaces formed by this feature will be called D-line fracture traces. The 3 dimensional fracture zone is more easily illustrated in the older fences studied. For this fence it is sufficient
Figure 5. Highway 150 surface near station 43 before coring in 1966.
Figure 6. Petrographic fence indicating three core locations for highway identified CD-66-58-150.
JOINT SURFACE

HIGHWAY SURFACE

MAJOR FRACTURES

INFERRED FRACTURE ZONES
to note that the distress which threatens the serviceability of the pavement is associated with the lower fracture zone which forms a trace on the bottom of the highway slab. Having presented the lateral relationship between core samples 1, 2, and 3, the individual descriptions of the cores, beginning with the most seriously distressed, will now be considered.

CD-66-58-150-1

The highway surface of this core is contained on two large pieces of concrete separated by a planar fracture surface rising about 60 degrees to the highway surface. Two semi-continuous hair line D-line cracks parallel the fracture plane and the trace of the joint on the highway surface. These cracks are found in the low places between the fine aggregate and commonly cross the core perpendicular to the ridges and grooves resulting from the highway surface finish. Low places, such as pits, have a blue-gray cast characteristic of concrete distress.

In side view the top of the core displays little variation in color density of the coarse aggregate particles, although a few pieces have developed inner rims. The top 1 and 1/2 inch shows frosting of fine aggregate quartz and feldspar particles characteristic of the development of voids or solution channels bordering these sand grains. Coarse aggregate boundaries show a light tan discoloration of the matrix. The tan discoloration commonly is related to the availability of moisture and consequently to the large interconnected matrix voids.
The upper fracture zone of the core appears as a warped plane with little relief visible in the side view. About the upper 1/3 of the fracture surface is covered with a gray filling. Where cross-sections of coarse aggregate are exposed in this zone, sinuous paths in the aggregate leading to the large voids are marked with the same gray material. The gray deposits are interpreted in this study as an older weathered fracture surface in contrast to the almost fresh fracture surfaces that lack secondary deposits. Coarse aggregates that are identified as weak lithologies appear on the fracture surface.

The center 2 inch band of the larger piece of concrete appears relatively undisturbed and the coarse aggregate looks sound. However, the lower portion of the core contains a fracture zone that separates the lower portion of the core as shown in the figure already presented. The lower fracture zone is more irregular than the upper fracture zone and the larger pieces of exposed coarse aggregate display onion skin fractures. Thus in comparison the lower zone contains the more highly fractured coarse aggregate and a matrix which contains more tan material.

The bottom of the core is represented by a series of disc shaped pieces of concrete which are badly fractured. This disintegrated part of the core accounts for between 1 and 1/2 to 4 inches of formerly solid concrete. The most distressed part of the core is closest to the joint. This particular core bottom is as badly broken as any core in the entire study and yet this is the youngest joint sampled.
The highway surface of the second core does not contain D-line cracking; however, the characteristic blue-gray cast is found in some of the surface depressions formed by finishing or pop-outs. In the side view, the top 1/4 inch of core contains a few coarse aggregate particles with minor cracks characteristic of the early stages of distress. The top inch of core contains abundant tan carbonate material added to the matrix. These observations indicate leaching of the upper part of the core. The upper piece of core extends downward to within 1/2 to 3/4 of an inch from the bottom of the highway slab. This piece contains severely fractured coarse aggregate within 3/4 inch from its irregular lower boundary. In the side view several fracture planes are noted sub-parallel to the core failure surface. As in the first core, the lower fracture surface contains onion skins formed in the weak lithology of the coarse aggregate.

The bottom of the core is represented by a single piece of concrete in which the aggregate and matrix are badly fractured sub-parallel to the highway surface. The coarse aggregate in this zone appears leached and contain vugs, well developed solution channels connecting the coarse aggregate to the matrix voids, and onion skin fractures. The tan deposits in the matrix appear to be related to the loss of colored material from the coarse aggregate. The bottom core surface is covered with a calcium hydroxide film characteristic of vibrated concrete. In addition to this film, tan secondary deposits assist in bonding the underlying polyethylene sheet to the lower surface of the highway slab.
The third core was also removed from the highway in two parts, the lower piece approximating a 1/2 inch disc. The highway surface of this core appeared less altered with more of the quarry color being retained by the coarse aggregates and less evidence of solution channels. About 1 and 1/4 inches from the bottom a lower fracture zone indicates leaching from below. Here the aggregate is bleached and associated with onion skins and fracturing sub-parallel to the highway surface. The onion skins are particularly well developed on the fracture surface by an unfavorable distribution of weak aggregate lithologies.

The bottom piece of core is a thinner equivalent of the lower leached zone as described for the other cores. As would be expected from its position from the joint, leaching has not progressed as far in this piece so the weak lithologies contain fewer vugs; and lesser amounts of limonite as pseudomorphs after pyrite are found as brown coloring for the tan materials leached from the coarse aggregate.

Comments fence CD-66-58-150 (station 43 and 80)

The D-line fractures found in this fence appear to be related to water entering the joint from the surface. During the life of the highway this moisture causes two kinds of distress patterns. The first is recognized by the appearance of the blue-gray deposits in surface depressions. These are further associated with the development of local solution channels and the availability of moisture through D-line cracking. These are thought to result from local changes in environment caused by evapora-
tion of moisture and consequent deposition of formerly soluble materials such as alkalies near the highway surface. The second characteristic of distress is a stress field that is developed around a highway joint and which controls the flow of moisture to form the upper and lower fracture zones. This may well be the result of freezing water in the joint system. The abrupt change in direction of local fracture features where the lower fracture surfaces intersect solution channels and aggregates indicate a control imposed on the general joint pattern. The development of coarse aggregate onion skins also control the fracture pattern.

The severity of the distress in this youngest fence deserves an explanation at this point. The distribution of coarse aggregate in the concrete was such that the weak lithologies (those susceptible to forming onion skins) were common in the lower part of these cores. This distribution permitted the highway to be sensitive to the presence of moisture. The change in construction practice that introduced paving on polyethylene sheeting which in time was sealed to the lower slab surface evidently permitted water to collect in the joint which now could not be drained into the material beneath the slab. This seal would encourage saturation and development of solution channels through the concrete, thus accelerating moisture induced highway distress such as D-line fracturing. The unfortunate coincidence of these factors is the author's explanation for the poor performance of this 8 year old highway slab.
The D-line fracturing developed in this 14 year old highway is particularly interesting because it clearly shows the relationship between coarse aggregate pop-outs, scaling and D-line cracking. The highway surface presented in Figure 7A shows the development of distress due to D-line fracturing. Note the missing interior corner and pattern of discoloration. An enlargement of the central portion of this area is shown in Figure 7B. Cracks containing deposits are shown as light linear features. These contrast the empty D-line cracks that are presented as dark linear features. These cracks interconnect exposed coarse aggregate surfaces or appear to outline areas of incipient or future pop-outs. A further enlargement of one of the largest pop-outs near the outer zone of D-line cracking is presented as Figure 7C. Here the local path of fracturing appears controlled by the location of the coarse aggregates and the fractures within them. In addition fragments which have been removed as pop-outs show the failure has generally occurred on the inner rims of coarse aggregate.

Surface scale may also be formed in the surface zone of D-line cracking. Scale fragments as large as 3 x 5 inches and including several coarse aggregate pieces are removed as a unit. Commonly such scale has a gray film on coarse aggregates exposed at the lower surface, indicating this is old weathered surface and that the piece is finally removed from the highway slab by failure of the fine aggregate and hydrated cement.
Figure 7A. D-line fracturing developed in highway CD-66-52-1.

Figure 7B. Highway surface of central portion of Figure 7A.

Figure 7C. Enlarged portion of area shown in Figure 7A from a slightly different angle.
bonds. Such failures may be due to traffic erosion or elastic rebound. Removal of scale is illustrated by the highway surface presented in Figure 8A. These core locations were marked in August as red circles on the pavement. By September the patches of scale illustrated were removed by traffic erosion including part of the marked circle. The two closeup pictures shown in Figure 8B and Figure 8C indicate that the scale is just another variation of the general D-line fracture distress problem. Note the pop-outs and dark line cracks that identify this joint controlled distress pattern.

A petrographic fence consisting of 4 cores is shown in Figure 9. The core sites are selected to show that distress is present on either side of the joint. Although surface scale is evident only on the down-stream side of the joint, the existence of major fractures at depth on both sides suggested by surface D-line cracks was confirmed by the cores. Please return to Figure 8A and note the surface discolored zone on both sides of this joint. In Figure 8B note also the discolored darkened zones of the highway surface which are approximately coarse aggregate size. The surface expression of this distress zone is thus shown to be more fully developed than the 1958 fence.

CD-66-52-1-2

The highway surface of the core is particularly interesting in that part of the surface was removed by traffic erosion after the core location was established, and the rest of the surface became detached during coring. The surface piece was 3/4 of an inch thick and remained as a
Figure 8A. Highway surface at petrographic fence location CD-66-52-1.

Figure 8B. Enlarged portion of surface shown in Figure 8A.

Figure 8C. Enlarged portion of Figure 8B showing exposed coarse aggregate.
Figure 9. Arrangement of cores for petrographic fence CD-66-52-1.
CD-66-52-1

CROSS JOINT

CENTER JOINT

MAJOR FRACTURES
unit during coring. This detached scale became broken into smaller pieces along hair line D-line cracks which extended to the base of the scale. On the highway surface of the scale a thin blue-gray deposit is present over the low area. The hair line cracks are found commonly between the fine aggregate boundary cracks but a few of them appear to shatter the larger fine aggregate pieces as well. The lower surface of the scale contains coarse aggregate fracture surfaces mostly covered by a brown film indicating they existed for a long time. Vertical sections of the scale show fractured coarse aggregate. The horizontal fracture planes characteristic of the lower fracture zone are not present in the surface scale; instead families of predominantly vertical planes denote the mode of failure.

The main section of core immediately below the scale is approximately horizontal with grooves trending in the direction of traffic and covered with a tan surface film. It appears as a base level for the upper surface fracturing of the coarse aggregate. Below this surface the coarse aggregate has only a few fractures to a depth of between 6 and 7 1/4 inches. The bottom surface is a flat plane containing a few onion skin fractures. About 1/4 of the core surface has the brown film that is characteristic of an old fracture surface.

