NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
REPORT 106

REVIBRATION OF RETARDED CONCRETE FOR CONTINUOUS BRIDGE DECKS

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REVIBRATION OF RETARDED CONCRETE FOR CONTINUOUS BRIDGE DECKS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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FOREWORD

By Staff

Highway Research Board

This report is recommended to design, construction, and maintenance engineers, and also to specification writers, researchers, and others concerned with concrete bridge deck durability. It contains evidence based on laboratory and field experiments that surface cracks and internal cracks at the level of the top reinforcement in plastic bridge deck concrete can be closed by the relatively easy and inexpensive technique of surface revibration.

Transverse, longitudinal, and horizontal plane-of-weakness cracking of continuous concrete bridge decks can be caused by changes in deflection and rotation over supports during construction, in addition to the possible effect of restraint to subsidence afforded by the top reinforcing steel. It is generally felt that such cracking is of significance with respect to the development of spalling. It was felt that revibration of retarded concrete could be useful in eliminating such occurrences in continuous bridge decks placed in one operation.

The University of Illinois approach to this research was first to conduct a survey to determine the extent to which delayed vibration or revibration has been used in placing bridge deck concrete. Following the survey, the researchers conducted a series of laboratory tests to determine the influence of revibration in closing surface cracks and internal cracks at the level of the top reinforcement in simulated reinforced concrete bridge decks. A portion of the experimentation was devoted to determining the effects of revibration on durability and finishing. In addition to the laboratory work, three bridges, or portions of bridges, were actually revibrated in the field to ascertain the feasibility of this technique. The report carefully details the equipment that was used for revibration, when to revibrate, and the possible benefits to be derived within the limitations of the parameters studied in this research.

The research findings include evidence that indicates that revibration is a promising technique that can be used now. On the other hand, the state-of-the-art in predicting the long-term effects of revibration is such that it precludes an estimate of the long-term benefits, if any. If one is prepared to accept the premise that surface and interior cracks in a bridge deck slab expedite spalling, and, further, to assume that if the cracks are eliminated spalling can be controlled, perhaps revibration is ready to be used as a construction technique. There are, of course, unanswered questions concerning equipment design, basic mechanisms of compacting concrete, and the economics of utilizing revibration.

CONTENTS

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The cooperation obtained from the Illinois Division of Highways and the State Highway Commission of Kansas in planning and executing the field experiments is gratefully acknowledged. J. E. Burke and R. C. Mulvey, of the Illinois Division of Highways, as well as T. Step, resident engineer, assisted in planning the field test near Champaign, Ill. The contributions of W. M. Stingley, State Highway Commission of Kansas, were essential for the success of the field experiments near Newton, Kans. In addition, the assistance given by J. E. Bukovatz, C. F. Crumpton, and R. Grant, of the State Highway Commission of Kansas, and the King Construction Company, Hesston, Kans., deserves special mention.

C. H Best, Kansas State University, was kind enough to make available to this project a survey on the use of revibration in the construction of reinforced concrete bridge decks

REVIBRATION OF RETARDED CONCRETE FOR CONTINUOUS BRIDGE DECKS

SUMMARY

Surveys of existing structures indicate that transverse cracks in bridge deck concrete are of significance with respect to bridge deck deterioration after exposure to freezing and thawing and deicing agents. Transverse cracks may be formed or initiated already in the fresh concrete, and may be caused by changes in deflection and rotations over supports during construction, owing to the dead weight of the concrete. An additional cause of cracking of concrete can be the restraint of subsidence due to bleeding of the fresh concrete afforded by the top reinforcing steel.

Laboratory studies were conducted to investigate the effectiveness of revibration of concrete in repairing cracks several hours after it was placed. In addition, the effect of revibration on concrete durability was investigated, and field experiments were conducted to verify the results from the laboratory tests and to investigate the feasibility of revibration in bridge deck construction. The laboratory tests showed that surface revibration with a vibrating screed is an effective method to close flexural cracks on the concrete surface as well as subsidence cracks at the level of the top reinforcement and internal cracks that do not penetrate to the concrete surface. Surface revibration is effective to a depth of at least 4 in. from the concrete surface. Revibration could be conducted successfully in the laboratory as long as the penetration resistance of the concrete according to ASTM C 403-68 did not exceed a value of 60 psi. Most concretes will reach this value approximately ½ hr to 1 hr prior to initial set (defined as the time at which penetration resistance reaches 500 psi.) If properly conducted, surface revibration results in a smooth concrete surface so that no additional finishing after surface revibration, except belting and brooming, is required. Compressive strength and abrasion resistance of concrete were little affected by revibration. However, after surface revibration a slight increase of the spacing factor of air voids close to the concrete surface was observed.

Accelerated freezing and thawing tests on concrete surfaces exposed to deicing chemicals showed no significant difference in surface scaling of revibrated and non-revibrated concrete. However, it is likely (although not proven in laboratory experiments) that surface revibration will improve the resistance of concrete against surface spalling.

Portions of three bridge decks were revibrated approximately 2 hr after the concrete was placed. It was shown that the entire width of a bridge deck can be revibrated with a vibrating screed in a continuous operation. The screed should be designed in such a way that its profile can be adjusted to match the profile of the deck prior to revibration. In addition, provisions should be made that during revibration the screed does not float freely on the concrete surface. Under these conditions surface revibration of bridge decks can be conducted successfully and no extensive finishing after revibration is required.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

STATEMENT OF THE PROBLEM

The deterioration of reinforced concrete bridge decks has been of much concern to highway engineers, researchers, and administrators throughout the United States. The frequent repairs of bridge decks that are necessary (particularly in urban areas with heavy traffic, and in regions with more severe climatic conditions) are costly. The public inconvenience because of temporary closing of highways is of equal concern.

Several surveys of deteriorated bridge decks in various parts of the U.S. (*1, 2, 3, 4*) have been conducted during recent years. Various research programs on this subject have been carried out or are presently under way. For example, a detailed literature review is given by Callahan et al. (*5*). The many bridge deck surveys and research studies have indicated that bridge deck deterioration was not limited to one cause or type of distress. However, spalling of the concrete surface and deterioration starting from transverse cracks in the bridge decks were the most common types of deterioration.

In most cases, concrete deterioration may be traced back to one of the following:

1. Use of unsound ingredients in the concrete mix.
2. Inadequate air void system of the surface mortar of the bridge deck.
3. Transverse cracking at locations of transverse reinforcement.

These deficiencies are particularly detrimental when deicing agents are used and when the concrete cover above the top reinforcement is too thin. The use of unsound ingredients is of least significance inasmuch as it can be controlled the easiest. An inadeqaute air voids system of the surface mortar may be caused, for example, by too low an initial air content of the concrete mix. Overfinishing, sprinkling of water on the surface during the finishing process, or late finishing may have similar effects.

Cracking of the bridge deck may lead to concrete deterioration if water can easily penetrate the crack and resaturate the adjacent concrete. More important, however, is the fact that moisture may penetrate through the cracks to the top reinforcement. The use of deicing salts, particularly, may cause the reinforcement to corrode. Because of the expansive nature of the corrosion products the concrete cover will be subjected to high stresses in planes parallel to the concrete surface. These stresses may eventually lead to the propagation of horizontal cracks and subsequent spalling of the concrete cover, particularly if its thickness is inadequate (*5*).

The formation of transverse cracks in bridge decks may be attributed to a variety of causes. They may be the result of flexural stresses due to the dead weight or vehicle loading in the negative-moment region of continuous bridge decks. It is generally assumed, however, that such load-induced transverse cracks occur comparatively infrequently (*5*). Shrinkage of the hardened concrete may contribute to transverse cracking. However, the formation of cracks while the concrete still is in a plastic state seems to be of more importance:

1. Early shrinkage of the cement paste is restrained by aggregates or steel reinforcement; this results in tensile stresses and subsequent cracking of the fresh concrete.
2. Deflections and rotations of the formwork or of the supporting structure of the bridge deck due to the dead weight of concrete may cause stresses in fresh concrete. In the case of continuous concrete decks, tensile stresses develop in the top fibers near the supports, which may lead to transverse cracking (*25*).
3. The top reinforcing steel may cause restraint to subsidence due to bleeding of the fresh concrete, particularly in deeper slabs. Such restraint may result in the formation of horizontal plane-of-weakness zones or cracks as well as vertical cracks extending from the top reinforcement to the surface of the concrete bridge decks. Formation of planes of weakness may be enhanced by surface crusting that is likely to occur at high temperatures and high wind velocities during casting.

OBJECTIVE

It has been suggested that cracks that develop in the fresh concrete due mainly to formwork deflection, but also due to restraint of subsidence, may be repaired by revibrating the concrete after most of the bridge deck has been cast. It was hoped that such revibration might significantly improve the durability of reinforced bridge decks. Because revibration should be carried out after most of the concrete in a certain segment of the structure has been placed, the use of retarded concrete would be essential to make revibration effective and to minimize the required revibration energy. The effectiveness of retarders to prevent cracking during construction of a bridge deck has been shown by Britton (*25*), for example.

The main objective of this investigation was to study the feasibility of this suggested construction practice.

RESEARCH APPROACH

Phase 1

Phase 1 of this study was a survey of current engineering practices regarding revibration or delayed vibration of bridge deck concrete. Forty-nine highway departments in the United States and six highway departments in Canada responded.

Phase 2

Phase 2 was a laboratory study to investigate the effectiveness of revibration in closing cracks in reinforced concrete slabs while the concrete is in the plastic state. Reinforced concrete slabs 8 ft long, 3 ft wide, and 6 in. thick were cast in flexible formwork with retarded and air-entrained concrete The slabs were deflected upward between 2 and 4½ hr after mixing in order to develop cracks on the surface of the specimens The procedures necessary to develop cracks in the fresh concrete were investigated in a series of pilot tests. Some time after deflection the concrete was revibrated either by means of a surface screed or of an internal vibrator. Both the time of revibration and the energy level of revibration were varied. To evaluate the effectiveness of a certain revibration procedure several hardened concrete slabs were sawed into three segments; the sawed sections were then carefully inspected to detect width and depth of cracks in the concrete. The type and extent of initial cracking, the percentage of reinforcement, the amount of retarder, and the curing conditions prior to revibration also were investigated. Seventy-nine test slabs were studied within this phase of the investigation.

Phase 3

Phase 3 was a study of the effect of revibration on bridge deck surface durability. In Phase 3a the effect of revibration on the general freeze-thaw characteristics of revibrated concrete was investigated by use of specimens 2 ft by 2 ft by 6 in. that were initially compacted and later revibrated on a vibrating table. Age at revibration, revibration energy level, presence of reinforcement, air content, and amount of retarder were the principal variables in this study Twenty-one days after casting, the surfaces of the specimens were exposed to deicing chemicals and subjected to cyclic freezing and thawing Visual ratings of deterioration were conducted in accordance with procedures developed in previous research studies (*5, 6*).

The results obtained from Phase 2 and Phase 3a were used to select the parameters to be studied on 21 large slabs of Phase 3b. Specimens 8 ft long, 3 ft wide, and 6 in. thick were revibrated with a surface screed The principal parameters were type and extent of initial cracking, age of concrete at the time of revibration, revibration energy level, amount of retarder, air content of the concrete, and finishing procedures.

Phase 4

In Phase 4 the results obtained in the previous phases of this investigation were evaluated to develop recommendations for the use of revibration in the construction of concrete bridge decks, including considerations regarding equipment and concrete properties. The feasibility of the recommended construction practice and the field performance of revibrated reinforced concrete bridge deck were studied by revibrating three bridge decks under construction in Illinois and Kansas.

To be able to describe the physical properties of the concrete that may influence its freeze-thaw durability, the following tests were conducted for most parts of this investigation:

1. Cylinder tests for compressive strength (ASTM C 39-61).
2. Modified point count for air void parameters (ASTM C 457-66T).
3. Pressure test for air content of the fresh concrete (ASTM C 457-66T).
4. Time of initial and final set of the fresh concrete (ASTM C 403-68).
5. Acceleration measurements in the fresh concrete during revibration.
6. Determination of density of revibrated and nonrevibrated concrete.
7. Pulse velocity measurements in revibrated and nonrevibrated concrete.
8. Freeze-thaw tests on prisms 3 by 3 by 15 in.
9. Determination of abrasion resistance (ASTM C 418-68).

Air-entrained, retarded concrete was used for most laboratory experiments. The concrete had a water-cement ratio of 0 64 by weight, a slump of 2 to 4 in., an air content of between 5.5 and 6 5 percent, and a maximum aggregate size of 1 in. Its compressive strength after 28 days was approximately 5,500 psi. The initial set of the retarded concrete ranged from 6 hr 30 min to 8 hr; the nonretarded concrete had an initial set of approximately 3 hr 45 min.

OUTLINE OF REPORT

Chapter Two summarizes the results obtained in this investigation. An interpretation of the findings, the conclusions to be drawn, as well as suggestions for future research appear in Chapters Three and Four.

Appendix A gives a review of related research. The survey on the use of revibration in the construction of reinforced concrete bridge decks is described in Appendix B. Detailed descriptions of experimental procedures and data are presented in Appendices C (Phase 2), D (Phase 3), and E (Phase 4). Additional experimental data appear in Appendix F. Appendix G describes observations on cores taken from experimental bridge decks in Kansas.

CHAPTER TWO

FINDINGS

SURVEY OF THE USE OF REVIBRATION IN THE CONSTRUCTION OF REINFORCED CONCRETE BRIDGE DECKS (PHASE 1)

Letters of inquiry (Fig. B-1) were sent to the highway departments of the 50 states of the U.S. and the District of Columbia as well as to 10 provinces of Canada The replies from 48 states, the District of Columbia, and 6 provinces of Canada are summarized in Table B-1. No known cases were reported of the use of revibration of retarded concrete bridge decks. One structure was described on which delayed vibration of retarded concrete had been employed. Six highway departments noted that their specifications did not permit the use of delayed vibration or revibration, and two highway departments specifically stated that such procedures were not being considered. Two agencies indicated that retarded concrete was frequently used for bridge decks of continuous structures to allow dead-load deflections to occur before the initial set of the concrete. Two cases of unintentional revibration of concrete bridge decks were reported, however, no unusual effects had been noted in either case. Apparently no experience in the use of revibration of bridge deck concrete existed prior to this investigation.

DEVELOPMENT OF CRACKS IN FRESH CONCRETE (PHASE 2)

To develop cracks in the concrete prior to revibration the concrete was cast in flexible formwork (Fig. C-1) and was deflected upward between 2 and 4½ hr after mixing. Deflection was continued until either slight, medium, or severe cracking was visible at the surface of the slabs. Cracks with a width of 0.001 to 0.002 in. and spaced between 5 and 10 in. apart were defined as slight cracking. A concrete curvature of approximately 5×10^{-4} in^{-1} was required to develop such cracks (The curvature is the reciprocal of the radius of curvature in the center portion of the slab.) Severe cracking corresponded to a crack width of 0.03 to 0.05 in. at a spacing of 1 to 2 in. and occurred at a curvature of approximately 2.5×10^{-3} in.$^{-1}$. The cracks were concentrated near transverse reinforcing bars and extended over the entire width of the slab. Variations in the time after mixing at which the concrete was deflected (between 2 and 4½ hr) had little effect on crack width and crack spacing (Fig. C-9). The cracks were shallow, and only a few cracks penetrated beyond the level of the top reinforcement (Fig C-11). Deflection of the concrete after 4½ hr resulted in deeper cracks (Fig. C-12). However, spacing and maximum crack width did not significantly deviate from the values observed on specimens that were deflected earlier In addition to the surface cracks, deflection resulted in the formation of internal cracks that did not penetrate to the concrete surface and that were located near transverse reinforcing bars (Figs. C-11 and C-12). Figure C-14 shows the average depth of surface cracks as a function of the penetration resistance of concrete at the time of deflection. An increase in penetration resistance results in an increase of the depth of surface cracks.

Under the normal laboratory environment no significant shrinkage cracking could be observed prior to or after initial set. Only under severe drying conditions (high wind and temperatures of 95 or 110 F) were shrinkage cracks penetrating beyond the level of the top reinforcement developed (Figs. C-28 and C-29). Subsidence cracking or the formation of planes of weakness with an increased porosity at the level of the top reinforcement could not be found either under regular laboratory conditions or under the simulated wind and high-temperature conditions. Artificial plane-of-weakness cracks were generated, however, by lifting the top reinforcement of the slabs 2 hr after mixing (Fig. C-11).

EFFECTIVENESS OF REVIBRATION IN CLOSING CRACKS IN FRESH CONCRETE (PHASE 2)

Internal revibration proved to be an inefficient and ineffective method to close cracks in fresh concrete, even if it was conducted several hours prior to the initial set of the concrete (Fig C-15). Experiments in which the concrete was revibrated with a surface screed were considerably more successful. Therefore, surface revibration was used in most experiments The surface screed consisted of an electrically powered vibrator mounted on a channel 8 in. wide (Fig. C-7). A frequency of 3,200 cpm and a speed of forward motion of the screed of about 7.5 ft per minute were kept constant in all tests. These values were chosen because they resulted in the smoothest surface of the concrete after revibration. A centrifugal force of the vibrator of 720 lb, corresponding to 80 percent of the maximum output of the vibrator, was defined as "high revibration energy level." At the "low energy level" the centrifugal force of the vibrator was 180 lb, or 20 percent of the maximum

At a high energy level, surface revibration was at least partially successful when conducted 1 hr or more before the initial set of the concrete. The penetration resistance of the fresh concrete according to ASTM C 403-68 proved to be a useful parameter to determine the time after mixing at which revibration may be conducted successfully. At the high energy level most cracks may be repaired as long as the penetration resistance of the concrete is below 60 psi. A penetration resistance of 30 psi is the limit for the low energy level employed in this investigation (see Fig. C-24) Because of the lack of a suitable method to measure and evaluate vibration energy in fresh concrete it is difficult to give a specific required minimum revibration energy. However, the experience gained during this investigation indicates that a revibration energy level that is sufficient to drive a slight moisture film to the entire concrete surface is also sufficient to close most cracks.

Variations of the layout of the top reinforcement or of the concrete cover had no apparent influence on the effectiveness of revibration (Figs. C-26 and C-27). The maximum penetration resistance at which concrete may be surface-revibrated is independent of the time of initial set or the amount of retarder in the concrete.

The concrete surface after revibration was in most instances sufficiently smooth so that no additional finishing after revibration, except brooming, was required. However, the experiments indicated that a better finish was obtained when the vibrator was mounted on the screed in such a way that the plane of rotation of the vibrator was perpendicular to the direction of forward movement of the screed.

Because surface revibration penetrates 2 to 4 in. from the surface of the concrete, revibration was equally effective in closing plane-of-weakness cracks (Fig. C-18).

Surface revibration at the high energy level closes early shrinkage cracks and can improve moderately crusted concrete surfaces. However, too low a revibration energy level may lead to the formation of additional, closely spaced surface cracks (Figs. C-28 and C-29). In all cases of moderate or severe crusting, however, extensive additional finishing after revibration was required.

INFLUENCE OF REVIBRATION ON STRENGTH AND AIR VOID CHARACTERISTICS OF CONCRETE (PHASES 2 AND 3)

Revibration had no statistically significant effect on the compressive strength of retarded concrete (Fig. C-30). The compressive strength of the nonretarded concrete, however, was slightly improved. These data were confirmed by measurements of sound velocity through the thickness of revibrated and nonrevibrated slabs. No significant variations in either the dynamic modulus or the unit weight of revibrated and nonrevibrated concrete were observed (Table C-11).

Surface revibration had no pronounced effect on the abrasion resistance of concrete (Table D-4).

The effects of revibration on the air void characteristics of concrete are shown in Figures C-31 to C-33 and given in Tables C-12 and C-13. The hand-finishing procedures prior to revibration resulted in all instances in a reduction of the air content and in an increase of the paste content of the surface layers of the concrete. However, the variations of the spacing factor over the thickness of the concrete were small. Surface revibration resulted in an increase of the spacing factor close to the concrete surface from an average value of 0.0070 in. prior to revibration to 0.0077 in. after revibration. Surface revibration had no measurable effect on the air void system of the concrete at a distance of more than 1 in. from the surface.

No significant effect of external revibration with a vibrating table on the air void characteristics and on the distribution of the paste content of concrete could be found (Tables C-13 and C-14).

INFLUENCE OF REVIBRATION ON THE DURABILITY CHARACTERISTICS OF UNCRACKED CONCRETE (PHASE 3A)

Plain and reinforced concrete specimens were revibrated on a vibrating table between 2 and 5 hr after mixing and for periods ranging from 10 to 40 sec. No statistically significant difference between the surface durability of revibrated and nonrevibrated concrete could be found, although the revibrated concrete was generally slightly more durable than the nonrevibrated concrete. This is shown in Figures D-3 and D-4, where surface deterioration rating is given as a function of the number of freeze-thaw cycles. The surface deterioration rating is defined in "Freeze-Thaw Testing" in Appendix D.

A comparison of the durability of retarded and nonretarded concrete showed that the nonretarded concrete was significantly more durable than the retarded concrete (Fig. D-7). Also, plain concrete specimens were more frost-resistant than reinforced specimens (Fig. D-8). It should be noted that the average spacing factor of retarded concrete was 0.0072 in., whereas nonretarded concrete (other parameters being equal) had a spacing factor of 0.0061 in. (Tables C-13 and C-14). Surface scaling was in all instances the only type of surface deterioration.

INFLUENCE OF REVIBRATION ON THE DURABILITY OF CRACKED CONCRETE SLABS (PHASE 3B)

The average surface deterioration ratings of cracked concrete slabs that were not revibrated are shown in Figure D-10. There was no clear indication that surface cracking or horizontal plane-of-weakness cracking results in reduced durability of the concrete surface when it is exposed to accelerated freezing and thawing in the laboratory. Only uniformly distributed scaling was observed, and no surface spalls developed during freezing and thawing. Scaling of the cracked slabs was slightly more pronounced in the vicinity of the cracks. Uniform scaling was found in uncracked or revibrated slabs (Figs. D-12 and D-13).

Surface revibration had no detrimental effect on surface durability of the concrete (Fig. D-11). Generally, the revibrated slabs were more frost-resistant than the nonrevibrated specimens. A statistical evaluation showed, however, that the difference between the average of all revibrated and all nonrevibrated slabs is not statistically significant.

Similar to the results from tests on uncracked slabs, the nonretarded concrete was considerably more frost-resistant than the retarded concrete (Fig. D-15). Because the compressive strength of the retarded concrete was between 15 and 50 percent higher than that of the nonretarded concrete, the air content of the retarded concrete could be increased from 6 to 8 percent, resulting in a concrete as durable as the nonretarded concrete and with a compressive strength still higher than that of the nonretarded concrete (see Fig. D-16).

Surface revibration resulted in an acceptable finish of the concrete, and hand-finishing prior to revibration may not be necessary. It was hoped that elimination of hand-finishing prior to revibration may offset the possible loss of air during surface revibration and thus improve surface durability. The data shown in Figure D-17 indicate, however, that hand-finishing prior to revibration had little influence on the surface durability of revibrated or nonrevibrated specimens. Late finishing of nonrevibrated concrete resulted in a slight increase of the surface deterioration of the concrete Additional finishing of concrete after revibration, however, had no significant effect on concrete surface durability.

FIELD APPLICATIONS

To investigate the feasibility of revibration of bridge deck concrete in the field, as well as to observe its long-time performance, portions of three bridge decks under construction in Illinois and Kansas were revibrated. On the basis of the laboratory experiments the following guidelines for the field experiments were chosen

1. The bridge deck concrete shall be revibrated with a vibrating screed when the penetration resistance of the concrete reaches approximately 25 psi.
2. The bridge deck concrete shall be finished prior to vibration, and additional finishing after revibration shall be kept to a minimum.
3 No particular requirements regarding concrete mix proportions in addition to those developed by the respective highway departments will be made.
4. The use of set-retarding admixtures is desirable but not mandatory.

On July 10, 1969, a portion of the deck of a noncomposite, skewed, and continuous-span bridge with structural steel I beams near Champaign, Ill., was revibrated (Fig. E-1). The revibrated section of the bridge deck was adjacent to the safety curb and was 3 ft 3 in. wide, extending 15 ft in each direction from the center support of the bridge. A longitudinal construction joint separated the curb areas from the center part of the deck that had been cast several days earlier. The vibrating screed that was used in the laboratory experiments was also employed for the revibration of the bridge deck. The retarded concrete had an air content of 4 to 5 percent, a slump of 2½ in., and an initial set 2 hr 40 min after casting. The air temperature during casting ranged from 84 to 89 F, the relative humidity was around 65 percent, and the day was sunny with only slight westerly winds. Revibration was conducted at the low energy level (defined previously in "Effectiveness of Revibration in Closing Cracks in Fresh Concrete") approximately 2 hr after placing the concrete. At that time a concrete sample that was kept moist until testing, and that was taken from the same batch as the bridge deck concrete, had a penetration resistance of approximately 25 psi. Revibration appeared to be effective inasmuch as a thin moisture film covering most of the concrete surface was developed during revibration. However, finishing after revibration was necessary in order to obtain a continuous transition from the revibrated sections across the longitudinal joint to the adjacent hardened concrete of the main deck. Because at that time the concrete had almost reached its initial set, finishing was difficult, and the experiment showed clearly that finishing after revibration should be avoided whenever possible. The revibrated sections were inspected several times after casting. No apparent differences between the vibrated and the nonrevibrated portions of the deck could be detected. The visual observations of the deck will be continued.

On August 27, 1969, a section of a continuous, noncomposite bridge with welded steel plate girders near Newton, Kan., was revibrated (Fig E-4). The revibrated area extended over the entire width of the deck from one abutment over a length of 82 ft A free-floating vibrating screed that was supported only by the fresh concrete was used. A vibrator with a frequency of 3,200 cpm vibrating parallel to the direction of the forward movement of the screed was mounted in the center of the screed (Fig. E-5). The bridge deck concrete was nonretarded and had an air content of between 5 and 7 percent and a slump from 1½ to 3 in. The initial set of the concrete was approximately 2 hr 50 min During most of the construction period the sky was overcast, with temperatures ranging from 72 to 78 F and with light winds. Prior to revibration the concrete was finished with a regular finishing machine. Immediately after finishing, a water emulsion of aliphatic alcohols was sprayed on the concrete surface to produce a monomolecular film that retards evaporation of bleeding water (*24*). Approximately 1½ hr after casting, revibration was commenced. At that time the penetration resistance of a control sample of concrete that had been kept moist until testing was approximately 25 psi. Two major problems were encountered in this field experiment Because the vibrator was free-floating it had a tendency to sink slightly into the fresh concrete. Furthermore, the shape of the vibrating screed did not precisely match the profile of the bridge deck surface, so the screed did not always touch the entire concrete surface. Therefore, portions of the bridge deck (particularly in the center of the deck) were not revibrated. Each time the forward movement of the vibrating screed was stopped the vibrator left a noticeable mark in the bridge deck surface (Fig. E-6). Because of these deficiencies rather extensive and cumbersome finishing after revibration was required. Finishing was particularly difficult because at that time the concrete had approached its initial set.

On the basis of the experience of the previous field experiments a new vibrating screed was constructed and was used to revibrate a similar bridge deck near Newton, Kan , on September 23, 1969. A vibrating pan with two small vibrators attached to the pan at about its third points was mounted to the frame of a finishing machine (Figs. E-7 and E-8). The equipment was supported by rails adjacent to the safety curbs of the bridge deck. The shape of the vibrating pan could be adjusted so that it closely matched the original profile of the bridge deck surface. The bridge deck concrete contained a set retarder and had an air content of between 4 and 5.5 percent and a slump ranging from 2 to 4 in The initial set of the concrete occurred 3 hr 30 min after placing the deck. The deck was finished immediately after casting and parts of the concrete surface were sprayed with the water-alcohol emulsion Sunny skies, with temperatures ranging from 70 to 80 F and moderate winds, prevailed during most of the day. Approximately 2½ hr after casting, when a control sample that had the same exposure as the bridge deck surface reached a penetration resistance of 28 psi, revibration of the bridge deck commenced and continued over the entire width of the deck and a length of approximately 133 ft. The field experiment was successful. Revibration resulted in a smooth concrete surface (Fig. E-9), and in most cases no additional finishing, except belting and brooming, was required after revibration In a few instances, however, revibration caused closely spaced surface cracks (Fig. E-10). These cracks had an appearance similar to the cracks that were observed in the laboratory after revibration of surface-crusted concrete. It is likely that the revibration energy level in the field experiment was insufficient to break up the entire surface crust. Such cracks were not observed in areas that had been sprayed with the water-alcohol emulsion immediately after finishing. No surface cracking was observed in the revibrated portions of the three bridge decks either before or after revibration except those cracks that appeared after revibration of surface-crusted concrete, as described earlier.

Cores have been taken from both bridges in Kansas They will be used to compare the air void characteristics of revibrated and nonrevibrated concrete. The air void characteristics are reported in Appendix G. The long-time performance of the revibrated decks will be observed by the Kansas State Highway Department

CHAPTER THREE

INTERPRETATION

The major emphasis of this investigation was placed on studies of the effectiveness of revibration in closing transverse cracks in reinforced concrete bridge decks which may have been formed as a consequence of formwork deflections due to the dead weight of the fresh concrete. The experimental data showed, however, that in order to develop substantial cracking in fresh concrete several hours before initial set, a curvature of the concrete surface in excess of 0.001 in.$^{-1}$ was required This value is larger than the deflection to be expected in the field as long as reasonable construction practices are maintained (*25*). Unless the concrete had a penetration resistance of more than 15 psi at the time of deflection the cracks were shallow and hardly penetrated to the level of the top reinforcement (Fig. C-14) It became apparent that during the first hours after mixing the fresh concrete used in this investigation could develop considerable plastic deformations without cracking or that the fluidity of the concrete was sufficient so that microcracks were healed soon after their formation More severe surface cracking may develop if deflections occur after the penetration resistance of the concrete exceeds 15 psi or when severe surface crusting has occurred. Such conditions may develop several hours before initial set of retarded concrete while the concrete is still sufficiently plastic to be revibrated.

The formation of planes or zones of weakness at the level of the top reinforcement could not be observed in the laboratory, even under the extreme environmental conditions of elevated temperatures and high winds Nevertheless, formation of planes of weakness has been observed in a number of instances in the field and has been reported as a major cause of bridge deck deterioration. It is likely that the laboratory conditions still were too favorable for the formation of planes or zones of weakness. Deeper specimens, concrete with a higher slump and water content, and concrete ingredients that lead to a higher bleeding rate of the concrete may in fact have produced planes of weakness, even in laboratory specimens. However, no information exists on the time after casting at which such planes of weakness may develop.

Independent of the cause of cracking, revibration is an effective and economically feasible method to close surface cracks, internal cracks, or planes-of-weakness cracks in the fresh concrete as long as the penetration resistance of the concrete is not in excess of 60 psi. This condition is reached between ½ hr and 1 hr prior to initial set. If the energy level is chosen such that revibration results in the formation of a moisture film over the entire concrete surface, no significant additional finishing after revibration is required A substantial number of cracks may be closed by revibration at a high energy level, even if the concrete is close to its initial set at the time of revibration. Then, however, surface revibration may be nonuniform and additional finishing may be required, which is very difficult to perform at such a late state. It is possible that revibration prior to initial set, even of uncracked concrete, may cause the relief of residual stresses due to early shrinkage and bleeding and thus may reduce the cracking tendency of the hardened concrete Because the depth of surface cracks caused by formwork deflection (and thus their severity) can be substantially reduced by the use of retarders, it appears that revibration is more important to prevent and repair planes of weakness than it is to repair flexural cracks on the concrete surface

The laboratory experiments showed no significant difference between the surface scaling resistance of revibrated and nonrevibrated concrete. It should be pointed out, however, that scaling is only one type of surface deterioration of concrete in the field. Spalling of the concrete surface may be the more severe form of deterioration and has been frequently observed in actual bridge decks. Surface spalling often has been attributed to corrosion of the reinforcing bars. Because the extent of corrosion depends on the total length of time the steel is exposed to a corrosive environment, particularly at higher temperature cycles between freezing cycles, accelerated freezing and thawing tests in the laboratory are normally not a measure of the spalling resistance of a concrete surface. Because the experiments showed that surface revibration is an effective way to close horizontal plane-of-weakness cracks as long as they are formed or initiated prior to initial set it is likely, although not proved in the laboratory, that revibration may indeed improve the frost resistance of bridge decks in cases where spalling is the dominant form of deterioration.

The differences in the scaling resistance between retarded and nonretarded concrete are not clearly understood. They may in part be attributed to influences of the particular retarder on the air void characteristics of the concrete. Because other investigations (*26*) showed the sufficient durability of retarded concrete, and because adjustments of the total air content of the retarded concrete used in this investigation resulted in a concrete as durable as nonretarded concrete, there is no indication that retarders necessarily impair concrete durability. However, sufficient information on the effect of a particular retarder on concrete freeze-thaw durability when exposed to deicing agents is essential prior to its use in the field. The period of time during which bleeding occurs may be longer for retarded concrete than it is for nonretarded concrete, thus increasing the crusting tendency of retarded concrete. The application of surface sprays as barriers against excessive moisture evaporation may, however, significantly reduce the danger of crusting, as has been shown in the field experiments.

The feasibility of revibration of bridge deck concrete in the field has been demonstrated, particularly by the second experiment conducted in Kansas. Surface revibration of the entire width of the deck in one operation appears to be the most practical approach. Provisions have to be made, however, to adjust the revibration energy level as well as the shape of the vibrating pan, and to support the surface vibrator so that it does not float freely on the concrete surface. In determining the time of revibration it proved to be advantageous to use the penetration resistance of a sample that is subjected to the same exposure conditions as the bridge deck surface. Batch to batch variation of the concrete in the deck requires close observation of the particular concrete properties and may necessitate changes in revibration energy as well as in the speed of forward movement of the revibration equipment during the operation

CHAPTER FOUR

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

The conclusions to be drawn from this research can be summarized as follows:

1. For the types of concrete studied in this investigation, and formwork deflections occurring within 4½ hr after mixing, significant surface cracking of the concrete was developed only if the deflections caused a curvature of the surface in excess of 0 001 $in.^{-1}$.

2. Exposure of the fresh concrete to high winds and temperatures above 95 F resulted in surface crusting and shrinkage cracks. However, reinforced concrete slabs 6 in. deep, with a 1½-in. cover above the reinforcement and made from concrete with a low bleeding rate, did not show planes of weakness at the level of the top reinforcement after exposure to heat and wind.

3. Internal vibration is an inefficient and impractical method to revibrate concrete bridge decks. Surface revibration, however, can be effectively employed to repair surface cracks, horizontal cracks at the level of the top reinforcement, and internal cracks up to a depth of at least 4 in. from the concrete surface. Surface revibration may be successful if conducted before the concrete reaches a penetration resistance of 60 psi. Most concretes will reach this value between ½ hr and 1 hr prior to initial set. The required revibration energy is sufficient as long as revibration results in the development of a thin moisture film on the entire concrete surface.

4. No additional finishing of the concrete, except belting or brooming, is required after sufficient surface revibration of a concrete with a penetration resistance of less than 60 psi.

5. Surface revibration at a high energy level can improve moderately crusted concrete surfaces. However, insufficient revibration of severely crusted surfaces can cause additional surface cracks.

6. Surface cracks had no measurable effect on the scaling resistance of the concrete. Revibration did not impair the scaling resistance of the concrete, although the average spacing factor of the surface layers of the concrete was increased by revibration from 0.0070 to 0.0077 in.

7. The retarded concrete was less durable than similar nonretarded concrete, although the difference in spacing factor between the two types of concrete was only 0.001. However, the use of retarders does not necessarily impair concrete durability, as has been shown in other investigations. Retarders may improve concrete durability if the concrete deterioration is related to cracking caused by formwork deflections while the concrete is still in a plastic state. This is because the time during which retarded concrete can be deflected without development of deep and therefore severe surface cracks can be several hours longer than it would be for similar nonretarded concrete. Retarders can, however, lead to more severe crusting because of the increased period of time during which bleeding can occur. The use of surface sprays to prevent excessive moisture evaporation may counteract this disadvantage.

8. Surface revibration of reinforced concrete bridge decks in the field is feasible. The vibrating screed should have an adjustable profile and vibrators with variable vibration energy. The screed should be supported by rails or similar setups. The time at which revibration is commenced should be determined on the basis of the penetration resistance of a concrete sample that is subjected to the same exposure conditions as the bridge deck surface.

SUGGESTED RESEARCH

The investigation reported herein was hampered by the lack of knowledge in several areas, and the following additional information is required before final and conclusive recommendations regarding revibration of field concrete can be made:

1. Spalling of the concrete surface associated with planes of weakness is recognized as a major type of bridge deck deterioration in the field. Revibration is a potential method to repair such planes of weakness if they have initiated prior to revibration. Nevertheless, planes of weakness in laboratory specimens could be generated only under extreme conditions. Therefore, the mechanism of plane-of-weakness cracking as well as the principal parameters controlling their formation need further clarification by laboratory experiments.

2. Because spalling of the concrete surface is a type of deterioration seldom found in accelerated laboratory tests, it is difficult to estimate reliably the durability of field concrete on the basis of laboratory investigations. The need for improved and more realistic laboratory procedures has been apparent for a long time.

3. The time at which formwork deflections may cause significant flexural cracking in fresh concrete has not been sufficiently explored. Therefore, careful measurements of the extensibility of fresh concrete and the basic parameters affecting it (such as age, curing conditions, and fluidity of the concrete) are needed.

4. The effect of revibration frequency, particularly high frequencies, has not been studied in this investigation.

5. The mechanism of the effect of retarders on the freezing and thawing resistance of concrete in the presence of deicing agents has not been clarified sufficiently.

6. The field of the experiments showed the feasibility of revibration of bridge deck concrete. The equipment used, however, was crude, and further development of equipment and construction procedures is encouraged. In addition, studies of the effectiveness of various types and combinations of vibrators, both for initial vibration and for revibration of various types of concrete, are necessary. Parameters defining the efficiency of vibrators as well as the vibration energy required for various types of concrete are urgently needed.

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APPENDIX A

REVIEW OF RELATED RESEARCH

This appendix includes a summary of the results of the recently conducted bridge deck surveys (*1, 2, 3, 4*). A more detailed discussion of freeze-thaw durability of concrete can be found in Callahan et al. (*5*) or Cordon (*7*), for example. The second part of Appendix A discusses research into the effect of revibration on concrete properties.

BRIDGE DECK SURVEYS

A thorough analysis of bridge deck survey data has been obtained from the cooperative survey recently conducted by the Divisions of Highways of Kansas, Michigan, California, and Missouri (*1, 2, 3, 4, 8, 9*) According to those surveys, scaling of the surface mortar, transverse cracking, and subsequent surface spalling were the main types of deterioration.

Scaling was associated with freeze-thaw action, and particularly with the use of deicing agents, and normally did not follow any particular pattern. In most cases, scaling can be attributed to one or more of the following causes: inadequate finishing practices such as excessive or too-late finishing, insufficient air void system of the surface mortar, poor drainage of the bridge decks, and excessive use of deicers. In addition, it was hypothesized (*5*) that differences in the thermal length change between the surface mortar and the coarse aggregate layers of the concrete may result in thermal stresses and, consequently, in surface scaling

Transverse cracking, which was found to be more severe in continuous spans, may be due to vehicle loading, plastic or drying shrinkage, long-time volume changes, improper placement of the reinforcing bars, stresses due to formwork deflections or rotations or due to the removal of formwork in continuous reinforced concrete bridge decks, and resistance to subsidence of concrete during the bleeding period by the rigidly held top reinforcement. Resistance to subsidence not only causes transverse cracks, but it may lead also to the formation of planes of weakness at the level of the top reinforcement At such planes the porosity of the cement paste is increased and horizontal cracking may occur Early crusting of the concrete surface may enhance the formation of planes of weakness An increased concrete cover does not necessarily prevent the formation of horizontal cracks but may delay the occurrence of subsequent spalling (*8, 9, 10*).

Transverse cracks are not necessarily concentrated in the negative-moment regions of continuous bridges, and no clear correlation between transverse cracking and flexibility of supporting steel stringers seems to exist (*11*). This observation underlines the significance of early shrinkage and restraint of subsidence as major causes of transverse cracking

In the bridge deck surveys surface spalling was attributed mainly to the following causes. resistance to subsidence of concrete, as previously described; early drying shrinkage and crusting of the concrete surface, and corrosion of reinforcement in the vicinity of transverse cracks. Corrosion may be particularly dangerous where planes of weakness have been formed. It was found that surface spalling or fracture plane deterioration was significantly greater when the depth of the concrete cover above the top steel was only 1½ in. or less. Traffic action and insufficient drainage of the bridge decks may accelerate surface spalling of inadequate concrete.

Recent laboratory investigations underline the detrimental effect of corrosion of the reinforcing bars at sections with transverse cracks (*5*) However, adequate finishing procedures and concrete properties that ensure sufficient air content of the surface mortar are considered equally important. It was found (*5*) that external stresses influence the rate of development of surface scaling to only a limited degree and stress does not seem to be a primary factor for the durability of bridge deck concrete.

Longitudinal cracking of bridge decks was found in only a few cases, indicating that the bridge decks are in most cases adequately designed for live loading.

EFFECT OF REVIBRATION ON THE PROPERTIES OF PLAIN CONCRETE

Revibration or delayed vibration of concrete is not a generally accepted construction procedure It was hypothesized for a long time that concrete, once it is placed, compacted, and finished, should not be disturbed until it gains sufficient initial strength. This, however, is an unrealistic viewpoint because concrete often is revibrated unintentionally by the initial vibration of subsequently cast concrete. Therefore, the effect of revibration on some concrete properties has been studied in the past in a number of investigations (*12-23*).

It is generally agreed that revibration of concrete between 2 and 6 hr after mixing may result in a 10- to 30-percent increase of the concrete compressive strength, compared to the strength of nonrevibrated concrete. This is true even for concrete that was initially compacted to an optimum density. It is assumed that this phenomenon is due to the closing of microcracks between paste and aggregates that are formed because of the restraint of early shrinkage of the cement paste It also has been found that the total pore volume of revibrated concrete is slightly less than the pore volume of nonrevibrated concrete. This increased density may be an additional reason for the improved strength characteristics of revibrated concrete. It has been suggested also that the structure of cement paste and possibly the hydration process may be influenced by revibration (*13, 22, 23*) This agrees with the observation that even revibration of neat cement paste may result in strength increase between 5 and 20 percent of the strength of nonrevibrated paste (*20*). Strength increases of the paste up to 130 percent were reported by Avram et al (*23*) This unusually high strength increase was associated with a significant reduction of the water-cement ratio during revibration

The effect of revibration on the tensile strength of concrete has not been clarified sufficiently It was shown in two investigations (*13, 20*) that revibration has little influence on the tensile strength of concrete. Apparently, this is contradictory to any of the concepts that were suggested to explain the increase of the compressive strength of concrete by revibration.

Revibration of concrete results in a slight increase of the modulus of elasticity, a slight reduction of shrinkage, but no significant change in the creep behavior of concrete (*19, 20*) However, also a marked reduction in creep of revibrated cement paste was reported in one case (*23*).

No detailed investigations on the effect of revibration on the bond strength between concrete and embedded reinforcing bars could be found in the literature However, it seems likely that, through a reduction of water pockets that may form under the reinforcement during bleeding, revibration may increase the bond strength.

The durability of concrete may be reduced by revibration if high revibration energies are used (*13*), mainly because of a reduction of the volume of entrained air No information regarding the abrasion resistance of revibrated concrete could be found. However, it may be possible that increased bleeding of the concrete during revibration may weaken the surface mortar and reduce its abrasion resistance.

It is generally agreed that the effect of revibration increases as the revibration energy is increased (*17, 19, 20*)

The time after mixing at which concrete is revibrated has a major influence on the effectiveness of revibration. Revibration only a few hours after mixing generally has little influence on concrete properties, and in one instance a slight reduction of the concrete compressive strength was observed (*20*). Revibration becomes more effective if it is conducted immediately before or after initial set. If revibration is delayed beyond the final set its effectiveness decreases and eventually becomes insignificant.

The influence of concrete mix design seems to be associated with the corresponding variations in setting time. The use of retarders may substantially increase the period of time during which revibration of concrete is beneficial (*21*)

Methods of revibration include the use of internal, external, or surface vibrators. No information on the effect of revibration by means of surface vibrators could be found. Improved freezing and thawing resistance due to initial surface vibration was, however, reported by Malisch et al. (*6*). The use of internal vibrators limits the time interval during which revibration may be conducted successfully. If the concrete is too stiff the vibrator may not sufficiently penetrate into the concrete. Segregation may occur with increased cement paste content in zones where the vibrator was inserted. External vibrators generally have been more effective in improving concrete properties, but the practical application of external vibration apparently is limited by structural size.

Laboratory investigations showed that revibration is more effective if the specimen is revibrated while subjected to a small compressive stress. This procedure, however, has only limited application in actual construction practice.

Delayed vibration using an external vibrator may result in a strength increase of approximately 10 to 20 percent if carried out shortly after the initial set of the concrete (*14*). Further delay, however, may result in a severe reduction of concrete strength.

It may be generally concluded that revibration in most instances improves strength and deformation characteristics of concrete. However, revibration may have an adverse effect on the frost and abrasion resistance of concrete.

APPENDIX B

SURVEY OF THE USE OF REVIBRATION IN THE CONSTRUCTION OF REINFORCED CONCRETE BRIDGE DECKS—PHASE 1

Prior to this investigation Dr. Best of Kansas State University conducted an inquiry into the use of revibration in the construction of reinforced concrete bridge decks or pavements. Dr. Best made his information available for this investigation.

Dear Sir

We have submitted a research proposal for Highway Research Board NCHRP Project 18-1   REVIBRATION OF RETARDED CONCRETE FOR BRIDGE DECKS+

In this connection, we would like to ascertain the extent to which either delayed vibration or revibration has been used in placing bridge deck concrete   I would therefore appreciate hearing of any such experience your state may have had or if you know of anyone who has had such experience, along with any references you may know of

If you have used delayed vibration or revibration, please describe your purpose, the methods and procedures employed, details of the structure the schedule of concrete placement the properties of the fresh concrete if available, the kind and amount of any admixture used, temperature, humidity, and wind conditions if known, and your evaluation of the results

I recognize that this request is an imposition, your cooperation will therefore be doubly appreciated

Sincerely yours,

Figure B-1. Sample letter used in survey on the use of revibration in bridge deck construction—Phase 1.

In this survey a letter of inquiry was sent to the highway departments of the 50 states and the District of Columbia and to 10 provinces of Canada. The letter requested the highway departments to describe their experience in the use of delayed vibration or revibration of retarded concrete bridge decks. Figure B-1 is a sample letter of this inquiry.

The replies from 48 states, the District of Columbia, and 6 provinces of Canada are summarized in Table B-1. There were no known cases of the use of revibration of retarded concrete bridge decks and only one structure on which delayed vibration of retarded concrete was employed. Six highway departments noted that specifications did not permit the use of delayed vibration or revibration, and two highway departments specifically stated that such procedures were not being considered.

Two highway departments indicated that retarded concrete was frequently used for bridge decks of continuous structures in order to allow dead-load deflections to occur before the initial set of the concrete occurs. However, neither delayed vibration nor revibration was employed. Two cases of unintentional revibration of concrete bridge decks were reported. No unusual effects have been noted

TABLE B-1

INQUIRY ON THE USE OF REVIBRATION IN THE CONSTRUCTION OF CONCRETE BRIDGE DECKS—PHASE 1

HIGHWAY DEPT.	SUMMARY OF REPLY [a]	SPECIAL NOTES
Alabama	1, 2	
Alaska	1	
Arizona	1, 3	
Arkansas	1, 2	
California	1, 2	
Colorado	1, 2	A concrete bridge deck was caught by earth tremor while setting. No adverse effects have been noticed.
Connecticut	1, 2, 3	
Delaware	1	A field test of revibrated 6- × 16-in. cylinders was conducted in 1957.
Dist. of Col	1, 3	
Florida	1, 2, 4	
Georgia	1	
Hawaii	1, 2	
Idaho	1, 2	
Illinois	1, 2	
Indiana	1, 2	
Iowa	1	Retarded concretes are used to allow dead-load deflections of continuous structures before setting
Kansas	1	Starting in Nov. 1967, specifications require revibration of pavements.
Louisiana	1	
Maine	1, 2	
Maryland	1, 2	
Massachusetts	1, 3, 4	
Michigan	1, 2	Retarded concretes are used to allow dead-load deflection of continuous structures before setting. An informal experiment indicated internal revibration of retarded concrete was ineffective.
Minnesota	1, 2	
Missouri	1, 2	
Montana	1, 2	
Nebraska	1, 2, 3	
Nevada	1, 2	
New Hampshire	1, 2	
New Jersey	1	
New Mexico	1	
New York	2	Concrete bridge deck was replaced while traffic on other half of bridge caused continuous vibration during setting.
North Carolina	1, 2	
North Dakota	1	
Ohio	1, 2	
Oklahoma	1, 2	Department offered to assist Okla State Univ. with similar research project
Oregon	1, 2	
Pennsylvania	1, 2	
Rhode Island	1, 2	
South Carolina	1	
South Dakota	1, 2	
Tennessee	1	
Texas	1, 2	Retarded concretes are used to allow dead-load deflection of continuous structures before setting.
Utah	1, 2	
Vermont	1, 2	
Virginia	1, 2	
Washington	1, 3	A 20- × 20-ft slab was revibrated because of equipment failure. No adverse effects have been noticed
West Virginia	1, 2	
Wisconsin	1	
Wyoming	1, 2	Retarded concretes are used to allow dead-load deflection of continuous structures before setting
Alberta	1, 2	
New Brunswick	1, 2	
Newfoundland	1	Limited use has been made of revibrated concrete for post-tensional concrete girders.
Nova Scotia	1, 2	
Prince Edward Is	1, 2	
Saskatchewan	1	The continuous floor slab of a 3-span structure was placed in one operation using a retarder and delayed vibration.

[a] 1. No experience with revibration of retarded concrete bridge decks.
2. No experience with delayed vibration of retarded concrete bridge decks
3 Specifications do not permit delayed vibration or revibration.
4 Delayed vibration or revibration not being considered.

in either case. The Department of Highways and Transportation of the province of Saskatchewan, Canada, mentioned the only use of delayed vibration of retarded concrete bridge decks. The work was done by a consulting firm for the municipal branch. The structure was a three-span continuous bridge with precast, prestressed girders and a cast-in-place deck. The continuous floor slab was placed in one operation using a retarder and delayed vibration. Additional data regarding the long-time performance of the bridge deck were not provided.

Kansas is aware of the possible usefulness of revibration and was considering revibration as a construction practice at the time of the survey. However, experience regarding the feasibility of the use of revibration as well as the long-time performance of revibrated decks was not available at the time of the inquiry.

APPENDIX C

EFFECTIVENESS STUDY—PHASE 2

OBJECTIVE AND SCOPE

The objective of Phase 2 of the investigation was to study the effectiveness of revibration in closing cracks in fresh concrete. The following main test series were conducted:

- Series 1: Method of revibration, revibration energy, and extent of initial cracking.
- Series 2: Time of revibration.
- Series 3: Percentage of reinforcement
- Series 4. Time of initial set.
- Series 5: Curing conditions prior to revibration.
- Series 7: Effectiveness of revibration in closing plane-of-weakness cracks.
- Series 8: Effectiveness of revibration in closing cracks that have been generated at a higher age.
- Series 9: Effect of direction of revibration.
- Series 10: Influence of revibration on air content distribution and abrasion resistance

Originally, a Series 6 was planned to study the influence of air content on effectiveness of revibration. This series, however, was considered of minor importance and, therefore, was omitted from the program. Studies on the effect of air content were, however, included in the durability studies (Phases 3a and 3b).

In addition to the main test series a pilot study (Series P) was conducted to determine methods to develop cracks in the slabs while the concrete was still plastic. The effect of revibration on concrete density and compressive strength was investigated in Series C. Accelerometer measurements were used to evaluate the depth to which the revibration energy may penetrate during surface revibration (Series ACC). A total of 79 large slabs were tested in Phase 2.

DESCRIPTION OF SPECIMENS

All specimens investigated in Phase 2 consisted of reinforced concrete slabs 8 ft long, 3 ft wide, and 6 in. thick. The specimens were cast in steel formwork, as shown in Figure C-1. The bottom plate of the formwork had a thickness of ⅜ in. The longer sides of the form were laminated plates made up of individual steel bars 1 in. × ½ in. in cross section. Two teflon strips were placed between the individual bars, which were clamped together with bolts spaced 2 ft apart. The surface of the sides facing the concrete was covered with plastic sheeting. Laminated plates for the sides of the formwork ensured high flexibility of the form that was required to develop severe flexural cracking in the fresh concrete. The formwork was supported by two concrete blocks and was tied to the test floor The formwork and the concrete could be subjected to a negative moment by means of hydraulic jack and load-distributing girders. To prevent relative movement of the reinforcement during deflection of the formwork, both top and bottom layers of the reinforcing bars were held to the bottom of the formwork by clamps and chairs, as shown in Figures C-2, C-3, and C-4. Three sets of forms were available for this investigation.

Most of the specimens were reinforced with two layers of reinforcement consisting of No. 5 bars spaced at 6 in longitudinally and No. 4 bars spaced at 9 in. laterally, as shown in Figure C-2. A concrete cover of 1½ in. was held constant for most slabs except for some specimens of Series 3, "Percentage of Reinforcement." The layouts of reinforcement used in this series are shown in Figures C-3 and C-4.

The specimens tested in Phase 2 were designated by a sequence of numbers or letters. The first term describes the method of revibration (SU for surface revibration and IN for internal revibration). The second number indicates the test series. The third term describes the extent of initial cracking (SL for slight cracking, ME for medium cracking,

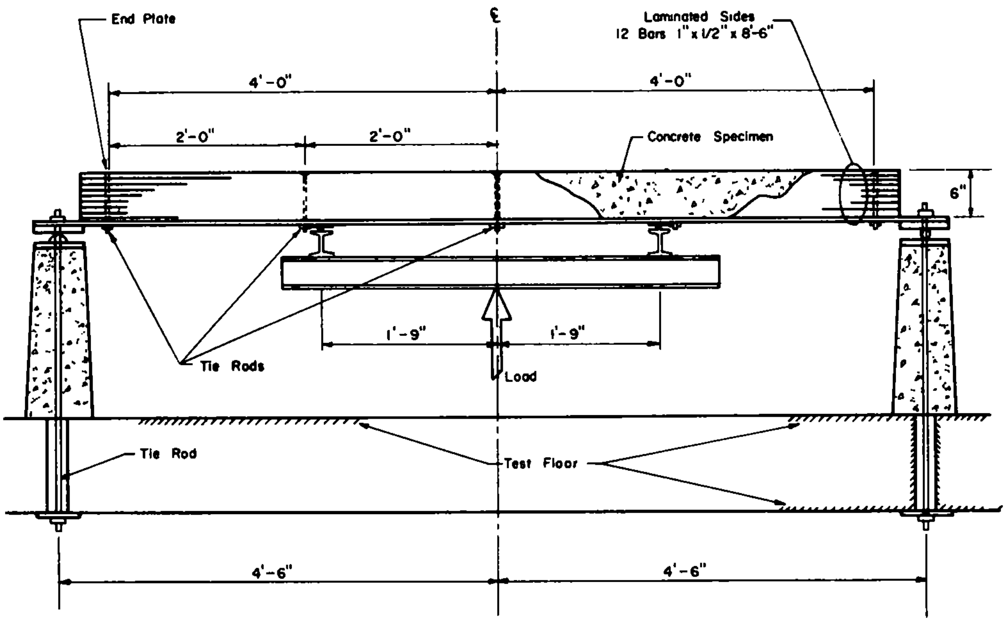


Figure C-1. Experimental setup for deflection of fresh concrete slabs in formwork

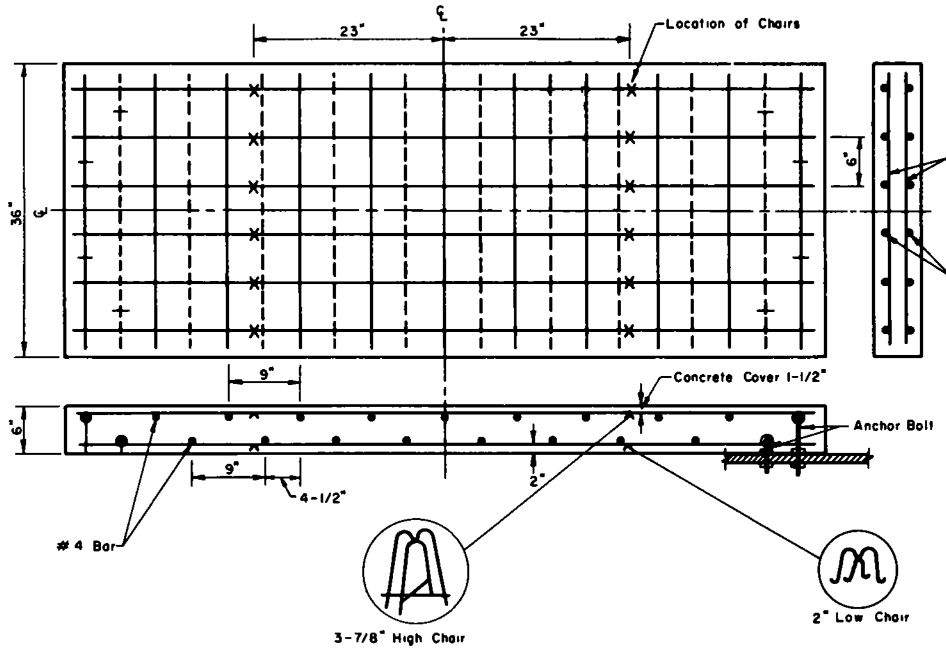


Figure C-2 Layout of reinforcement, Type A—Phase 2.

SE for severe cracking). The last term describes the extent of revibration energy (0 for no revibration, 20 for a low revibration energy, and 80 for a high revibration energy) For example, SU-2-SE-80 designated a specimen of Series 2 that was revibrated with a surface screed at an energy level of 80 percent and was severely cracked prior to revibration. In a number of instances additional terms were used to describe a particular specimen. Their description is given in Tables C-1 through C-7, in which the most significant data of all specimens tested in Phase 2 of this investigation are summarized.

MATERIALS

Type 1 cement with an initial set of 3 hr 45 min and a final set of 5 hr 45 min after casting under laboratory conditions was used throughout this investigation The physi-

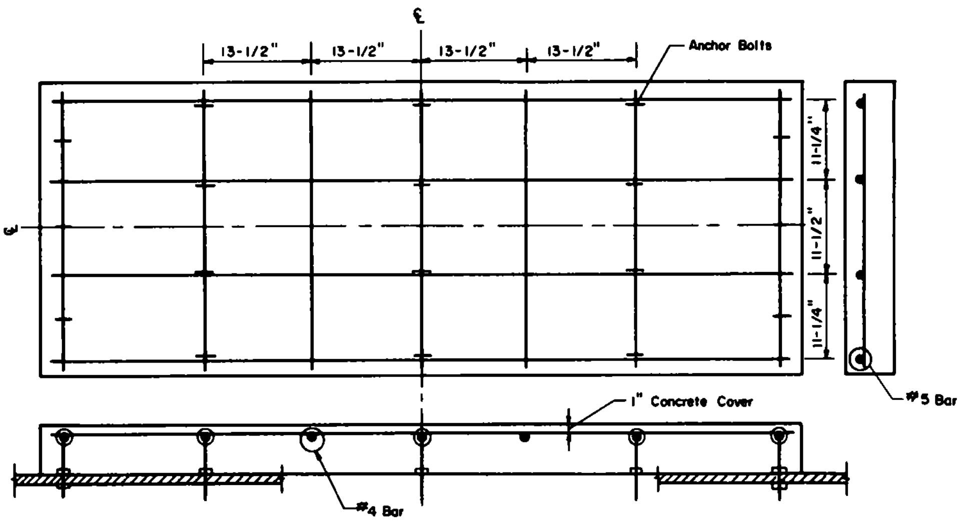


Figure C-3. Layout of reinforcement, Type B—Phase 2

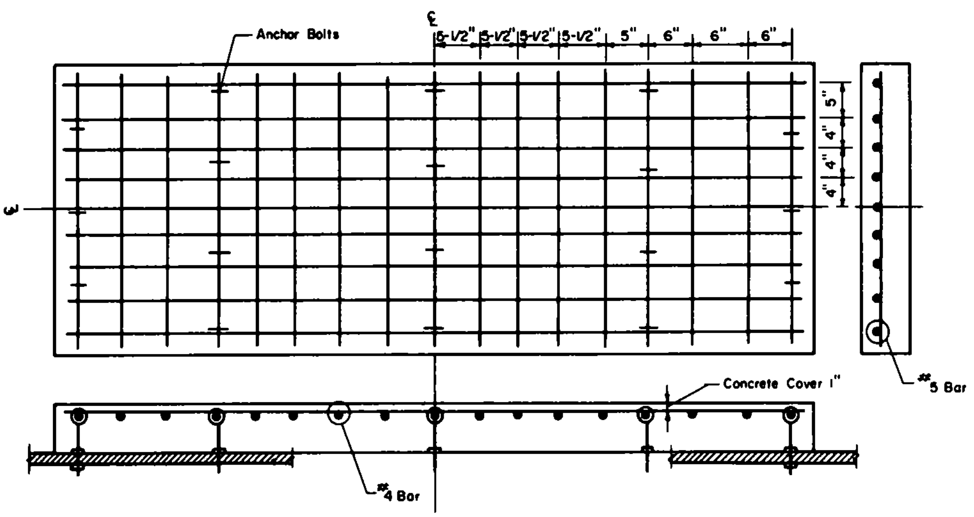


Figure C-4 Layout of reinforcement, Type C—Phase 2

cal and chemical properties of the cement according to a certified analysis obtained from the manufacturer are summarized in Table C-8. The coarse aggregate consisted of crushed limestone with a maximum size of 1 in. and was obtained from a quarry near Fairmount, Ill. This particular aggregate had good service records. The fine aggregate was primarily quartz and is an outwash of the Wisconsin glaciation. The aggregate properties appear in Table C-9

A neutralized vinsol resin (1.2 fl oz per 100 lb of cement) was used as an air-entraining agent to produce an average air content as determined by the pressure method between 5 and 7 percent, except in such cases where a lower air content was required. A water-reducing and -retarding admixture (Type D according to ASTM C 494) was used. The admixture is a hydroxylated polymer of which 4.5 fl oz per 100 lb of cement were used, resulting in an initial set of the concrete approximately 7 to 8 hr and a final set at approximately 9 hr after mixing under laboratory conditions with a temperature of 72 F and a relative humidity of 50 percent Typical results of a penetration test to determine final and initial set of the concrete are shown in Figure C-5.

Experimental data obtained from an independent testing laboratory showed that retarded concrete containing a blend of Type 1 cements from three different sources, 4 fl oz of the retarder used in this investigation, and a water-cement ratio of 0.55 had a durability factor of 95, according to ASTM C 290. The durability factor of a similar, nonretarded concrete was 92. The concrete with a set-retarding admixture passed all other requirements

TABLE C-1

EFFECTIVENESS STUDY—PHASE 2. DESCRIPTION OF SPECIMENS IN SERIES P AND ACC PILOT STUDIES AND ACCELEROMETER TESTS

No.	Specimen Designation	Ai Content (%) 1st Batch	2nd Batch	Initial Set (hr min)	Cracking Type	Time After Mixing (hr min)	Maximum Defl. (in)	Revibration Type	Time After Mixing (hr:min)	Energy Level (%)	Reinforcement According to Fig C-2
1	PT-0	>/	>/	-	-	4 00	1 1/2	Surface	4 00	20	A
2	PT-1	-	-	-	None	-	-	Internal	4 20-7 20	-	A
3	PT-2	>7	5 8	7 40	-	3 00	1 1/2	Surface	3 40	20, 40, 60, 80	A
4	PT-3	>7	>7	7 40	-	2 00	2 1/2	None	-	-	A
5	PT-4	>7	>7	6 20	-	4 00	2 1/4	None	-	-	A
6	PT-5	5.4	5.4	7 30	-	3 00	1 1/2	None	-	-	A
7	APT-1	5.9	5 5	6 30 6 50	-	2 00	3 7/8	Surface	4 00, 5 00, 7 10	20, 80	A
8	APT-2	6.0	5.0	7 50 6.15	-	2 00	3 1/2	None	-	-	A
9	APT-3	4.0	5.0	5 50 5 45	-	2 00	3 1/2	None	-	-	A
/	ACC-1	5.9	5.5	6 30 6 50	-	2 00	3 7/8	Surface	4 00, 5 00, 7 10	20, 80	A
10	ACC-2	6.1	>/	7.00	None	-	-	Surface	4 00, 5 00	20, 80	A
96	ACC-3	7.0	5.5	-	None	-	-	Surface	4 00	80	A

TABLE C-2

EFFECTIVENESS STUDY—PHASE 2. DESCRIPTION OF SPECIMENS IN SERIES 1 METHOD OF REVIBRATION, REVIBRATION ENERGY, AND EXTENT OF INITIAL CRACKING

No.	Specimen Designation	Air Content (%) 1st Batch	2nd Batch	Initial Set (hr min)	Cracking Type	Time After Mixing (hr min)	Max Defl. At Midspan (in)	Revibration Type	Time After Mixing (hr min)	Energy Level (%)	Reinforcement According to Fig. C-2
11	SU-1-SL-0	5.5	5.5	6 00	Slight	2 00	1 1/4	None	-	-	A
12	SU-1-SL-20	6.3	/ 3	6 30	Slight	2 00	1 1/4	Surface	4 00	20	A
13	SU-1-SL-80	6.4	6.3	6 45	Slight	2 00	1 1/4	Surface	4 00	80	A
14	SU-1-ME-0	5.8	4.8	7 45	Medium	2 00	2 1/2	None	-	-	A
15	SU-1-ME-20	6.8	6.9	8 50	Medium	2 00	2 1/2	Surface	4 00	20	A
16	SU-1-ME-80	5.4	5 8	7 15	Medium	2 00	2 1/2	Surface	4 00	80	A
17	SU-1-SE-0	6.7	7.0	7 45	Severe	2 00	3 1/2	None	-	-	A
18	SU-1-SE-20	6.5	6.5	7 45	Severe	2 00	3 1/2	Surface	4 00	20	A
19	SU-1-SE-80	6.2	6.5	5 50	Severe	2 00	3 1/2	Surface	4 00	80	A
20	IN-1-SL-0	7.0	6.3	8 30	Slight	2 00	1 1/4	None	-	-	A
21	IN-1-SL-20	6.7	6.0	7 15	Slight	2 00	1 1/4	Internal	4 00	Low	A
22	IN-1-SL-80	6.5	6.0	7 00	Slight	2 00	1 1/4	Internal	4 00	High	A
23	IN-1-ME-0	4.8	6.0	6 00	Medium	2 00	2 1/2	None	-	-	A
24	IN-1-ME-20	5.2	5.8	6 45	Medium	2 00	2 1/2	Internal	4 00	Low	A
25	IN-1-ME-80	5 8	6.0	6 45	Medium	2 00	2 1/2	Internal	4 00	High	A
26	IN-1-SE-0	6.5	5.0	8 10	Severe	2 00	3 1/2	None	-	-	A
27	IN-1-SE-20	5.7	6.1	7 30	Severe	2 00	3 1/2	Internal	4 00	Low	A
28	IN-1-SE-80	4.8	5.0	7 05	Severe	2 00	3 1/2	Internal	4 00	High	A

TABLE C-3

EFFECTIVENESS STUDY—PHASE 2 DESCRIPTION OF SPECIMENS IN SERIES 2· TIME OF REVIBRATION

No.	Specimen Designation	Air Content (%) 1st Batch	2nd Batch	Initial Set (hr min)	Cracking Type	Time After Mixing (hr min)	Max. Defl at Midspan (in)	Revibration Type	Time After Mixing (hr min)	Energy Level (%)	Reinforcement According to Fig. C-2
29	SU-2-SE-0	4.5	6.5	/ 30	Severe	2 00	3 1/2	None	-	-	A
30	SU-2-SE-20	5.5	5.5	8 05	Severe	2 00	3 1/2	Surface	4 00	20	A
31	SU-2-SE-80	5.5	6.0	9 00	Severe	2 00	3 1/2	Surface	4 00	80	A
35	SU-2-SE-0A	5.7	6.1	9 15	Severe	2 00	3 1/2	None	-	-	A
36	SU-2-SE-20-3	5.8	6.1	8 35	Severe	2 00	3 1/2	Surface	3 00	20	A
37	SU-2-SE-20-7	5.0	5.2	8 15	Severe	2 00	3 1/2	Surface	7.00	20	A
38	SU-2-SE-0-B	5.2	5.0	7 55	Severe	2 00	3 1/2	None	-	-	A
39	SU-2-SE-80-7	5.4	4.8	8 50	Severe	2 00	3 1/2	Surface	7 00	80	A
40	SU-2-SE-80-8 1/2	5.9	6 0	8 20	Severe	2 00	3 1/2	Surface	8 30	80	A
43	SU-2-SE-0C	5.1	6.3	7.15	Severe	2 00	3 1/2	None	-	-	A
44	SU-2-SE-20-5	5.7	5.3	7 50	Severe	2 00	3 1/2	Surface	5 00	20	A
45	SU-2-SE-80-5	5.7	6.1	8 40	Severe	2 00	3 1/2	Surface	5 00	80	A
32	IN-2-SE-0	6.4	6.7	7 45	Severe	2 00	3 1/2	None	-	-	A
33	IN-2-SE-80-2	5.8	6.2	7 30	Severe	2 00	3 1/2	Internal	2 15	High	A
34	IN-2-SE-80-3	7.0	6.7	8 45	Severe	2 00	3 1/2	Internal	3 00	High	A

TABLE C-4

EFFECTIVENESS STUDY—PHASE 2. DESCRIPTION OF SPECIMENS IN SERIES 3 AND 4· PERCENTAGE OF REINFORCEMENT AND TIME OF INITIAL SET

No	Specimen Designation	Air Content (%) 1st Batch	2nd Batch	Initial Set (hr min)	Cracking Type	Time After Mixing (hr min)	Max. Defl. at Midspan (in)	Revibration Type	Time After Mixing (hr min)	Energy Level (%)	Reinforcement According Fig. C-2,3,4
	Series 3 - Percentage of Reinforcement										
49	SU-3G-SE-0	5.2	5.7	8 05	Severe	2 00	3 1/2	None	-	-	C
50	SU-3G-SE-80	5.5	5.6	7 45	Severe	2 00	3 1/2	Surface	4 00	80	C
51	SU-3L-SE-0	5.5	5.5	7 55	Severe	2 00	3 1/2	None	-	-	B
52	SU-3L-SE-80	5.8	5.3	8 15	Severe	2 00	3 1/2	Surface	4 00	80	B
59	ANCH-1	4.5	6.0	5 30	-	2.00	1 3/4	None	-	-	A*
	Series 4 - Time of Initial Set										
53	SU-4-SL-0	4.0	4.4	3·45	Slight	2.00	1 1/4	None	-	-	A
54	SU-4-SL-20	4.3	3.8	3.45	Slight	2.00	1 1/4	Surface	3 00	20	A
55	SU-4-SL-80	3.5	3.7	3.20	Slight	2 00	1 1/4	Surface	3 00	80	A
56	SU-4-SE-0	7.0	4.2	3:20	Severe	2 00	3 1/2	None	-	-	A
57	SU-4-SE-20	4.5	4.6	3.25	Severe	2 00	3 1/2	Surface	3.00	20	A
58	SU-4-SE-80	4.9	6.1	3·45	Severe	2 00	3 1/2	Surface	3.00	80	A

*Ends of the longitudinal reinforcement were anchored to the formwork.

TABLE C-5

EFFECTIVENESS STUDY—PHASE 2. DESCRIPTION OF SPECIMENS IN SERIES 5. CURING CONDITIONS PRIOR TO INITIAL SET

No	Specimen Designation	Air Content (%) 1st Batch	Air Content (%) 2nd Batch	Initial Set (hr min)	Revibration Type	Revibration Time After Mixing (hr min)	Revibration Energy Level (%)	Heating Surface Temperature (°F)	Heating Distance of Lamp From Surface (in)
63	SU-5-NO-0	6 8	6 9	7 35	None	-	-	110	3
66	SU-5-NO-0A	5.8	5.8	7 15	None	-	-	110	9
71	SU-5-NO-80	6.5	6.5	8 00	Surface	0 45	80	110	9
78	SU-5-NO-0B	6.6	6 8	7 05	None	-	-	95	12
85	SU-5-NO-80B	6.0	6 0	7 15	Surface	1 30	80	95	12

Reinforcement Type A according to Fig. C-2

No Flexural Cracking

TABLE C-6

EFFECTIVENESS STUDY—PHASE 2 DESCRIPTION OF SPECIMENS IN SERIES 7 EFFECTIVENESS OF REVIBRATION IN CLOSING PLANE-OF-WEAKNESS CRACKS

No.	Specimen Designation	Air Content (%) 1st Batch	Air Content (%) 2nd Batch	Initial Set (hr min)	Cracking Type	Cracking Time After Mixing (hr min)	Cracking Max. Defl at Midspan (in)	Upward Deflection of Reinforcement (in)	Revibration Type	Revibration Time After Mixing (hr min)	Revibration Energy Level (%)	Reinforcement According to Fig. C-
46	SU-7-T-M-2	5.6	5.8	7 50	Medium	2 00	2 1/2	0.08	None	-	-	A
47	SU-7-T-M-4	5.8	5 6	9 35	Medium	2 00	2 1/2	0 16	None	-	-	A
48	SU-7-T-M-6	5.7	5.9	7 40	Medium	2 00	2 1/2	0 24	None	-	-	A
67	SU-7-SE-0-2	6 7	6.1	7 40	Severe	2 00	3 1/2	0.08	None	-	-	A
68	SU-7-SE-80-2	6.9	6.1	7 40	Severe	2 00	3 1/2	0.08	Surface	4 00	80	A
86	SU-7-SE-50-2	6.0	5.4	7 05	Severe	2 00	3 1/2	0 08	Surface	4 00	50	A
69	SU-7-SE-0-1	7.0	6.5	8 00	Severe	2 00	3 1/2	0.04	None	-	-	A
70	SU-7-SE-80-1	7.0	6 9	8 00	Severe	2 00	3 1/2	0.04	Surface	4 00	80	A

TABLE C-7

EFFECTIVENESS STUDY—PHASE 2 DESCRIPTION OF SPECIMENS IN SERIES 8, 9, AND 10 DEFLECTION AT LATER AGE, DIRECTION OF REVIBRATION, AND EFFECT OF REVIBRATION ON AIR CONTENT DISTRIBUTION AND ABRASION RESISTANCE

No.	Specimen Designation	Air Content (%) 1st Batch	Air Content (%) 2nd Batch	Initial Set (hr min)	Cracking Type	Cracking Time After Mixing (hr.min)	Cracking Max. Defl. At Midspan (in)	Revibration Type	Revibration Time After Mixing (hr:min)	Revibration Energy Level (%)	Reinforcement According to Fig. C-2
	Series 8 - Deflection at Later Age										
72	SU-8-SE-0	6.7	5.5	6.50	Severe	4.30	3 1/2	None	-	-	A
73	SU-8-SE-20	6.3	6.5	7.35	Severe	4.30	3 1/2	Surface	5.00	20	A
74	SU-8-SE-80	6.0	6.1	6:50	Severe	4:30	3 1/2	Surface	5.00	80	A
	Series 9 - Direction of Revibration										
75	SU-9-SE-0	5.9	6.2	7.40	Severe	2 00	3 1/2	None	-	-	A
76	SU-9-SE-80P	6.3	6.3	7 20	Severe	2.00	3 1/2	Surface	4 00	80	A
77	SU-9-SE-80V	6.2	6.1	6:35	Severe	2:00	3 1/2	Surface	4 00	80	A
83	SU-9-SE-50P	6.6	6.2	6:50	Severe	2:00	3 1/2	Surface	4:00	50	A
84	SU-9-SE-50V	5.2	5.0	6:00	Severe	2 00	3 1/2	Surface	4.00	50	A
	Series 10 - Effect of Revibration on Air Content Distribution and Abrasion Resistance										
87	SU-10-NO-20	6.1	5.4	7:05	None	-	-	Surface	4 00	20	A
88	SU-10-NO-80	5.8	6.0	6.35	None	-	-	Surface	4 00	80	A
89	SU-10-NO-50	6.7	5.8	7.15	None	-	-	Surface	4 00	50	A

TABLE C-8

PHYSICAL AND CHEMICAL PROPERTIES OF CEMENT

Fineness: 3,521 cm²/g
Autoclave expansion· 0 025 per cent
Initial set· 2·30 hr
Final set: 4 30 hr
Air content: 10.0 per cent
Compressive strength, 3 days. 2,908 psi
7 days· 4,525 psi

COMPOUND	%	CALCULATED COMPOSITION COMPOUND	%	ALKALI CONTENT COMPOUND	%
SiO_2	21.42	C_3S	59.2	Na_2O	0.15
Al_2O_3	5.01	C_2S	17.0	K_2O	0.38
Fe_2O_3	2.09	C_3A	9 7		
CaO	65.14	C_4AF	6.3		
MgO	1 85				
SO_3	2 26				
Loss on ignition	1 78				
Insoluble residue	0 42				

TABLE C-9

PROPERTIES OF AGGREGATES USED IN THE LABORATORY STUDIES

TYPE	CUMULATIVE PERCENT PASSING 1 IN.	¾ IN.	½ IN	⅜ IN.	NO. 4	NO. 8	NO. 16	NO. 30	NO 50	NO. 100	FINENESS MODULUS	BULK SPEC GRAVITY, SSD
Sand	100	100	100	100	100	92	74	43	14	3	2 74	2.60
Coarse aggregate	98	87	42	14	4	—	—	—	—	—	6 97	2 66

specified in ASTM C 494. The retarder used in this investigation was purchased directly from the manufacturer It conformed to the specifications of the manufacturer and was similar to the sample used in the experiments of the independent testing laboratory. This was verified by a chemical analysis conducted by the manufacturer.

Intermediate grade deformed bars conforming to ASTM designations A 15-64 and A 305-64 were used as reinforcement The materials used in this investigation are approved by most state highway departments.

CONCRETE MIX PROPORTIONS

The following mix was used throughout this investigation:

Water 300 lb/cu yd.
Cement. 467 lb/cu yd.
Coarse aggregates. 1,500 lb/cu yd; SSD.
Fine aggregates. 1,510 lb/cu yd, SSD

These values correspond to a water-cement ratio of 0 65 and a cement factor of 5 bags/cu yd. The slump of the concrete ranged between 2 and 4 in All aggregates were dried on a heated floor prior to casting The water-cement ratio is higher and the cement content is lower than the values normally recommended for concrete bridge deck construction. This choice was made to keep the compressive strength of the retarded concrete below 6,000 psi and to make the effect on concrete durability of the parameters to be studied in this investigation more apparent

FABRICATION OF SPECIMENS

The mixing and casting procedures employed for all specimens were as follows A 7 5 cu-ft batch was mixed in a batch plant with a horizontal tub mixer. The dry ingredients were first mixed for 1 min. Then, some water containing the air-entraining agent and an additional amount of water containing the retarder were added to the mix The wet mixture was then mixed for 4 min. Then, the concrete was placed in the formwork described previously in "Description of Specimens" and shown in Figure C-1 Two batches were required for each slab, and one-half of each slab was cast from one batch The concrete was initially vibrated with an internal vibrator After the excess concrete was struck off, the surface was hand-finished with a magnesium trowel.

Compression test cylinders were cast for several batches of concrete to determine the 28-day strength. Time of initial and final set were determined for each batch from a penetration test in accordance with ASTM C 403-68.