The bottom of the core consists of two highly fractured disc shapes with dark brown films shown as vuggy old fracture surfaces. The bottom surface of the slab contains tar without evidence of secondary deposits. Channel ways between the large voids are well developed in this bottom zone of deterioration.
The highway surface of this 14 year old core shows a different relationship than that described for the 8 year old fence cores. The younger cores have a blue-gray cast to the fine matrix of the highway surface, but this core has a light gray pitted (air entrained) surface. The pits smaller than the enclosed sand grains commonly contain iron rich material. To the unaided eye such a surface appears as a light gray frosting of the highway surface. A few hair line cracks are developed locally around the fine aggregate; however, these do not appear to be continuous in any direction. The core extends through the entire 8 inch depth of the highway slab in one piece. In the upper one third of the core, a few coarse aggregate particles show local fractures extending from the aggregate into the large matrix voids. The coarse aggregates appear bleached with outer rims of iron rich material commonly bordering the bleached aggregates. The remainder of the core shows little evidence of weathering except for the last 1 and 1/2 inches which forms the lower leached zone. The leached zone again shows cracking in the coarse aggregate, development of secondary minerals which mark the boundary of the aggregate and solution channels within the matrix. The bottom of the slab is covered with tar and broken pieces of concrete less than 1/4 inch deep expose coarse aggregate and solution channels leading upward into the lower leached zone.

The highway surface of this core has a frosted brown appearance. Several hair line cracks are present on this surface. These cracks
commonly expose the fine aggregate surfaces. This core is relatively sound and extends the full 8 inches of the highway slab. Traces of solution channels or cracking are restricted to the lowest 1/4 inch; however, the beginnings of inner rim formation are evident throughout the core. The bottom of the core is covered with tar through which pass several solution channels. This core closely resembles the center of the slab cores taken as a control for this petrographic fence study.

CD-66-52-1-1

The highway surface of this core contains two exposed coarse aggregates and many hairline D-line cracks. The top 6½ inches of the core was removed as one piece, but the coarse aggregate in the top part of the core is highly fractured. Study of the fracture surfaces was facilitated by sawing the core at the 3 inch depth and then sawing vertical sections of the core in the direction of highway travel. For this core the direction of highway travel is also the direction toward the joint. Such sawed sections make possible a 3 dimensional description of the fracture surfaces. The lower 1½ inches of core were brought out in small pieces. Disintegration of the lower part of the core was associated with the introduction of moisture from the joint.

Comments fence CD-66-52-1 (station 110 and 50)

The general fracture pattern shows distress on both sides of the highway joint. The lower fracture zone is more completely developed, but the fracture pattern extends sub-parallel to the highway surface. The extent of the small fractures shown in the peel figure may help
to explain why zones adjacent to patched joints are pre-conditioned to progressive distress.

CD-66-51-W

A single core was taken to test the extent of D-line fracturing on county highway W. Three views of a single core are presented in Figures 10A-C. In each view the arrow indicates the direction of travel away from the joint under study. The center view is of the core facing the joint and indicates the major fractures cutting the core surface. Two flanking side views give a 3 dimensional perspective to the fracture surfaces. It should be noted that the lower fracture zone extends farther into the slab than the upper zone which is destined to develop into D-line cracks.

The highway surface of the core consists of gray hydrated cement and worn fine aggregate with the tops of the coarse aggregate barely exposed. In the side view the coarse aggregates are fractured where the D-line fracture zone intercepts the highway surface. Other zones of the core show the effects of leaching but are without evident fractures. The lower piece of core is highly leached and fractured, commonly showing shattered coarse aggregate. The tar base of the core shows the development of several solution channels.

Comments CD-66-51-W

The pattern of D-line fracturing found in this core is consistent with the fractures found near other D-line fractured joint systems. This again emphasizes the importance of the lower fracture zone.
Figure 10A. Right side view of core CD-66-51-W.

Figure 10B. Front view of core CD-66-51-W.

Figure 10C. Left side view of core CD-66-51-W.
CD-66-51-W-1

TOWARD JOINT

D-LINE FRACTURES
This fence represents a functioning highway that has been bypassed by rerouting highway 30. Major portions of old 30 were covered with asphalt because of distress associated with D-line fracturing. This petrographic fence consists of 2 cores located as shown in Figure 11.

The highway surface of this core is smooth, indicating the removal of much of the original fine aggregate by wear rather than by plucking of the sand particles from the surface. However, a few large voids are present which may indicate removal of fine aggregate particles as units from the highway surface. In side view, the top 1/2 inch of core on the side nearest the joint was fractured not only through the coarse aggregate but also along the fine aggregate boundaries. One zone has lost sufficient bonding to more closely resemble jolt packed sand than concrete. Below this zone and extending down to about 3 1/2 inches in depth, fractures are commonly found in the coarse aggregate. Fractures through the matrix connect major fracture zones within the coarse aggregate to matrix void channels. The core below 3 1/2 inches contains few fractured coarse aggregates but the matrix becomes more porous. In the direction of the highway joint the last inch of core matrix resembles swiss cheese.

The highway surface of this 18 year old highway is slightly rougher than that of the core near the highway joint. Less of the coarse aggregate surface is exposed on the highway and although the surface has a
Figure 11. Arrangement of cores for fence CD-66-48-old 30.
CD-66-48-OLD 30

PERSASIVE DISCONTINUOUS FRACTURES
frosted gray appearance few fine aggregate pits are present. In the side
view the top inch of core contains fractured coarse aggregate, but these
fractures are not commonly interconnected with matrix voids. In general,
the concrete matrix appears to be sound in spite of the fractures. The
rest of the core excluding the lowest 1\(\frac{1}{2}\) inches displays little damage.
The lowest zone again shows an increasing porosity that resembles swiss
cheese; however, the coarse aggregate does not appear fractured. The
solution channels here are not well marked by secondary mineralization.

Comments fence CD-66-48-old 30

Because of increased porosity in the bottom of the cores the lower
D-line fracture zone did not form to the same extent as would be expected
from the other cores studied. Since the lower fracture zone did not
develop, only the upper fracture zone was active in the distress reported
for this location.

This section of highway was constructed with non-air entrained
concrete. In 1966 the center of the slab control sample for this study
indicated a compressive strength of about 9,800 psi and 92 percent
saturation of the air entrainment size voids. It is believed that al-
though adequate drainage prevented collection of water in the joint at
a time when it could form ice in the lower fracture zone, the gradual
filling of the air entrainment size voids was sufficient to cause the
upper fracture zone distress when combined with changes due to carbona-
tion in the zone of scaling.
The petrographic fence location next to a contraction joint is shown in Figure 12. This distress pattern will be contrasted with that taken from an expansion joint in the same highway materials.

The highway surface of this 20 year old core is smooth from the wearing down of fine aggregate particles. The surfaces of coarse aggregate particles are well exposed in this location. Hair line D-line cracks interconnect some of the surface depressions. In the side view, the top 1/4 inch shows fractures above and below the coarse aggregate boundaries which may be related to carbonation and surface scaling. Below this the coarse aggregate is fractured over the length of the core.

This core was sawed into vertical sections along its mid plane in a direction parallel to the flow of traffic. The generalized fracture pattern obtained is shown in Figure 13. The distress pattern may be better visualized by considering the fracture lines as the edge of a set of warped planes. This set of planes or surfaces constitute the zones of weakness which have failed in service and it is along these surfaces that the interactions that prepare the system for failure are most evident.

Figures 14A-D show the D-line fracture traces for the top, bottom and side views of the sawed 1/2 core pieces of core shown in Figure 13. In general, the top and bottom views of a particular fracture trace are
Figure 12. Arrangement of cores near contraction joint fence CD-66-46-1.
CONTRACTION JOINT

A

B

C

PERVASIVE DISCONTINUOUS FRACTURES

MAJOR FRACTURES
Figure 13. Fracture pattern core CD-66-46-1-1.
Figure 14A. Location of fracture pattern in surface core slice.

Figure 14C. Location of fracture pattern on this core slice.

Figure 14B. Location of fracture pattern on sawed core slice surfaces.

Figure 14D. Location of fracture pattern on core slice and lower failure surface.
perpendicular to the edge (side) view of the trace. This supports the concept of nested warped planes that strike roughly parallel to the contraction joint, and have been previously discussed as D-line fracture surfaces. In the series of figures the coarse aggregate is shown in relation to the fracture path through the concrete. Fractures entering the coarse aggregate show refraction within the aggregate and in some weak lithologies a horse tail pattern is found where the fracture changes direction. Fractures crossing the matrix between coarse aggregate particles commonly are found in straight lines between voids and along the boundaries of fine aggregates. The fractures shown are considered to be D-line fractures because the morphology of the fracture is similar to those cutting the highway surface to form D-line cracks. Additional evidence supporting this interpretation is found in the pattern of distress within the slab and the absence of these fracture features in the center of the slab control samples obtained from this highway at the same time as the fence cores.

CD-66-46-1-2

The smooth highway surface of this core has almost all of the worn fine aggregate in place. The hydrated cement appears strong; however, it has the characteristic blue-gray color. In the side view, the coarse aggregate is not commonly fractured. The larger voids and aggregate show little color change or secondary deposits indicative of leaching activity. The bottom of this core shows a few solution channels. In general, this core appears to be as sound as the center of the slab.
control cores.

Comments fence CD-66-46-1 (station 840 and 65)

The distress pattern of the contraction joint appears as a nested set of warped surfaces that are related to the introduction of water into the slab from the highway joint. The lower fracture zone appears to be more developed than the upper zone that forms D-line cracks. Again it is the lower fracture zone that fails first in service. The formation of horse tail fractures within selected coarse aggregate is a mechanism for multiplication of fracture paths through the concrete and may help to explain why certain lithologies are susceptible to D-line fracturing. The resistance to this mode of failure is considered an attribute of the better service coarse aggregate materials.

CD-66-46-1 Expansion Joint

The petrographic fence from the expansion joint of this highway is shown in Figure 15. The distress pattern viewed only from the highway surface appears to associate a more intense distress with expansion rather than contraction joints.

CD-66-46-1-3A

The highway surface of this core is gray with worn fine aggregate particles. Pits on the surface indicate missing fine aggregate, and hair line D-line cracks are almost interconnected through the low spots in the surface finish. The average direction of the D-line cracks approaches the joint direction.
A view of the core is presented in Figure 16. The core surface has been replicated, unrolled to form a flat surface and shown with its center as the closest approach to the joint and the outer edges as the farthest distance from the joint. This core was removed in several pieces as indicated by the failure surfaces. The reader should note the familiar lower fracture zone pattern and the lack of major fractures shown above the steel rod.

The upper piece of core appears without fractured coarse aggregate above the steel. However, away from the steel a few cracks are found in the coarse aggregate and matrix which border the D-line cracks observed on the highway surface.

The second piece of concrete core from the top is best considered as being split into 2 pieces. Its upper surface is controlled by the location of the steel rod. D-line fractures form the top and bottom surfaces of this piece. This concrete is split parallel to the surface expression of the fracture zone (D-line crack) and contains onion skin coarse aggregates. The split is interpreted as a later interconnection of 2 well developed D-line fracture bands.

The 3rd piece of core shows less relief on the fracture surface. Although onion skins are formed they exert less control on the location of local fracturing.

The lowest piece of core has highly fractured coarse aggregate. Onion skin partings of certain coarse aggregate lithologies are common.

The highway surface of this core is well covered with blue-gray deposits. Solution channels are starting to develop, but few of the
Figure 15. Arrangement of cores near expansion joint CD-66-46-1.
HIGHWAY SURFACE

MAJOR FRACTURES

A  B
CORE 4  CORE 3A  B

EXPANSION JOINT C
Figure 16. Side view of expansion joint fence core CD-66-46-1-3A.
CD-66-46-1-3A

UNROLLED PEEL OF CORE SURFACE

AGGREGATE
STEEL ROD
VOID
FRACTURE
FAILURE
coarse aggregate surfaces are exposed. In the side view, the top of the core shows a few fractures less than an inch in length. The central portion of the core is sound. A \( \frac{3}{8} \) inch steel rod is present down about \( 4\frac{1}{2} \) inches from the surface. The bottom 1/3 of the core contains isolated coarse aggregates with fractures that do not extend into the matrix. The bottom surface of the slab shows many solution channels passing through a tar surface into a clay-like base material.

**Comments fence CD-66-46-1**

The lower fracture surfaces below the steel are better developed than similar contraction joint surfaces. The steel appears to have prevented fracturing of the core above its location. Again the problem appears to be associated with failure of the lower fracture surface for which the location of the steel affords little protection. Although the lower fracture surface is well developed in core CD-66-46-1-3A, core CD-66-46-1-4 indicates that the distress does not extend far into the slab. The good subslab drainage found in these cores may explain why the distress pattern was not more persistent.

**CD-66-41-1 Expansion Joint**

This petrographic fence across a 25 year old expansion joint consists of 3 cores as shown in Figure 17. It is particularly interesting in that it was constructed with brand B cement. Since this concrete should contain more tobermorite than one made from brand A at any age, its comparative resistance to D-line fracturing in aged concrete is a
Figure 17. Arrangement of cores for fence near expansion joint CD-66-41-1.
HIGHWAY SURFACE

CD-66-41-1

PERVASIVE DISCONTINUOUS FRACTURES

MAJOR FRACTURES
measure of the cement contribution to D-line fracturing.

CD-66-41-1-2

The highway surface of this smooth core is an excellent example of D-line cracking. This core was removed from the highway as 3 pieces of concrete. The upper piece containing the highway surface was chosen as an example of the development of the upper D-line fracture zone. The lateral core surface of this piece is shown in Figure 18. The cylindrical surface is unrolled and presented as a flat surface such that the center of the figure is the farthest part of the core from the joint. This view differs from others presented in that leading edges rather than trailing edges of the distress pattern form the central part of the figure. This pattern is typical of D-line fracture patterns which show a characteristic spacing between fracture bands and a multiplication of fracture paths in certain coarse aggregates. Note the increased density of lines toward the bottom of the piece. The bottom surface of this piece is controlled by the steel rod located just below this surface. The lower surface is covered with white deposits, void channels and a few onion skin fractures of the coarse aggregate.

The second piece of concrete resembles a horizontal disc with an irregular top and bottom surface. The thickness of the disc is evidently controlled by the location of the steel rod and the space between them. If the side view of the piece is considered, the D-line fracture traces are parallel and follow the surfaces of the steel rod so that the expected fracture pattern is modified to approach a horizontal pattern of fractures in the vicinity of the steel rod.
Figure 18. Fracture pattern in core CD-66-41-2.
UNROLLED PEEL OF CORE SEGMENT

CD - 66 - 41 - 1 - 2

AGGREGATE

MAJOR FRACTURES

INDEX

3 INCHES
The bottom piece of concrete core is marked by D-line fractures that approach the lower surface of the highway slab. A major failure surface is masked with a brown film and is interpreted as an old failure surface. This surface is controlled by onion skin fractures of the coarse aggregate.

CD-66-41-1-3

The highway surface of this core is smooth due to wear of the fine aggregate particles. Three coarse aggregate particles are partially exposed at the highway surface. Only a few incomplete hair line D-line cracks are observed. This core was removed in one piece. In side view, the top 5 inches of core contains fractured coarse aggregate and fractures through the matrix are evident. The bottom 3 inches of core shows increased porosity in the direction of the joint. Some coarse aggregates are locally fractured and interconnected to matrix voids.

CD-66-41-1-4

The brown stained highway surface of this core is rough in comparison with the other two members of this fence. The fine aggregate is less worn and no coarse aggregate pieces are exposed at the highway surface. The 8 inch 25 year old highway core was removed in one piece. The top of the core appears sound, but the bottom 2 inches shows slightly increased porosity and some fractures within the coarse aggregate. In general, the matrix portion of this core appears sound in contrast to the other cores of this fence.
Comments fence CD-66-41-1 (station 665 and 4)

The expected D-line fracture pattern of this fence appears disturbed by the location of the steel rods. In the first core, CD-66-41-1-2, this was apparent from the disc shaped second piece of core. In CD-66-41-1-3, the deranged fracture pattern through the central zone of the cross-section also was unexpected.

Cracking along the matrix portion at the top of the core is more severe in this fence than for the older Otis cores made with brand A cement. This requires an explanation since the stronger cement B is being associated with poorer highway performance of the upper fracture zone.

An explanation may be found by considering the supplemental information obtained from the control cores of this highway. The compressive strength reported for the center of the slab cores averaged 9600 psi in 1966 and the percent saturation of the air entrainment size voids was 82 percent. These values were surpassed only by the Otis 1948 control core samples made with brand A cement. It should be remembered that the 1948 fence also had a well developed distress pattern at the top of the core. It would appear from these data that the distress characterized by the upper fracture zone was correlated with changes in compressive strength and percent saturation rather than the amount of tobermorite in the hydrated cement fraction of the slab. This explanation supports mechanisms such as freeze and thaw action as the cause of D-line fracturing. It also points out the pitfalls of attempting to explain highway distress without supplemental information to test the correlation of single parameters such as brand of cement.
The core locations for the contraction joint fence are shown in Figure 19. This 28 year old highway is the oldest sampled in this study and therefore should display the best example of D-line fracturing. Construction joints of this age are commonly patched in highways built of Otis aggregate concrete.

The highway surface of this core is very smooth because the fine aggregate sand grains have been rounded by wear and many coarse aggregate surfaces are exposed. Small D-line cracks are observed in the low places of the highway surface and crossing shattered coarse aggregate pieces in the high and low relief surfaces. In the side view, the entire length of the core displays shattered coarse aggregates. Many of the fractures are interconnected through the matrix. A lower fracture zone composed of sub-parallel fractures is found in the lowest two inches of core. The bottom of the core shows that solution channels connect the large core voids into the material beneath the slab.

In cross-section the upper three inches of core contains many fractures within the coarse aggregate and within the hydrated cement. The main pattern through the coarse aggregate is that of an upper fracture zone. Fracture traces through the matrix are superimposed on the main pattern and interconnect the large matrix voids. These traces follow the boundaries of the fine aggregate particles. Minor voids and grain
Figure 19. Arrangement of cores for contraction joint fence CD-66-38-38.
CONTRACTION JOINT

PERVASIVE DISCONTINUOUS FRACTURES
boundaries that intersect the fine aggregate surface contain iron rich material and are commonly interconnected by fracture traces. The lower fracture zone in the bottom part of the core has a piece missing that varies in thickness from 0 to $\frac{1}{2}$ inches. Fractures parallel to this boundary denote the lower fracture zone. Two other solution channel fractures connect the lower fracture zone to the upper zone mostly between interconnected voids in the matrix.

CD-66-38-38-2

The highway surface of this core is also smooth and contains a few hair line D-line cracks that border exposed coarse aggregate surfaces. Most fine aggregate sand grains appear to be in place between the exposed coarse aggregate surfaces. In the side view, the top 2 inches appear fairly sound. About 1/3 of the coarse aggregate in the zone have multiple hair line fractures which are mostly restricted to the coarse aggregate. Isolated fractures also connect the larger matrix voids; however, between fractures the concrete appears dense and solid with little leaching evident. In the lower four inches of core there are fewer fractured coarse aggregate found. The lowest $\frac{1}{2}$ inch of core shows the sub-parallel fracture bands typical of the lower fracture zone. In building this highway a tarred interface was located immediately below the slab. The bottom of the core is irregular with white powder deposits on the underside of the slab's lower surface coating of tar. Solution channels through the tar lead into the larger voids within the slab.

The cross-section the lowest $\frac{1}{2}$ inch of core is discolored in the same way as the highway surface. This is interpreted as indicating
carbonation of the concrete from the lower slab surface. In general, the concrete is remarkably sound for its age and appears to have concentrated all leaching to a few paths through the dense concrete.