All specimens were covered with a plastic sheet approximately 7 hr after casting. Specimens that had to be tested in the hardened state were moist-cured for a period of 7 days in a fog room and were then exposed to air drying at a relative humidity of approximately 50 percent and a temperature of 70 F Specimens that were used only to determine cracking and effectiveness of revibration of fresh concrete received no curing treatment beyond the first day

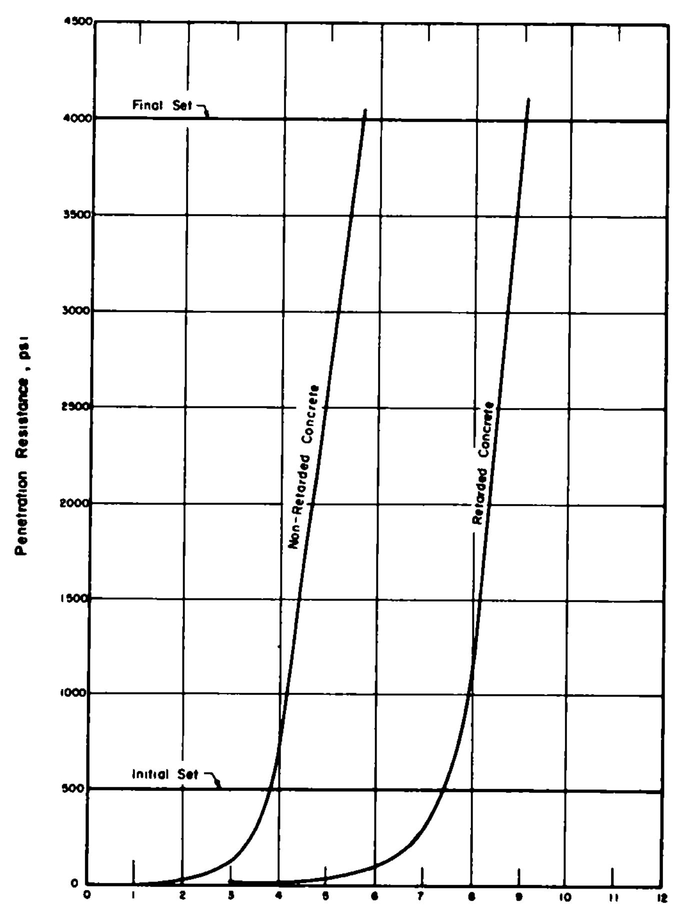


Figure C-5 Typical results from penetration test of retarded and nonretarded concrete

TEST PROCEDURES

Development of Cracks in Fresh Concrete

Between 2 and 4½ hr after mixing the concrete slabs and the formwork were deflected upward by means of a hydraulic jack (Fig. C-1). The slabs were deflected in increments of approximately ⅜ in. After each increment the deflection was kept constant for a period of approximately 2 min. Deflection was continued until either slight, medium, or severe cracking (as defined subsequently) was developed. The deflection of the formwork was kept constant at the desired final value until the hardened concrete slabs were removed from the formwork. The extent of cracking was defined as follows:

CRACKING	MAXIMUM CRACK WIDTH AT SURFACE (IN.)	AVERAGE CRACK SPACING AT SURFACE (IN.)	MIDSPAN DEFLECTION (IN.)
Slight	1 to 2 $\times 10^{-3}$	5 to 10	0.5
Medium	5 to 10 $\times 10^{-3}$	2 to 3	2.0
Severe	30 to 50 $\times 10^{-3}$	1 to 2	3.5

After deflection, the surfaces of the slabs were inspected for cracks, the cracks were marked, and in some tests the crack width was measured by means of a microscope. Figure C-6 shows a deflected slab and formwork.

Initially the major emphasis was placed on the study of the effectiveness of revibration in closing cracks that may have been caused by formwork deflections. However, during the course of this investigation it became apparent that revibration may be at least as significant as a means of repairing subsidence cracks, although subsidence cracking or the formation of planes of weakness with an increased porosity could not be observed to any significant extent in the standard specimens. Nevertheless, it was desirable to investigate the effectiveness of revibration in closing plane-of-weakness cracks. Such cracks were, therefore, generated artificially by lifting the top reinforcement of the slabs some time after casting. For this, ¼-in. bolts were attached to the top reinforcement and protruded through the bottom plate of the formwork near the center of the slab. Horizontal cracks at the level of the top reinforcement were generated 2 hr after mixing by pushing the bolts upward by an amount of 0.04 or 0.08 in. In addition, the slabs were deflected as described previously.

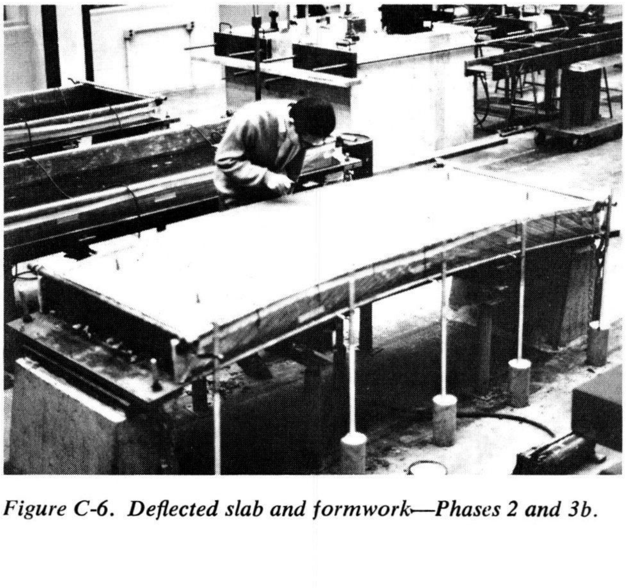


Figure C-6. Deflected slab and formwork—Phases 2 and 3b.

Revibration Methods

Most specimens were revibrated between 2 and 7 hr after mixing. Either a surface screed or internal vibrators were employed.

For internal vibration a vibrator tube with a diameter of 2 in. was immersed in the concrete for a period of 20 sec. The revibration energy was varied by varying the distance between insertions of the vibrator. Distances of 12 and 24 in. were selected for high and low energy levels, respectively. The vibrator had a frequency of approximately 7,000 rpm.

A surface screed used for surface revibration is shown in Figure C-7. An electrically powered vibrator was mounted on a channel 8 in. wide. A metal plate ⅛ in. thick was attached to the bottom of the channel and bent upward on both ends to assure easy gliding of the screed. The vibrator could be mounted on the channel in such a way that the direction of vibration was either parallel or perpendicular to the forward movement of the screed. During revibration the vibrating screed could slide along the sides of the formwork. Rubber cushions between the screed and the formwork kept transmission of vibration energy from the screed directly into the formwork to a minimum. The vibrator mounted on the vibrating screed had an adjustable eccentricity and frequency. The frequency chosen for this investigation was approximately 3,200 cpm. The vibrator could produce a maximum centrifugal force of 900 lb. A value of 720 lb, corresponding to 80 percent of the maximum, was selected for the high revibration energy level; a value of 20 percent of the maximum, corresponding to a centrifugal force of 180 lb, was selected for the low energy level. In a few cases an intermediate energy level equivalent to a centrifugal force of 50 percent of the maximum, or 440 lb, was employed. The speed of forward movement of the screed was approximately 7.5 ft per min.

Determination of the Effectiveness of Revibration

Approximately 20 days after casting some concrete slabs were sawed lengthwise, with a portable saw, into three segments 1 ft wide. The sawed sections were then inspected for cracks with a microscope; subsequently, the cracks were marked and recorded.

Severe Curing Conditions

In Series 5 an attempt was made to simulate severe exposure conditions of the fresh concrete that might lead to surface crusting. Approximately 45 min after casting, the surfaces of specimens in Series 5 were heated to temperatures of 95 and 110 F, respectively, over a period of

1½ hr or 45 min, respectively. At the same time an air current generated by an electric fan was blown across the concrete surfaces. The heat was generated by 250-watt heating lamps that were spaced 8 by 12 in. apart and that were placed either 12 or 9 in., respectively, above the concrete surfaces. After heating, some of the slabs were revibrated, as indicated in Table C-5.

Determination of Air Content

The air content of the fresh concrete mix was determined by the pressure test according to ASTM C 457-66T.

The air void parameters of the hardened concrete were obtained by using the modified point count apparatus in accordance with ASTM C 457-66T. Cores with a diameter of 4 in. were taken from hardened concrete slabs. The finished surfaces of the cores were lapped only slightly until the surface roughness was eliminated. Thus, it was possible to determine the air content near the surface. To obtain the air content distribution over the entire thickness of the specimen the cores were then sawed at distances of ¼, ½, ¾, 1, 3, and 5 in. from the top surface. Each section was prepared by lapping. The air voids were then counted by using the modified point count apparatus. This procedure also was used to calculate the cement paste content. Each slice was traversed individually, and eventually all traversed for one specific series were combined into a single calculation of air void parameters.

Because of batch to batch variations in the air content of the fresh concrete it was difficult to determine conclusively the influence of surface revibration on the air content distribution in the concrete. Therefore, three additional slabs (Series 10) were cast and revibrated at energy levels of 20, 50, or 80 percent. Only half of the surface of the concrete from each batch was subjected to revibration. Cores were then taken from both the revibrated and the nonrevibrated sections of the slabs. Thus, the effect of revibration on air content distribution could be determined on concrete samples that were cast from the same batch.

Determination of the Effect of Revibration on Concrete Compressive Strength and Concrete Density (Series C)

Three groups of tests were conducted to determine the influence of revibration on compressive strength and density of concrete. In the first group, prisms 6 by 6 by 18 in. were cast horizontally using the same mix as described for the main test series. Four hours after mixing several prisms were revibrated on a vibrating table in a horizontal position for a period of 40 sec, as described in "Revibration Methods" in Appendix D. During revibration a metal plate producing a vertical static pressure of 0.3 psi was placed on the surface of the prisms. Either retarded or nonretarded concrete was used. The compressive strength of the specimens was then determined after 3, 7, 28, and 90 days, respectively.

In an additional series the velocity of a sonic pulse through revibrated and nonrevibrated concrete slabs 3 ft by 8 ft by 6 in. was determined. It was assumed that an increase of concrete density due to revibration or due to the closing of cracks may result in a marked increase of the pulse velocity. The pulse velocity was determined both through the thickness of the slabs and along the slab surface.

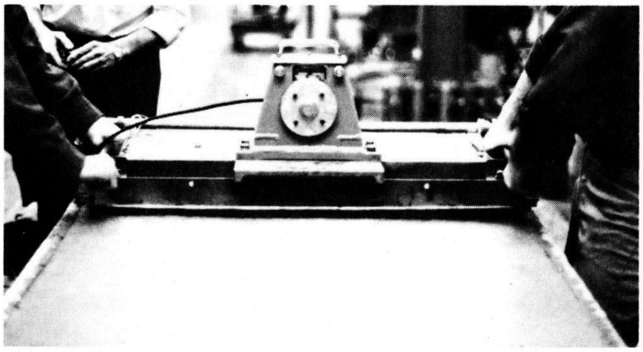


Figure C-7. Surface screed used for revibration of reinforced concrete slabs.

The results from the pulse velocity measurements were inconclusive, and additional cores with a diameter of 4 in. were taken from both revibrated and nonrevibrated slabs. Their density and compressive strength were determined.

Distribution of Revibration Energy Across the Thickness of a Slab (Series ACC)

To obtain some information regarding the distance from the top surface at which surface revibration may still be effective, accelerometers were placed vertically in three concrete slabs at various depths from the surface. The accelerometers were covered with an impermeable layer and then were cast in a cube of plaster of paris with side lengths of approximately ¾ in. Thus, the over-all specific weight of the accelerometers was reduced and was comparable to that of the coarse aggregates used in the concrete mix. The accelerometers were placed approximately 0.75, 2.5, 3.75, and 5.25 in. from the concrete surface. They were tied with string to a small metal frame consisting of individual ¼-in. steel bars. This metal frame in turn was fastened to the reinforcement of the slab. During surface revibration the output of the accelerometers was measured and recorded on an oscillograph and magnetic tape.

EXPERIMENTAL RESULTS

Development of Cracks in Fresh Concrete (Series P, 3, 4, 5, and 7)

Flexural cracks were generated by deflecting the formwork supporting the fresh concrete 2, 3, or 4 hr after mixing. Figure C-8 relates maximum crack width at the concrete surface with the deflection and the curvature of the concrete at midspan. Maximum and average crack width are summarized in Table C-10. Crack spacing as a function of midspan deflection is shown in Figure C-9. Figure C-10 shows crack patterns on the concrete surface for "slight," "medium," and "severe" cracking, corresponding to midspan deflections of 0.5, 2, and 3.5 in., respectively.

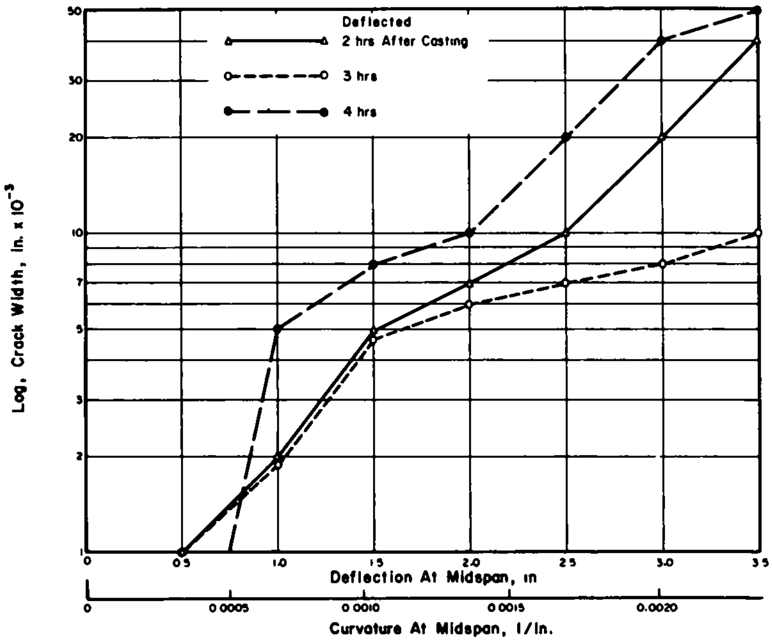


Figure C-8 Maximum crack width in concrete slabs deflected 2, 3, or 4 hr after mixing. Series P—Phase 2

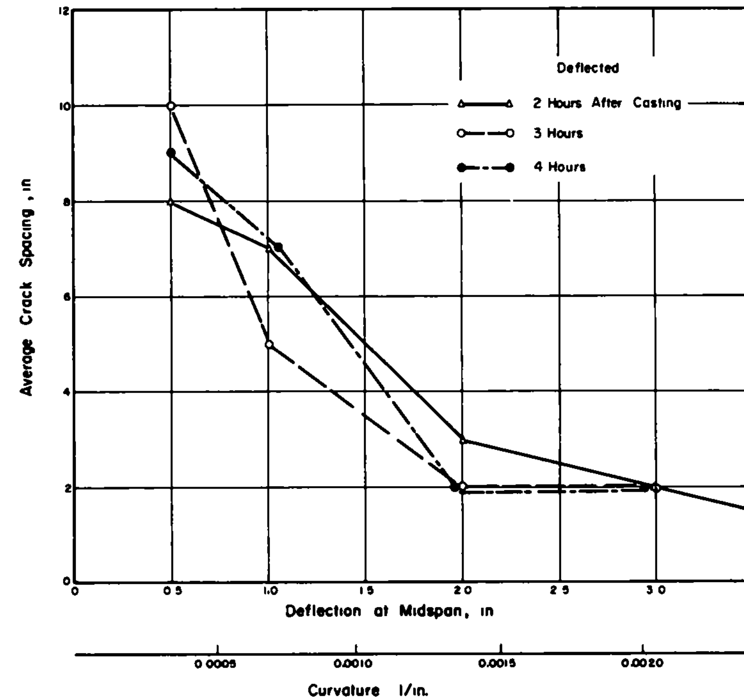


Figure C-9. Average crack spacing in concrete slabs deflected 2, 3, or 4 hr after mixing Series P—Phase 2.

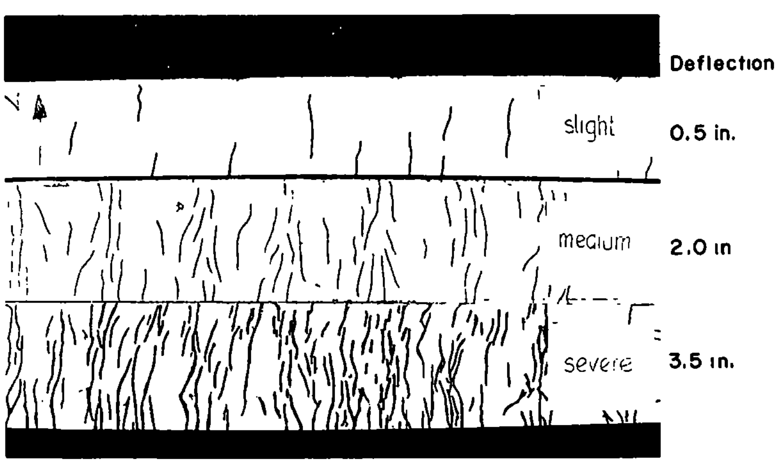


Figure C-10 Crack patterns on concrete surface Time of deflection 2 hr after mixing

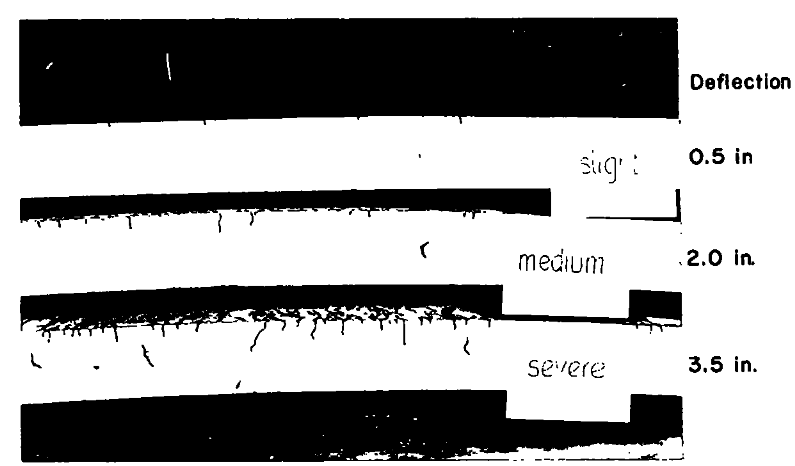


Figure C-11 Sections of cracked slabs Time of deflection. 2 hr after mixing

TABLE C-10

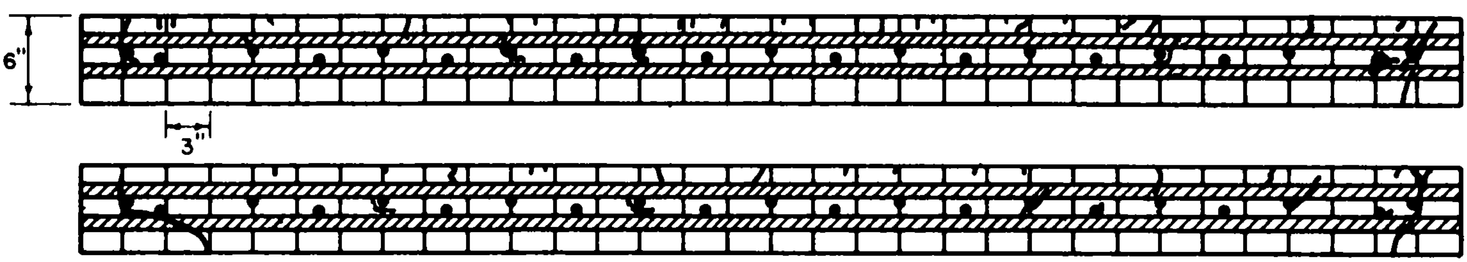
MAXIMUM AND AVERAGE CRACK WIDTH, AND AVERAGE CRACK SPACING IN DEFLECTED CONCRETE SLABS, SERIES P—PHASE 2

	TIME OF DEFLECTION								
	2 HR AFTER CASTING			3 HR AFTER CASTING			4 HR AFTER CASTING		
	CRACK WIDTH (IN)		AVG CRACK SPACING	CRACK WIDTH (IN.)		AVG CRACK SPACING	CRACK WIDTH (IN)		AVG. CRACK SPACING
DEFLECTION (IN)	MAX.	AVG	(IN)	MAX.	AVG.	(IN)	MAX.	AVG	(IN)
½	0.001	0.0005	8	0.001	0 0005	10	0 0005	0 0005	9
1	0.002	0 001	7	0 002	0 001	5	0.005	0 001	7
1½	0.005	0 002	—	0 005	0 002	—	0.008	0.002	—
2	0.008	0 002	3	0 006	0 002	2	0 010	0.004	2
2½	0 015	0 003	—	0 007	0 003	—	0 020	0 008	—
3	0.020	0 004	2	0 008	0 004	2	0.040	0.009	2
3½	0 040	0.005	1	0 009	0.005	—	0 050	0 010	—
4	—	—	—	0.010	0.007	—	0.050	0.010	—

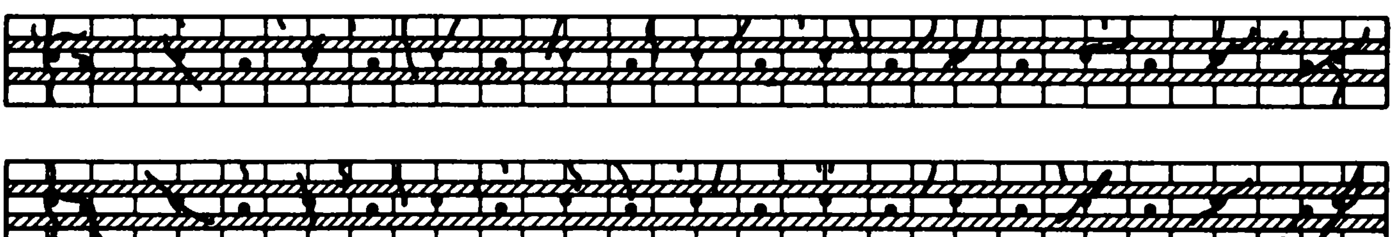
Figure C-11 shows crack patterns in sections of concrete that were deflected 2 hr after mixing and sawed into segments 14 days later.

The data indicate that maximum and average crack width and average crack spacing are little affected by variations of the age of concrete at the time of deflection. For slabs deflected between 2 and 4 hr after mixing, a curvature in excess of 0.0015 in $^{-1}$ is required to generate cracks exceeding a depth of ½ in. Even at a deflection of 3½ in., only a few cracks penetrated to the level of the top reinforcement. However, tests conducted at a later time indicated that specimens deflected 4½ hr after mixing, or approximately 2 hr before initial set, had deeper cracks, although the spacing and maximum and average crack width did not significantly deviate from the values observed on specimens that were deflected earlier This is shown in Figure C-12, where cracked sections of specimens deflected 2 or 4½ hr after mixing are compared. The penetration resistance of the concrete in some of the slabs when deflected 4 hr after mixing was still zero, or only slightly larger, whereas the resistance of slab SU-8-SE-O, deflected 4½ hr after mixing, had a penetration resistance of 17 psi.

During deflection of the slabs the concrete started to separate from the ends of the formwork at a deflection of approximately ¼ in., corresponding to a curvature of 1.9×10^{-4} in.$^{-1}$. The gap between concrete and formwork



Severe Deflection After 2 Hours   Specimen SU-2-SE-O; Series 2



Severe Deflection After 4-1/2 Hours   Specimen SU-8-SE-O; Series 8

Figure C-12 Section of severely cracked concrete slabs Time of deflection 2 hr and 4½ hr after mixing may be considered a crack, and it was hypothesized that the concentration of deformation at this gap may be responsible for the shallowness of the flexural cracks in the center part of the slab. Therefore, the longitudinal reinforcement of one specimen (ANCH-1) was anchored to the ends of the formwork to avoid the separation of the concrete from the formwork. The slab was deflected 2 hr after mixing, and separation of the concrete from the formwork was indeed avoided. However, spacing, width, and depth of the cracks did not significantly deviate from those observed in previous tests

Two distinctive types of cracks were found in most specimens Cracks either extended from the concrete surface (referred to as surface cracks) or formed around the reinforcement without reaching the surface (referred to as internal cracks). It is likely that the latter cracks are due to relative movement of the fresh concrete with respect to the reinforcement that may occur during deflection of formwork and concrete.

The flexural cracks were concentrated near reinforcing bars perpendicular to the applied moment, particularly for slight and medium cracking. A more even distribution of cracks was observed in severely cracked slabs.

Under the normal laboratory environment of 72 F and 50 percent relative humidity no significant shrinkage cracking or subsidence cracking were observed prior to or after initial set. In the case of severe drying conditions before initial set (wind; 95 and 110 F), which were studied in Series 5, severe shrinkage cracks penetrated beyond the level of the top reinforcement (Figs. C-28 and C-29).

Subsidence cracking or formation of planes of weakness could not be observed either under regular laboratory conditions or under simulated wind and high-temperature conditions. Planes of weakness were, therefore, generated artificially as described previously for a study of the effectiveness of revibration in repairing such cracks. A surface and a cross section of a specimen with artificial and horizontal cracks and flexural cracks is shown in Figure C-13. The horizontal cracks at the level of the top reinforcement had a width of approximately 30×10^{-3} in. In addition, cracks appeared on the concrete surface that were perpendicular to the flexural cracks and that had a width of approximately 10 to 40×10^{-3} in.

Nonretarded concrete slabs with an initial set 3 hr 45 min after mixing were deflected 2 hr after casting. These specimens had cracking characteristics similar to those observed in retarded concrete (Fig. C-23). Variations in percentage of reinforcement had little effect on flexural cracking (Figs. C-26 and C-27). In Figure C-14 the average depth of surface cracks of all nonrevibrated specimens that were deflected severely is given as a function of the penetration resistance at the time of deflection. Included in this diagram are the results from specimen SU-4-SE-20 which was revibrated at a low energy level when the concrete had already reached a penetration resistance of 45 psi. Revibration was ineffective and it is reasonable to assume that the cracks observed after revibration were already present prior to revibration. Figure C-14 shows clearly that the surface cracks become deeper as the penetration resistance increases. For values of the penetration resistance larger than 15 psi, most cracks reached the level of the top reinforcement and thus may be detrimental to concrete durability.

In conclusion, it may be stated that cracking in a bridge deck due to formwork deflection without surface crusting several hours before initial set is insignificant because the cracks are comparatively shallow and because deflections required to develop severe cracking are considerably larger than the deflections that may be expected in the field as long as reasonable construction practices are maintained. However, deflections occurring shortly before initial set or after the penetration resistance has reached approximately 15 psi may cause severe and deeper cracking.

Effectiveness of Revibration in Closing Cracks in Fresh Concrete

Method of Revibration; Revibration Energy and Extent of Initial Cracking (Series 1, 7, and 9)

A survey of available equipment and consultation with highway departments indicated that at present it is not feasible to revibrate bridge deck concrete with external vibrators. The formwork may not be sturdy enough to withstand the stresses resulting from external vibration. In addition, mounting of vibrators under the formwork would be difficult, time-consuming, and uneconomical. Furthermore, laboratory tests indicated that external revibration may require the application of a dead weight to the concrete surface during revibration to prevent the formation of additional cracking and a reduction in concrete density. Such precautions are not practical in the field construction of bridge decks. Therefore, the effectiveness of external vibration in closing cracks in the fresh concrete was not studied.

Figure C-15 shows the surface of a slab that was se-

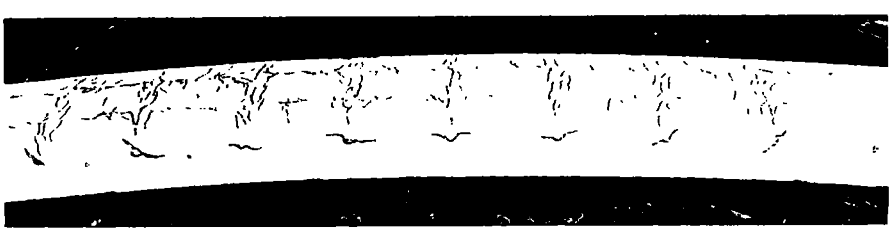


Figure C-13. Concrete slab with artificial plane-of-weakness cracks

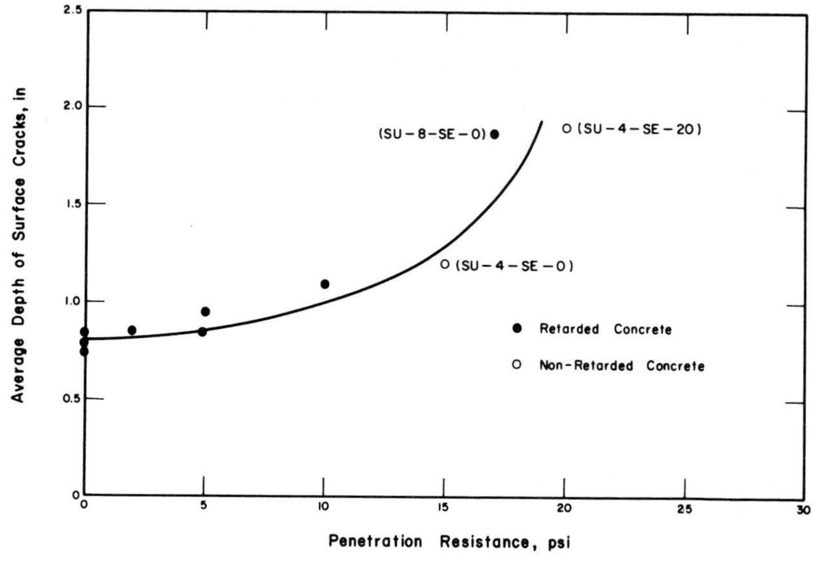


Figure C-14. Influence of age of concrete at time of deflection on depth of surface cracks. Results from Series 1, 2, 4, 8, and 9. Severe cracking.

verely cracked and internally revibrated 4 hr after mixing. Half of the slab was hand-finished after internal revibration. Cracks on the concrete surface of the unfinished half are marked. Figure C-15 shows that internal revibration closes cracks only in the immediate vicinity of the area at which the vibrator was inserted. Some surface cracks can be closed by subsequent hand-finishing as long as the concrete has sufficient workability, but this is a cumbersome and time-consuming operation.

Figure C-16 shows the distribution of cracks within the cross section of slabs that were severely cracked and internally revibrated 4 hr after mixing. The slabs were not finished after revibration. Internal revibration did not close all surface cracks or cracks around reinforcing bars. Variation in revibration energy (i.e., the spacing between vibrator insertions) had little influence on the effectiveness of internal revibration. Because of this limited success, internal revibration was not investigated further.

Cross sections of cracked concrete slabs that were revibrated with a surface screed 4 hr after mixing are shown in Figure C-17. Most surface and internal cracks in the center part of the slab were closed at the low and the high

Figure C-15. Internally revibrated concrete slab. Right half of slab finished after revibration.

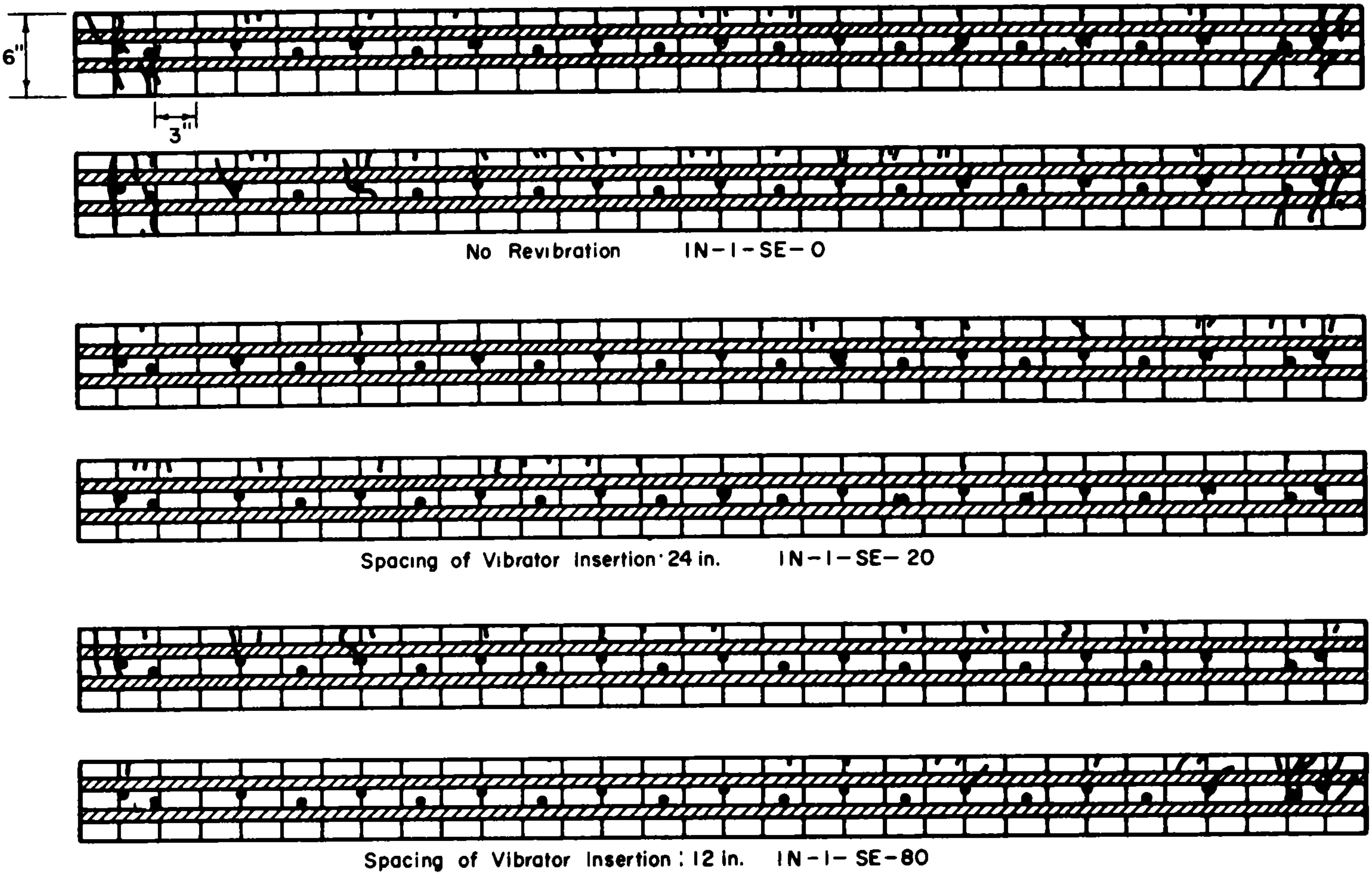


Figure C-16 Sections of severely cracked concrete slabs Internal revibration at low or high energy level 4 hr after mixing.

energy level of revibration The areas up to 6 in away from the ends of the slabs were not revibrated The surface appearance of the slabs after revibration was very good, and no additional finishing, except brooming or belting, would be necessary. Additional finishing immediately after revibration is, however, possible, because surface revibration tends to drive some moisture to the surface.

The effectiveness of surface revibration in closing horizontal plane-of-weakness cracks is shown in Figure C-18. Cross sections of slabs from Series 7, in which flexural cracks and horizontal cracks were generated 2 hr after mixing, are shown. The specimens were revibrated with a surface screed 4 hr after mixing at an intermediate or high energy level Surface revibration was very effective. With the exception of the end regions, which were not revibrated, all cracks were closed.

With the exception of the tests in Series 9, the vibrator was mounted on the screed with the plane of rotation of the vibrator parallel to flexural cracks and perpendicular to the forward motion of the vibrating screed. In Series 9 the vibrator was mounted with the plane of rotation parallel to the direction of forward motion of the screed. Both methods were equally effective in closing cracks. However, at high energy levels the surface of the concrete was not as smooth, and required additional finishing after revibration in the latter case. Vibration perpendicular to the forward motion of the screed is therefore preferable.