Comments fence CD-66-38-38 (station 208)

Apparently the density of the concrete matrix has retarded the leaching of the coarse aggregates so the expression of the upper and lower fracture zones is not as well developed as would be expected for a 28 year old contraction joint. The second core was quite sound; however, the first core was severely fractured by the interconnection of the upper fracture zone pattern through the matrix-void system. This fence differs from other fences in the severity of the fractures through the hydrated cement at the surface of the fine aggregate particles. Interconnection of these small voids at the fine aggregate interface with the larger voids of the matrix defines both the iron stained solution channels and the fracture paths through the matrix-void system. Such paths appear restricted to the volume of concrete influenced by the fracture zone pattern.
HIGHWAY DISTRESS CHARACTERISTICS

The presence of deposit cracks that signal the approach of progressive spalling of pavements around joints or patches is typical of Otis type failure identified by Welp and De Young (57) as D-line cracking. For the purpose of this study a composite description is obtained by combining all the information from the petrographic fence cores. Since the core materials do not act uniformly from top to bottom, the description is presented in terms of four somewhat arbitrary depth zones which appear to have more uniform behavior within the zone. The zones may be represented as follows:

1. Zone of scaling -- Top 1/16 to 1/2 inch.
2. Upper zone of fracture -- upper 1/3 of core.
3. Zone of resistance -- middle 1/3 of core.
4. Lower zone of fracture -- lower 1/3 of core.

Zone of Scaling

One of the first signs of failure is the brown stain which appears on the highway surface near joints or natural fractures. When wet, these brown stained areas appear blue-gray at a distance as the result of higher moisture content. Early stages in distress show removal of the fine aggregate particles and the casts of their former positions. Locally coarse aggregate particles are exposed at the surface. Acetate peels of cross-sections of sawed surfaces show a highly birefringent zone representing carbonation of the matrix at the surface and bordering
coarse aggregates. The morphology of the iron-bearing phases in the birefringent region consist of either characteristically spherical clusters or finely divided films as an isotropic gel. In the bulk hydrated cement, the iron particles appear as inclusions between the hydrated cement grains unless the matrix has become shattered.

Exposed coarse aggregate particles serve to fix the common location of D-line cracks. Because the coarse aggregate position influences the crack pattern, it is assumed that some cracks are propagated from the coarse aggregate to the matrix. Other cracks become multiple bands or horsetail fractures within the coarse aggregate and commonly follow the fine aggregate matrix particle boundaries. In most deteriorated areas the D-line cracks form semi-continuous bands as close as ¼ to 1 inch apart in the map view of the highway surface which follow the edge of the slab and curve across corners. Such cracks resemble the traces of equipotential surfaces with minor anomalies where coarse aggregate is exposed.

In spring the water released from the pavement dries in these D-line cracks filling them to overflowing with calcite, halite or epsomite. Fillings at other times appear as a white powder with clear transparent crystals, brown iron stain and isolated scattered dark gray particles. The dark particles have been described by other authors as blue line cracks. When dry the powder is easily removed from the minor cracks and these remain unfilled part of each year.

The coarse aggregate immediately below the surface has access to
moisture through interconnected voids and D-line cracks. Some of the coarse aggregates form onion skins causing zones of weakness which fail in service and become coated with secondary carbonate films prior to dislodgement of the loosened scale from the highway. Pieces of loosened scale up to 6 inches square have been removed as a unit. Scale formed from the D-line cracked zones is more commonly well developed on the downstream side of traffic flow across the joints.

The fine aggregate is composed primarily of quartz and minor feldspar. At the surface the fine aggregate may be broken but casts show that the cement-fine aggregate bond has allowed removal of the fine aggregate particles intact. Around some particles the hydrated cement matrix appears lighter in color and softer than the interior material. Iron-stained fine aggregate particles near cracked zones occasionally are found to have developed an onion skin. More common are ridges and grooves representing removal of fine aggregate material from the pieces of concrete bordering the D-line cracking. Much of the blue color is due to the exposed fine aggregate bond surfaces.

The hydrated cement matrix has been removed from the surface either as large pieces of scale together with the associated fine and coarse aggregate or as small wedge shaped blocks within the crack. The wedges show characteristic transparent films of altered discolored matrix material in association with brown films.
Upper Zone of Fracture

Fracture paths appear as cracks sub-parallel to the highway surface. Although the density of cracks is localized by the position of coarse aggregate particles, the fractures are generally concentrated 2 to 3 inches below the highway surface. The cracks become multiple within the coarse aggregate and attain their greatest width in this environment. Many fractures terminate within the boundary of the coarse aggregate but parallel traces of other fractures pass through the coarse aggregate and along the boundaries of hydrated cement, fine aggregate and into other coarse aggregate particles. Where such fractures intersect the pointed end of a particle the fracture trace is deflected and commonly follows both upper and lower surfaces of the particle. Fractures that intersect the highway surface have been described as D-line cracks. Some coarse aggregates are associated with large air voids in the matrix near their surfaces. Such combinations also locate preferred paths or traces of cracking.

The coarse aggregate particles in this zone are bleached equivalents of the quarry ledge material. Some aggregates show differential removal of color (iron rich material) as inner rims. Some of the aggregates are surrounded with a dark brown impregnated matrix outer rim which represents deposits of the colored material. Inner rims, particularly their inner boundaries, serve as a locus for minor cracks. The onion skin fractures typical of failure surfaces in the distressed zone are formed by parting along the minor cracks. Bleached zones follow the braided
crack pattern within the coarse aggregates leaving wedges of more highly colored material.

The fine aggregate particles in this zone appear fractured only within older hydrated cement D-line fractures or on failure surfaces. Voids are coated with white powder and are commonly in the path of small discontinuous fractures. The matrix is less carbonated than the surface zone, however some coarse aggregate surfaces show a highly birefringent reaction zone in the surrounding matrix indicating local carbonation and discoloration of the hydrated cement.

Zone of Resistance

Near expansion joints the middle third of the core may contain steel reinforcing rods, with or without the steel the incidence of fracturing is less evident in this zone. However, flanges on the reinforcement rod act as notches and serve to localize cracks in the matrix near the rod. In general the reinforcement rod in the fence samples showed little corrosion of the steel in service. Failure surfaces tended to break sub-parallel to the steel rod so that the steel and concrete came out as a unit. Without steel the failure surfaces break upward or downward depending on the stress pattern and intersection of the horizontal crack with the onion skin forming coarse aggregate.

The coarse aggregate particles show less bleaching and less well developed inner rims in this zone. Local features such as large voids are important in influencing the degree of bleaching. Except for fractures or failure surfaces the birefringent reaction zone is commonly
absent from coarse aggregate interfaces.

The fine aggregate particles show little interaction with their environment in this zone except on fractured surfaces. The white coatings of voids are present but less well developed than in the other zones.

**Lower Zone of Fracture**

Fracture paths appear sub-parallel to the highway surface, however cracks commonly intersect the lower concrete surface. The older failure surfaces contain a brown film that covers all particles. Broken pieces of matrix found on the brown surfaces are larger than would be expected from observation of interior failure surfaces.

The coarse aggregate is bleached and fractured as in the corresponding upper failure zone. The proximity to the brown surface favors multiple fractures within the coarse aggregate particles. Pathways interconnecting the large voids and coarse aggregate particles with the lower surface show solution activity and cracking.

The fine aggregate is shattered within the cracks and shows ridges and grooves. Well developed brown failure surfaces show rounded but not shattered fine aggregate particles. Voids toward the bottom of the zone show an increasing amount of white powder. Where drainage of water through the slab has been restricted by efficient barriers such as polyethylene sheet, the bottom concrete surface is covered with a white film in addition to the characteristic calcium hydroxide surface and in some cases a brown film over the white film. In many cases the distinction
between white film and white powder is more descriptive of the amount, continuity, and access to moisture than to differences in kind of material present.
DISCUSSION OF RESULTS

Introduction

In this section the observations are interpreted in the form of general statements. Where necessary the statements are immediately followed by supporting evidence either from this study or from the work already cited. To assist the reader an outline form of presentation is used to separate the general statements from the other supporting evidences so that a continuity of thought may be followed by reading the statements of equal outline rank. The kinds of evidence which support the statements are designated by lower rank. Only summary statements will be used to prevent reintroduction of material already cited.

The purpose of this section is to relate the present study to the current state of the art. To accomplish this, aspects are presented such that the contributions are blended into the summary of the literature cited. Each aspect is closed with a listing of the unique contributions of this study.

General Aspects

1. D-line cracking as discussed by Welp and De Young (57) was confirmed as the major symptom of Otis aggregate concrete distress in the highways studied.

2. It is believed by the author that freeze and thaw failure as postulated by Cordon (6) is the ultimate cause of disintegration in these highways. However the pathway and sites of such failures in Otis ag-
Aggregate concrete appears to be more sensitive to the lithology of the coarse aggregate than Gordon's mechanism of developing progressive disintegration by permitting water to travel through cracks to feed capillaries further from the edge of the slab.

3. The details of the D-line cracking type failures in Otis aggregate concrete are consistent with the following sequence of events.

a. A local stress pattern is induced into the concrete surrounding a joint probably by the freezing and thawing of water standing in the large voids of the joint.
   1) The parallel fracture patterns formed in the top 1/3 of the cores are interpreted as a result of failure in response to this stress pattern.
   2) The broad curved fracture planes are larger scale features than the individual pieces of concrete material, and are related to the surface trace of the joint.

b. The interconnection of small voids possibly by capillary action is a first sign of highway distress.
   1) The dark wet zones that outline susceptible zones around joints which are visible after a rain are present before other evidence of failure.

c. The highway survives several winters without further signs of distress.
   1) The compressive strength of the highway is increasing (Elwell (12)).
2) The preferred mode of failure for compressive strength core samples is along the bond zone of the coarse aggregate, regardless of what lithology is observed.

3) This agrees with pavement condition data (Welp and De Young (57)).

d. Fractures are generated within selected coarse aggregate lithology particles in favored stress environments.

1) Compressive strength of the highway concrete continues to increase with time.

2) Breaking studies of the longer service core samples show the bond zone is no longer the preferred path of failure, (Alexander et al. (1) and the author, Elwell (12)).

Two classes of lithologies are observed, those which fail in matrix and those which fail in the coarse aggregate under normal stresses.

3) In service failures of highway concrete are believed to be caused by normal stresses because of the onion skin failure surfaces.

4) Lithologies identified as commonly exhibiting failure surfaces are members of the class of material that fails first in the coarse aggregate.

5) Fractures of a type commonly associated with the disintegration of this concrete are found entirely within the coarse aggregate located in the highly stressed zone. Similar coarse aggregate from the same core sam-
pie but located outside the stress zone are not fractured.

e. Formation of fractures in the coarse aggregate reduces the ability of the matrix to withstand stress.

1) Part of the load along the fracture path is transferred to the fine aggregate and matrix.

2) The presence of the coarse aggregate fractures serves as a notch in the matrix material.

3) Water freezing in the coarse aggregate cracks will increase the stress on the system. Even if the water does not freeze, the presence of additional water storage within the coarse aggregate places an additional burden on the small air-entrainment size voids to contain the additional water.

4) Material leached from the coarse aggregates lines the fracture paths and voids. Iron rich films form outer rim zones and coat voids or fine aggregate particles.

f. Fractures propagate from coarse aggregate particles to large voids of matrix.

1) Coarse aggregate particles exposed at the highway surface show cracks leaving the coarse aggregate and stopping in the matrix. The local surface expression of D-line cracking is established by the interconnection of these propagated fractures.
2) Cross-section observations of core microstructure reveal that connecting main fractures change direction at voids between coarse aggregates.

g) Fractures and voids in matrix are coated with materials leached from the coarse aggregate fracture zones.

1) Efflorescent material coat fracture path and voids.
2) Iron films form outer rim zones around aggregates.
3) Iron rich films are found on fine aggregate grooves.

h) At surfaces subject to traffic erosion pieces of concrete containing coarse and fine aggregate are removed as scale exposing void systems in the underlying concrete. Such exposed surfaces serve as additional sources of moisture and leaching products.

1) Interconnected channels between the large voids show deposits.

2) Fractures at surfaces show deposits which form on drying of the fracture surface. Halite, epsomite and calcite are common secondary minerals.

i) Removal of successive blocks of material due to freezing and thawing is the form of progressive disintegration that terminates the useful life of the Otis aggregate concrete.

4. The sequence is interpreted as demonstrating that with increasing service life the coarse aggregate and matrix interact to form a new composite material that has different properties, such as freeze and thaw resistance. Because of changes of materials within the concrete,
short time test results obtained on the starting materials may not be extrapolated with confidence over the expected service life of the highway. Observations indicate it is the altered materials that are associated with the pathways of fractures.

a. Dolar-Mantuani (11) reported different test results and different highway service for fresh and weathered materials taken from the same quarry ledge. If materials weathered in the quarry behave differently from fresh material it is evident that materials weathered in the concrete should also behave differently.

b. The amount of time that is required to initiate fracturing in susceptible lithologies and the additional time required to propagate these fractures are long compared to the time required to initiate D-line cracking next to a patch. This suggests that the material is pre-conditioned or altered by weathering.

5. In non-air entrained concrete containing Otis aggregate, Welp and De Young (57) first noticed deterioration on pavements ranging in age from 14 to 20 years. Data from the center of the slab cores show a maximum in compressive strength after 12 to 14 years. Because the change from bond zone failure to coarse aggregate crack formation occurs much earlier in the life history of the pavement, the decrease in compressive strength is associated in time with propagation of coarse aggregate cracks through the matrix.
6. At this stage in the investigation there appear to be two critical events that lead to the untimely limitation of useful life of Otis aggregate concrete.
   a. Fractures are formed within specific lithologies depending on stress level and moisture content.
   b. The newly formed fractures are propagated through the matrix at a later time. Elimination of either of the steps would lengthen the expected service life of this concrete.

7. There are at least four ways that the Otis aggregate problem may be solved to lengthen the life of Iowa highways.
   a. The stress field at the joint may be reduced by either eliminating the construction joints as in continuous pavement or other practices of sealing the joints with a continuous asphalt surface. Such practices avoid the problem for the moment but are either temporary or costly.
   b. The Otis aggregate concrete ledges may be eliminated from the approved list of material sources. This is the present policy of the Iowa State Highway Commission.
   c. Since fractures are formed in lithologies that have been classified as weak, removal of only the weak lithologies would prevent formation of cracks within the coarse aggregate. Better selection of material on a weak-strong lithology basis would not only solve the Otis aggregate problem but would form a basis of testing for similar early fractured material among the other sources of coarse aggregate material.
d. Inhibit the propagation of coarse aggregate fractures through the matrix.

8. Practical reasons for the detailed study of the Otis aggregate concrete system are found in the following objectives.

   a. Describing weak lithology characteristics so they may be identified in other systems.

   b. Understanding the interaction between coarse aggregate and matrix that enables the cracks to be propagated through the matrix may lead to ways which inhibit the propagation of cracks through better highway design specifications.

9. The unique contributions of this study to the understandings of the general aspects of the problem were as follows:

   a. Recognition of the problem as one concerning a materials response to stress, rather than as a series of separate distress features. For example, consideration of D-line cracking as a three dimensional feature.

   b. Identification and recognition of lithologies that are subject to the development of fractures.

   c. Associating in time and space the change in the mode of compressive test failure with the initiation of fractures in sensitive lithologies.

   d. Association in time of the maximum compressive strength found in the center of the slab samples with the propagation of fractures through the matrix.
e. Recognition that "weathering" of the aggregates and matrix materials in concrete results in their interaction such that fractures are facilitated in the weathered material resulting from certain aggregate-matrix combinations. Such contributions establish that failure is the result of differential material response rather than just the availability of moisture.

Coarse Aggregate Changes

1. In reflected light study of carbonate rocks one of the characteristic properties of a lithology is its color when viewed as a "wet" surface.

2. The use of acetate peel coverings on the surface of concrete samples permits the retention of wet surfaces for comparison purposes.

3. Since the coarse aggregate introduced into the concrete came from Otis lithologies the range in color of the unaltered material taken from the highway should be the same as that displayed by fresh and weathered rocks in the Otis Quarry. Colors which fall outside this range are assumed to result from interaction between the coarse aggregate and its concrete environment.

4. Weathering studies of the Otis aggregate lithologies (Elwell (12)) established that the lithologies become bleached with time by the fading of the normal gray or brown color.

5. Fading rates are conditional on the availability of moisture. Non-air entrained concrete and the least disturbed zones of the petrographic fence cores are least faded materials.
6. Observations indicate that as the coarse aggregate becomes bleached with time, the matrix becomes darker through addition of colored material removed from the coarse aggregate and deposited in voids forming films on interfaces and fracture surfaces.

7. Two types of differential fading behavior are recognized.
   a. An absence of color just inside the particle boundary is identified as an inner rim.
   b. An absence of color flanking a fracture or vein is interpreted as indicating differential leaching.

8. Inner rims are developed within the concrete environment.
   a. Indirect evidence showed an increasing width of inner rim with time and type of exposure (Elwell (12)).
   b. Brown iron material stained the matrix surrounding some rimmed particles.

9. Staining methods indicate that the color change which identifies the inner rim is partially caused by a change in the oxidation state of iron.
   a. Inner rim material contains iron in the ferric state.
   b. Interior material contains iron in the ferrous state.

10. If one representative lithology is studied by observations in successively older samples, staining will reveal more and more oxidized inner rim material until the entire aggregate particle appears to progressively acquire properties of the oxidized rim. In this case the inner rim may not be distinguished by color since the material has again become homogeneous when the iron in the entire aggregate particle is
11. The formation of inner rims on the coarse aggregate define local zones of weakness which are preferred paths of in service fractures.

a. Paragenesis - the sequence developed in susceptible aggregate lithologies found in older concretes reveals a progressive change consisting of unaltered aggregate, rimmed aggregates, and aggregates with fractures in the rims.

b. Thin slices of concrete show the fractures are controlled in three dimensions by the location of rim material. Fractures have been known to completely border an individual aggregate, however, commonly the curvature of the fracture surface does not change as abruptly as the shape of the aggregates surface so the piece is bordered by fractures on only three sides.

12. The onion skin coarse aggregate surfaces that are commonly associated with disintegrated and scaling concrete are composed of inner rim material that has become detached.

a. Staining of opposite surfaces across natural fractures from short cores of the petrographic fence identify the onion skins as the oxidized equivalent of susceptible lithologies.

b. In the older concretes, fracture surfaces may deviate from simple planes to follow inner rim paths. Commonly horizontal fracture planes will change to vertical trending surfaces coincident with the favorable location of rim forming lithologies.
13. The unique contributions of this study to the understanding of coarse aggregate changes were as follows:

a. Correlating the formation of the inner rim with the change in the oxidation state of iron.

b. Introduction of acetate peel and staining techniques that permit identification of particles that have become all inner rim material.

c. Removal of inner rims from their status as a petrographic curiosity by demonstrating their correlation to onion skins which are known to be associated with disintegrated concrete.

d. Since bleaching of the aggregate and the oxidation and removal of brown material to form inner rims are associated with the localization of fracture paths, attention is focused on the role of iron rich phases and minerals of an aggregate in creating fracture susceptible lithologies.

Iron-Rich Aggregate Material Changes

1. The Beekmantown dolomite (Dolar-Mantuani (11)), the Kingston dolomite limestone (Swenson and Gillott (56)), and the Otis calcitic dolomites (Lemish and Moore (38)) are all different mixtures of the same general kinds of material.

a) Each carbonate rock system is susceptible to dedolomitization when placed in the concrete environment.
b. Each rock system contains the following minerals:
   1) Illite as the dominate clay mineral
   2) Limonite after pyrite or original crystals of pyrite
   3) Minor amounts of chlorite
   4) Ankerite, if present, was below the limits of detection by routine X-ray methods.

2. As a first approximation these sources of coarse aggregate differ chemically only in terms of constituent proportions and textures that control the rates of chemical reactivity.

3. Each of these rock sources is related to a different aspect of concrete deterioration in terms of their physical effects on highway pavement.

   a. Beekmantown dolomite weathered in the quarry differed from fresh rock in that the weathered material had reduced freezing and thawing resistance in laboratory tests. Although both were tested, only the weathered aggregate highway test strips proved unsatisfactory.

   b. Kingston dolomitic limestone expanded in high alkali cement sufficiently to cause map cracking and disintegration of concrete highways.

   c. Otis calcitic dolomite showed neither of the immediate distress symptoms but after 12 to 14 years of service began to display the progressive deterioration associated with D-line cracking.
4. Each of the coarse aggregates failed under slightly different conditions.

   a. Beekmantown dolomite, weathered in the quarry, underwent changes that affected the durability of concrete in the oxidation zone of the quarry.

   b. Kingston dolomitic limestone reacted and expanded within the concrete environment. This alkali-carbonate rock reaction was attributed by Gillott (21) to the exposure of "active" illitic clay by dedolomitization reactions. Swelling was caused by the introduction of sodium into the clay structure and formation of the hydrous double layer.

   c. Otis calcareous dolomite weathers in the concrete environment forming fractures within the coarse aggregate that are later propagated through the matrix to form D-line cracking. These lithologies dedolomitized but did not expand in alkaline environments.