No specific value for the required minimum revibration energy can be given because of the lack of a suitable method to measure and evaluate vibration of fresh concrete. However, experience gained during this investigation indicates that a revibration energy level that is sufficient to drive a slight moisture film to the entire concrete surface is also sufficient to close most cracks

Time of Revibration (*Series 2, 4, and 8*)

Because cracking either due to formwork deflection or due to subsidence of the concrete will be severe and harmful only if it occurs several hours after mixing, it is essential that revibration be conducted as late as possible. However, the period of time during which revibration is possible is limited because the workability of the fresh concrete decreases rapidly as the concrete approaches its initial set. Three test series were conducted to determine the maximum age of concrete at which revibration may be successful

Figures C-19 and C-20 show sections of slabs that were deflected at an age of 2 hr and that were revibrated between 3 and 7 hr after mixing at an energy level of 20 per-

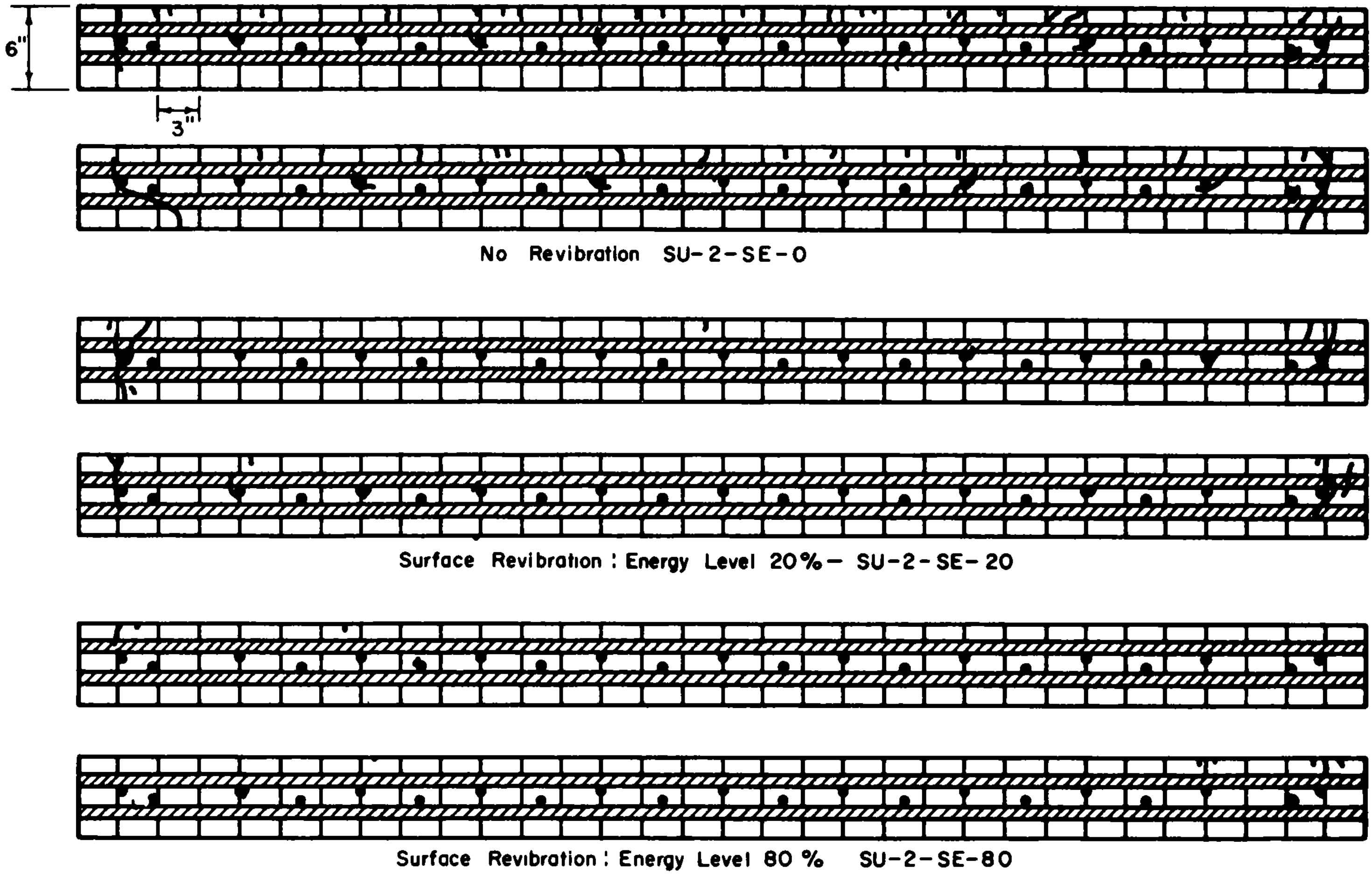


Figure C-17 Sections of severely cracked concrete slabs Surface revibration 4 hr after mixing. Energy level 20 or 80 percent

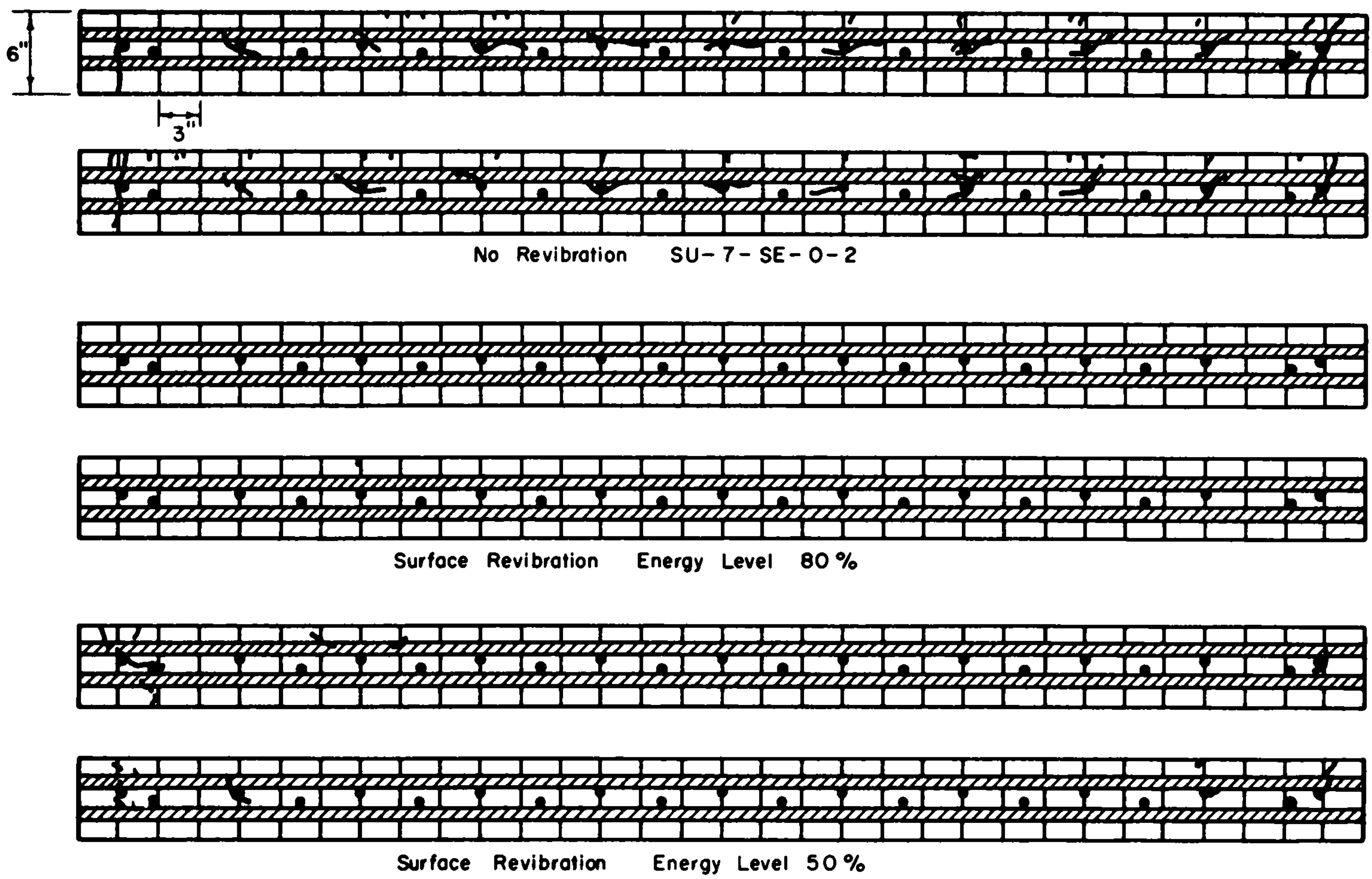


Figure C-18 Sections of concrete slabs with horizontal cracks. Surface revibration 4 hr after mixing. Energy level 50 or 80 percent.

cent. Figures C-21 and C-22 show crack patterns that were observed in slabs revibrated between 3 and 8½ hr after mixing at an energy level of 80 percent. Crack patterns for nonretarded concrete revibrated after 3 hr are shown in Figure C-23. Revibration at the lower energy level was reasonably effective in repairing cracks in retarded concrete up to 5 hr after mixing. Most cracks in retarded concrete could be closed up to 7 hr after mixing at the higher energy level. The time during which surface revibration may be effectively conducted depends on the particular concrete and curing conditions. It is, however, more instructive to use a parameter that depicts the stiffness of the concrete at the time of revibration. Therefore, the number of external and internal cracks observed in slabs that were surface-revibrated at various ages are shown in Figure C-24 as a function of the penetration resistance of the concrete according to ASTM 403-68. The regions within 12 in. of the ends of the specimens were excluded in determining the number of cracks, inasmuch as they were not revibrated. Figure C-24 includes all data obtained from retarded and nonretarded concrete slabs as well as from specimens that were deflected 4½ hr after mixing. The number of surface cracks in slabs that were not revibrated ranged from 13 to 21, with an average of 17. Between 3 and 7 internal cracks were observed in the nonrevibrated specimens. Revibration at an energy level of 20 percent is effective if conducted at a penetration resistance below 30 psi. Revibration at an energy level of 80 percent is effective at a penetration resistance below 60 psi. The relationships of Figure C-24 are valid for both retarded and nonretarded concrete. Thus, the influence of retarder, setting time, and time of revibration on effectiveness of surface revibration can be expressed by one parameter—the penetration resistance.

Figure C-25 shows crack patterns that were obtained from specimens deflected 4½ hr after mixing. As noted previously, late deflection resulted in cracks deeper than those observed in slabs that were deflected between 2 and 4 hr after mixing. Figure C-25 shows that most cracks could be closed by surface revibration 5 hr after mixing at an energy level of 80 percent; the number of cracks observed after revibration can be expressed by the same relationship shown in Figure C-24 for the slabs deflected 2 hr after mixing.

The criterion for the required minimum revibration energy given in the previous section was confirmed by the tests conducted in Series 2, 4, and 8. Revibration is effective as long as a thin moisture film appears on the entire concrete surface. If the concrete is too stiff to be revibrated effectively the surface screed tends to ride on the high spots of the concrete surface, and the areas between the high spots remain virtually unrevibrated.

Effect of Reinforcement Detailing (Series 3)

A study of reinforcement detailing was included in an attempt to form planes-of-weakness cracks and subsidence cracks. As mentioned earlier, variations in reinforcement did not have this effect. Figures C-26 and C-27 show crack patterns in concrete slabs with a percentage of the top reinforcement perpendicular to the cracks of 0.57 and 1.28, respectively. The slabs were cracked severely 2 hr after mixing and were revibrated 4 hr after mixing. The observed crack patterns are not significantly influenced by the reinforcement. Revibration at the 80-percent energy level repaired most of the cracks.

Effect of Curing Conditions (Series 5)

In the first subseries, concrete slabs were exposed to hot, dry air generating a temperature of 110 F at the concrete surface for a period of 45 min. This treatment resulted in severe crusting of the surface and the formation of deep shrinkage cracks, as shown in the top portion of Figure C-28. The specimens were revibrated with the surface screed at the 80-percent energy level immediately after heating. The crack patterns observed in a specimen after revibration are shown in the lower part of Figure C-28. Although most of the deep cracks could be closed by revibration, the surface crust was not broken, and a large number of shallow surface cracks was generated by revibration. The concrete surface was rough, and finishing after revibration was difficult.

Figure C-29 shows the crack patterns in slabs that were heated for 90 min to a temperature of 95 F at the concrete surface. The exposure to hot and dry air resulted in crusting and shrinkage cracks, as shown in the top half of Figure C-29. Most of the cracks were repaired by surface revibration. The surface crust was partially broken. However, finishing after revibration was still necessary to obtain a smooth surface.

In these tests it became apparent that surface revibration can improve moderately crusted concrete surfaces. However, it cannot completely eliminate the effects of severe exposure of fresh concrete to warm and dry air, because the extensive finishing required after revibration will cause considerable problems in actual bridge deck construction.

Effect of Revibration on Concrete Strength (Series C)

Figure C-30 shows the influence of revibration on the compressive strength of prisms 6 by 6 by 18 in. Four specimens were tested for each combination of variables. Revibration had no statistically significant effect on the compressive strength of retarded concrete. The compressive strength of the nonretarded concrete was increased slightly by revibration.

These data agree with the findings of previous investigations described in Chapter Two. According to these studies, revibration several hours before initial set has little influence on the compressive strength of concrete. Revibration shortly before or after initial set may, however, lead to a noticeable increase of concrete compressive strength. At the time of revibration the retarded concrete was 3 hr away from its initial set. Consequently, revibration had little effect on compressive strength. The nonretarded concrete was revibrated 1 hr before its initial set; this resulted in the strength increase observed by other investigators.

Pulse velocity measurements through the thickness of revibrated and nonrevibrated slabs were used to evaluate the effect of surface revibration on strength and density of

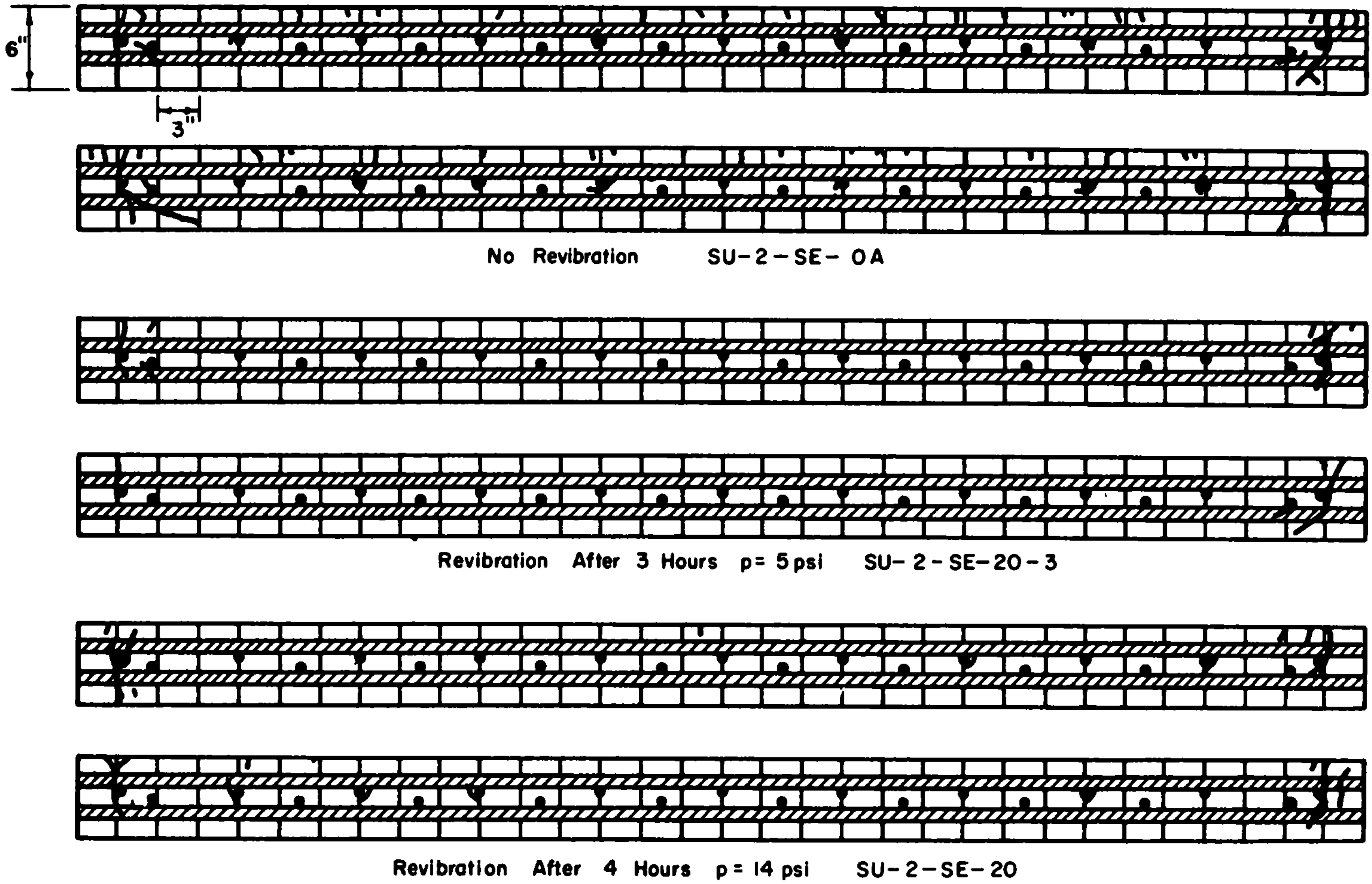


Figure C-19. Influence of concrete age on effectiveness of surface revibration. Retarded concrete Energy level· 20 percent.

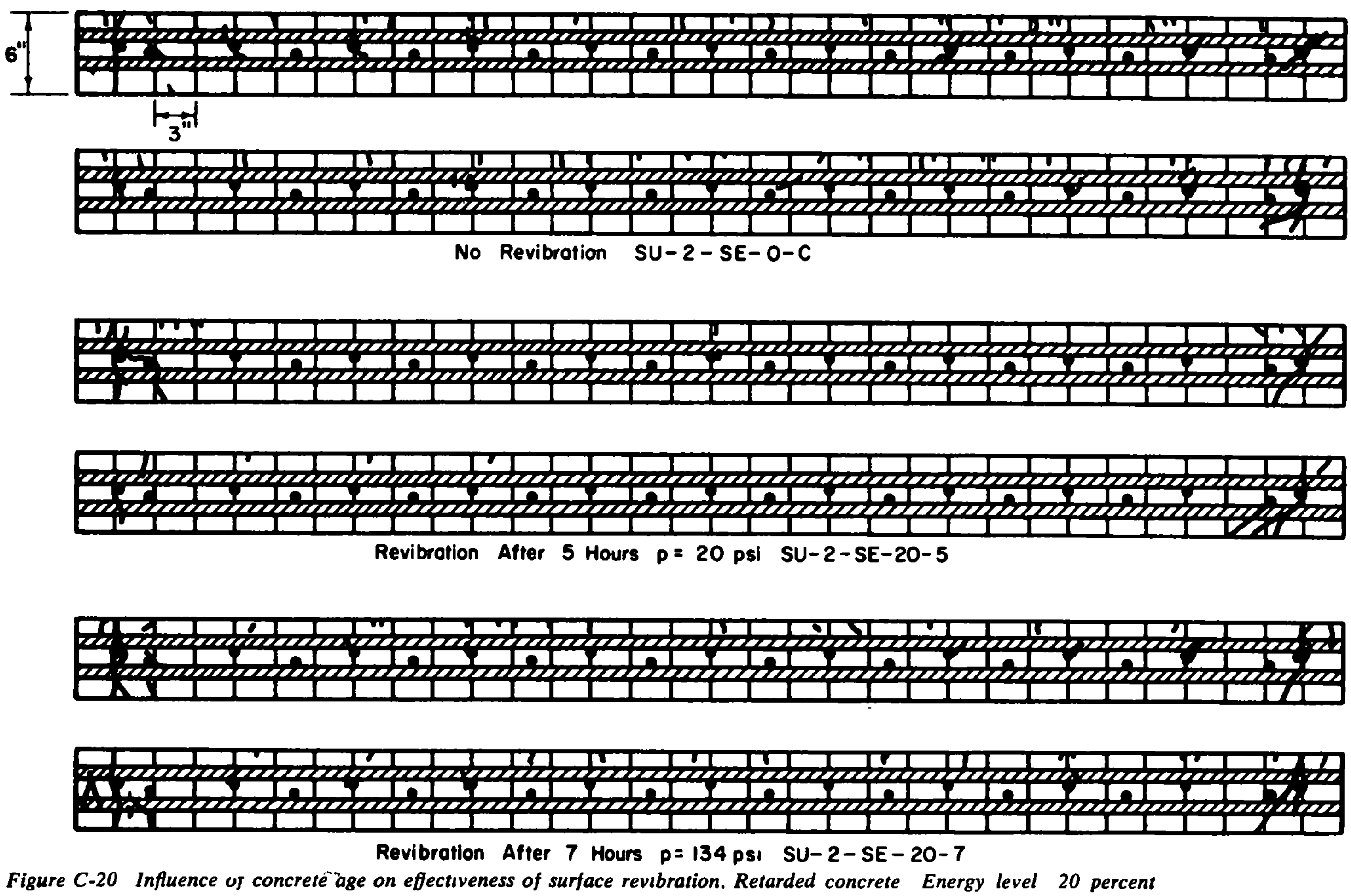


Figure C-20 Influence oj concrete age on effectiveness of surface revibration. Retarded concrete Energy level 20 percent

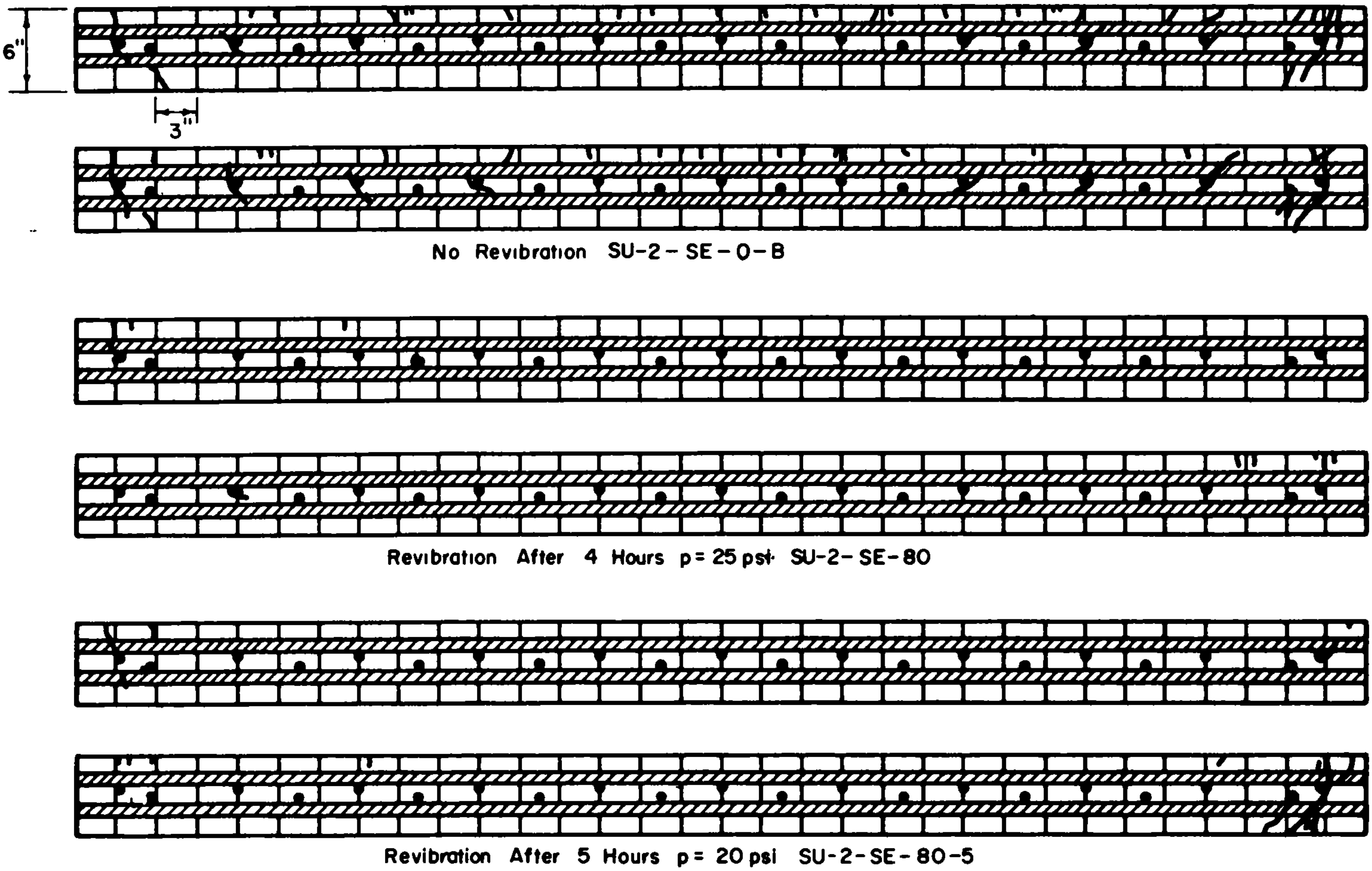


Figure C-21 Influence of concrete age on effectiveness of surface revibration. Retarded concrete Energy level 80 percent.

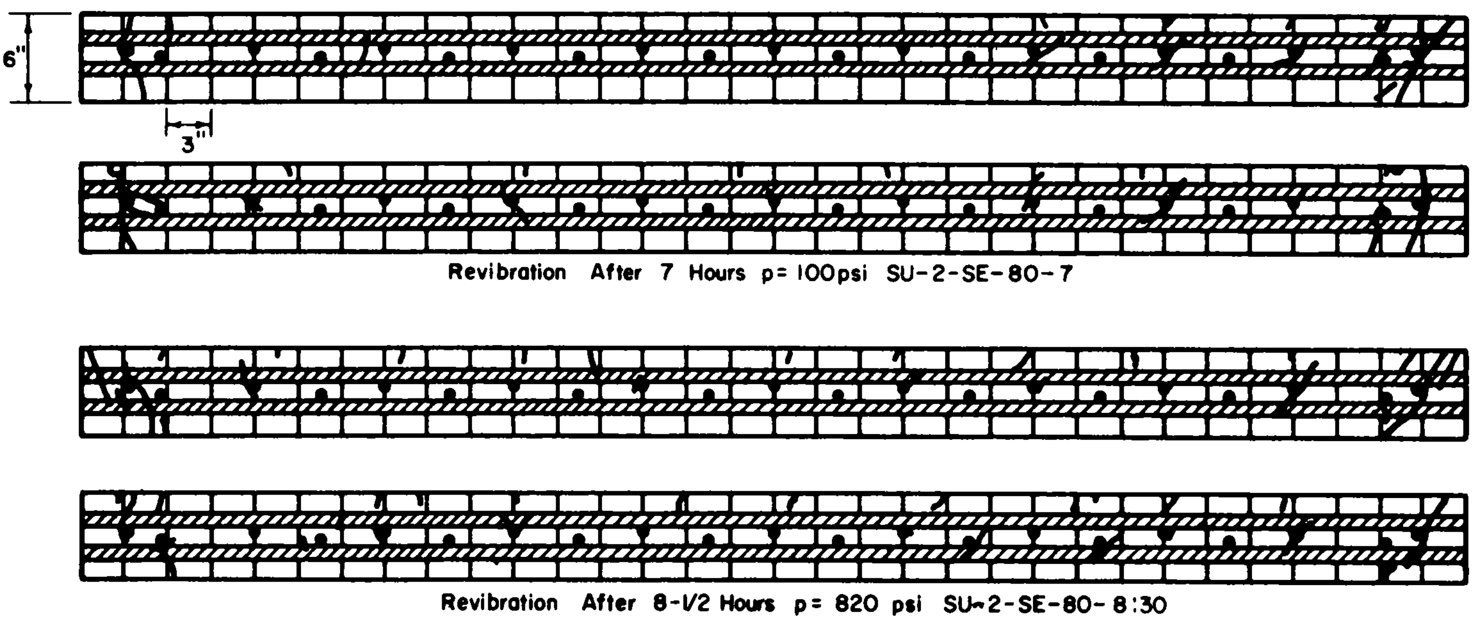


Figure C-22 Influence of concrete age on effectiveness of surface revibration. Retarded concrete. Energy level· 80 percent.

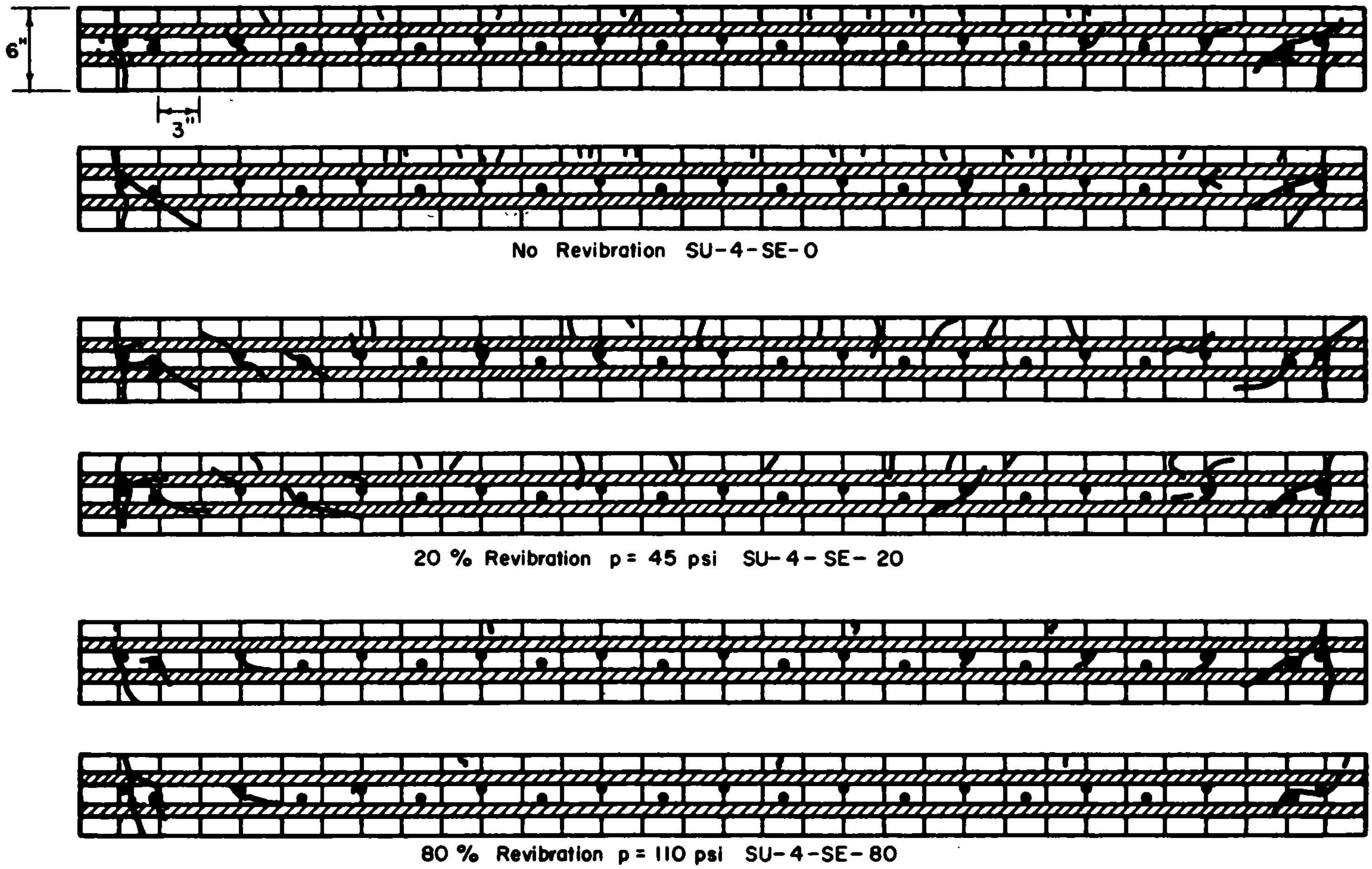


Figure C-23. Effectiveness of surface revibration in closing cracks in nonretarded concrete Energy level 20 and 80 percent. Time of revibration 3 hr after mixing

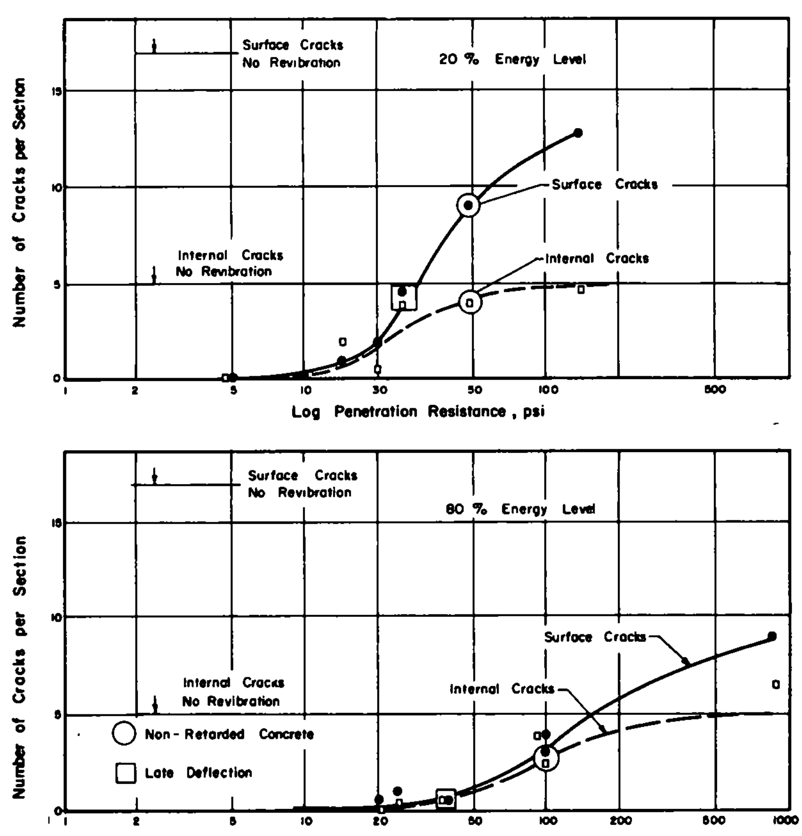


Figure C-24. Influence of concrete age on effectiveness of surface revibration. Severe initial cracking. Series 2, 4, and 8—Phase 2.

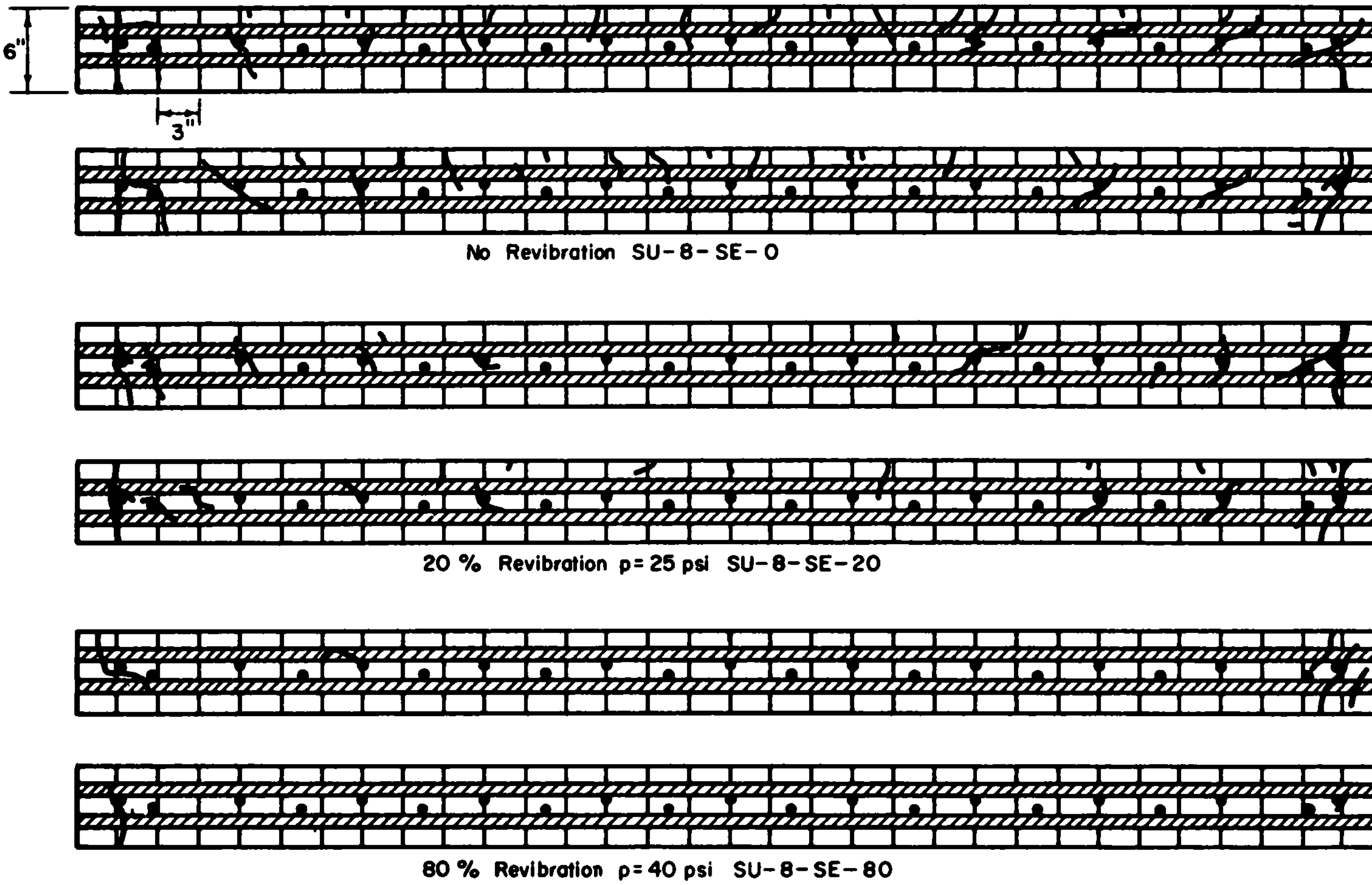


Figure C-25 Effectiveness of revibration in closing cracks that were formed 4½ hr after mixing. Time of revibration· 5 hr

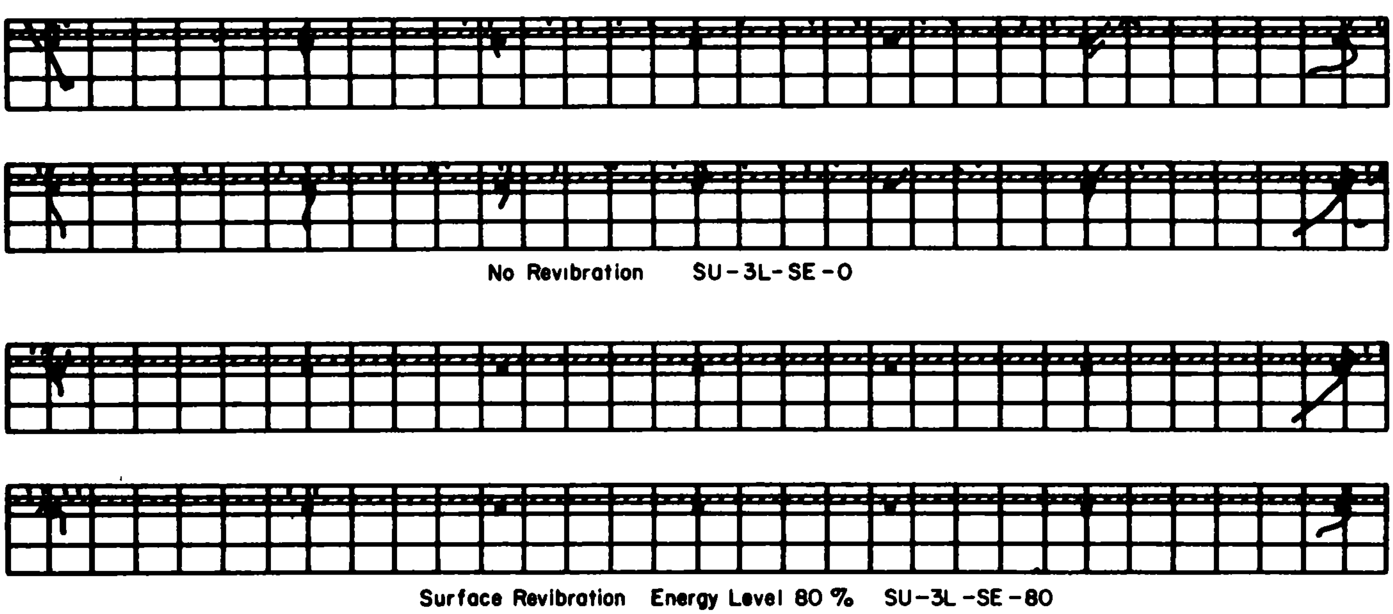
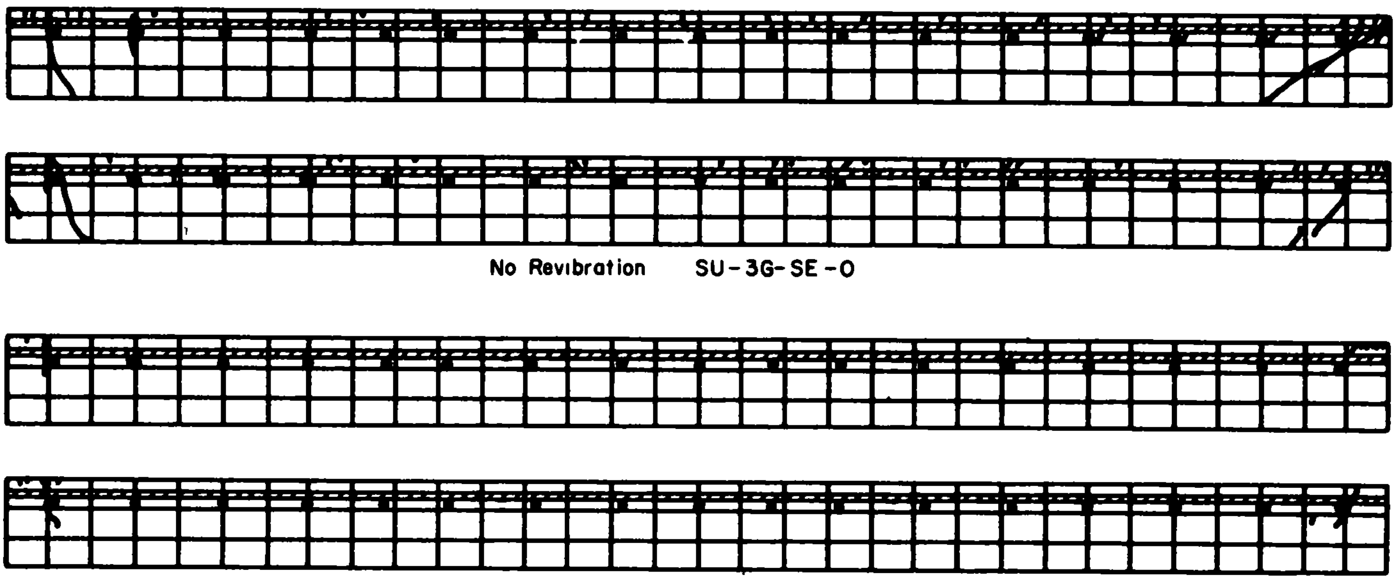


Figure C-26. Influence of top reinforcement on effectiveness of surface revibration Reinforcement: Type B. Concrete cover: 1 in. Time of revibration. 4 hr after mixing.