5. Common to all problems is the addition of charge during the oxidation of fresh rock. Although the minerals present in the rock are the same, the proportion of these materials and the environmental stress are different. What heretofore has been considered as three different problems may be readily explained as three examples of variations on a continuum of one basic problem of carbonate aggregate behavior in concrete. If attention is focused on the common problem of the response or adjustment of a rock to its new oxidizing environment in concrete, then for systems of thermodynamic instability, variable proportions of minerals
and rates of reaction will yield different physical symptoms. Undoubtedly several reactions are taking place concurrently so the establishment of a single reaction such as dedolomitization is considered insufficient evidence for a causal relationship. Information is needed that will permit estimation of the stress caused by placing material in a new environment as well as a measure of the material's initial ability to absorb this change without failing. Attempts to study the "disease" rather than the individual symptoms must start with an understanding of the stability of minerals in the concrete environment.

6. Under these conditions illitic clay appears to be thermodynamically unstable.

   a. Dapples (7) indicates in a generalized Eh-pH diagram that chlorite is more stable than illite in the slightly reducing environment.

   b. Garrels and Christ (20) have calculated stability zones for iron oxides, carbonates, sulfides, and silicates at 25°C, and 1 atmosphere total pressure in the presence of water. Other conditions: total activity of dissolved CO₂ = 10⁰; and dissolved sulfur = 10⁻⁶; amorphous silica is present. Using iron metasilicate rather than illite they calculated that the stable phases in environments equivalent to highway conditions would be either hematite and water or the ferrous metasilicate depending on the Eh value. It is estimated that a system having an Eh value greater than -0.4 would contain iron oxide and water at thermodynamic equilibrium. In this region they found the
stability of ferrous metasilicate remarkably similar to that of magnetite and thus an approximation to actual iron silicate systems.

7. Metastable products persist in the alkaline environment.
   a. Garrels and Christ (20) cite the persistence of the ferric hydroxide in experimentally practical systems of freshly precipitated hydroxides as the metastable equivalent of the hematite stability field.
   b. Qualitative tests performed by the author have demonstrated that hematite powder remains insoluble for three years in a pH 12 sodium hydroxide solution, thereby supporting the conclusion that hematite is the experimentally stable form. On the other hand, claystones subjected to the same pH had a different behavior. Ferrous iron leached from the claystone went into colloidal suspension as the hydrated ferric oxide, limonite. For at least three years the suspended limonite has remained as the metastable product at pH 12.

8. Limonite (FeO(OH)·n H₂O) may be present as a product derived from many sources as the common metastable equivalent of hematite.
   a. Dapples (7) reports that biotite reacts to form illite and limonite upon oxidation sometime after burial. This indicates the stability of limonite is such that it may be as old as the illite.
   b. Limonite may also be one oxidation product of illite.
c. Limonite is commonly associated as the oxidation product of pyrite. In the Otis aggregate studied this appears to be the major source of limonite.

9. Pseudomorphs of limonite after pyrite are characteristic of the distress environments but its interpretation is not well understood.
   a. Petrographic observation of the weathered Beekmantown dolomite reported limonite after pyrite.
   b. Mielenz (46) recognized that the presence of hyroxyl ion in excess of the normal concentration in water causes the oxidation of pyrite and the formation of ferrous sulfate. Resulting interactions produce ferric hydroxide and calcium sulfate which changes to calcium sulfaluminate.
   c. Garrels and Christ (20) suggest that the hydroxyl ion not only affects the stability of the ferrous form of iron in pyrite but that at increasing pH the sulfide form becomes unstable relative to the sulfate ion. At Eh values greater than -0.5 at pH 12 the sulfate form is considered stable. These Eh values occur within all of the stability field relationships for pyrite indicating that the sulfide instability may hasten the rate of pyrite reaction.
   d. Epsomite found as efflorescence on weathered quarry walls indicates the mobility of the sulfate ion in natural weathering.

10. Limonite tends to segregate in the carbonate grain boundaries.
a. Pettijohn (47) indicates that ferrous carbonate forms a solid solution with dolomite structures but not the calcite structure. Dedolomitization would tend to release ferrous carbonate to the grain boundaries if present. Limonite derived from ferrous carbonate in the grain boundaries could not be distinguished from limonite contributed by pyrite which is also segregated to the grain boundaries.

11. Segregated centers of brown limonite within the coarse aggregate serve as points of weakness in Otis aggregate.
   a. Fractures run from point to point controlled by the location of limonite centers or inner rims.
   b. Limonite films cover fracture surfaces within the coarse aggregate.

12. Microscopic examination of fracture-aggregate interfaces revealed a characteristic angular serrated surface indicating removal of rhombic dolomite grains. The serrated surface grades into an adjacent zone where the similar sized dolomite grains are marked by a wide limonite border and at a greater distance, into an area of carbonate cemented grains.

13. Branching fractures connecting pockets of limonite form the characteristic woven pattern of Otis aggregate fractures that are associated with in-service cracking of the weak lithologies.

14. Limonite released from the Otis coarse aggregate coats surfaces in the surrounding matrix forming outer rims or is transported in the solution channels of the matrix.
15. The unique contribution of this study to the understanding of the iron rich material changes were as follows:

a. Restatement of the problem so attention is focused on material behavior rather than on the physical symptoms of immediate practical interest. Attempts to study the disease rather than the individual symptoms must start with an understanding of materials stable in the concrete environment.

b. Recognition that although hematite and water were the stable forms at service 
Eh and pH conditions of concrete, limonite is the metastable product expected.

c. Establishment through staining techniques that the bleaching of the gray or brown color of the coarse aggregate is associated with the oxidation of ferrous to ferric iron.

d. Rediscovery that the proportion of materials, their combined rates of reaction and the nature of the rock framework govern the physical symptoms of distress. Pyrite, ferrous carbonate and illite will alter to form limonite; however, the reaction rates are slow and markedly influenced by other concurrent reactions such as dedolomitization.

e. The distribution of limonite denotes the zones of weakness within the coarse aggregate and explains the local fracture pattern of Otis coarse aggregates.

f. As the carbonate rock continues to respond to the new oxidizing environment more and more limonite is formed, changing
physical properties of the aggregate and releasing limonite into the matrix.

**Matrix Material Changes**

Until now the matrix has been considered as the hydrated cement and fine aggregate that enclose coarse aggregate. In this section the matrix will be considered as being composed of either hydrated cement compounds, fine aggregate or secondary materials introduced as the result of weathering. This admittedly simplified partition will serve as a materials list for the matrix system. The interaction of these materials and the development of the stress pattern within them constitute matrix material changes in service.

1. Materials added to the system that result in consistent changes most likely originate from the following sources:

   - **Atmosphere**
   - Groundwater from the soil or highway base materials
   - Deicing chemicals
   - Fine aggregate
   - Coarse aggregates.

2. Atmospheric carbon dioxide is perhaps the best understood of all the environmental factors that influence the behavior of highway concrete.

   a. Because it attacks the exposed surface at a much greater rate than the bulk material of the slab interior, the hydrated cement of the concrete matrix acts as if it were composed of two different materials. Hydrated cement in
the surface zone commonly develops cracking leading to scale formation, but the interior matrix displays less interaction with carbon dioxide and fewer fractures.

b. The carbon dioxide attack of the matrix is especially well documented in the Otis aggregate concrete system. The control samples of this study were examined by Lentz and the results compiled by the author were reported by Lemish (37) in reference to two brands of cement. If a curve is plotted for a single brand of cement, then the ratio of the monomer, dimer and polymer forms of the silicate structure show that with increasing time in service the monomer is converted to dimer and the dimer to polymer. Since tobermorite gel is associated with one type of dimer structure (Simon (53)), these findings indicate destruction of the structural glue (tobermorite) with increasing service life. Fixation of carbon dioxide by the hydrated cement is one mechanism for the destruction of the tobermorite structure.

c. Simon (53) has shown that the carbon dioxide content of this Otis aggregate concrete is variable throughout the core sample. He finds a distribution of carbon dioxide that is consistent with fixation of atmospheric carbon dioxide at the highway surface. For example the raw weight percent data for the surface, \( \frac{1}{4}'' \), 1'', 3'' and 5'' depths of CD-66-52-1 were 11.41, 3.93, 3.03, 2.84 and 3.28 respectively.
3. The chemical environment influences the stability of the concrete matrix.

   a. Copeland et al. (5) have shown that other methods for destroying the tobermorite structure include attack by aluminates, ferrites and sulfates. Sulfur apparently substitutes for silicon; aluminum and ferric iron substitute for both silicon and calcium.

   b. Various salts deposited as deicing chemicals or leached from the soil were thought by Slate (54) to be deposited above the water level within the pavement or to be deposited in the surface pores of the concrete by capillary action.

4. Deposition of salts at the highway surface changes the environment of the highway surface in service.

   a. The addition of new materials and their concentration at the surface by this means would create additional chemical stress at the highway surface. These stresses would assist the carbon dioxide attack at the surface. For example the accumulation of sodium or magnesium sulfate could cause disintegration of the concrete by converting calcium aluminate to calcium aluminate sulfate.

   b. Simon (53) has shown for the center of the slab control samples of the Otis aggregate concrete that alkalies were indeed concentrated at the highway surface.

5. Silica in the form of fine aggregates are chemically unstable in the changed environment of the highway surface.
a. The quartz and feldspar fine aggregate sand grains react slowly in the surface zone of the highway. Because of the high pH, Krauskopf (34) predicts the dissolved silica concentration as between 1,000 and 5,000 ppm SiO$_2$ at 25°C. The larger value was determined for amorphous silica and the smaller for quartz.

b. Geochemical studies of sandstones by Dapples (7) would suggest replacement of quartz by calcite under the environmental conditions of moist highway service. Because of the higher energy of grain boundaries, preferential attack of these boundaries within sand grains would be expected and were recognized in this study.

6. Fine aggregate sand grains are physically unstable in the changed environment of the highway surface.

a. Fine aggregate exposed to mechanical forces such as traffic erosion will be removed from the surface either by abrasion of particles or as larger units by a material response such as elastic rebound. Changes in fine aggregates are reflected in the surface roughness (Elwell (12)) and by an increase in the relative amount of fine insoluble residue (Simon (53)).

7. Study of the characteristics of the surface zone of carbon dioxide attack have been facilitated by the adoption of acetate peel studies of concrete core slices. This technique had not previously been used for the study of concrete.
a. The highly birefringent carbonate material that could be observed in acetate peels under crossed nicols, was recognized as defining the carbonated matrix surface zone of the core and allowed detailed study of this zone. In particular the interface of this material with the bulk hydrated cement was well defined. The lower interface of this surface zone of carbonation follows the surfaces of aggregate particles reflecting the higher porosity and permeability of these interfaces. Hair line semi-continuous fracture zones follow the lower boundary of the birefringent surface zone of hydrated cement. Some of these fractures enter underlying coarse aggregate to form onion skin fractures. Some fractures appear to be initiated at the hydrated cement interface below the fine aggregate.

b. In addition to being highly birefringent the surface zone of hydrated cement is marked by a change in the morphology of the iron bearing compounds. Reactions in the zone of carbonation modify the material so that ferric iron may be detected by staining techniques. The iron in the lower non-birefringent hydrated cement is unaffected by the stain.

c. Fractures of the bulk matrix of the D-line fractured cores resemble the surface zone of carbonation. Instead of the expected brown grains of hydrated cement these fractured zones are bordered by shattered colorless grains of hydrated cement. The local discoloration of the matrix and the
formation of clots of iron rich material are characteristic of the leached distress zones of this study. Such zones are especially evident on the "wet" surfaces preserved by attached acetate peels of older distressed highways. Such discolored hydrated cement grains may be a source of the iron that forms a film on old fracture surfaces.

8. Material changes are associated in time with the distress characteristics of the Otis aggregate concrete.

a. One of the first changes noted is a brown stain found on the highway surface near joints. This is related to the passage of moisture since after a spring rain the same zone appears dark with moisture. The brown color is that of the ferric iron gel.

b. The iron gel has been known to influence the behavior of the fine aggregate quartz particles. Fridland and Tsyurupa (18) have established this for the exchange capacity of quartz. Eventually the iron film marks grain boundaries and grooves of the fine aggregate and lines pathways from the aggregate to the surface depressions.

9. Another form of surface change is the appearance of isolated dark spots. These appear over covered coarse aggregates.

a. The hydrated cement and fine aggregate have been removed over some dark spots exposing the coarse aggregate. Naturally exposed coarse aggregates commonly have the conical shape of fracture surface that is associated with pop-outs.
It should be mentioned that these features differ from the pop-outs described by Mielenz (46) in at least three ways as follows:

1) Otis aggregate features lack the profusion of brown stain which surrounds the iron stone pop-outs of Mielenz.

2) Otis aggregate features appear only after years of service.

3) Unlike Mielenz pop-outs the Otis aggregate features are related to the location of D-line cracking.

b. Although the claystone iron pop-outs of Mielenz do not describe these Otis coarse aggregate features, a few of the fine aggregate claystones in the Otis aggregate concrete studied did show the behavior described by Mielenz as iron stone pop-outs. In agreement with their described behavior these fine aggregate features did not appear to be related to the D-line fracture distress.

10. In addition to the brown staining of concrete fracture surfaces the matrix may take on a blue color which is characteristic of a weathered broken surface.

   a. What appears blue macroscopically does not appear blue under the microscope. At present all blue material studied can be resolved into one of three conditions as follows:

1) Blue material is identified as the hydrated cement-fine aggregate bond zone.
2) Blue material is identified as a thin limonite film coating a hydrated cement grain surface.

3) Blue material is an illusion created by diffraction of light.

The completely shattered surfaces of hydrated cement grains appear a diffuse blue under reflected light. However, under transmitted light on the rotation stage of a microscope the blue color did not exist and light and dark zones depending on the path of light through the clear crystals were evident. The blue line cracks identified as D-line cracks in this study were commonly found to be blue because of condition 3. The blue-gray deposits found in the low areas of the highway surface of some cores also owe their color to condition 3. Deposition of alkalies in these same locations may help to explain these locally shattered zones.

11. The coarse aggregates release materials into the matrix as the result of leaching, cracking and hydroxyl ion attack.

a. The commonly observed products include outer rims of iron rich material and calcite. Minor amounts of illite, brucite and sulphate oxidation products of pyrite are released into the matrix. These materials move through the interconnected voids in the hydrated cement to create local zones or concentrations.

b. One consequence of the leaching of materials from the coarse aggregate is the partial filling of the voids with calcite and iron gel. Other secondary minerals are probably present but are not commonly observed.
12. The effect of the deposition of iron gel in the air-entrainment size voids of the matrix may be to impair the frost resistance of the concrete.

a. The effect of limonite is difficult to assess because it becomes dehydrated over a range of temperatures and is difficult to rehydrate. Because of this behavior it would act like trapped moisture in high pressure meter tests of the air entrainment size voids. Such tests performed on center of the slab cores in this study indicated approximately the same air contents for standard Iowa State Highway Commission testing procedures. This would suggest that almost all of the original air entrainment size voids remained isolated and unfilled in service.

b. However, special tests that prevented the cores from drying before testing gave different results. The results may be interpreted two ways: (1) either these voids are partly filled with moisture which communicates slowly with its surroundings, or (2) they are filled with secondary materials such as limonite that may be dehydrated upon heating but not readily rehydrated upon soaking. In either event, filling of the air entrainment size void seriously impairs frost resistance of air entrained concrete. Because cracking of the coarse aggregates provides additional space for moisture in the saturated zone, this fracturing increases the amount of water that must be accommodated in air entrain-
ment size voids during freezing of hydrated cement. With continued service it appears that a time will arrive when the volume of water will be too large to be accommodated by empty air entrainment size voids during the time of freezing. At this time moisture will freeze in solution channels between coarse aggregates and large matrix voids. After further local weakening, the coarse aggregate fractures are interconnected across the matrix along old discolored solution pathways. Because these new fracture zones will probably contain more water during the next freezing cycle, the capillary voids are more likely to be saturated and this mechanism accelerates destruction along local failure surfaces. Blocks of material loosened from the slab by this mechanism would fit the description of material removed during progressive spalling of the D-line cracked zones. This then can be considered an explanation for the timing of propagation of coarse aggregate cracks and a reason for the avoidance of weak lithologies.

13. The unique contributions of this study to the understanding of matrix material changes were as follows:

   a. Release of iron rich material from the coarse aggregate to form outer rims was associated with filling of the matrix with limonite.

   b. Acetate peel studies defined the carbonated surface layer by its high birefringence. This permits optical identification of the morphology of the carbonated zone.
c. Recognition of the apparent oxidation change of iron in the carbonated zone by staining techniques. The positive test for the ferric state indicates either release of iron by silica or oxidation of the ferrous ion.

d. The brown stain of the highway surface results from release of iron from the carbonated zone of the highway.

e. The blue line cracks were explained in terms of reflected light.

f. It was recognized that pop-outs in the D-line cracking zone locate the coarse aggregate positions that control the locations of D-line cracking. Today's pop-outs mark tomorrow's D-line cracks.

g. It was recognized that the coarse aggregate fractures within the concrete occur first, and that the timing of ultimate failure is related to the resistance of hydrated cement to the interconnection and propagation of coarse aggregate fractures.

h. It was observed that the propagation of cracks was also related to filling of voids by iron rich material and other secondary minerals.

i. Confirmation of the reduced air entrainment size void volume measured on center of slab control samples in the moist condition supports the interpretation of a reduced volume of air available for frost resistance in older Iowa highways regardless of the initial air content.
j. Because standard tests which require pre-drying the samples failed to detect the filling of the air entrainment size voids, this author recommends adoption of a test procedure that will measure only the air filled voids. Recognition that voids are being filled should be reflected in new designs that allow for additional air space or sampling programs that would permit scheduling of sealing of the surface before the space is reduced below the critical value which permits disintegration of hydrated cement solution channels.

Concrete Failure

During the discussion of material changes three types of fractures were discussed. These included fractures introduced into the weak lithologies of the coarse aggregate, fractures formed along the lower interface of the zone of highway surface carbonation, and fractures propagated through the hydrated cement solution channels by frost activity. Interaction of the fractures causes spalling of blocks of concrete material from the highway slab which is interpreted as a service failure. The remaining subject to be discussed is the relationship between the symptoms of failure and the special occurrences of the failure.

1. The following features will be considered:
   Scaling
   D-line fractures that intersect the upper highway surface
   D-line fractures that intersect the lower slab surface
   Weak and strong coarse aggregate.
2. Scaling occurs in the carbonated zone just beneath the highway surface, but much of the material removed as scale is not carbonated; rather it is the carbonated fracture zones interconnected with the onion skin rims of the coarse aggregate that form scale.
   a. Freshly removed scale indicates that only the coarse aggregate surfaces are filmed. This is interpreted as evidence that final failure, which separates the scale from the slab, involved only fine aggregate and hydrated cement. Scale is commonly removed by frost action or in some cases by traffic erosion.

3. D-line cracks form the boundaries of many scale segments.

4. Since halite deposits commonly stand 1/16 to 1/8 inch above the highway surface in D-line cracks, local high alkali reactions may be possible in this zone.

5. Urban roads protected by curb and gutter characteristically do not develop the depth of scale found in the primary road system. Whether this difference in scale development results from better drainage or more traffic erosion is not yet well understood.

6. D-line fracturing that intersects the upper highway surface appears to be related to the collection of surface moisture in cracks and joints.
   a. Exposure of coarse aggregate and matrix to saturated conditions over the years permits moisture and secondary minerals to fill part of the space originally filled with air. This is especially evident in the critical air entrainment size voids.
7. Interconnection of the voids by fracturing of the concrete system, particularly the coarse aggregate weak lithologies, further complicates the problems of frost resistance.

   a. D-line fracturing of this type is correlated with high compressive strength and high percent saturation of air entrainment size voids. The correlation is particularly good for those samples that contain fracture paths predominantly through the matrix.

8. These highways appear to reach a maximum compressive strength after which the core samples show decreasing strength and an increasing density of fractures.

9. If highways are sealed after maximum strength has been reached the fractures already present will within a short time destroy the smooth capping surface.