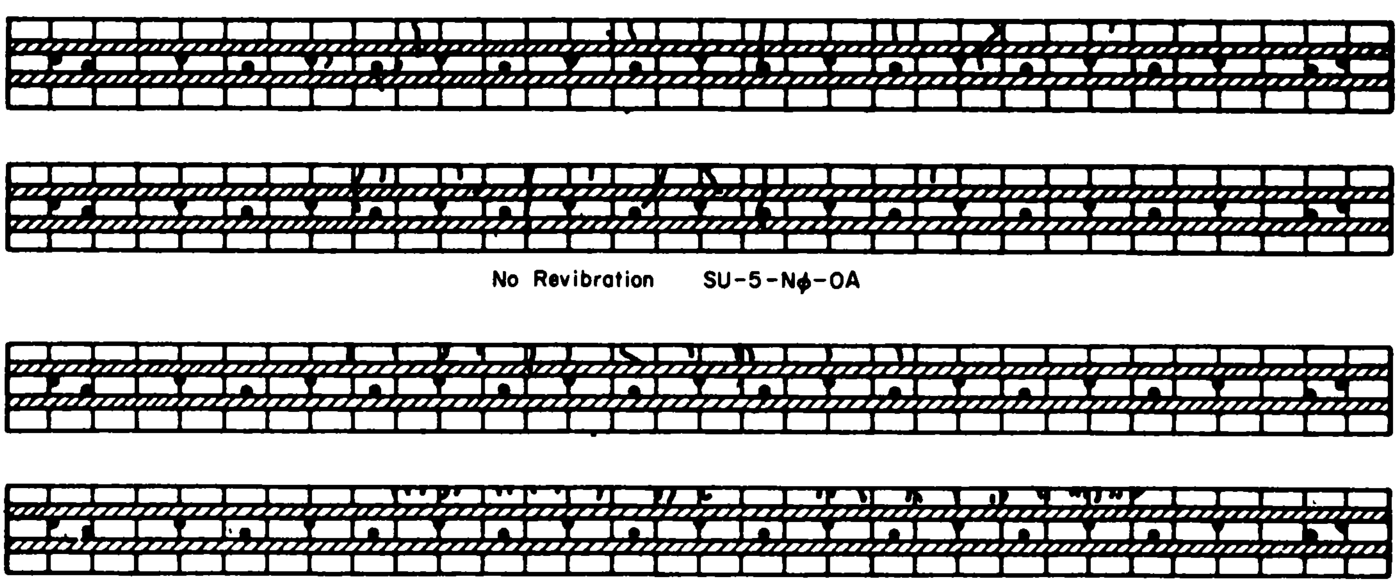


No Revibration SU-3G-SE-0

Surface Revibration Energy Level 80 % SU-3G-SE-80

Figure C-27. Influence of top reinforcement on effectiveness of surface revibration Reinforcement Type C Concrete cover 1 in revibration· 4 hr after mixing

retarded concrete. The results of these studies are summarized in Table C-11. According to these data, surface revibration at an energy level of 20 percent resulted in a slight reduction of unit weight, compressive strength, and relative dynamic modulus, compared to the corresponding values for the nonrevibrated slabs. The observed differences for these three values are consistent with each other but are not statistically significant. Surface revibration at the 80-percent energy level led to an increase of unit weight, strength, and relative dynamic modulus. From these data as well as from the results of previous studies it is concluded that revibration has very little damaging effect on concrete compressive strength and density At higher energy levels it may lead to a slight improvement of these concrete properties



No Revibration SU-5-Nϕ-0A

Surface Revibration Energy Level 80 % SU-5-Nϕ-80

Figure C-28. Effectiveness of surface revibration in closing early shrinkage cracks due to severe exposure conditions Concrete surface ture· 110 F Duration of heating: 45 min

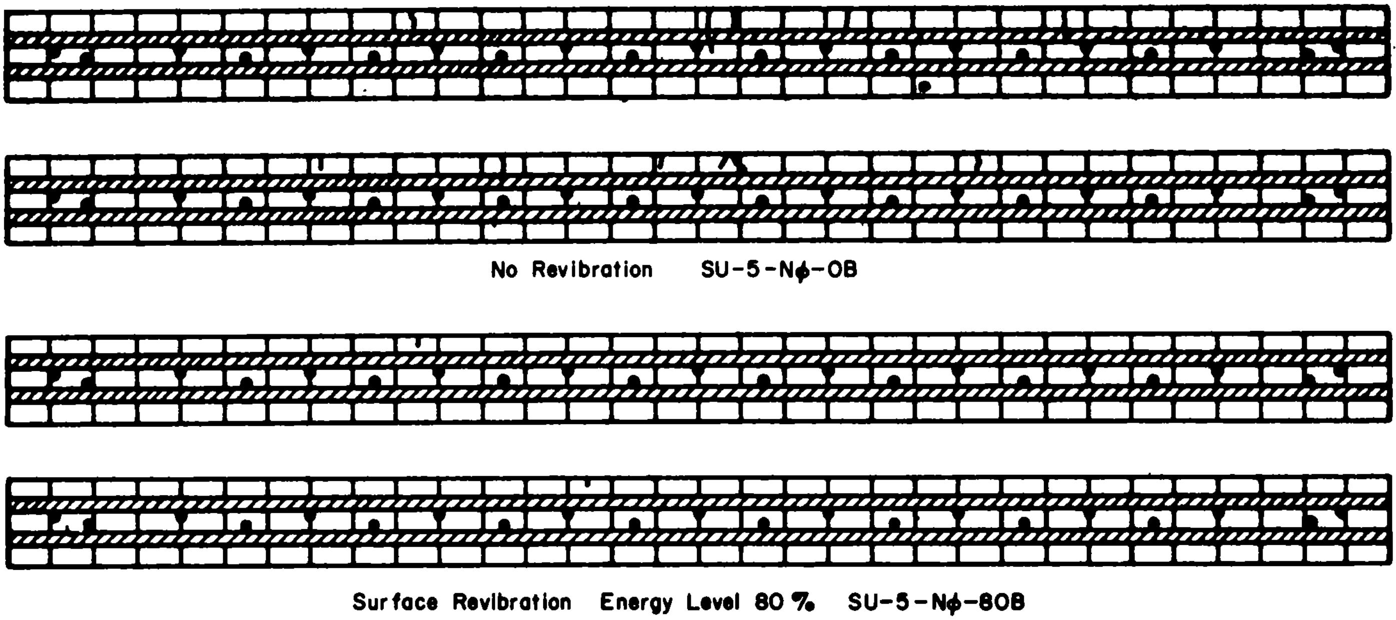


Figure C-29. Effectiveness of surface revibration in closing early shrinkage cracks due to severe exposure conditions Concrete surface ture· 95 F Duration of heating 1½ hr

Effect of Revibration on Air Void Characteristic of Concrete (Series 10 and Phase 3b)

The distributions of air content, paste content, and spacing factor in revibrated and nonrevibrated concrete are shown in Figures C-31, C-32, and C-33 The data are summarized in Table C-12. According to Figures C-31, C-32, and C-33, the hand-finishing procedures resulted in a reduction of the air content and in an increase of the paste content close to the concrete surface, even in concrete that was not revibrated. Surface revibration increased this effect.

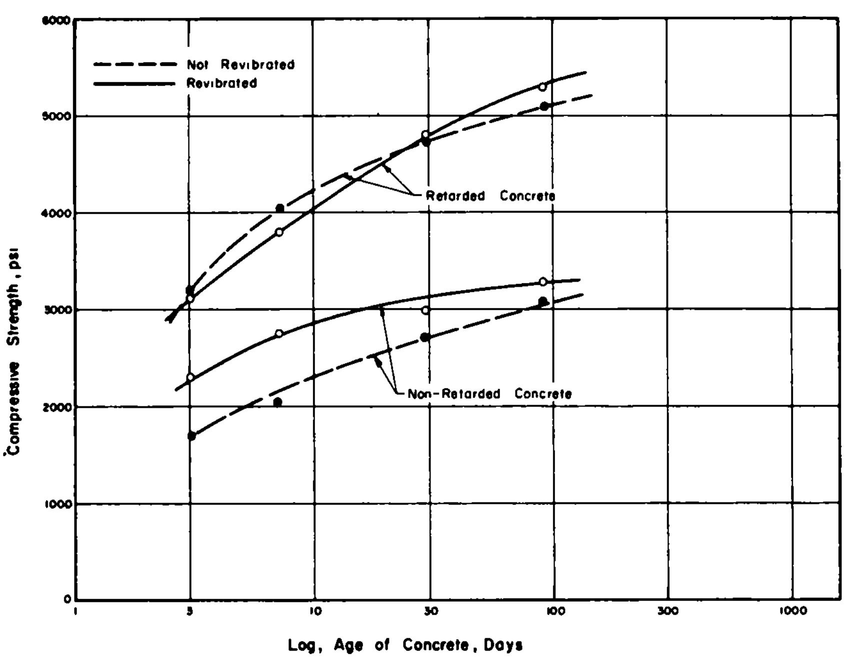


Figure C-30. Effect of revibration on compressive strength of retarded and non-retarded concrete prisms 6 by 6 by 18 in. Revibrated for 40 sec on a vibrating table. Time of revibration. 4 hr after mixing.

The following summarizes the spacing factors of the surface layers of surface revibrated and nonrevibrated sections of three slabs

ENERGY LEVEL (%)	SPACING FACTOR AT SURFACE (IN.)	
	NO REVIBRATION	REVIBRATION
20	0.0068	0.0074
50	0 0067	0 0078
80	0.0073	0.0079

Revibration caused an increase of the spacing factor that was small and should not be of major significance for concrete durability as long as the initial air content of the concrete is sufficient. Revibration did not affect the air void system of concrete at a distance of more than 1 in from the concrete surface.

The influence of external revibration on the air void characteristics was investigated in Phase 3a of the durability studies. The data appear in Tables C-13 and C-14. No pronounced effect of external revibration on the air void characteristics and the paste content of the concrete could be observed inasmuch as the differences between the properties of revibrated and nonrevibrated concrete are within the accuracy of the experimental procedures and the variations to be expected in concrete.

Distribution of Revibration Energy (Series P and Series 1, Phase 3a)

Three specimens 3 ft by 8 ft by 6 in of the pilot Series P, Phase 2, were used to measure the distribution of vibration energy in surface-revibrated concrete. Six companion specimens 22 by 22 by 6 in. of Series 1, Phase 3a, contained accelerometers to determine the distribution of vibration energy during external revibration. The specimens were revibrated 4 hr after mixing at different energy levels

The vertical acceleration of aggregate particles in concrete during external revibration of small slabs on a vibrating table described in "Revibration Methods" of Appendix D is shown in Figure C-34 as a fraction of the acceleration of gravity, *g*, for specimens with and without a dead weight on the concrete surface. Inasmuch as the vibration energy is introduced into the specimen through the bottom of the formwork, the acceleration decreases with increasing distance from the bottom. However, placement of a steel plate on the concrete surface markedly reduced this tendency and resulted in a more uniform distribution of the revibration energy.

The results of accelerometer measurements at the center of the large slabs that were surface-revibrated at an 80-percent energy level are shown in Figures C-35 and C-36. The data obtained at a 20-percent energy level are shown in Figures C-37 and C-38. Generally, the acceleration decreases with increasing distance from the concrete surface (see Figs. C-35 and C-37). However, particularly at the high energy level, revibration is transmitted from the surface screed through the sides of the formwork that supports the screed into the bottom plate of the formwork Consequently, the concrete at the bottom of the specimen is accelerated more than the regions at midheight of the specimen. It is likely that the amount of revibration energy that may be transmitted through the sides of the formwork decreases as the width of the slab is increased and, therefore, may be negligible in actual bridge decks. Figures C-36 and C-38 show that the acceleration at the center of the slabs decreases as the distance of the vibrating

TABLE C-11

EFFECT OF SURFACE REVIBRATION ON UNIT WEIGHT, COMPRESSIVE STRENGTH AND RELATIVE DYNAMIC MODULUS OF CONCRETE SLABS, SERIES C (SAME SPECIMENS AS SERIES 1)—PHASE 2

Specimen Designation	Revibration (%)	Unit Weight (lbs/ft^3)	From Cores Compressive Strength (psi)	From Pulse Velocity Relative Dynamic Modulus of Elasticity***
SUI-SE-0	none	142.4*	5800*	1.00**
SUI-SE-20	20	141.4	5760	0.98
SUI-SE-80	80	143.5	6050	1.06
SUI-ME-0	none	-	-	1.00
SUI-ME-20	20	-	-	1.04
SUI-ME-80	80	-	-	1.08
SUI-SL-0	none	-	-	1.00
SUI-SL-20	20	-	-	0.96
SUI-SL-80	80	-	-	1.06

*average of 6 values
**average of 21 readings
***The relative dynamic modulus of elasticity given above corresponds to the ratio of V_n^2/V_1^2 where V_n is the sonic velocity determined for the slab in question while V_1 is the average sonic velocity through the non-revibrated slab within each group.

TABLE C-12

EFFECT OF SURFACE REVIBRATION ON AIR VOID CHARACTERISTICS OF CONCRETE, SERIES 10—PHASE 2

Specimen Designation	Section	Distance From Bottom (in)	Revibration (%)	Air Content No Rev. (%)	Air Content Rev. (%)	Paste Content No Rev. (%)	Paste Content Rev. (%)	Spacing Factor No Rev. (in.)	Spacing Factor Rev. (in.)
SU-10-NO-20	A	6.00	20	4.02	3.51	35.0	38.2	0.0068	0.0074
	B	5.75		5.50	5.10	22.1	29.2	0.0064	0.0058
	C	5.50		6.22	5.82	20.0	18.4	0.0062	0.0068
	D	5.25		5.90	6.18	24.9	27.1	0.0066	0.0061
	E	5.00		5.55	5.82	23.8	25.2	0.0070	0.0074
	F	3.00		5.38	5.18	24.4	22.3	0.0066	0.0063
	G	1.00		5.38	5.88	22.0	24.2	0.0073	0.0069
Air Content From Pressure Method			6.10%						
SU-10-NO-50	A	6.00	50	4.62	2.93	38.7	43.4	0.0067	0.0078
	B	5.75		4.93	4.24	20.5	22.8	0.0069	0.0068
	C	5.50		4.40	5.58	23.3	23.9	0.0068	0.0057
	D	5.25		4.24	4.56	24.4	23.3	0.0088	0.0066
	E	5.00		3.99	4.30	21.3	22.6	0.0078	0.0066
	F	3.00		5.44	4.12	25.6	25.2	0.0063	0.0083
	G	1.00		6.35	5.00	31.2	24.7	0 0061	0.0072
Air Content From Pressure Method			5.8%						
SU-10-NO-80	A	6.00	80	3.20	3.00	35.5	41.6	0.0073	0.0079
	B	5.75		4.15	4.50	23.6	26.6	0.0088	0.0059
	C	5.50		3.65	5.25	22.6	25.8	0.0074	0.0053
	D	5.25		4.10	4.40	24.4	23.2	0.0079	0.0067
	E	5.00		4.60	4.75	25.6	24.2	0.0060	0.0069
	F	3 00		4.90	4.50	24.1	23.2	0.0076	0.0074
	G	1.00		4 36	4.35	25.3	21.4	0.0069	0.0068
Air Content From Pressure Method			5.8%						

screed from the center increases. However, surface revibration is still noticeable, even if the screed is 3 ft away from the center.

A comparison of the accelerometer measurements at the 20-percent and 80-percent energy level indicates that the acceleration of aggregate particles in fresh concrete varies approximately linearly with the centrifugal force of the vibrator. The accelerometer measurements were useful in selecting the revibration parameters for this investigation and gaining an insight into the distribution of revibration energy in the concrete. However, the required experimental setup and the precautions necessary to obtain reliable data prohibit extensive use of accelerometer tests as a measure of the required revibration energy for concrete in the field.

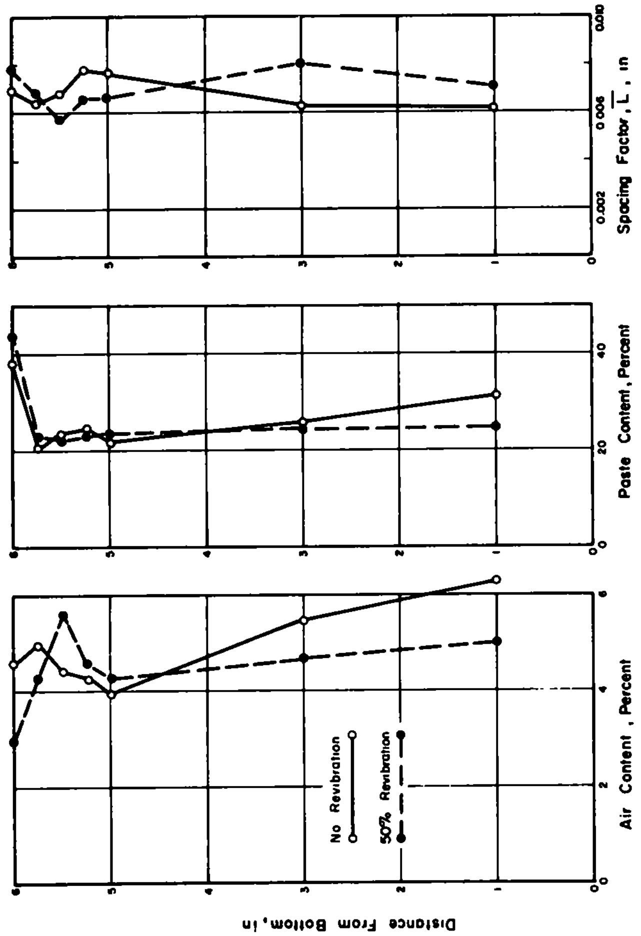


Figure C-32 Effect of surface revibration on air void characteristics of concrete. Energy level: 50 percent.

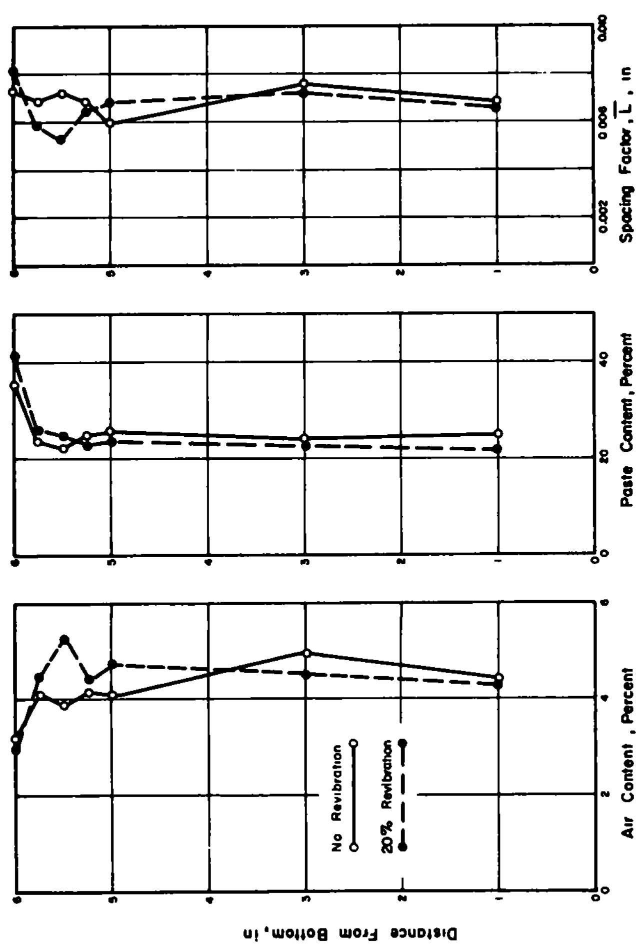


Figure C-31. Effect of surface revibration on air void characteristics of concrete. Energy level: 20 percent.

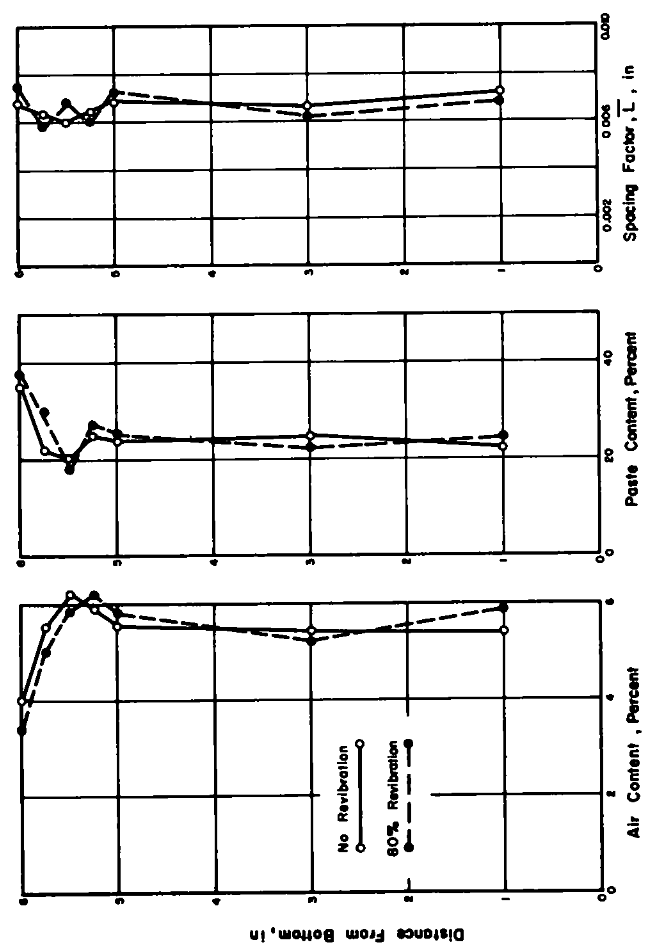


Figure C-33 Effect of surface revibration on air void characteristics of concrete. Energy level: 80 percent

TABLE C-13

EFFECT OF EXTERNAL REVIBRATION ON AIR VOID CHARACTERISTICS OF CONCRETE, SERIES 1A AND 2C—PHASE 3A

Section	Distance From Bottom (in.)	Series 1A Normal Air - Retarder						Series 2C Normal Air - No Retarder					
		Air Content		Paste Content		Spacing Factor		Air Content		Paste Content		Spacing Factor	
		No Rev. (%)	Rev. (%)	No Rev. (%)	Rev. (%)	No Rev. (in.)	Rev. (in.)	No Rev. (%)	Rev. (%)	No Rev. (%)	Rev. (%)	No Rev. (in.)	Rev. (in.)
		*	**	*	**	*	**	+	++	+	++	+	++
A	6.00	3.85	5.00	30.7	29.5	0.0070	0.0069	4.0	4.6	32.0	31.8	0.0064	0.0066
C	5.50	-	5.15	-	21.9	-	0.0071	-	-	-	-		
D	5.25	-	5.05	-	26.8	-	0.0073	-	-	-	-		
E	5.00	5.82	5.60	21.0	22.4	0.0077	0.0072	5.2	5.8	20.9	23.1	0.0059	0.0056
F	3.00	6.20	5.10	25.3	24.3	0.0072	0.0075	5.4	6.0	24.4	24.6	0.0059	0.0062
G	1.00	6.10	5.56	26.6	23.0	0.0065	0.0070	6.1	6.0	25.2	21.0	0.0060	0.0064
Average Air Content, % From Pressure Method		5.8	6.3					6.5	6.4				

*Specimen 1A-4-8
**Specimen 1A-1-7; T_1 = 2 hours; e_2 = 25 sec.
+Specimen 2C-1-8
++Specimen 2C-2-1, T_1 = 2 hours e_2 = 25 sec.

TABLE C-14

EFFECT OF EXTERNAL REVIBRATION ON AIR VOID CHARACTERISTICS OF CONCRETE, SERIES 2A AND 2B—PHASE 3A

Section	Distance From Bottom (in.)	Series 2A Low Air - Retarder						Series 2B Low Air - No Retarder					
		Air Content		Paste Content		Spacing Factor		Air Content		Paste Content		Spacing Factor	
		No Rev. (%)	Rev. (%)	No Rev. (%)	Rev. (%)	No Rev. (in.)	Rev. (in.)	No Rev. (%)	Rev. (%)	No Rev. (%)	Rev. (%)	No Rev. (in.)	Rev. (in.)
		*	**	*	**	*	**	+	++	+	++	+	++
A	6.00	3.1	2.9	29.1	30.2	0.0094	0.0114	2.9	2.7	31.0	29.9	0.0089	0.0100
E	5.00	3.7	4.4	23.1	24.1	0.0114	0.0112	3.9	3.6	22.7	23.0	0.0123	0.0104
F	3.00	4.2	3.8	24.5	23.9	0.0123	0.0092	3.3	3.4	24.6	22.7	0.00117	0.0117
G	1.00	4.1	4.0	22.9	22.0	0.0096	0.00122	3.3	3.9	23.0	23.7	0.00137	0.0094
Average Air Content, % From Pressure Method		4.5	4.9					4.4	4.5				

*Specimen 2A-3-8
**Specimen 2A-2-6, T_2 = 4 hours, e_2 = 25 sec.
+Specimen 2B-1-7
++Specimen 2B-2-2, T_2 = 4 hours, e_2 = 25 sec.

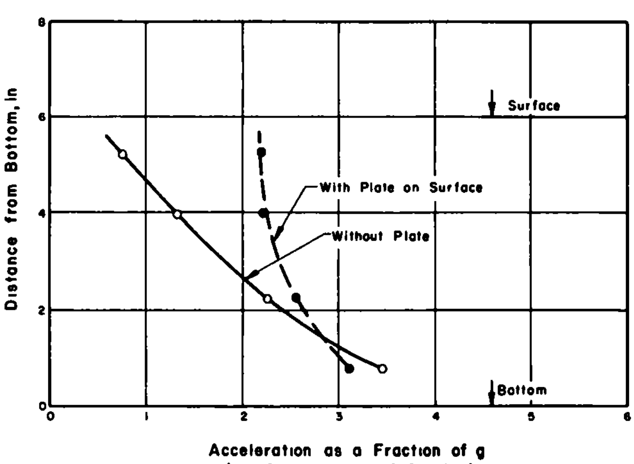


Figure C-34 Distribution of acceleration during revibration. External revibration of specimen 22 by 22 by 6 in.

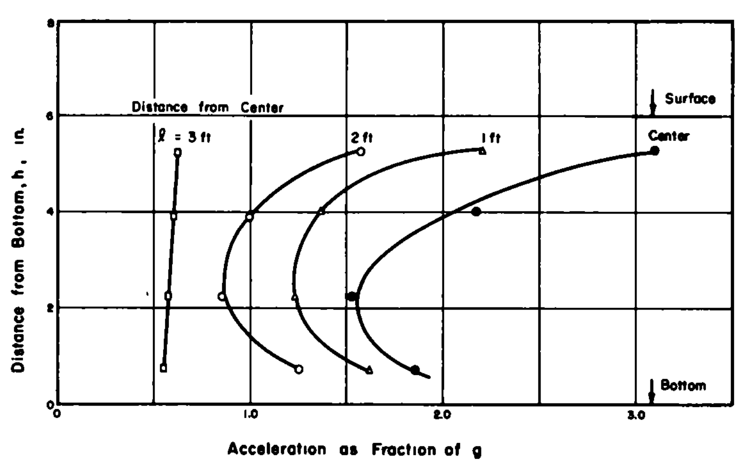


Figure C-35. Distribution of acceleration during revibration. Surface revibration of specimen 3 ft by 8 ft by 6 in. Energy level: 80 percent

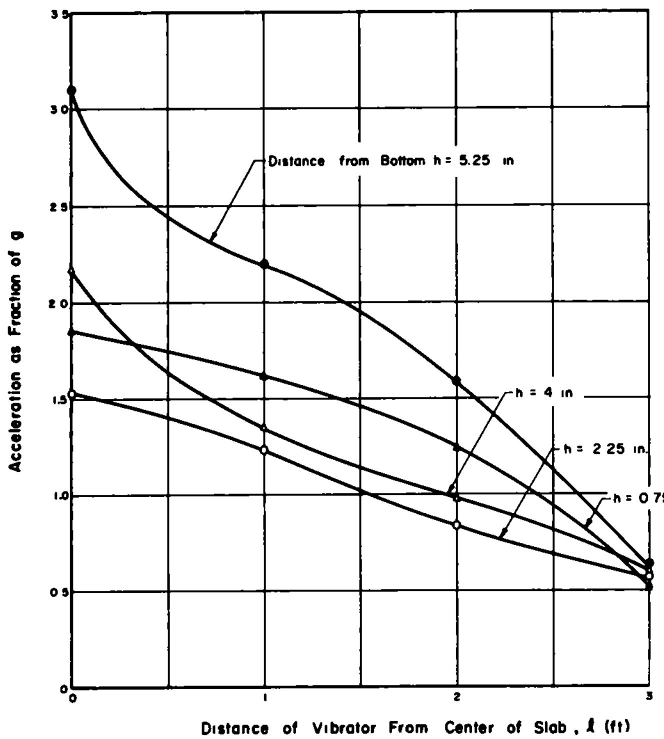


Figure C-36. Acceleration during revibration as function of position of vibrator. Surface revibration of specimen 3 ft by 8 ft by 6 in. Energy level 80 percent.

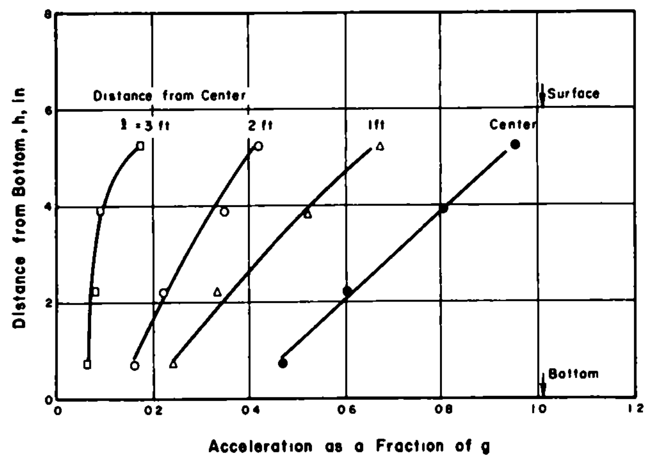


Figure C-37 Distribution of acceleration during revibration Surface revibration of specimen 3 ft by 8 ft by 6 in. Energy level. 20 percent

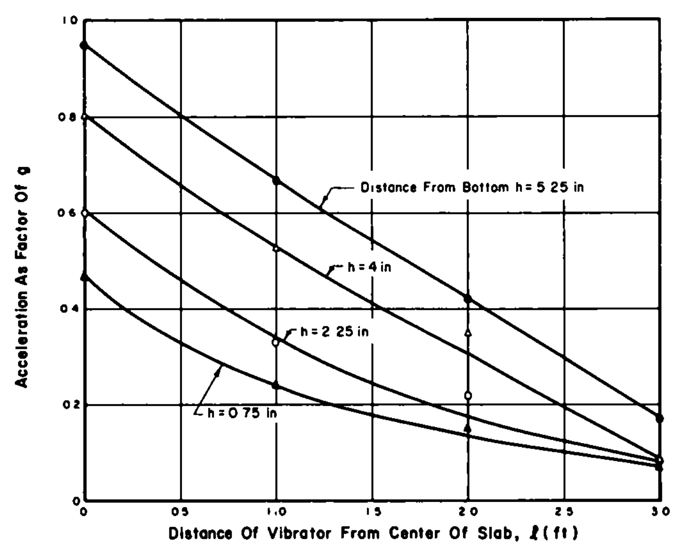


Figure C-38 Acceleration during revibration as function of position of vibrator Surface revibration of specimen 3 ft by 8 ft by 6 in. Energy level: 20 percent.

APPENDIX D

DURABILITY STUDIES—PHASE 3

OBJECTIVE AND SCOPE

Phases 3a and 3b

The durability studies were divided into two subphases The objective of Phase 3a was to conduct a general survey of the effect of revibration on freeze-thaw durability and abrasion resistance of concrete For Phase 3b the results obtained from Phase 2 and Phase 3a were then used to select the parameters to be studied on large slabs as models of actual reinforced concrete bridge decks

Phase 3a is divided into five subseries. Within each series the age of concrete at the time of revibration as well as the revibration energy level were varied However, different concrete properties were investigated for each subseries The following subseries were studied.

- Series 1A: Retarded concrete, air content between 5.5 and 7 percent, reinforced specimens.
- Series 2A: Retarded concrete, air content between 4 and 5 percent, reinforced specimens.
- Series 2B: Nonretarded concrete, air content between 4 and 5 percent, reinforced specimens.
- Series 2C: Nonretarded concrete, air content between 5.5 and 7 percent, reinforced specimens
- Series 3: Retarded concrete, air content between 5.5 and 7 percent, specimens without reinforcement.

Phase 3b consisted of five subseries.

- Series 1D. Revibration energy and extent of initial cracking.
- Series 2D: Time of initial set
- Series 3D. Effect of plane-of-weakness cracks.
- Series 4D: Effect of air content
- Series 5D: Finishing procedures.

One hundred specimens were tested in Phase 3a. In Phase 3b, 22 specimens were investigated

The test data showed a pronounced difference in the freeze-thaw resistance of retarded and nonretarded concrete. To further investigate this observation plain concrete prisms 3 by 3 by 15 in. were subjected to freezing and thawing while exposed to deicing salts. Both retarded as well as nonretarded and revibrated and nonrevibrated concretes were studied.

DESCRIPTION OF SPECIMENS

Phase 3a

In Phase 3a plain and reinforced specimens 22 by 22 by 6 in. were used. The layout of the reinforcement is shown in Figure D-1.

The specimens were designated by a sequence of terms describing the test series, the age at revibration, T, and the revibration energy level, e. The following values were chosen for T and e

T_1 = revibration 2 hr after mixing,
T_2 = revibration 4 hr after mixing;
T_3 = revibration 5 hr after mixing,
e_1 = duration of revibration 10 sec;
e_2 = duration of revibration 25 sec, and
e_3 = duration of revibration 40 sec

Control specimens used to determine air void distribution and abrasion resistance are designated "C." The particular properties of each specimen tested in Phase 3a are summarized in Table D-1.

Phase 3b

In Phase 3b reinforced concrete slabs 8 ft by 3 ft by 6 in. were tested. The reinforcement pattern was similar to the layout for the Phase 2 specimens, as described in Appendix C and shown in Figure C-2. All specimens are described in Tables D-2 and D-3

MATERIALS AND MIX PROPORTIONS

The same materials and mix proportions that were used for the Phase 2 specimens also were used for the specimens in Phase 3. They are described in Appendix C

FABRICATION OF SPECIMENS

Phase 3a

The test slabs 22 by 22 by 6 in. were cast in rigid steel forms. The layout of the reinforcement is shown in Figure D-1. A concrete cover of 1½ in. was maintained throughout this phase. The mixing and casting procedures employed were as follows

An 8-cu-ft batch was mixed in a batch plant with a horizontal tub mixer. The dry ingredients were mixed for 1 min before some water containing the air-entraining agent and additional water containing the retarder were added. The wet mixture was then mixed for 3 additional minutes. The concrete was placed in each form and initially vibrated on a vibrating table for approximately 15 sec. Because the volume required for each subseries was larger than the capacity of the mixer, several batches had to be cast for each series, as indicated in Table D-1.

Control slabs to determine abrasion resistance and air content distribution as well as compression test cylinders to determine the 28-day strength of the concrete were cast with most batches.

All specimens were struck off and finished with an aluminum trowel immediately after casting They were covered with wet burlap approximately 7 hr after mixing. The specimens were then moist-cured for an additional

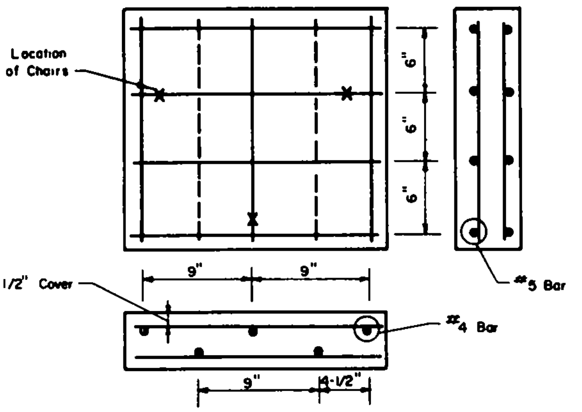


Figure D-1 Layout of reinforcement—Phase 3a

6 days. The moist-curing period was followed by 14 days of air drying at a relative humidity of 50 percent and a temperature of 70 F. During this drying period rubber strips were attached to the surface of the specimens to form dikes. The specimens were ponded with tap water approximately 2 days before exposure to freezing and thawing at an age of 21 days.

Phase 3b

For most of the specimens tested in Phase 3b the casting procedures already described for the Phase 2 specimens in Appendix C were used. All specimens were moist-cured up to an age of 7 days. They were then dried for an additional 14 days at a relative humidity of 50 percent and a temperature of 70 F. Prior to freezing and thawing, rubber strips were glued on the concrete surface and the specimens were ponded with tap water 2 days before exposure to freezing and thawing at an age of 21 days.

TEST PROCEDURES

Finishing

All specimens tested in Phase 3a were finished with an aluminum trowel immediately after casting. No additional finishing after revibration was employed. The same procedure was used for the specimens of Phase 3b except for the slabs of Series 5D. If properly conducted, revibration with a surface screed resulted in a smooth finish. Because each additional finishing step tends to reduce the air content of the surface mortar, the initial hand-finishing was omitted for some specimens of Series 5D and finishing was obtained only by surface revibration. In the same series some specimens were tested that were not finished prior to revibration but were finished with an aluminum trowel after revibration.

Revibration Methods

The specimens tested in Phase 3a were revibrated externally on a vibrating table. For this, the same vibrator that was used for the surface screed was attached to the vibrating table. An eccentricity of 80 percent (corresponding to a centrifugal force of 720 lb) and a frequency of 3,200 cpm were kept constant. Revibration energy was varied by changing the duration of vibration between 10 and 40 sec. During revibration the formwork containing

TABLE D-1

DURABILITY STUDIES—PHASE 3A DESCRIPTION OF SPECIMENS

Series	Batch	Air Content %	Retarder	Reinforced	Time of Revibration, T and Duration of Revibration, e for Specimen No. 1	2	3	4	5	6	7	8	Initial Set (Hours)	f'_c 28 (psi)
1A	1	6.3	yes	yes	C	T_1, e_3	T_2, e_3	$T_3; e_1$	T_3, e_2	T_3, e_3	$T_1; e_2$	-	8:10	5650
	2	6.5			T_1, e_3	C	T_2, e_3	$T_3; e_1$	$T_3; e_2$	$T_3; e_3$	$T_2; e_2$	-	8:20	4950
	3	5.5			$T_1; e_3$	$T_2; e_3$	C	$T_3; e_1$	T_3, e_2	T_3, e_3	$T_1; e_1$	-	8:10	5760
	4	5.8			$T_1; e_1$	$T_1; e_2$	$T_2; e_3$	C	$T_1; e_3$	$T_2; e_1$	T_2, e_2	C	-	5880
	5	6.3			$T_2; e_1$	T_2, e_1	$T_2; e_2$	$T_1; e_1$	C	$T_1; e_2$	C	-	6:00	4410
2A	1	5.7	yes	yes	C	T_1, e_1	$T_2; e_1$	C	T_2, e_2	$T_1; e_1$	$T_2; e_1$	-	6:50	5700
	2	4.9			$T_1; e_2$	$T_2; e_2$	$T_1; e_1$	$T_2; e_1$	$T_1; e_2$	$T_2; e_2$	T_1, e_2	-	6:40	6255
	3	4.5			C	$T_1; e_1$	$T_2; e_1$	T_1, e_2	$T_2; e_2$	$T_1; e_1$	$T_2; e_1$	C	-	5680
2B	1	4.4	no	yes	C	$T_1; e_1$	C	$T_1; e_2$	C	$T_1; e_1$	C	-	3:45	4950
	2	4.5			$T_1; e_2$	T_2, e_2	$T_1; e_1$	C	T_1, e_2	C	C	-	3:30	5210
2C	1	6.5	no	yes	C	$T_1; e_1$	T_2, e_1	$T_1; e_2$	T_2, e_2	T_1, e_1	$T_2; e_1$	C	3:45	4240
	2	6.4			$T_1; e_2$	T_2, e_2	T_1, e_1	T_2, e_1	T_1, e_2	$T_2; e_2$	C	-	-	3900
3	1	5.8	yes	no	C	T_1, e_1	T_2, e_1	T_1, e_2	$T_2; e_2$	$T_1; e_1$	$T_2; e_1$	-	8:00	5650
	2	5.8			$T_1; e_2$	$T_2; e_2$	T_1, e_1	T_2, e_1	T_1, e_2	$T_2; e_2$	C	-	8:20	5580

Time of Revibration

T_1 = 2 hrs. after casting

T_2 = 4 hrs.

T_3 = 5 hrs.

Duration of Revibration

e_1 = 10 sec.

e_2 = 25 sec.

e_3 = 40 sec.