10. If the highway is sealed before the fractures are introduced the seal will allow an increased service life of smooth highway performance.

11. Because of this correlation, routine compressive strength tests are recommended in order to determine when a highway should be sealed in sufficient time so that sealing it may become a normal budget item.

   a. In addition, patching of D-line fractures should recognize the general pattern around the joint and remove sufficient material to obliterate occurrence of the cracked aggregate pattern around the joint.

12. D-line cracking that intersects the lower highway surface is related to the availability of moisture and the type of coarse aggregate.
a. Here drainage of the lower surface of the slab becomes increasingly important.

13. The change in construction practice that resulted in placing a polyethylene sheet immediately beneath the slab has created a sealing of the lower slab surface.

a. This is accomplished by depositing calcium hydroxide or other secondary deposits between the sheet and the slab. Water entering through the highway surface of the joint is no longer drained but is trapped in the neighborhood of the joint.

14. All three cores in the 1958 fence were removed in two or more pieces. Evidently moisture held in the joint by the polyethylene sheet barrier accelerated failure of the lower slab surface.

15. Because of this it is recommended that the use of polyethylene sheet directly under the highway slab should be reconsidered and some type of drainage for joints be provided.

16. The concentration of susceptible weak lithologies in the zone of failure of the 1958 fence cores was considered to contribute to the early failure of this joint.

a. In this zone onion skinned weak aggregate evidently had sufficient moisture to develop planes of weakness so that the earliest failure surfaces are locally controlled by the position and boundaries of the weak coarse aggregate lithologies.
17. The problems of recognition and identification of weak and strong lithologies from the Otis stone quarry have been discussed in a previous study (Elwell (12)).

a. In that study the strong aggregate in the quarry samples was characterized by having a uniform grain size, little or complete recrystallization and an absence of brown gel (limonite). In contrast, the weak lithology was associated with banding of carbonate materials, partial recrystallization and a saturation of voids with brown iron gel.

18. In this study the weak lithology was associated with onion skin fractures and multiple fractures within the coarse aggregate.

19. Fractures occurred when a weak lithology was unfavorably located within a stress zone around a joint.

20. Because of the association of the weak lithology with fractures such lithologies are considered detrimental to the service life of the highway.

21. In this study identification of the weak lithologies was only accomplished by observing in service failures or the testing of aged highway core samples.

a. After the service behavior of the material was established the quarry ledge from which it came could be identified as a source of weak aggregate.

b. Because mechanical testing of the coarse aggregate prior to service failed to discriminate between weak and strong lithologies, and weak lithologies perform satisfactorily
for several seasons, identification of weak lithologies by physical testing requires several years.

22. Chemical studies on the weak and strong lithology source materials were undertaken to determine if the Otis lithologies could be identified by characteristic chemical compositions.
   a. Chemical analysis of three weak and three strong lithologies from Otis quarry samples are shown in Table 3.
   b. The pairs of lithologies 16-19, 23-22, and 13-10 have similar grain sizes and are identified by bed number.

23. Most of the chemical differences between lithologies are found to overlap the boundaries of weak and strong behavior. An exception to this is the SO$_3$ content reported for the quarry samples.

24. The weak lithologies have approximately 100 times the SO$_3$ reported for the strong lithologies.

25. The weak lithologies found in Otis quarry may be recognized and distinguished from the strong lithologies on the basis of reported SO$_3$ contents greater than 0.05 weight percent.

26. Further study of SO$_3$ contents of other systems is indicated as possible means for the improvement of highway performance such as increasing early resistance to D-line fracturing by the elimination of high SO$_3$ quarry lithologies from acceptable coarse aggregate sources.

27. Because the association of high SO$_3$ content and limonite in the weak lithologies is interpreted as the reaction products of reactive pyrite, such pyrite is considered characteristic of weak aggregates.
Table 3. Comparison of the chemical analyses of Otis concrete ledge quarry samples previously classified as weak or strong lithologies on the basis of the preferred failure mode in aged highway concrete core samples from highways constructed of these materials

<table>
<thead>
<tr>
<th>Wt. %</th>
<th>Weak lithologies Grain size</th>
<th>Strong lithologies Grain size</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>0.51</td>
<td>0.91</td>
</tr>
<tr>
<td>CaO</td>
<td>48.87</td>
<td>30.40</td>
</tr>
<tr>
<td>MgO</td>
<td>5.23</td>
<td>21.11</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>0.26</td>
<td>--</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>0.66</td>
<td>0.30</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.03</td>
<td>0.06</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.03</td>
<td>0.04</td>
</tr>
<tr>
<td>SO₃</td>
<td>0.122</td>
<td>0.060</td>
</tr>
<tr>
<td>Less at 950°C</td>
<td>46.71</td>
<td>46.56</td>
</tr>
<tr>
<td>Total</td>
<td>102.44</td>
<td>99.71</td>
</tr>
</tbody>
</table>
28. Observations by Evamy provide a mechanism which may explain why the high \( \text{SO}_3 \) reported for the weak coarse aggregate lithologies may influence the formation of the interconnected rhombohedral pores within the aggregates that are associated with D-line fracturing of highway concrete in this study.

a. Evamy (17) has proposed that the rhombohedral pores found in coarse aggregates formed of cloudy centered dolomite crystals are caused by the selective leaching of mineralogically unstable high-magnesium calcite or aragonite, believed in many cases to be the initial product of dedolomitization. Such pores are only likely to be found shortly after dedolomitization since he found that ancient dedolomitized rocks are more mineralogically stable. He mentioned that calcium sulfate in solution accelerated the conversion of dolomite to the high-magnesium leachable product of dedolomitization.

b. Since dedolomitization of the cloudy-centered dolomites in the concrete environment has long been accepted, the pinpoint solubility of this reaction product may well explain zones of weakness in banded aggregates containing pockets of sulfate.

29. The unique contribution of this study to the understanding of concrete failure is as follows:

a. Scale which may be removed by traffic erosion or frost action ultimately fails by breaking the hydrated cement-fine aggregate bonds.
b. The depth of scale is different in urban and country service conditions.

c. The polyethylene sheet under joints becomes sealed to the lower slab surface and traps surface water near the joint which results in early D-line fracturing of the lower portion of the highway slab.

d. Otis stone weak coarse aggregate lithologies have 100 times more SO₃ present than in the strong lithologies from the same quarry. This indicates that reactive pyrite may be related to the poor service life of these highways and that improved resistance to D-line fracturing may be possible by limiting the SO₃ permitted for acceptable quarry stone. Further research to determine acceptable limits for SO₃ in other source materials appears indicated.
CONCLUSIONS

This investigation has provided observations that allow conclusions to be drawn in the following areas:

1. Highway distress related to the use of Otis stone may be divided into three types which are separated on the basis of factors that appear to influence the severity of deterioration.

2. Relationships between isolated petrographic curiosities have been integrated into meaningful descriptions of highway distress.

3. The physical basis for development of quality control tests for describing the condition of highway concrete has been provided.

4. Study of the history of the pavement as a geological problem has allowed the combining of behavior of different highways to approximate the history of one highway. This provides a test of the interval of service life that may be included in the extrapolation of short time tests.

5. The combination of the results of many different specialties to yield a self consistent explanation of observations on many levels is the task of the highway geologist.

The highway distress characteristics are considered the result of stresses introduced into the edge of the highway slab by the collection of water in natural and construction joints. The characteristics of distress change with service life, core depth and distance from the joint. For convenience this distress has been partitioned as follows:

1. Scale - The formation of scale is related to the following parameters.
a. The location of D-line cracks.
   1) The fractures and onion skins of weak coarse aggregate.
   2) The low places in the highway surface finish.
   3) The concentration of alkalis in the surface pits.

b. The wear of fine aggregate.
   1) Urban-country design (i.e. curb and gutter).
   2) Traffic load and direction.
   3) Elastic rebound of aggregate.
   4) The presence of air entrainment and solution channels.

c. The carbon dioxide attack of exposed hydrated cement.
   1) Iron morphology change.
   2) Onion skin failures of coarse aggregates.
   3) Failure of fine aggregates.

2. Upper Zone Failure - These fractures belong to a family of fractures that form traces on the highway surface. Because they are probably related to the generation of ice crystals from gel water they are sensitive to the following parameters.

   a. The location of fractured weak aggregate lithologies.
      1) The location of D-line cracks.

   b. Air entrainment to impart frost resistance.
      1) This is zone of effective air entrainment.
      2) Loss of air entrainment protection by filling of air entrainment size voids during service life.

   c. Fracture paths in hydrated cement are associated with a critical percent saturation of the air entrainment size voids.
d. Decrease in a maximum compressive strength of highway cores is also associated with percent saturation and fracture paths through the hydrated cement.

1) Short time compressive strength tests measure only strength of the bond zone. Compressive strength at this age is limited either by the strength of the aggregate or the strength of the matrix.

e. The locations of steel rods in the central portion of the core inhibit the formation of an upper fracture zone.

3. Lower Fracture Zone - These fractures are commonly sub-parallel to the highway surface or tend to intersect the lower slab surface. They are probably related to the formation of ice from the water present in the joint.

a. Fractures of this kind formed several old failure surfaces that resulted in short cores.

b. The fractures are related to solution channels and development of onion skins on coarse aggregate weak lithologies. The presence of susceptible lithologies hastens development of this distress.

c. Development of lower fracture zones are related to drainage from beneath the highway slab. Barriers such as polyethylene sheets hasten joint deterioration.

4. Introduced techniques that facilitate the study of highway concrete include the following:
a. Attached and mounted acetate peels.

b. Staining of concretes to determine oxidation state of iron.

c. Methods of sampling to determine percent saturation of air entrainment size voids.

5. Relationships have been found between petrographic features and highway distress of the Otis type.

a. The following features have been interpreted as meaningful to highway distress:

1) inner rims
2) onion skins
3) pop-outs
4) D-line cracks
5) D-line fractures
6) iron stains.

b. This study has provided a physical basis for the quality control of highway materials.

1) Maximum compressive strength of highway cores suggests those highways that are susceptible to upper zone failure.

2) Critical percent saturation of air entrainment size voids suggest those highways that no longer have frost resistance.

3) The relatively high SO\textsubscript{3} values reported for quarry samples of weak coarse aggregate lithologies suggest elimination or blending of these materials.
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