TABLE D-2

DURABILITY STUDIES—PHASE 3B. DESCRIPTION OF SPECIMENS, SERIES 1D, 2D, 3D, AND 4D

No.	Specimen Designation	Air Content (%) 1st Batch	Air Content (%) 2nd Batch	Initial Set (hr min)	Cracking Type	Cracking Time After Mixing (hr min)	Cracking Max. Defl. at Midspan (in)	Revibration Type	Revibration Time After Mixing (hr min)	Revibration Energy Level (%)	$f'_{c\,28}$ (psi)
Series 1D-Revibration Energy and Extent of Initial Cracking											
41	SUD-SL-0	5.7	5.7	7 30	Slight	2 00	1 1/4	None	-	-	-
42	SUD-SL-0	5 5	5.5	7 00	Slight	2 00	1 1/4	Surface	4 00	20	-
60	SUD-SE-0	5.9	6.3	5 55	Severe	2 00	3 1/2	None	-	-	5250
61	SUD-SE-80	6.0	6.6	5 30	Severe	2 00	3 1/2	Surface	4 00	80	5420
64	SUD-SE-0	5.9	5.8	7 00	Severe	2 00	3 1/2	None	-	-	5700
65	SUD-SE-80	6.8	6.4	7 20	Severe	2 00	3 1/2	Surface	4 00	80	5780
94	SUD-SE-0A	6.0	6.3	6 30	Severe	2 00	3 1/2	None	-	-	5210
95	SUD-SE-80A	6.0	6.5	6 45	Severe	2 00	3 1/2	Surface	4.00	80	5700
Series 2D-Time of Initial Set											
79	SU-4D-SE-0	6.0	6.2	3 15	Severe	2 00	3 1/2	None	-	-	4740
80	SU-4D-SE-80	5.9	5.5	3 30	Severe	2 00	3 1/2	Surface	3 00	80	4490
90	SLD-RET	6.6	6.6	7 15	None	-	-	None	-	-	5660
91	SLD-NON	6.9	6.8	4 10	None	-	-	None	-	-	4070
Series 3D-Effect of Plane of Weakness Cracks											
81	SU-7D-SE-0-2	6.1	6.3	6 30	Severe & Horizontal	2 00	3 1/2	None	-	-	5560
82	SU-7D-SE-80-2	6.5	7.0	6 20	Severe & Horizontal	2 00	3 1/2	Surface	4:00	80	5100
Series 4D-Effect of Air Content											
98	SDH-FIN-0	8.0	8.0	-	Severe	2 00	3 1/2	None	-	-	4850
99	SDH-STR-80	7.8	8.4	7 15	None	-	-	Surface	4 00	80	4900

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TABLE D-3

DURABILITY STUDIES—PHASE 3B. DESCRIPTION OF SPECIMENS, SERIES 5D: FINISHING PROCEDURES

No.	Specimen Designation	Air Content (%) 1st Batch	Air Content (%) 2nd Batch	Initial Set (hr:min)	Cracking Type	Cracking Time After Mixing (hr·min)	Cracking Max. Defl. at Midspan (in)	Revibration Type	Revibration Time After Mixing (hr:min)	Revibration Energy Level (%)	Finishing	f'_{c28}(psi)
92	SU-D-STR-0	6.1	6.4	6:30	None	-	-	None	-	-	None	5410
93	SU-D-STR-80	6.7	6.3	7:05	None	-	-	Surface	4:00	80	None	5780
97	SDN-STR-80	6.0	6.4	6:55	None	-	-	Surface	4·00	80	None	5320
100	SU-D-SE-0-LF	5.8	6.2	8.15	None	-	-	None	-	-	After 4 1/2 Hours	5520
101	SU-D-SE-80-LF	6.8	6.5	8:15	Severe	4:00	3 1/2	Surface	4:20	80	After Revibration	5410

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the concrete was rigidly attached to the vibrating table. A steel plate generating a vertical static pressure of 0 3 psi was placed on the concrete surface during the revibration process. This method proved to be necessary in order to avoid the development of surface cracks during revibration which may have been caused by the relative movement of the concrete with respect to the reinforcing bars. In addition, the steel plate ensured revibration of the surface layers of the concrete and resulted in a more uniform distribution of revibration energy, as indicated in Appendix C.

For the specimens of Phase 3b a surface screed as described in "Revibration Methods" of Appendix C was used for revibration.

Freeze-Thaw Testing

During freeze-thaw testing of all specimens in Phase 3a and Phase 3b, the specimens remained ponded with a 4-percent sodium chloride solution that was replaced only at the time of the rating of scaling. The solution was contained by rubber chamfer stripping cut to size and attached to the specimens by means of plastic rubber cement. Because the specimens within Phase 3b were deflected prior to hardening, their surface was curved. Therefore, the surface was subdivided into three sections, and each section was ponded separately as shown in Figure D-2. All specimens were subjected to cycles of freezing and thawing in an environmental testing unit as described by Callahan et al. (*5*). This unit was designed to allow the removal of two 4- × 12-ft roof sections, by use of an overhead crane, thereby permitting direct placement by crane of the slabs into their respective locations. Up to 30 small slabs from Phase 3a and up to 6 large slabs from Phase 3b could be tested simultaneously. During freezing and thawing the small slabs were supported along two lines approximately 15 in. apart. The large slabs were supported approximately 5 in. from their ends. The environmental test-

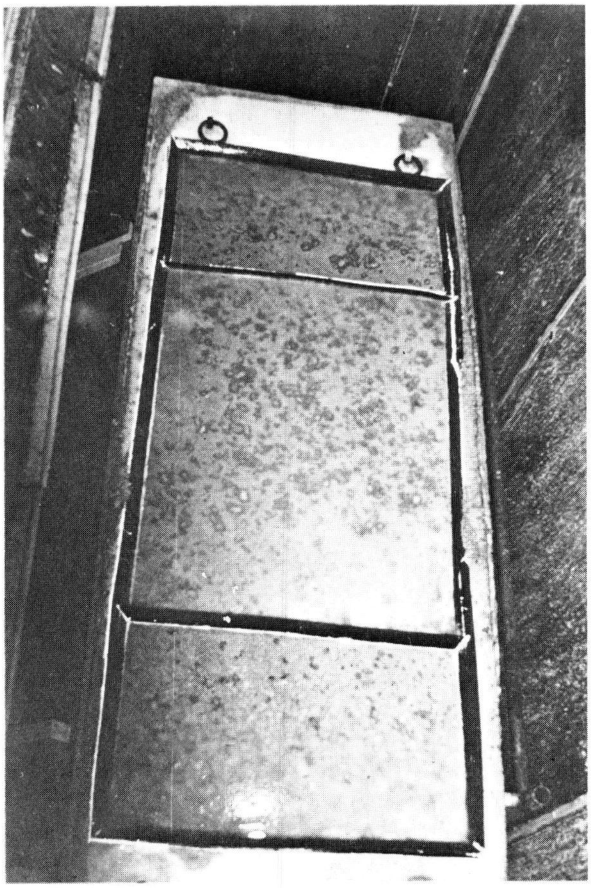


Figure D-2. Ponded slab for freeze-thaw tests—Phase 3b.

ing unit was programmed in such a way that the specimens were subjected to one freezing and thawing cycle per day, with internal concrete temperatures ranging from 0 F to 40 F. The temperature was monitored by thermocouples embedded in the center of a control specimen.

After every seven cycles each specimen was removed from the testing unit, hosed off, and then rated according to the following numerical scale:

0 = no scale;
1 = scattered spots of very light scale;
2 = scattered spots of light scale;
3 = light scale over about half the surface;
4 = light scale over most of the surface;
5 = light scale over most of the surface, a few moderately deep spots;
6 = scattered spots of moderately deep scale;
7 = moderately deep scale over half the surface;
8 = moderately deep scale over the entire surface;
9 = scattered spots of deep scale, remainder moderately deep scale; and
10 = deep scale over the entire surface.

A similar rating scale has been used in two previous investigations conducted at the University of Illinois (*5, 6*). A scaling was considered to be *very light* when it consisted of loss of a paper-thin film of mortar from the finished surface. *Light scaling* occurred when particles of mortar generally 1/8- to 1/4-in. in thickness were lost. Scaling was described as *moderate* when additional mortar was removed together with smaller aggregate particles. Surface deterioration resulting from "pop-out" was also considered to be scaling. *Deep scaling* was said to have occurred when larger aggregate particles could easily be removed from the scaled surface at the time of rating.

Photographs of the specimens were taken in addition to according the rating. For the small slabs of Phase 3a one photograph was taken per specimen. For the specimens in Phase 3b each specimen was subdivided into eight subareas, and photographs were taken for each area.

Immediately following the rating, the specimens were again ponded with a 4-percent sodium chloride solution; then, freezing and thawing cycles were resumed. In most cases, the periodic rating of specimens continued until the ratings became high enough to denote failure of the surface. In a number of instances testing had to be interrupted for comparatively short periods to repair leaking dikes.

The small prisms 3 by 3 by 15 in. were tested in an automatic freezing and thawing cabinet. The test procedure used for these tests was similar to the procedure described in ASTM C 290, except that all specimens were frozen and thawed in a 4-percent sodium chloride solution. Earlier tests had shown that freeze-thaw deterioration was concentrated mainly on the surface of the specimen. Therefore, the specimens showed an appreciable weight loss but a less pronounced change in the dynamic modulus. Therefore, weight loss during freezing and thawing was used as the only measure of concrete deterioration. The concrete prisms were hosed off, surface-dried, and weighed approximately every 20 cycles. The tests were discontinued after 140 cycles, at which time the specimens were photographed.

Determination of Air Content

The same procedures for determination of air content described for the tests in Phase 2 were employed for the studies in Phases 3a and 3b.

Determination of Abrasion Resistance

The abrasion resistance of revibrated and nonrevibrated concrete was determined in accordance with the test method described in ASTM C 418-68. Cores with a diameter of 4 in. were taken from the large slabs 8 ft by 3 ft by 6 in. The cores were then brought to a saturated-surface-dry state, and the specimens were tested in a sandblast cabinet. After each test the specimens were washed and weighed to determine the amount of material abraded. A total of five tests was conducted on each core.

EXPERIMENTAL RESULTS

Influence of Revibration on the Durability Characteristics of Uncracked Concrete—Phase 3a

The main variables to be studied in Series 1A and 2A were the age of concrete at the time of external revibration, *T*, the duration of revibration, *e*, and the air content. In Figure D-3 the surface deterioration ratings of retarded concrete with an air content varying from 5.5 to 6.5 percent are shown as a function of the number of cycles of freezing and thawing. Each curve represents the average of two to four similar specimens. The results of the individual tests appear in Appendix F.

Figure D-3 shows that external revibration conducted 2 hr after mixing may slightly improve the frost resistance of concrete. A similar trend is found in Figure D-4, which shows the surface deterioration ratings of retarded concrete with an air content ranging from 4 5 to 4.9 percent However, owing to the considerable scatter of the individual data the difference between revibrated and nonrevibrated concrete is statistically insignificant and is overshadowed by batch to batch variations in the air content of the concrete. The same is true for the effect of duration of revibration and age of concrete at the time of revibration on concrete durability. The influence of the air content on the surface deterioration of concrete after 21 cycles is shown in Figures D-5 and D-6. Surface deterioration decreased as the air content increased; however, no clear distinction between revibrated and nonrevibrated concrete can be made

Figure D-7 shows the results of the freezing and thawing tests on nonretarded concrete (Series 2B and 2C) with air contents of 4.5 and 6.5 percent, respectively. No statistically significant difference between revibrated and nonrevibrated concrete was found. However, the nonretarded concrete was considerably more durable than retarded concrete. The characteristics of the air void systems of retarded and nonretarded as well as revibrated and nonrevibrated concrete are summarized in Tables C-13 and C-14. External revibration had no marked effect on air content, spacing factor, and paste content of the surface layers of the concrete. However, in all observed cases, the spacing factor of the retarded concrete was slightly larger than that of the nonretarded concrete, which may at least in part be responsible for the differences in the surface durability of the two concretes. Differences in the time of finishing or revibration relative to the time of initial set between retarded and nonretarded concrete are probably not responsible for the differences in durability, inasmuch as variations in the time of revibration for a given concrete had no significant influence on surface deterioration of the retarded concrete or of the nonretarded concrete It also should be noted that both the air-entraining agent and the retarder were considered compatible and were added separately to the fresh concrete mix.

In Series 3 of Phase 3b, unreinforced retarded concrete specimens were subjected to freezing and thawing. This test series was included in the investigation because it was expected that cracks would be less likely to develop due to early shrinkage in unreinforced specimens than in reinforced specimens. Consequently, revibration should have less influence on the surface deterioration of plain concrete than it might have on reinforced specimens. Figure D-8 shows that the unreinforced specimens were more durable than the reinforced specimens However, no convincing explanation for this unexpected difference can be given

Typical examples of the type of surface deterioration

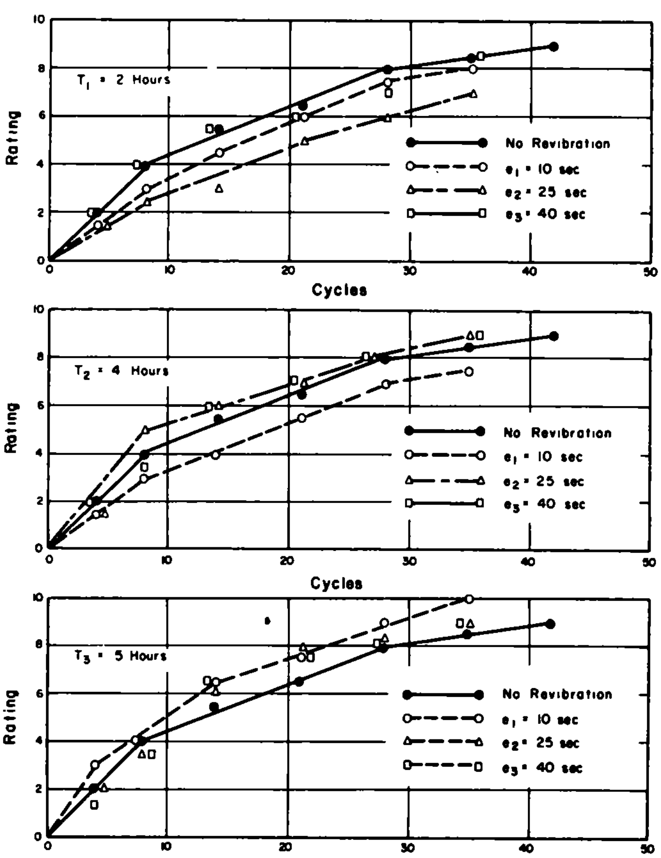


Figure D-3. Influence of external revibration on surface deterioration of reinforced, retarded concrete Air content of concrete: 5 5 to 6 5 percent Series 1A—Phase 3a

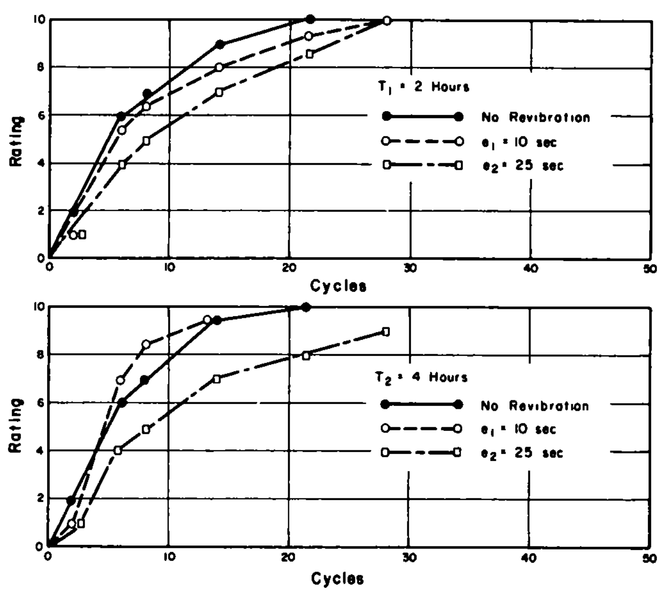


Figure D-4 Influence of external revibration on surface deterioration of reinforced, retarded concrete. Air content. 4 5 to 4.9 percent Series 2A—Phase 3a.

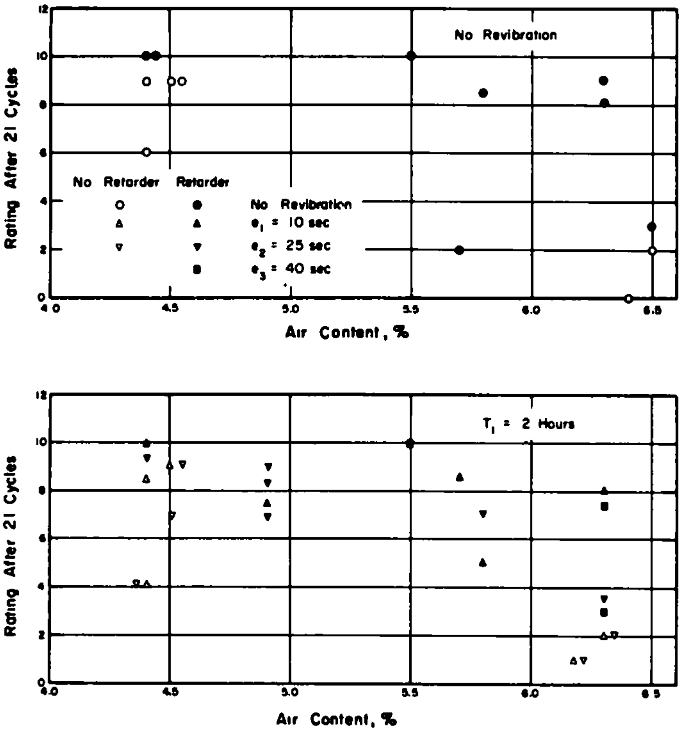


Figure D-5. Effect of air content of concrete on surface deterioration after 21 freezing and thawing cycles Series 1A, 2A, 2B, and 2C—Phase 3a.

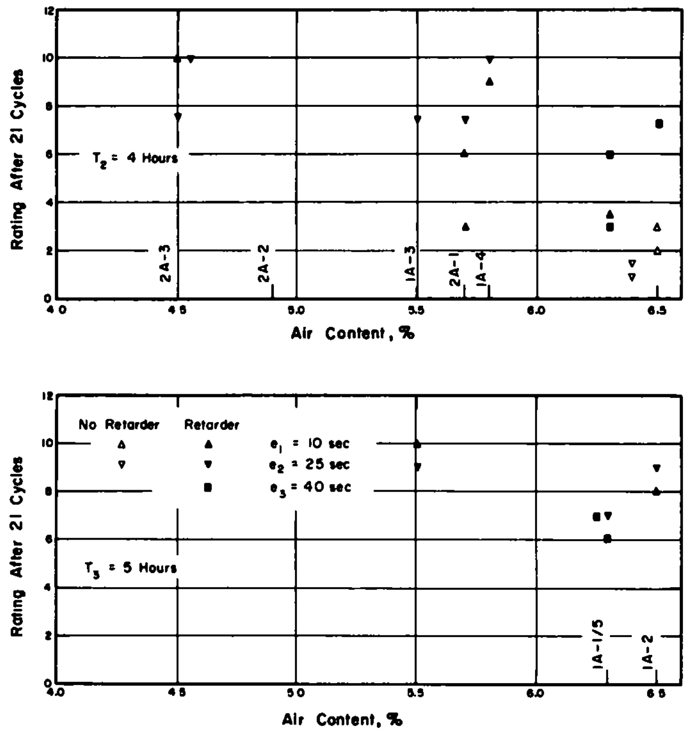


Figure D-6. Effect of air content of concrete on surface deterioration after 21 freezing and thawing cycles Series 1A, 2A, 2B, and 2C—Phase 3a.

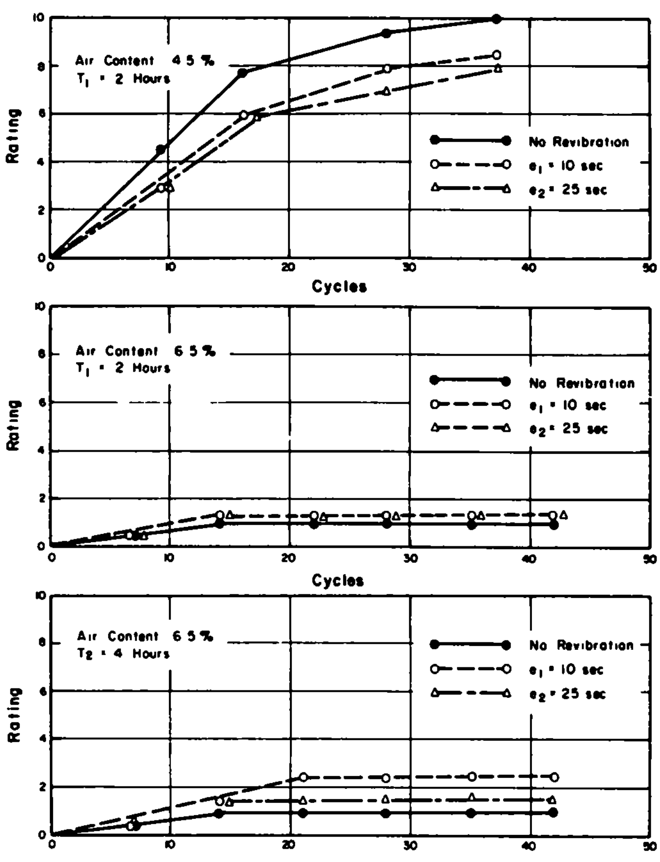


Figure D-7. Influence of external revibration on surface deterioration of reinforced, nonretarded concrete Series 2B and 2C—Phase 3a.

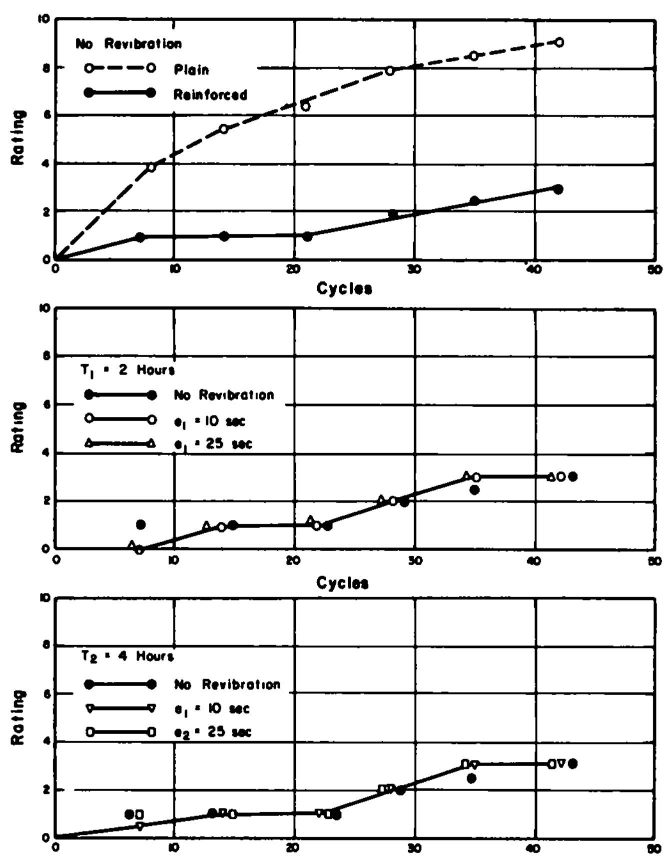


Figure D-8 Influence of external revibration on surface deterioration of plain, retarded concrete. Series 3—Phase 3a.

observed in Phase 3b are shown in Figure D-9. In all cases the deterioration consisted of spotty scaling and was independent of the location of the reinforcement.

Influence of Revibration on the Durability of Cracked Concrete Slabs—Phase 3b

Effect of Extent of Cracking and Revibration Energy (Series 1D and 3D)

Figure D-10 shows the average surface deterioration ratings of concrete slabs that were cracked to various degrees 2 hr after mixing. The individual data obtained in the tests in Phase 3b appear in Appendix F. There is no clear indication that surface cracking or horizontal plane-of-weakness cracking resulted in reduced durability of the concrete surface when it was exposed to accelerated freezing and thawing in the laboratory. In uncracked slabs, uniformly distributed scaling was observed. Scaling of the cracked slabs was slightly more pronounced in the vicinity of the cracks for approximately 14 freeze-thaw cycles; then, scaling was essentially uniform. No surface spalling was observed.

The surface durability of surface-revibrated cracked slabs and cracked slabs without revibration is shown in Figure D-11. The relationship between deterioration rating and number of freeze-thaw cycles for concrete without revibration shown in Figure D-11 corresponds to the average of all data from Figure D-10. Figure D-10 shows that revibrated slabs performed better than did unrevibrated specimens. A statistical evaluation of all data showed, however, that the difference between the average of all revibrated and all nonrevibrated slabs is not statistically significant. It can be stated that revibration does not impair concrete durability, despite the fact that the spacing factor of the surface layer may be slightly increased by revibration, as is shown in "Effect of Revibration on Air Void Characteristics of Concrete (Series 10 and Phase 3b)" in Appendix C. It is likely that the increase in spacing factor is offset by the improved compaction and strength of the concrete surface layers. A similar observation has been reported by Malisch et al. (*6*).

The only type of deterioration observed in these tests was scaling. Typical views of the concrete surface after various cycles of freezing and thawing are shown in Figures D-12 and D-13. The cracked slabs showed more deterioration in the vicinity of the cracks, whereas the revibrated slabs deteriorated uniformly over the surface.

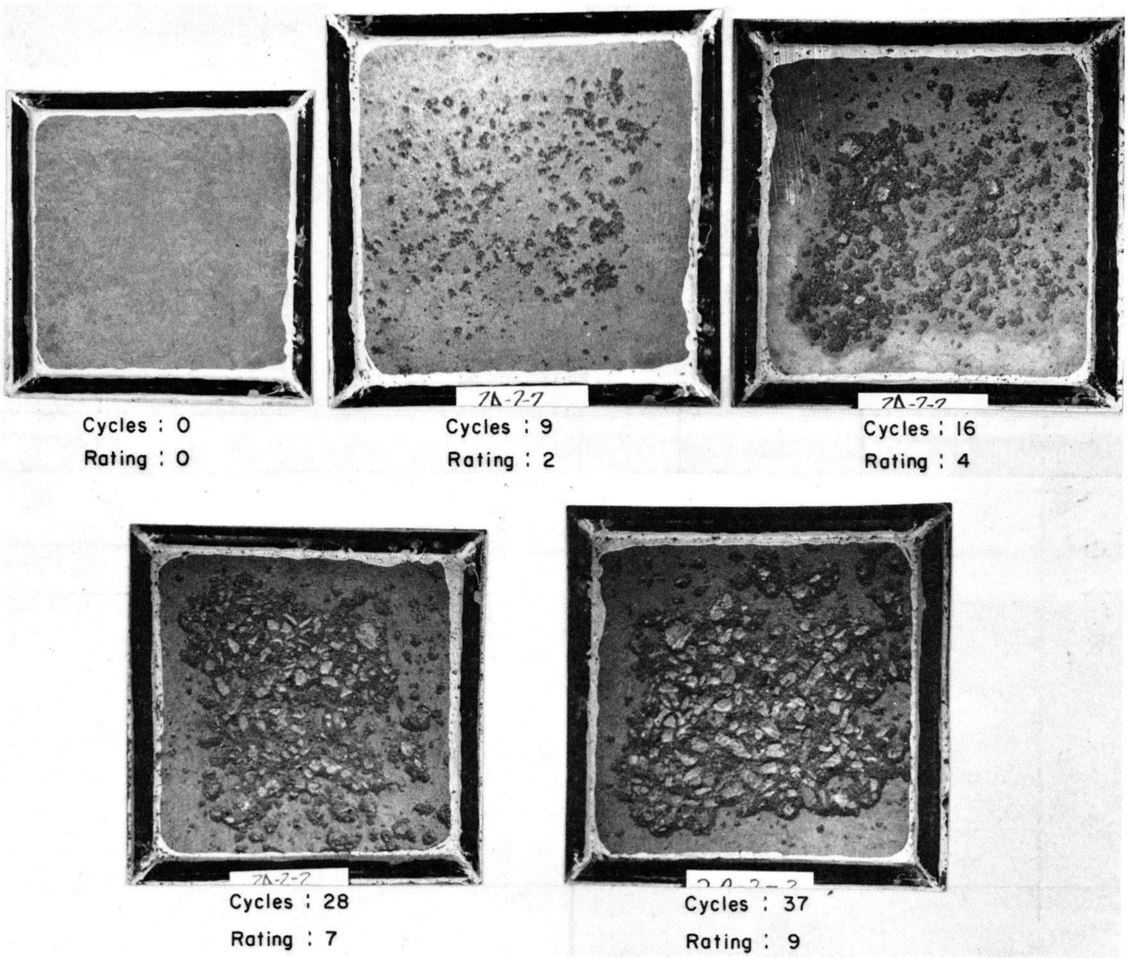


Figure D-9. Surface deterioration of specimen 2A-2-2. Series 2A—Phase 3a. External revibration; T=*4 hr,* e=*25 sec.*

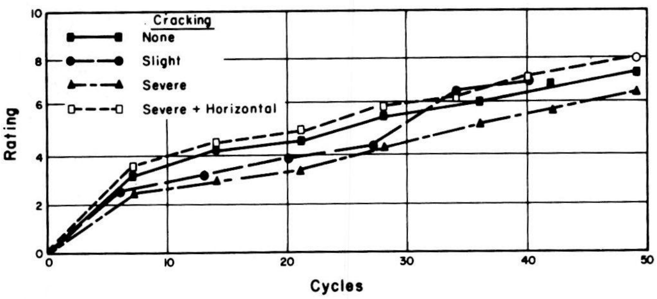


Figure D-10. Effect of extent of cracking on surface deterioration of retarded concrete. Series 1D and 3D—Phase 3b.

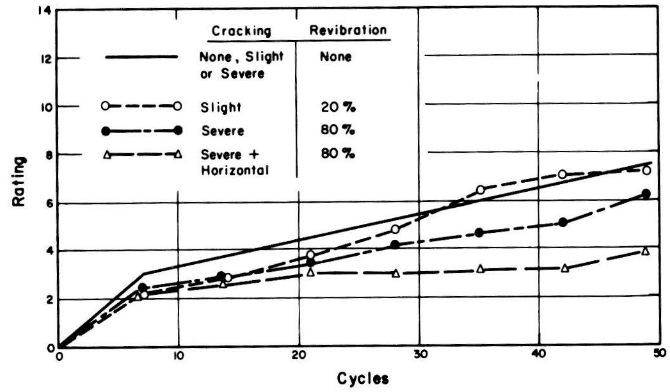
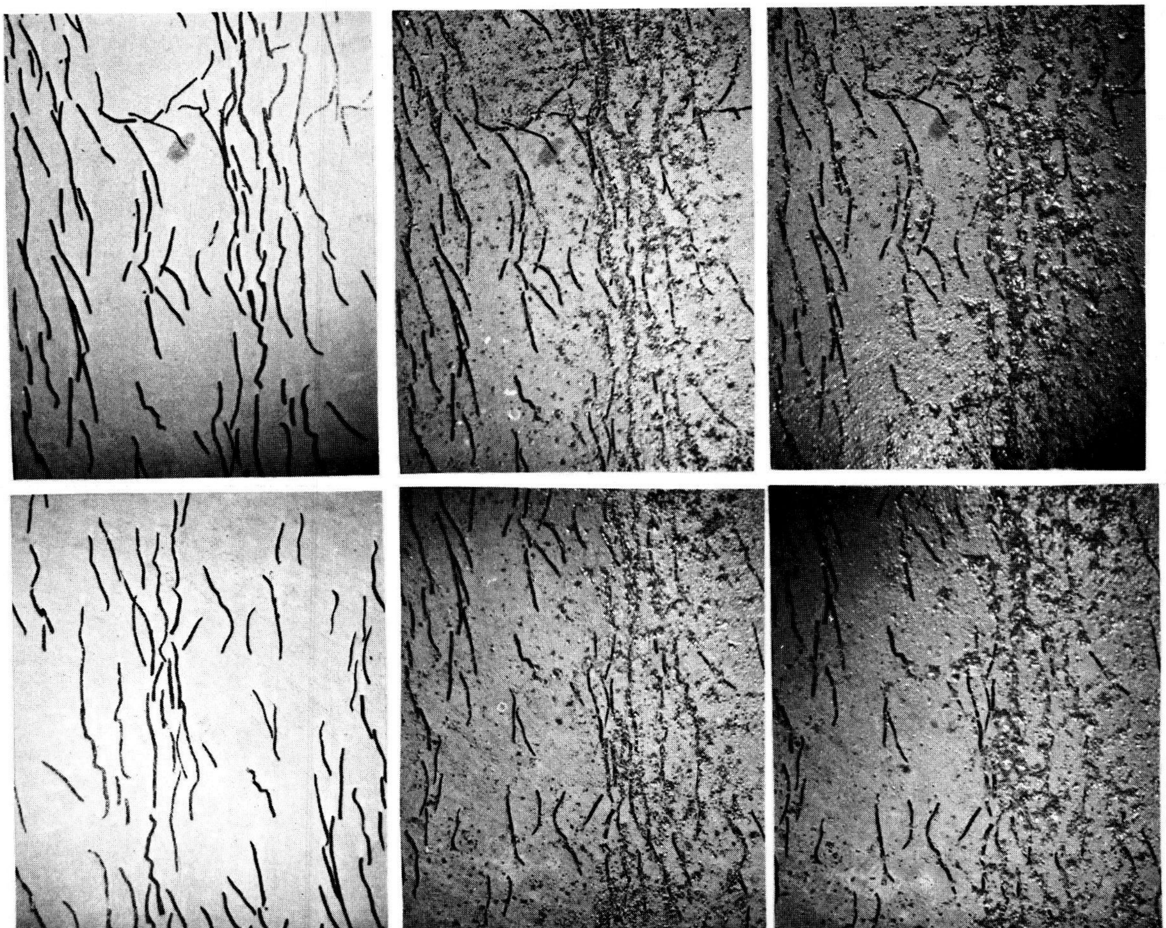


Figure D-11. Effect of surface revibration energy on surface deterioration of retarded concrete. Series 1D and 3D—Phase 3b.

Effect of Retarder (Series 2D)

Figure D-14 shows that the durability of nonretarded concrete was considerably better than that of retarded concrete. This is in agreement with the test results obtained in Phase 3a. A comparison of the specimens made with nonretarded concrete shows that severe surface cracking reduced concrete durability. Subsequent revibration re-



Cycles: 0 Rating: 0

Cycles: 7 Rating: 2-1/2

Cycles: 21 Rating: 4

Figure D-12. Surface deterioration of specimen SUD-SE-OA. Series 1D—Phase 3b. No revibration; severe cracking.

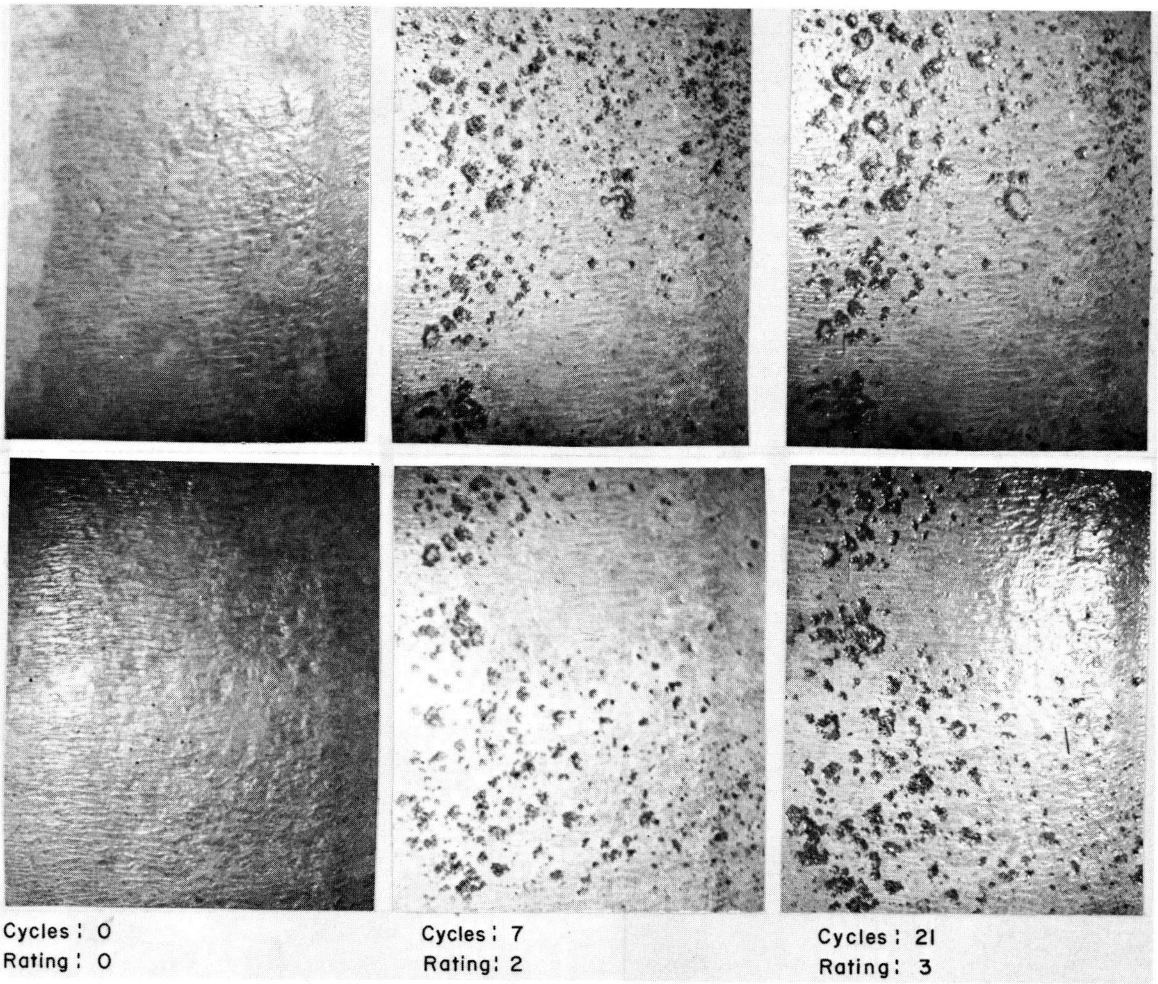


Figure D-13. Surface deterioration of specimen SUD-SE-80. Series 1D—Phase 3b. Surface revibration. Energy level: 80 percent.

sulted in a slight increase of the frost resistance of the nonretarded concrete.

To further verify the effect of the particular retarder used in this study on concrete frost resistance, prisms 3 by 3 by 15 in. were exposed to 112 cycles of freezing and thawing in an automatic freezing and thawing cabinet. The results of this test series are shown in Figure D-15, where the average weight loss as determined on six specimens for each variable is given as a function of the number of cycles of freezing and thawing. Again, the nonretarded concrete was significantly more frost-resistant than the retarded concrete.

Effect of Air Content (Series 4D)

The retarded concrete had a higher compressive strength than the nonretarded concrete if the volume of entrained air was approximately equal in both concretes. Therefore, in tests conducted in Series 4D the air content of the retarded concrete was raised to such a level that the compressive strength of the retarded concrete approached that of the nonretarded concrete. The increased air content resulted in a marked increase of the surface durability of the retarded concrete, as shown in Figure D-16. The following tabulation gives average compressive strength, air

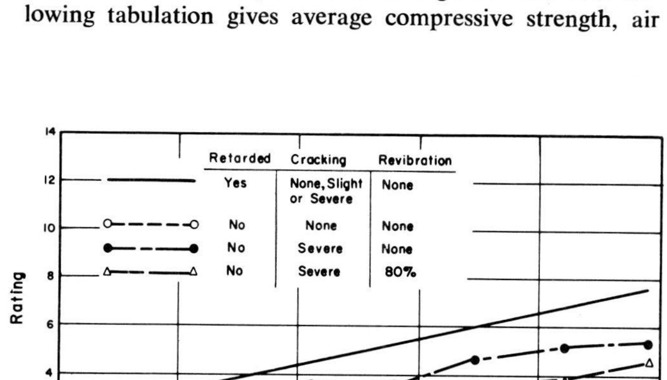


Figure D-14. Effect of surface revibration energy on surface deterioration. Nonretarded concrete. Series 2D—Phase 3b.

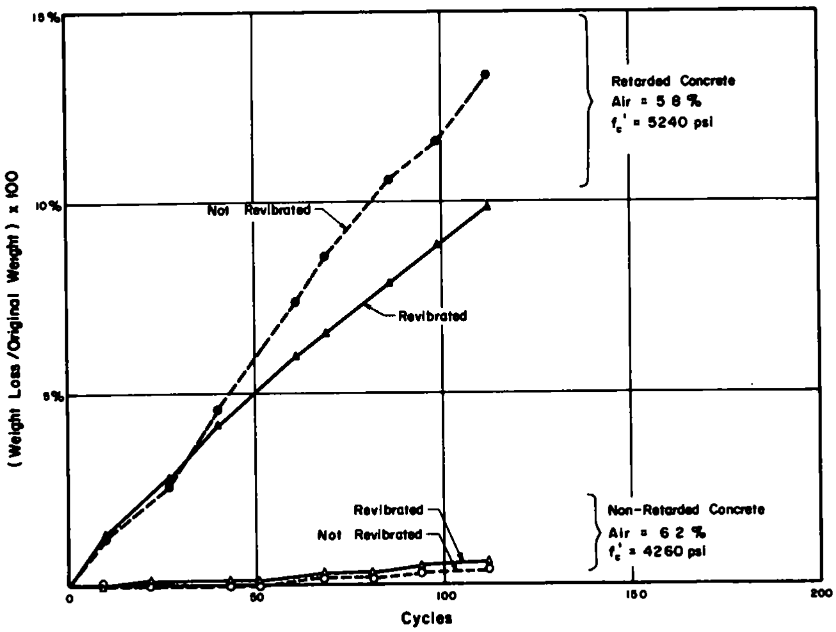


Figure D-15 Freezing and thawing resistance of retarded and nonretarded concrete

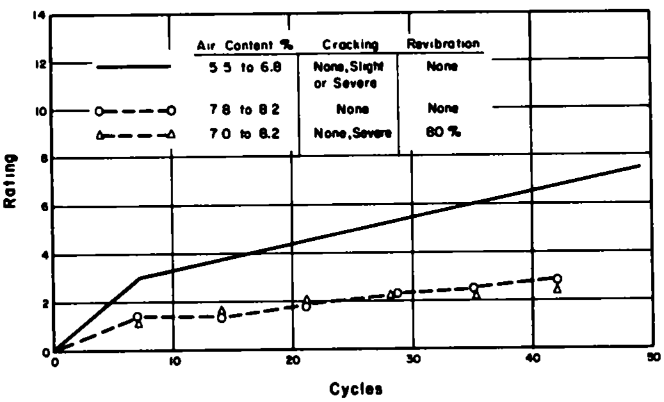


Figure D-16. Effect of increased air content of retarded concrete on surface deterioration. Series 4D—Phase 3b

TABLE D-4

EFFECT OF SURFACE REVIBRATION ON ABRASION RESISTANCE OF CONCRETE, SERIES 10—PHASE 2

AIR CONTENT (%)	REVIBRATION (%)	ABRASION COEFFICIENT [a] (CM^3/CM^2)
6.1	—	1 98
6 1	20	1 95
5.8	—	1.54
5 8	50	1.52
6.7	—	2.02
6.7	80	2.09

[a] Defined as the ratio of the volume of abraded material to the area of the abraded surface

content, and surface deterioration of retarded and nonretarded concrete after 40 cycles of freezing and thawing.

RETARDER	AIR CONTENT (%)	28-DAY COMPRESSIVE STRENGTH (PSI)	SURFACE DETERIORATION RATING AFTER 40 FREEZING AND THAWING CYCLES
Yes	6.2	5,460	6.4
Yes	8.1	4,860	2.3
No	6.2	4,400	3.1

Apparently it is possible with the particular retarder used in this investigation to produce retarded concrete with a strength and surface durability that at least equals that of nonretarded concrete.

Effect of Finishing Procedures (Series 5D)

Surface revibration resulted in an acceptable finish of the concrete surface. Inasmuch as every manipulation of the fresh concrete surface tends to alter the air content of the surface layer it was hoped that elimination of hand-finishing prior to revibration may offset the possible loss of air due to surface revibration and may result in an improved surface durability. However, the data in Figure D-17 indicate that elimination of hand-finishing immediately after casting had little influence on the durability of revibrated or nonrevibrated specimens.

Figure D-17 also shows the influence of hand-finishing 4½ hr after mixing. The durability of a specimen that was revibrated immediately before hand-finishing was comparable to the durability of specimens that were finished immediately after casting. Late finishing without revibration, however, increased the surface deterioration of the concrete. Because the concrete of this particular specimen was still 2 hr away from its initial set, the late finishing may have interrupted the bleeding process and thus reduced surface durability. Improved compaction due to revibration may offset this effect.

Effect of Surface Revibration on Abrasion Resistance of Concrete (Phase 2, Series 10)

Cores were taken from specimens of Series 10, Phase 2, to compare the abrasion resistance of concrete with and without surface revibration. The data obtained appear in Table D-4 and show that surface revibration had no pronounced effect on abrasion resistance. Batch to batch variations in the air content were considerably more significant.

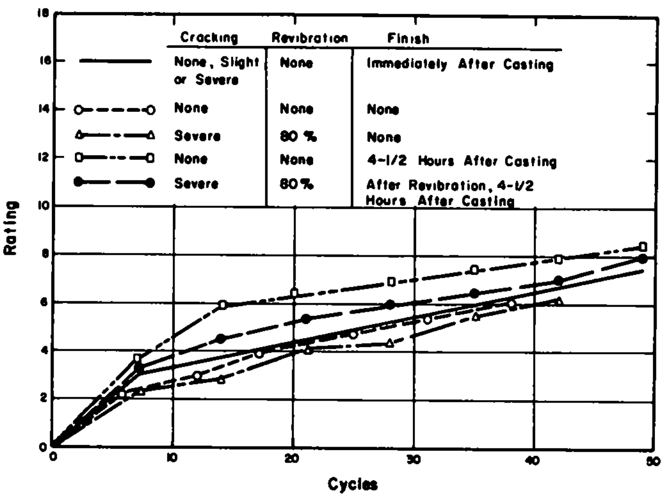


Figure D-17. Effect of finishing procedures on surface deterioration of retarded concrete. Series 5D—Phase 3b.

APPENDIX E

FIELD APPLICATIONS—PHASE 4

To investigate the feasibility of revibration of bridge deck concrete in the field, and to observe their long-time performance, portions of three bridge decks under construction in Illinois and Kansas were revibrated.

On the basis of the laboratory experiments the following guidelines for the field experiments were selected:

1. The bridge deck concrete shall be revibrated with a vibrating screed.
2. Revibration shall be conducted after the penetration resistance of the concrete reaches a value of approximately 25 psi.
3. The bridge deck concrete shall be finished prior to revibration, and additional finishing after revibration shall be kept to a minimum.
4 No particular requirements regarding concrete mix proportions in addition to those developed by the respective highway departments will be made. The use of set-retarding admixtures is desirable but not mandatory.

BRIDGE DECK IN ILLINOIS

Field work was conducted on the reinforced concrete deck of a skewed, continuous-span, noncomposite bridge with structural steel I beams. The bridge is located on Illinois route 110, approximately 12 mi west of Champaign, Ill., and crosses Interstate 172. The spans of the bridge are 51 ft 1¼ in., 81 ft 1¼ in., 81 ft 1¼ in., and 51 ft 1¼ in., respectively. A schematic view and a cross section of the bridge are shown in Figure E-1.

On July 10, 1969, a section of the bridge deck 3 ft 3 in. wide and extending 15 ft in each direction from the center support of the bridge was cast and revibrated. This section is adjacent to the safety curbs along the south edge of the bridge (Fig. E-1) and is separated from the main lanes of the deck by a longitudinal construction joint. The main deck had been cast a week prior to the experiment, and the safety curbs were cast a few days after casting of the revibrated segment. The mix proportions of the concrete are given in Table E-1. The results of a standard penetration resistance test of the bridge deck concrete according to ASTM C 403-68 are shown in Figure E-2. The air temperature during the casting period ranged from 84 to 89 F, the relative humidity was approximately 65 percent, and the day was sunny with only slight westerly winds.

The same vibrating screed that was used in the laboratory experiments (Fig. C-7) was used to revibrate the bridge deck concrete. A revibration energy level of 20 percent (as defined in "Revibration Methods" of Appendix C) and a direction of revibration perpendicular to the forward movement of the screed were selected. During revibration one edge of the vibrating screed rested on the hardened concrete of the main deck. The other edge of the screed was supported by a 2- by 4-in. wooden beam. The concrete was struck off and hand-finished with aluminum floats immediately after it had been placed and compacted by internal vibration. The concrete surface was revibrated approximately 2 hr after placing. At that time the penetration

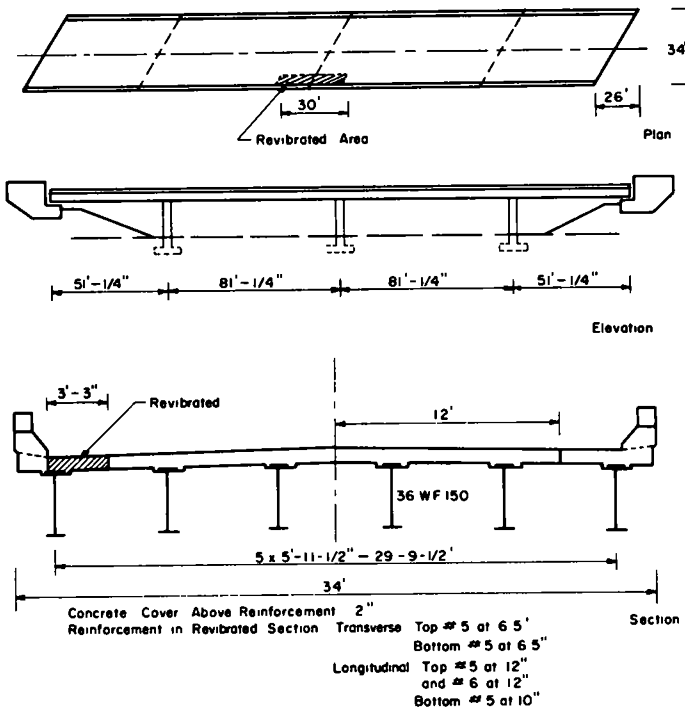


Figure E-1 Cross section of bridge for the field experiment near Champaign, Ill.

TABLE E-1

PROPERTIES OF FIELD CONCRETE—PHASE 4

ITEM	BRIDGE SITE ILLINOIS	KANSAS I	KANSAS II
Mix proportions (lb/cu yd)			
Water	216	283	287
Cement	602	639	647
Sand	1,148	1,884	1,952
Gravel	899	928	834
Retarder	Yes	No	Yes
Type of cement	I	II	II
Max aggregate size (in.)	1½	¾	¾
Slump (in.)	2–2½	1¼–3¼	2–4
Initial set (hr)	2:40	2:50	5:00
Air content (%)	4.0–4.5	4.9–6.7	4.2–5.4
f_c' 28 (psi)	—	5,130	6,520

resistance of a concrete sample taken from the same batch as the bridge deck concrete was approximately 25 psi. This sample was treated in accordance with ASTM C 403-68, which requires the sample to be covered with moist burlap following casting. The bridge deck concrete was partially exposed to sunshine and wind so that the concrete in the bridge deck set faster than the control specimen. Therefore, at the low revibration energy level used for this experiment only about 80 percent of the revibrated concrete

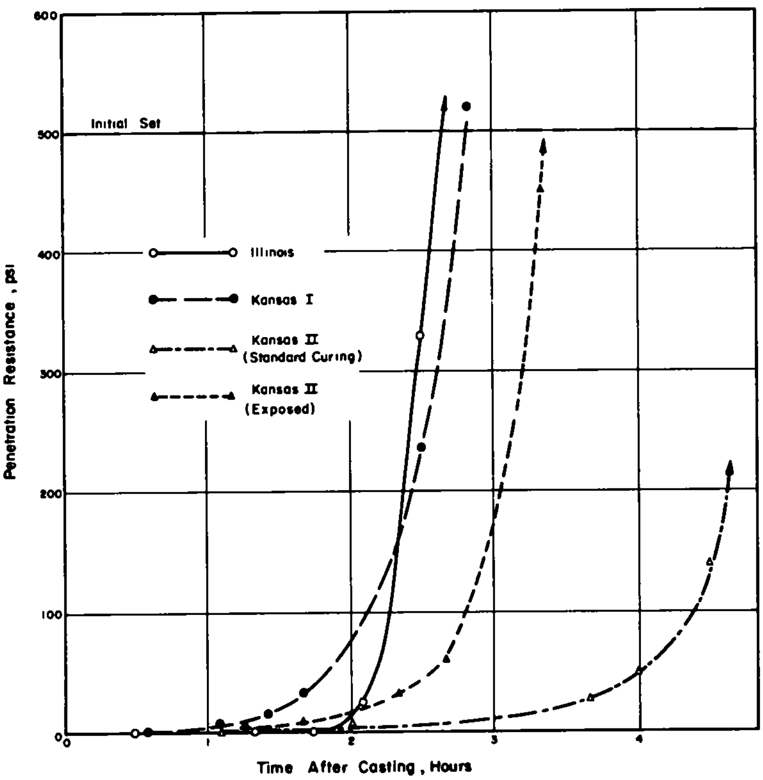


Figure E-2 Penetration resistance of bridge deck concrete surface showed a thin moisture film after revibration. In addition, revibration caused the concrete to settle slightly below the level of the hardened concrete of the adjacent main lanes of the bridge deck. To achieve a smooth and continuous transition across the longitudinal construction, joint hand-finishing after revibration was required. At that time the concrete approached its initial set and was very difficult to finish. No cracks were observed before or after revibration in either the nonrevibrated or the revibrated sections of the deck.

The experiment was a partial success because it showed that bridge deck concrete indeed can be revibrated if suitable equipment is available and if the time of revibration is properly selected. The study was helpful in planning the subsequent tests to be conducted in Kansas, and demonstrated clearly that finishing after revibration should be eliminated as far as possible.

The bridge deck was moist-cured for 7 days after casting, and was inspected several times subsequently. No apparent differences between the revibrated and the nonrevibrated sections of the deck could be found. There was no indication of cracking except a fine transverse hairline crack through the revibrated section directly above the center support of the bridge (Fig. E-3). This crack started at an expansion joint in the safety curb and continued across the revibrated section and the longitudinal construction joint a few inches into the main deck. It is very unlikely that this crack can be attributed to revibration of the bridge deck concrete. It may be due rather to the dead weight of the superstructure and may have formed after stripping the form work.

Observations of the bridge deck will be continued.

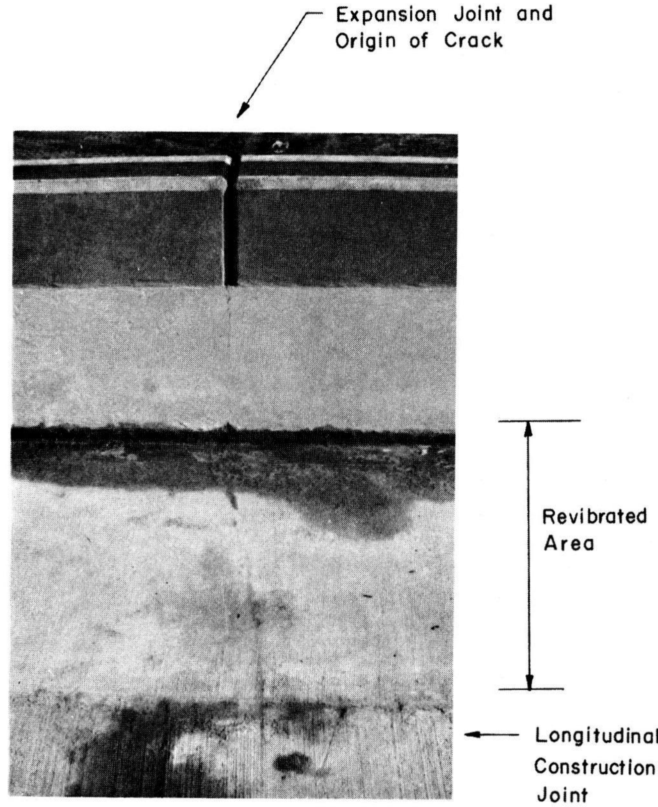


Figure E-3. Hairline crack in revibrated bridge deck near Champaign, Ill.

BRIDGE DECKS IN KANSAS

The studies were conducted on two identical bridges, Br. No. 35W-40-2.00 and Br. No. 35W-40-5.00, which cross Interstate 135W near Newton, Kan. The noncomposite bridges were continuous, with spans of 43 ft, 92 ft, 92 ft, and 43 ft, and consisted of welded steel plate girders with a reinforced concrete deck. Elevation and cross section of the bridges are shown in Figure E-4. Placement of the deck concrete was started at the west end and was discontinued just short of the second pier for each bridge; then, casting was continued starting from the east end of the bridges up to a header. This casting sequence was used to prevent uplift of the short spans of the bridges at the abutments.

The mix proportions and properties of the bridge deck concrete appear in Table E-1. Figure E-2 shows the penetration resistance of the concrete. One test specimen used to determine initial set was covered with wet burlap during setting in accordance with ASTM C 403-68. A second sample was left uncovered and placed next to the bridge deck to expose it to the same environment as the bridge deck surface. The concrete for the deck of Br. No. 35W-40-2.00 contained no retarder; for Br. No. 35W-40-5.00, retarded concrete was used.

On August 27, 1969, the deck of Br. No. 35W-40-2.00 was cast. During the earlier part of the day the sky was overcast, with temperatures ranging from 72 to 78 F. There were only light winds; relative humidity was around

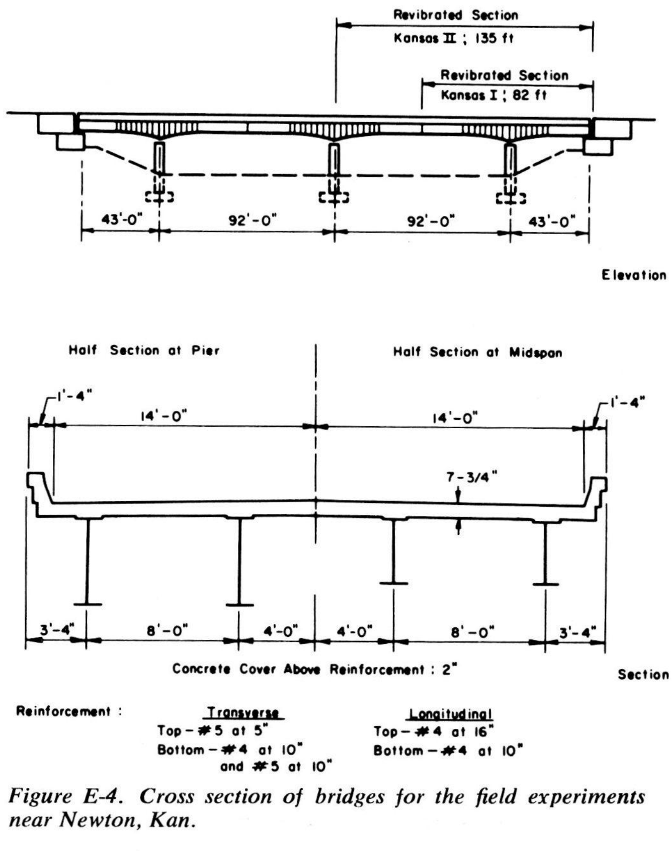


Figure E-4. Cross section of bridges for the field experiments near Newton, Kan.

60 percent. The entire width of the deck, extending from the east abutment over a length of 82 ft, was revibrated. The vibrating screed used for this experiment is shown in Figure E-5. The screed was designed and constructed by the local contractor. It consisted of a steel pan, 12 in. wide and ¼ in thick, stiffened by a steel T-beam of variable depth. A vibrator with variable eccentricity and frequency was driven by a 3-hp gasoline motor and was mounted at the center of the screed in such a way that the direction of revibration was parallel to the forward movement of the screed. During the experiment the frequency of the vibrator was approximately 3,200 cpm. An intermediate setting of the eccentricity of the vibrator was chosen but no data on the magnitude of the centrifugal force of the vibrator were available. To move the screed, steel cables were firmly attached to the formwork approximately 30 ft in front of the screed. These cables ran through hooks welded to the screed stiffners to rotating drums in the center of the screed. The drums were driven by the same motor used to operate the vibrator (Fig. E-5). Rotation of these motor-driven drums resulted in a forward movement of the screed.

After placing and internal vibration the concrete was struck off with a finishing machine. Then, a thin spray of a water emulsion of aliphatic alcohol was applied to the concrete surface. (Use of the spray was suggested by W. M. Stingley, State Highway Commission of Kansas.) It was hoped that this spray would result in the formation

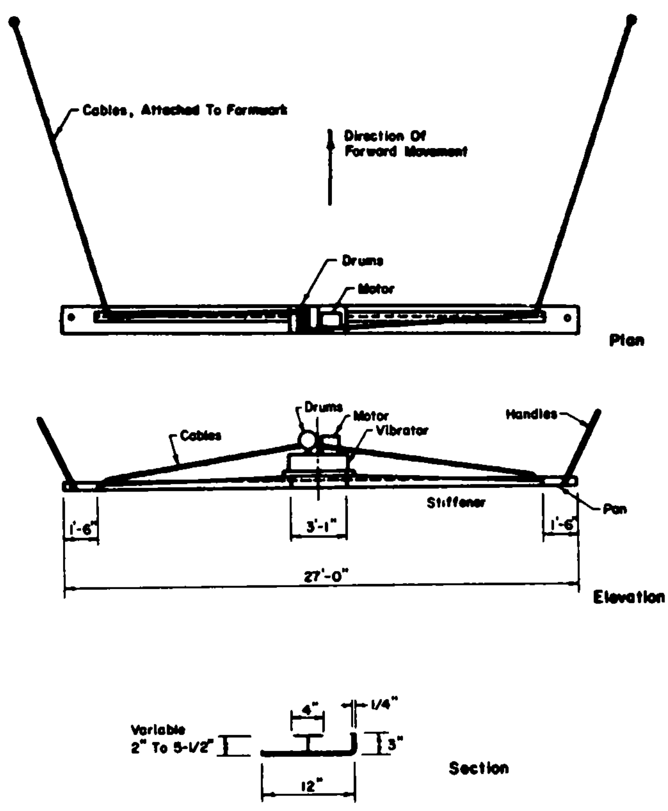


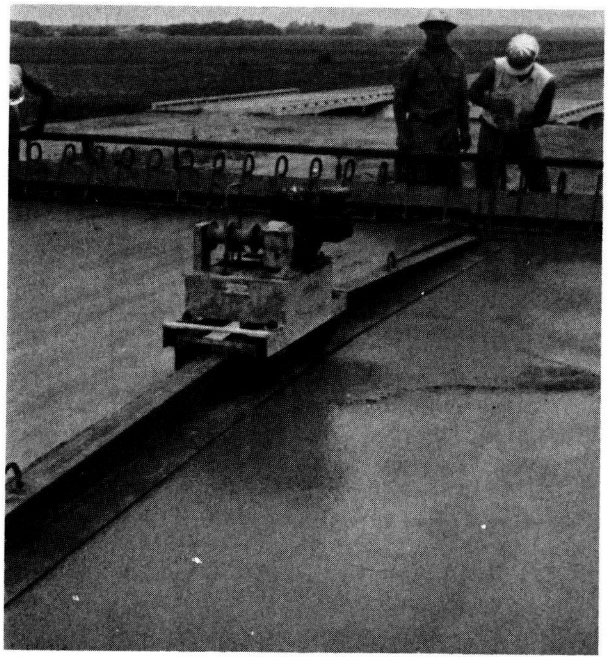
Figure E-5. Vibrating screed used to revibrate the deck of Br No 35W-40-2.00 near Newton, Kan.

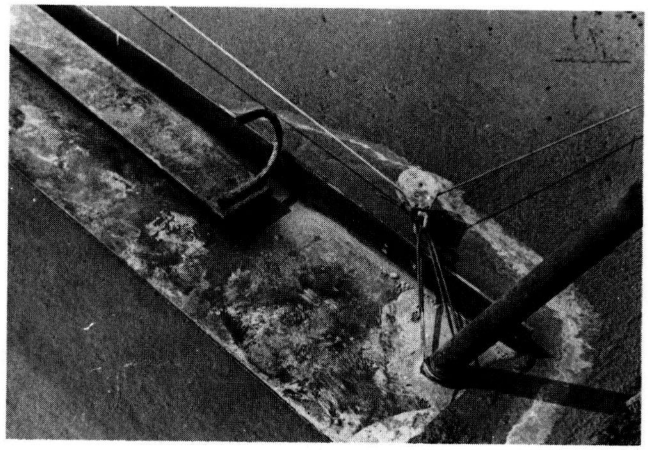
of a monomolecular layer on the concrete surface that retards the evaporation of bleeding water and prevents crusting (*24*). Revibration of the bridge deck was started approximately 1½ hr after casting. At that time the entire concrete of the deck within the 43-ft span of the bridge had been placed. At the beginning of revibration a covered control specimen showed a penetration resistance of approximately 25 psi. During revibration the screed was free-floating on the concrete surface and traveled at a speed of about 1 ft/min.

The revibration energy was sufficient to drive additional moisture to the concrete surface. However, the screed did not precisely match the profile of the bridge deck surface, and areas near the longitudinal axis of the bridge deck remained unrevibrated (Fig. E-6). In addition, the free-floating screed tended to sink into the concrete. By slightly adjusting the location of the pulling cables and by lifting the screed on the handles attached to both ends, sinking of the screed could be reduced but not avoided. Finally, each time the vibrator was stopped a noticeable mark was left on the concrete surface. Extensive and cumbersome hand-finishing after revibration was required because of these shortcomings. The experiment showed, however, that continuous revibration of the entire width of the bridge deck is possible if the screed is supported during revibration and if its shape can be adjusted to match closely the profile of the bridge.

A new vibrating screed was designed and constructed by the contractor on the basis of the experience gained during revibration of the deck of Br. No. 35A-40-2.00. A pan 15¾ in. wide was attached to the strike-off screeds of a finishing machine (Figs. E-7 and E-8). The distance of the strike-off screeds to the supporting structure of the finishing machine could be adjusted at five points spaced approximately 60 in. apart. By adjusting the strike-off screeds it was possible to adapt the vibrating pan to the desired profile of the bridge deck. Two surface vibrators driven by 1-hp electric motors and rotating in a plane perpendicular to the forward movement of the screed were fixed to the pan approximately at its third points (Figs. E-7 and E-8). No information about the centrifugal force of the vibrators was available. The vibration frequency was uniform over the length of the pan and was approximately 3,500 cpm. However, on the basis of visual observation it is likely that the vibration amplitude was not uniform and probably was lower at the extreme ends of the pan. The finishing machine to which the vibrating pan had been attached had four wheels on each side and was running on water pipes that were firmly fixed to the formwork of the bridge deck.

On September 23, 1969, the vibrating equipment described previously was used to revibrate the deck of Br. No. 35W-40-5.00. The entire width of the deck, starting from the east end and extending over a length of 133 ft, was revibrated. Sunny skies with temperatures ranging from 70 to 85 F, a relative humidity around 60 percent, and moderate winds prevailed during most of the day. The concrete was internally vibrated after placing and struck off with a finishing machine. Following these procedures, parts of the concrete surface were sprayed with the water emulsion of aliphatic alcohols described previously.





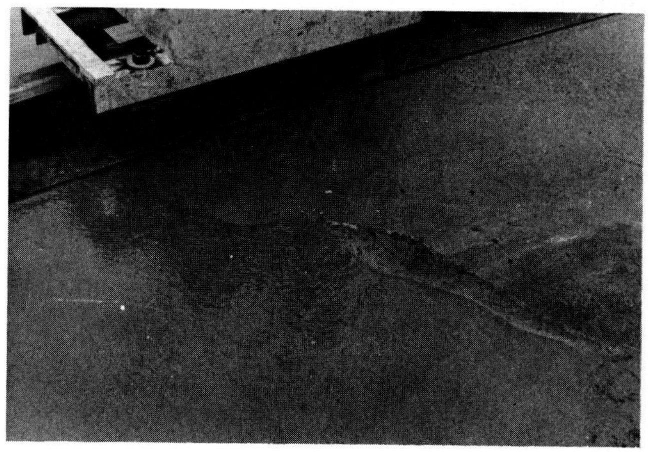


Figure E-6. Vibrating screed and deck after revibration.

Prior to revibration the second finishing machine with the attached vibrating pan was placed into position and adjusted to the profile of the bridge deck. Approximately 2½ hr after casting started, revibration of the bridge deck was commenced. At that time placement of the concrete had progressed up to the center of the second span. At the beginning of revibration the uncovered control sample had a penetration resistance of 28 psi, whereas the covered

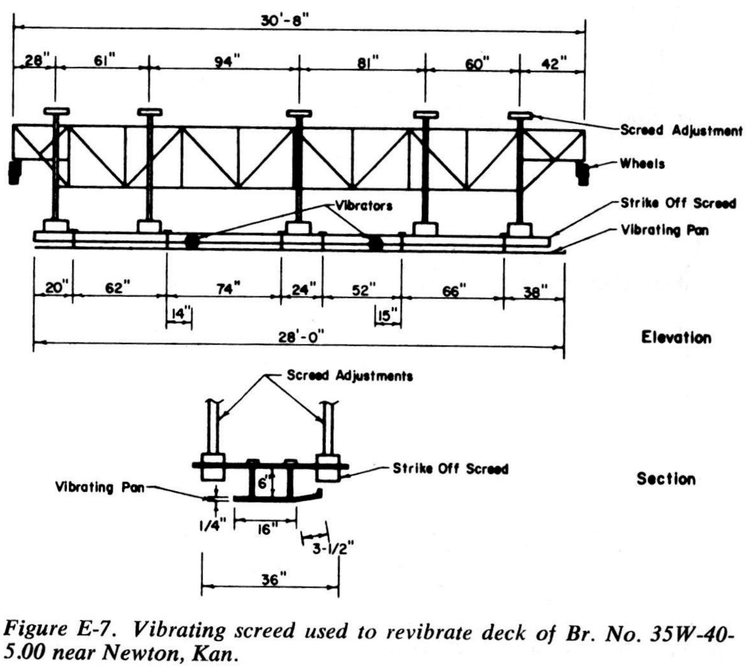
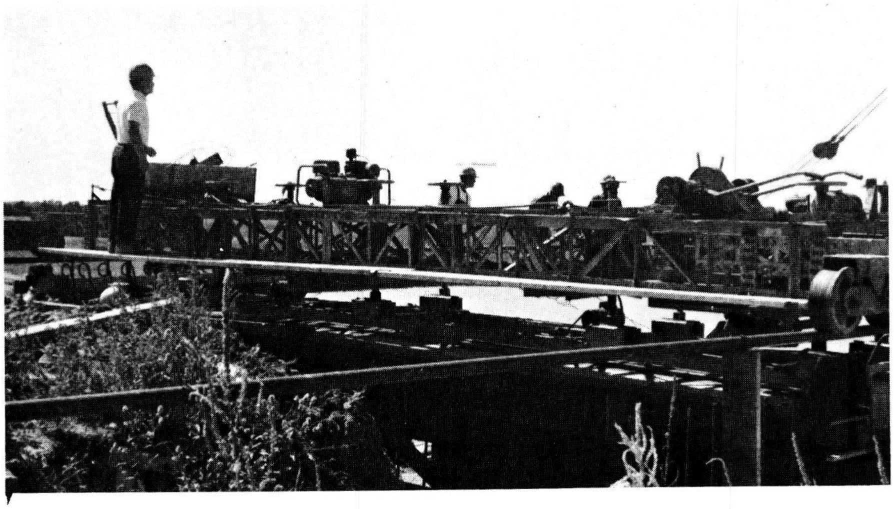


Figure E-7. Vibrating screed used to revibrate deck of Br. No. 35W-40-5.00 near Newton, Kan.



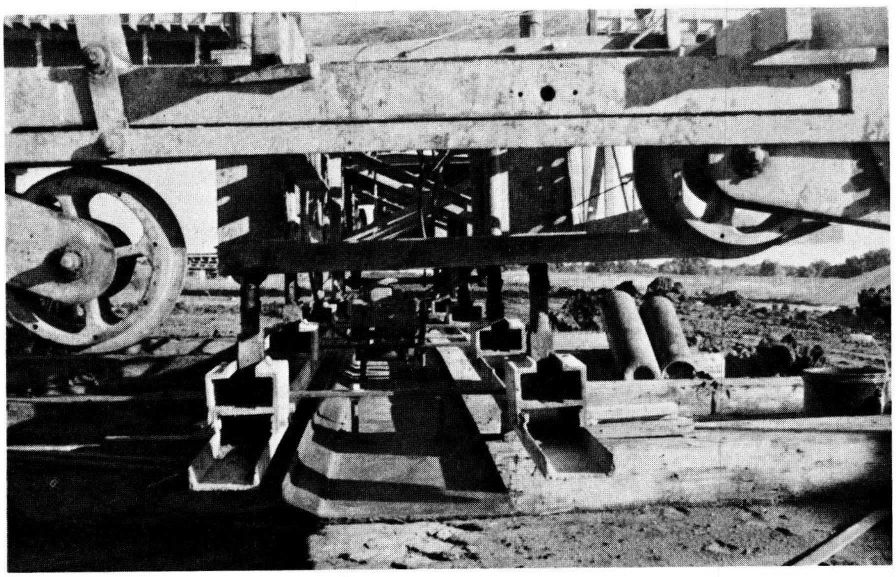
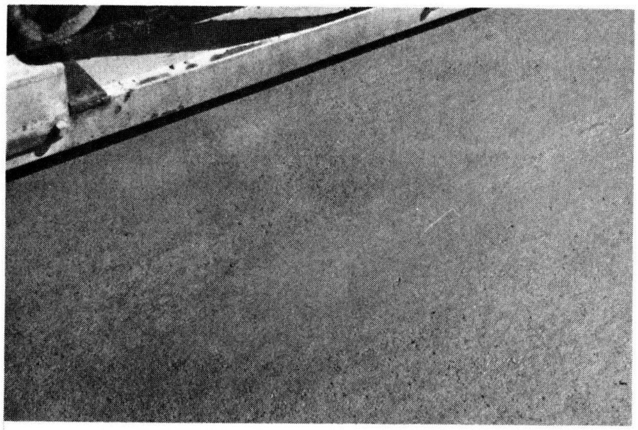


Figure E-8. Vibrating screed used to revibrate deck of Br. No. 35W-40-5.00.

sample showed a value of 18 psi. The speed of forward movement of the vibrator was varied between 4 and 8 in./min. After minor readjustments the vibrating pan followed the profile of the bridge deck very closely, and the entire width of the deck appeared to be sufficiently revibrated. Very little additional finishing, except belting and brooming, was required after surface revibration in those areas that were sprayed with the water-alcohol emulsion immediately after the initial finishing procedures. The concrete surface after revibration is shown in Figure E-9. A narrow segment of the bridge deck next to the east abutment and approximately 20 ft long was not sprayed after placing, and light crusting of the concrete surface may have occurred. In this case the revibration energy near the ends of the screed was insufficient to break the crust, and cracks in the concrete surface were formed (Fig. E-10). Similar cracks were found in the laboratory studies, Series 5, Phase 2, where the effectiveness of revibration following extreme curing conditions was studied. In those cases additional hand-finishing was required. However, the laboratory experiments showed that increased revibration energy may break up the crust and may result in a satisfactory concrete surface.

After revibration was completed it became apparent that the surface of the bridge deck was not true but had a slightly wavy appearance. This was probably because the water pipes supporting the finishing machine with the attached vibrating pan were coupled by sleeves at close intervals. Each time a wheel of the finishing machine had to pass over such a sleeve the entire machine was slightly lifted, resulting in the uneven surface of the concrete. In addition, it is possible that interference between the two independent vibrators mounted on the vibrating pan may have caused variations in the vibration amplitude.



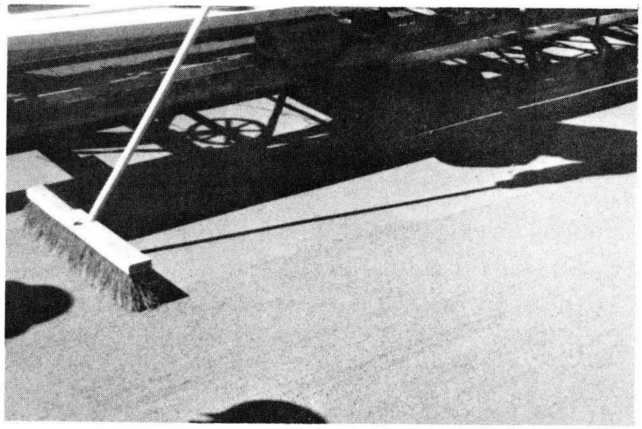
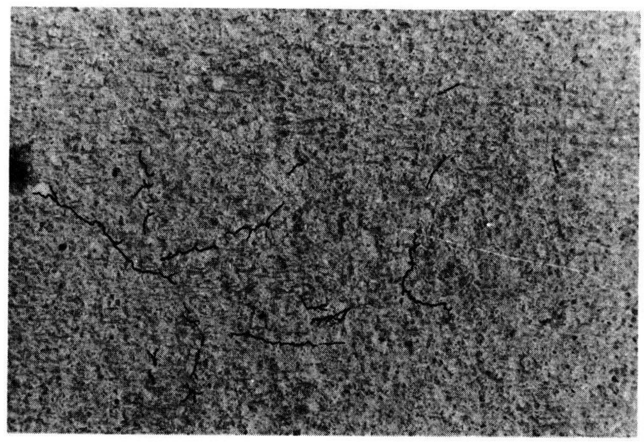


Figure E-9. Deck of Br. No. 35W-40-5.00 after revibration.

The second experiment in Kansas clearly showed that revibration of bridge deck concrete is feasible and, if properly timed, can be conducted without additional finishing. The equipment used in the second experiment was efficient, although it has some obvious disadvantages that may be corrected in the future. Stiff springs placed between the finishing machine and the supporting wheels would eliminate the effect of a local unevenness of the supporting pipes or rails. Vibrators with a larger and adjustable centrifugal force are required. One vibrator placed at the center of the vibrating pan may eliminate possible interference between several individual vibrators. The use of a spray to slow down surface moisture evaporation and to prevent surface crusting (particularly when retarded concrete is used) appears to be very promising. Further studies and development of equipment may show that the use of several smaller vibrating screeds, or one small screed that can travel laterally along a supporting structure, may have definite advantages in comparison to the continuous, large screed used in these experiments because it would be easier to adjust locally the revibration energy or duration of revibration. Such adjustments may be necessary because of batch to batch variations or because of localized variations of the exposure conditions of the concrete within a bridge deck. No surface cracking was observed in the revibrated



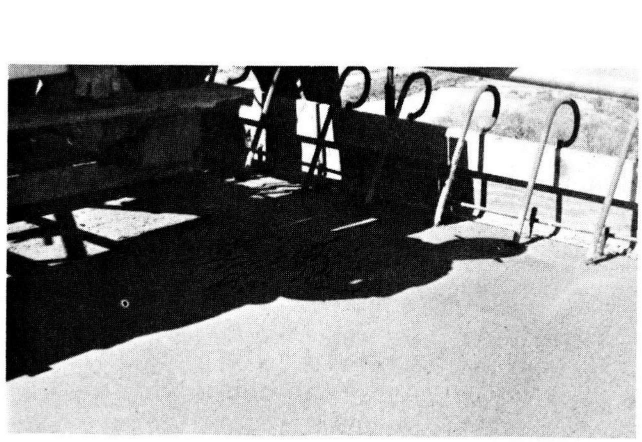


Figure E-10. Cracks after revibration of surface-crusted concrete, deck of Br. No. 35W-40-5.00.

portions of the Kansas bridge decks either before or after revibration, except those cracks that appeared after revibration of surface-crusted concrete, as described earlier. Several hours after completion of casting a few surface cracks 3 to 4 in. long were found in the unrevibrated section of the first revibrated bridge deck. The cracks were located about 2 ft from the revibrated section, near the edge of the bridge. Because the cracked concrete was placed after revibration of the adjacent section of the deck the cracks were not caused by revibration of the bridge deck concrete.

Inspection of the bridge decks by the staff of the Highway Commission of Kansas soon after construction showed no apparent differences between revibrated and nonrevibrated concrete. Cores have been taken from the decks. Microscopic studies of these cores by the Highway Commission of Kansas and by the University of Illinois are reported in Appendix G.

APPENDIX F

ADDITIONAL EXPERIMENTAL DATA

In the previous sections only the average values of the results of the freezing and thawing tests are discussed. Individual values obtained for each specimen are shown in Figures F-1 through F-10.

Additional experimental data from Phase 2, Effectiveness Study, are shown in Figures F-11 through F-18. These data were of minor significance and, therefore, are not discussed in detail in Part I of this report

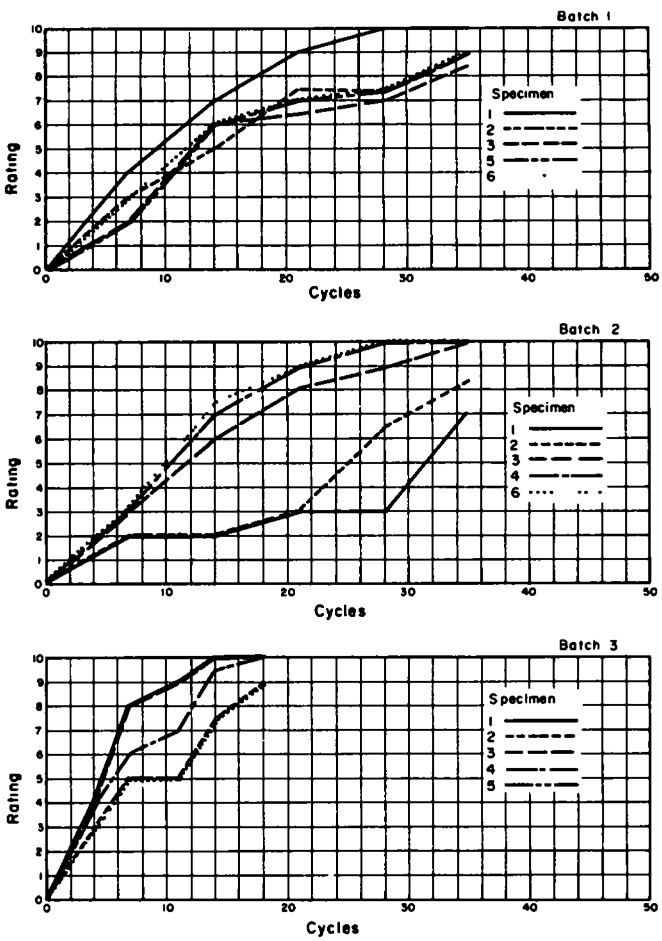


Figure F-1 Individual test results, Series 1A—Phase 3a, Batch 1 to 3.

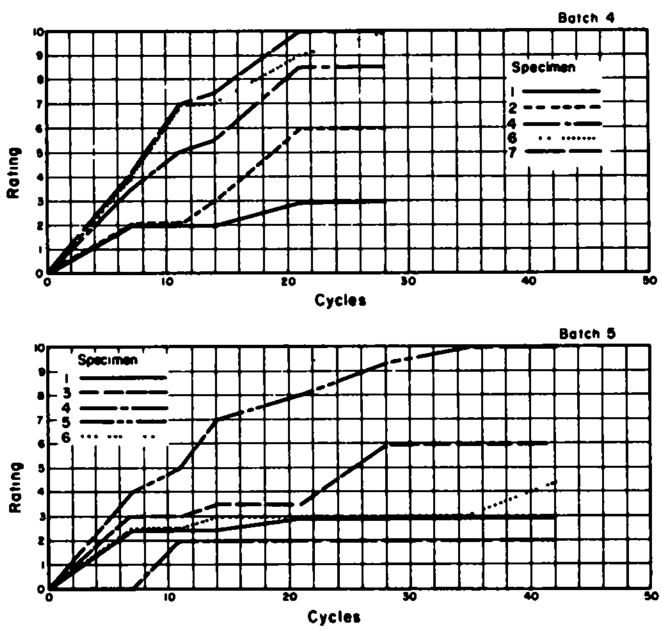


Figure F-2 Individual test results, Series 1A—Phase 3a, Batch 4 and 5

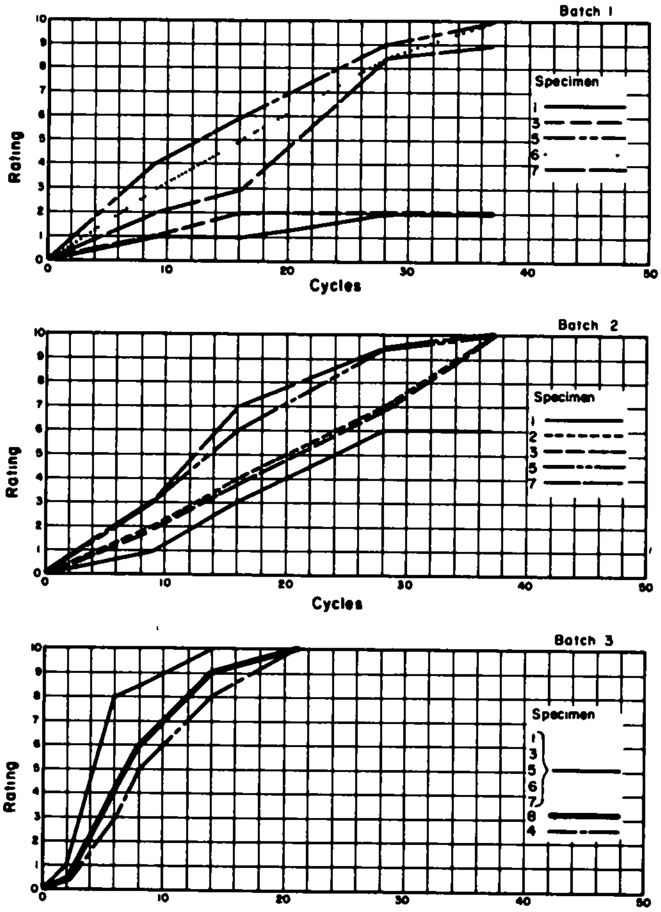


Figure F-3 Individual test results, Series 2A—Phase 3a

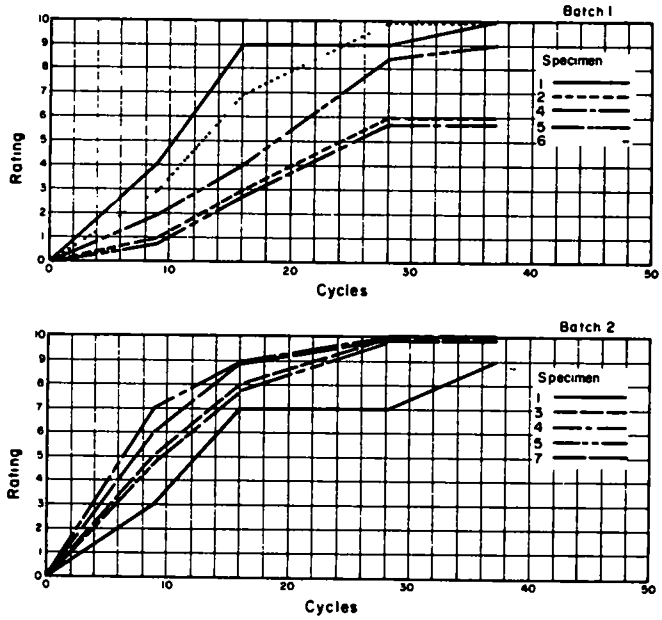


Figure F-4 Individual test results, Series 2B—Phase 3a

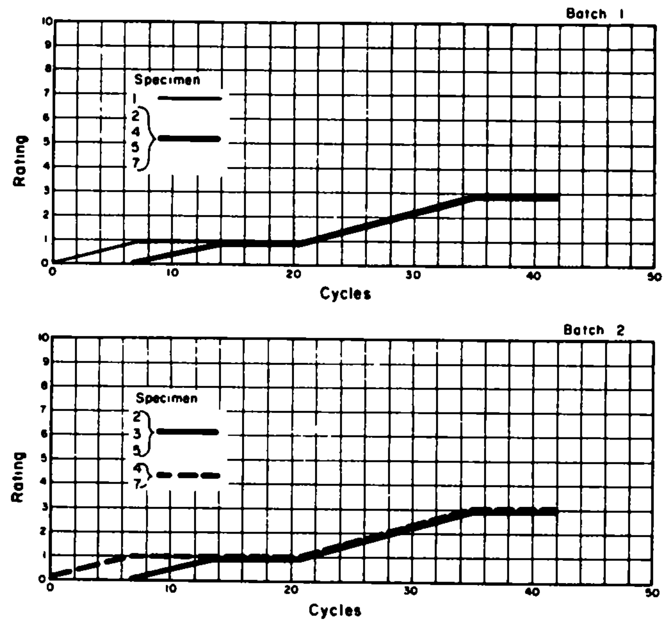


Figure F-6 Individual test results, Series 3—Phase 3a

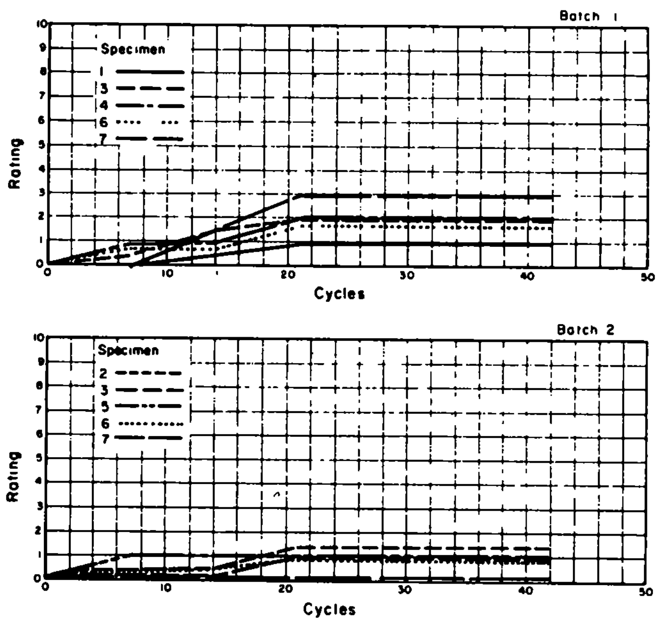


Figure F-5 Individual test results, Series 2C—Phase 3a

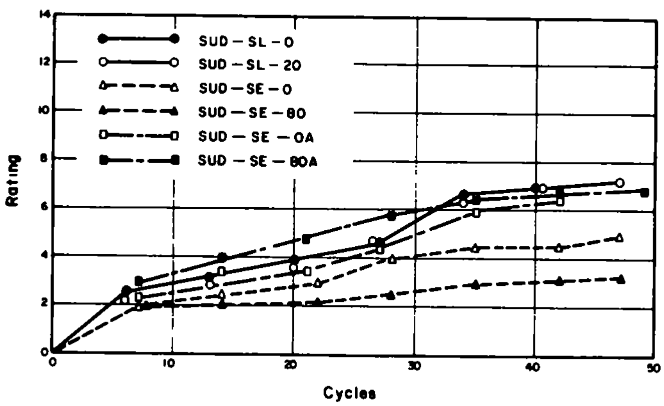


Figure F-7 Individual test results, Series 1D—Phase 3b.

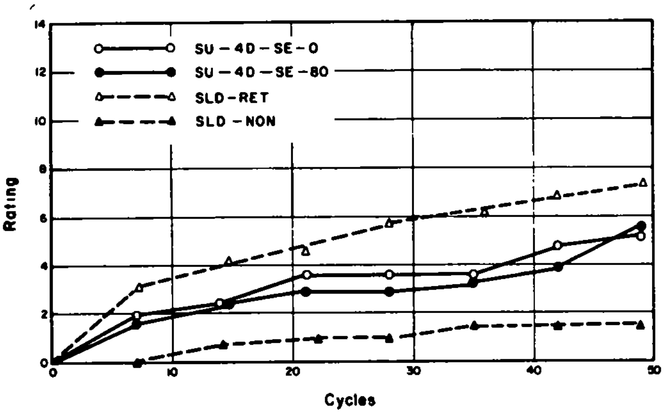


Figure F-8. Individual test results, Series 2D—Phase 3b.

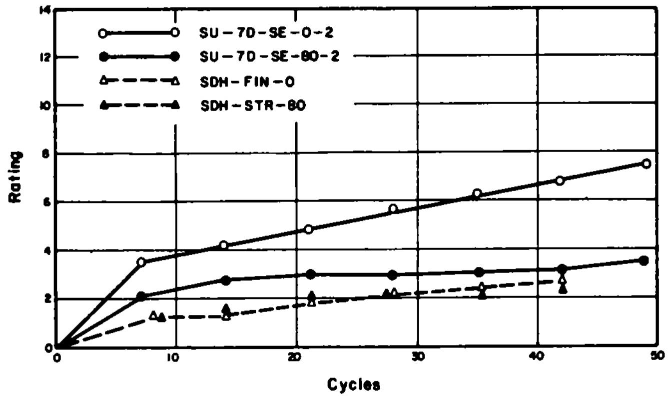


Figure F-9. Individual test results, Series 3D and 4D—Phase 3b

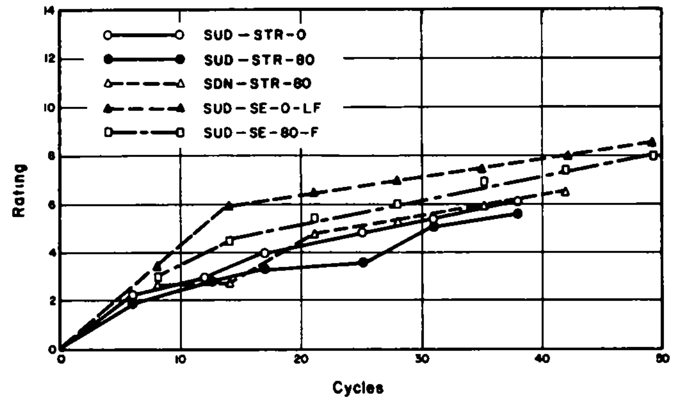


Figure F-10 Individual test results, Series 5D—Phase 3b.

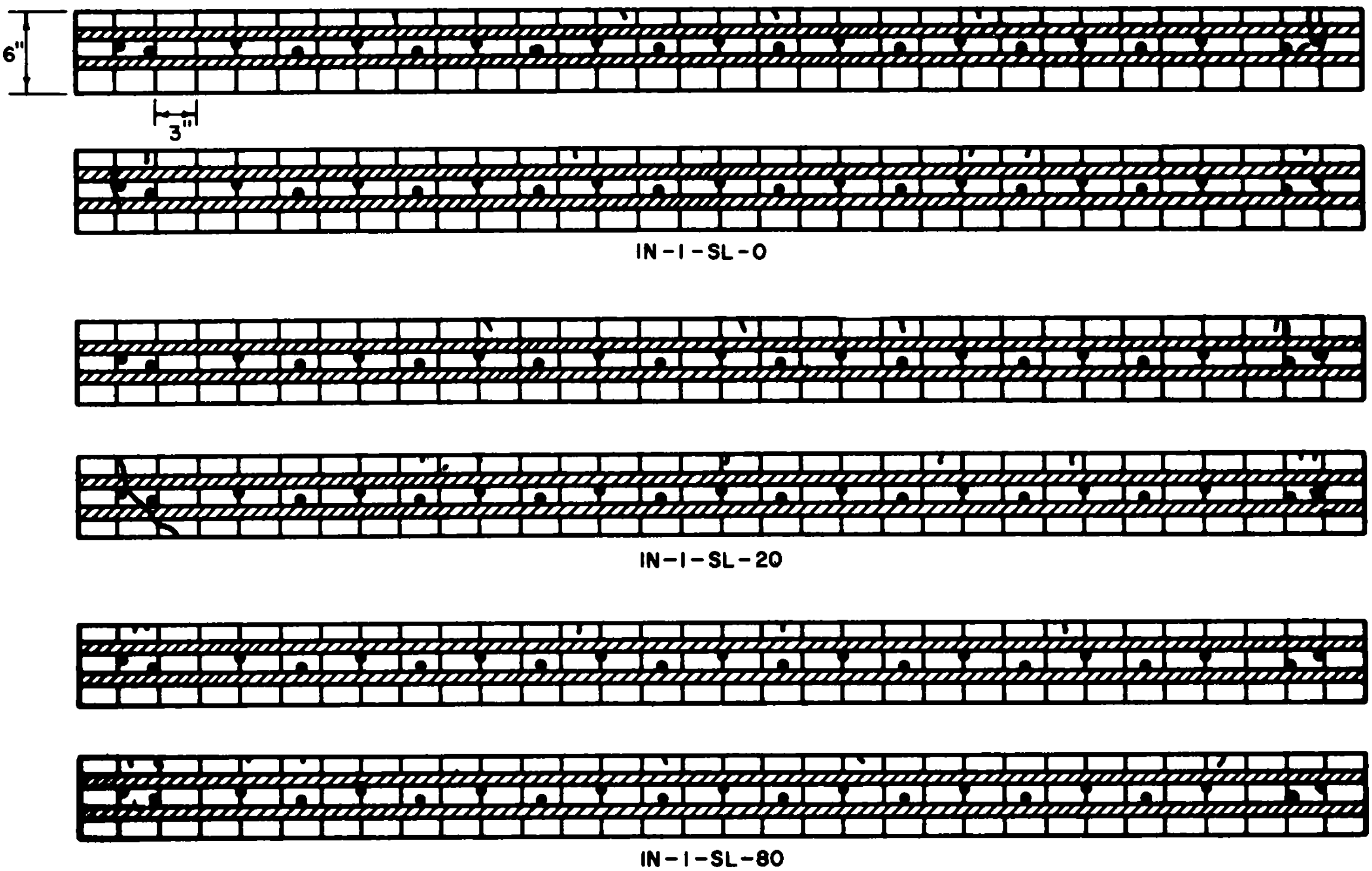


Figure F-11. Crack pattern in specimens, Series 1—Phase 2.

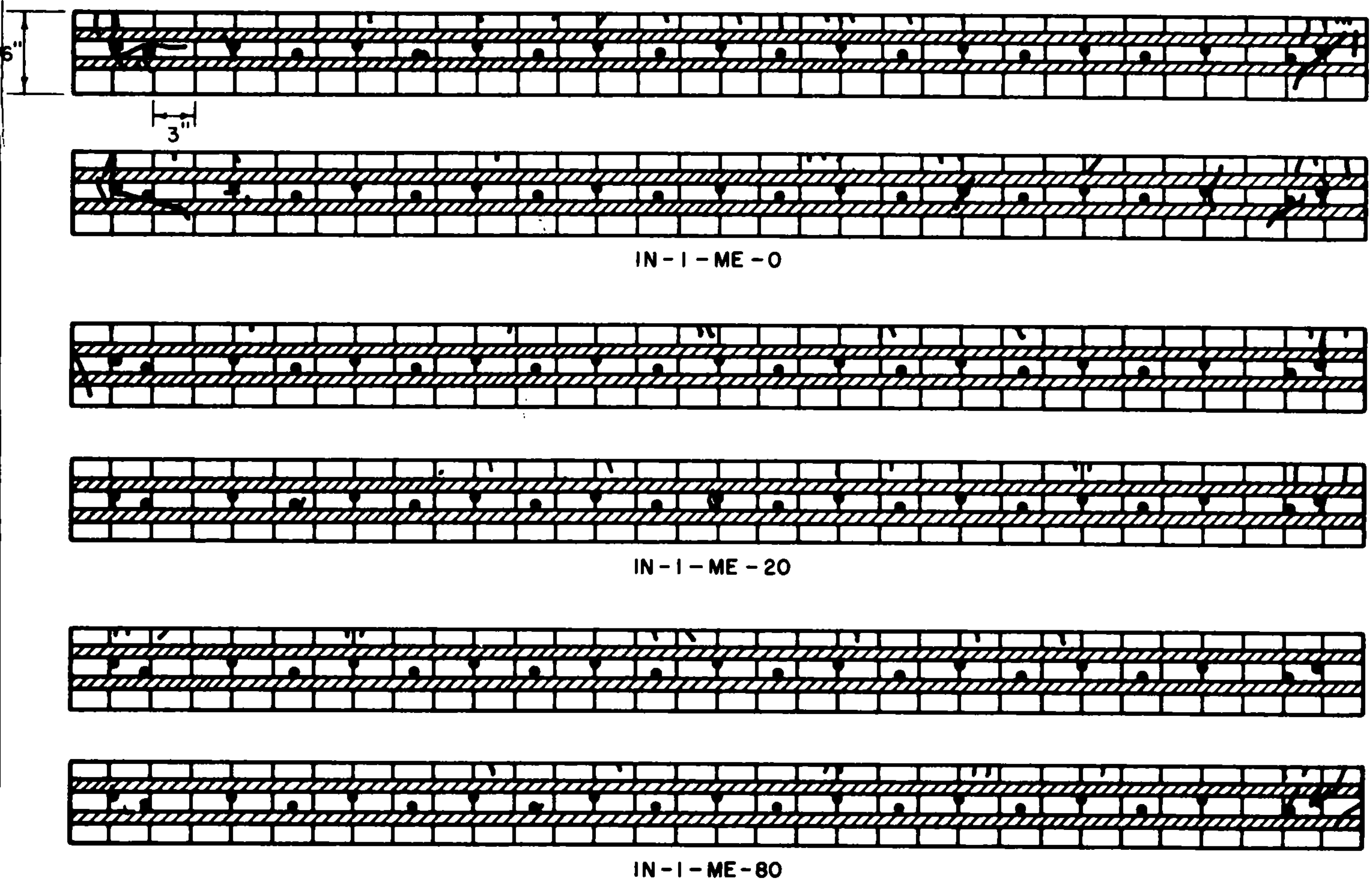


Figure F-12. Crack pattern in specimens, Series 1—Phase 2.

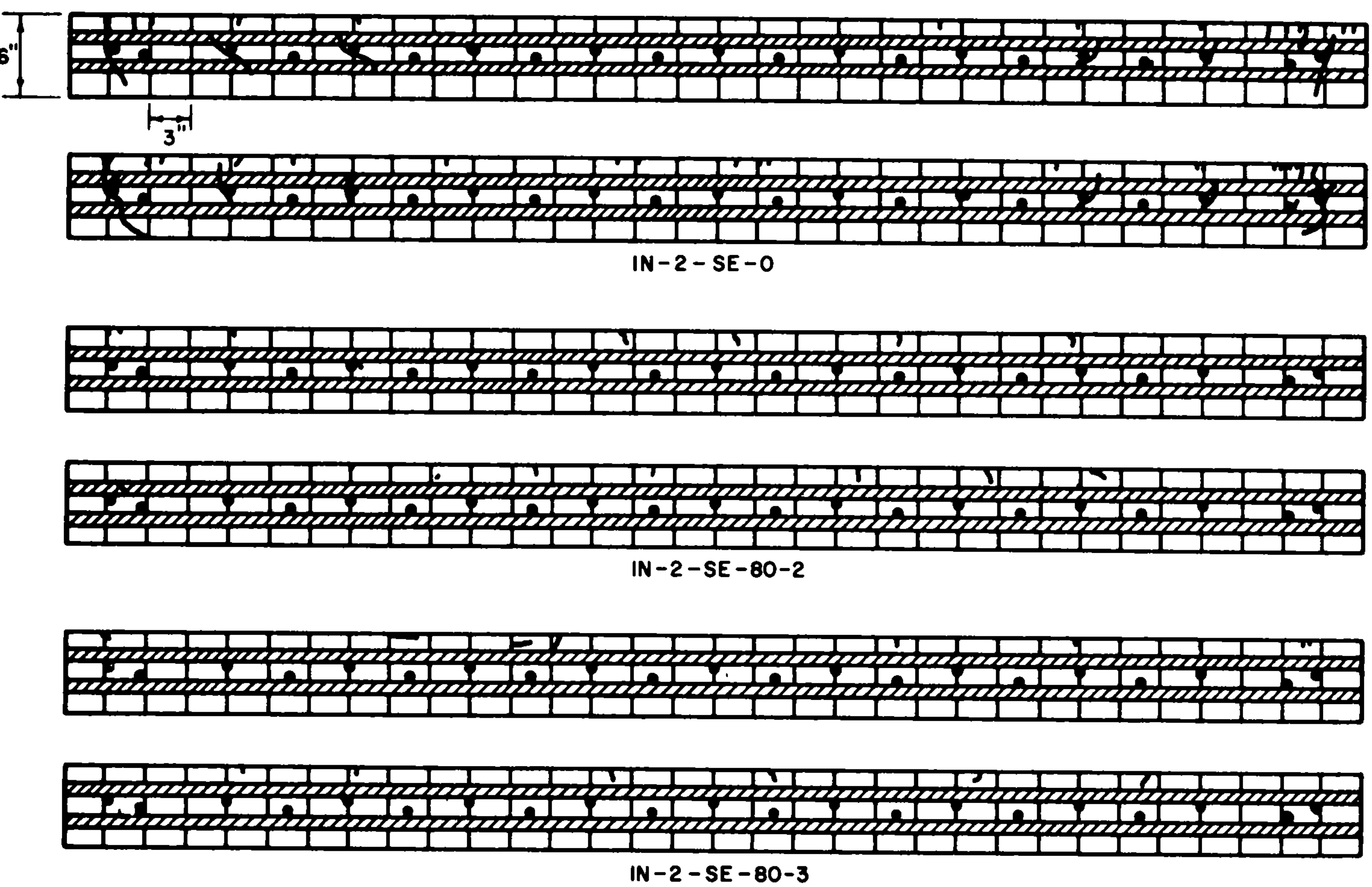


Figure F-13. Crack pattern in specimens, Series 2—Phase 2.

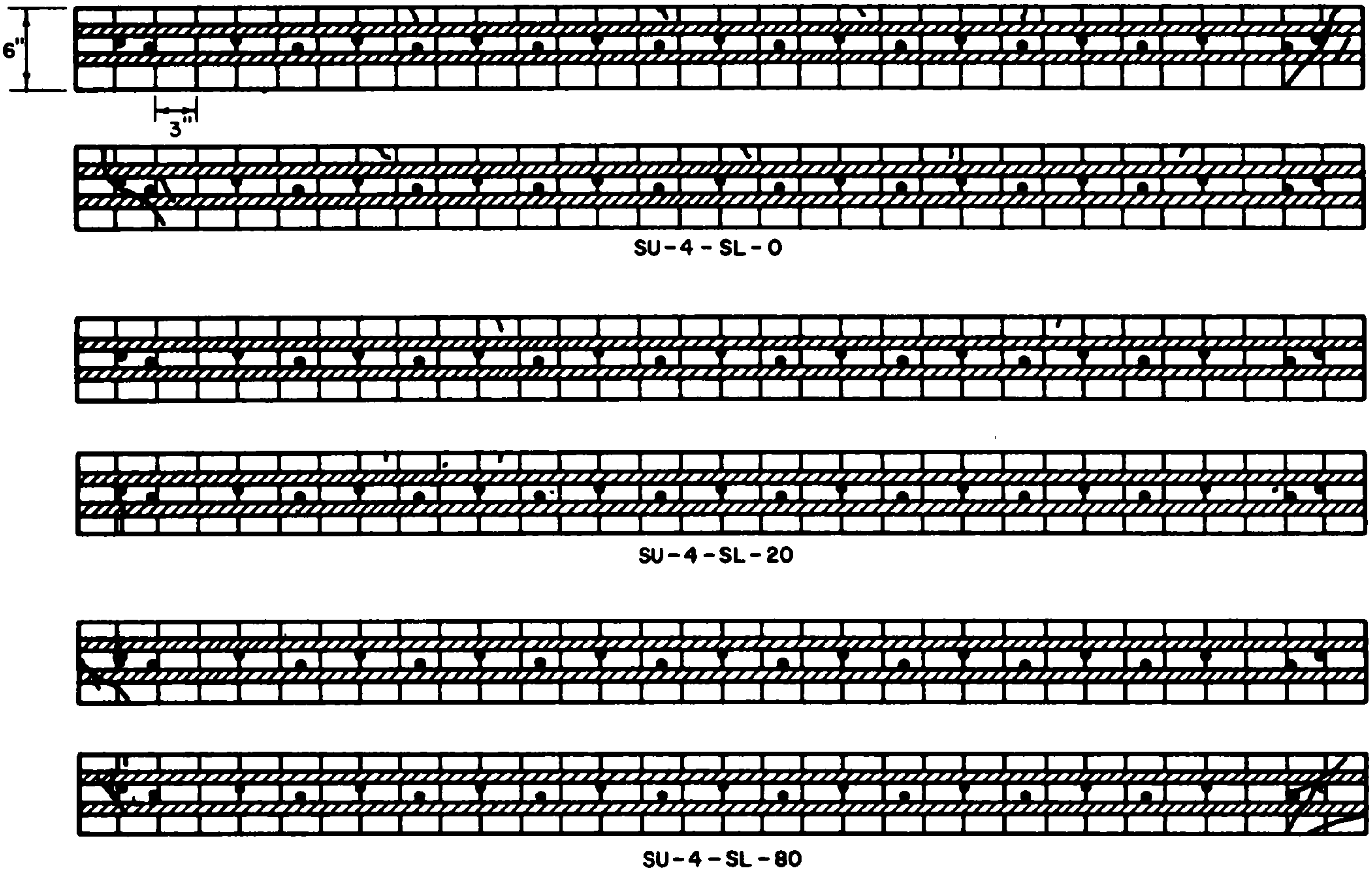


Figure F-14. Crack pattern in specimens, Series 4—Phase 2

Figure F-15. Crack pattern in specimens with anchored reinforcement, Series 5—Phase 2.

Figure F-16. Crack pattern in specimens, Series 7—Phase 2.

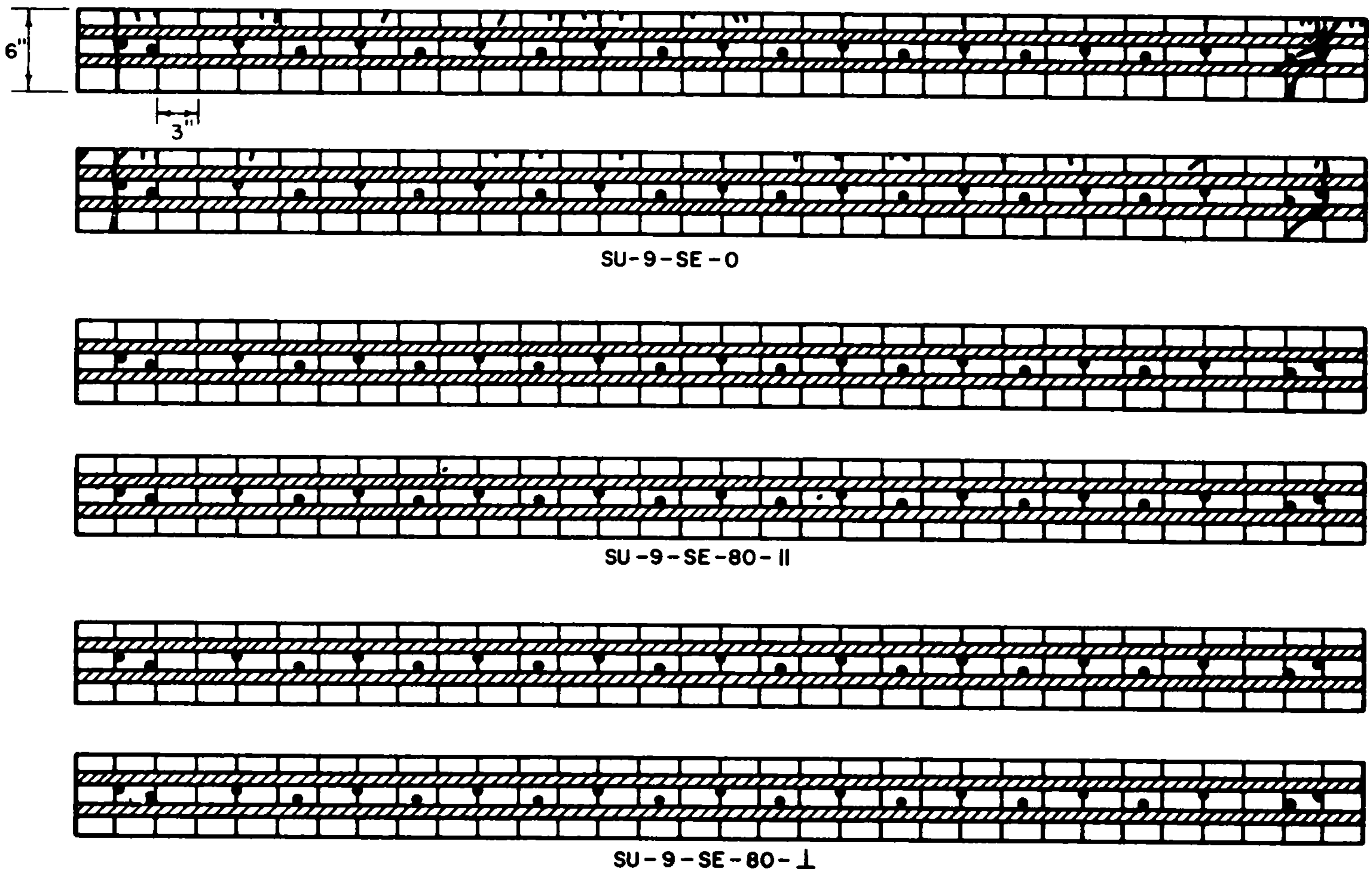


Figure F-17 Crack pattern in specimens, Series 9—Phase 2

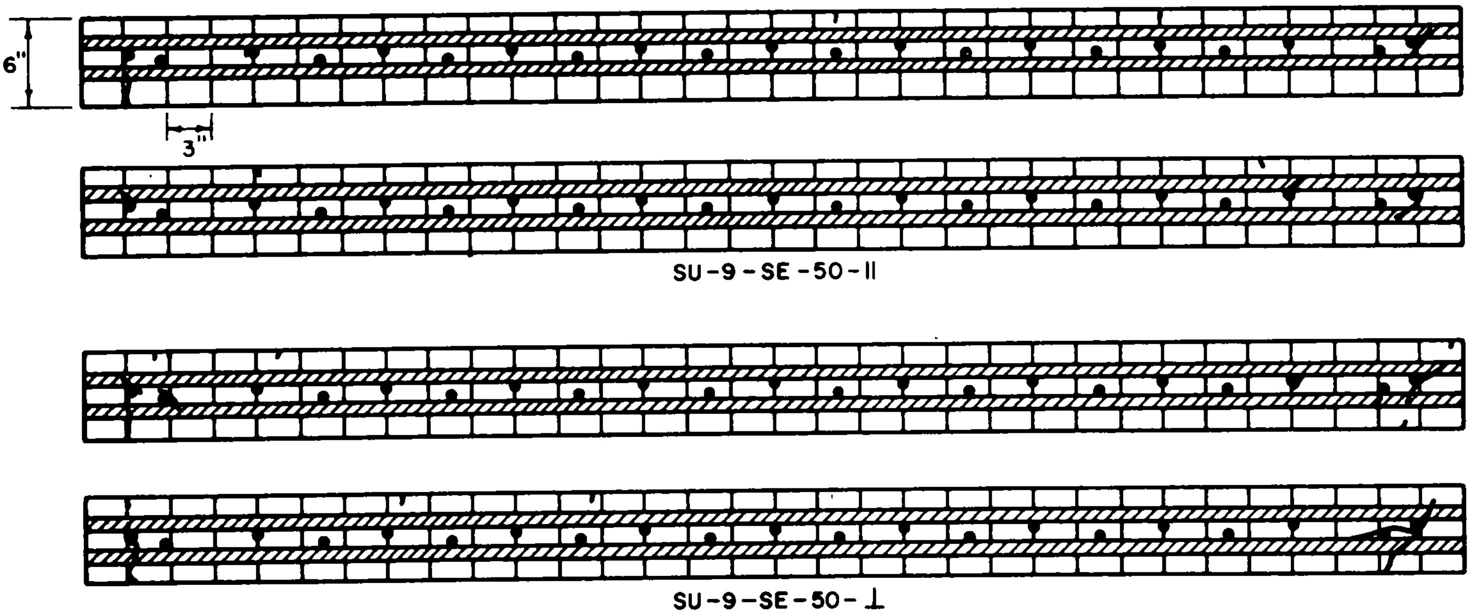


Figure F-18 Crack pattern in specimens, Series 9—Phase 2

APPENDIX G

OBSERVATIONS ON CORES TAKEN FROM EXPERIMENTAL BRIDGE DECKS IN KANSAS

The work reported in the following was conducted after the main body of this report was completed. It therefore is not included in the summary and conclusions in Part I of this report

Cores were taken from the revibrated and nonrevibrated sections of the experimental bridge decks in Kansas (described earlier in this report). At the time, the concrete was 22 and 28 days old. The locations in the bridge decks from which cores were taken are shown in Figures G-1 and G-2. The cores had a diameter of 3 in. and a height ranging from 4 in. to 7 in Their dimensions, as well as the location of the top and bottom steel intersecting the cores,

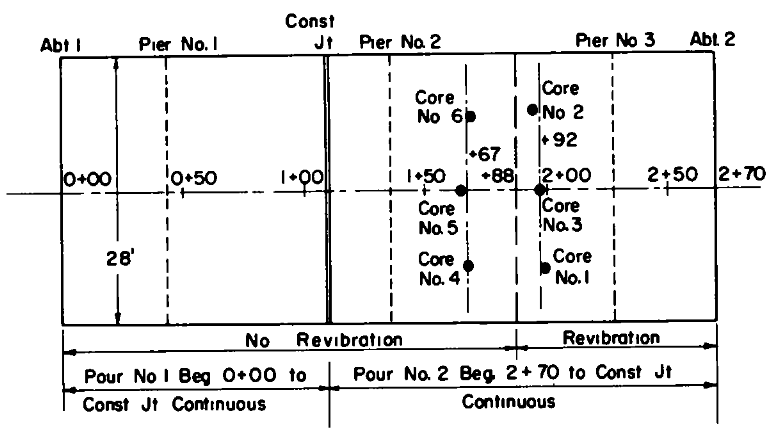


Figure G-1 Location of cores from deck of Br No 35W-40-2 00 near Newton, Kan

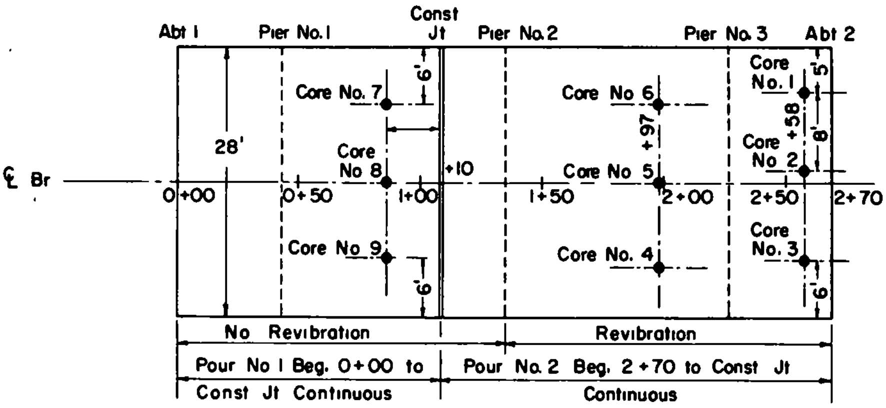


Figure G-2 Location of cores from deck of Br No. 35W-40-5 00 near Newton, Kan

are given in Table G-1. According to this table the concrete cover was in all cases larger than 2 in All cores were sliced longitudinally in halves. One-half of each core was examined in the laboratories of the Highway Commission of Kansas The other halves of the cores were studied at the University of Illinois

Inspection of the cores from both the revibrated and the nonrevibrated bridge decks revealed several voids and microcracks. No voids were found in the revibrated cores from Br. No 35W-40-2.00. However, one nonrevibrated core showed a large air void above the top reinforcing bar In one revibrated core from Br. No 35W-40-5 00 an air void approximately ½ in. long was located 4 in. from the surface of the deck. All nonrevibrated cores showed air voids ½ to ¾ in. long above the top reinforcing bars. All revibrated and nonrevibrated cores exhibited microcracks around reinforcing bars which were detected during observation of the cores under a microscope with a magnification of 50 times. The cracks also were made visible by means of a penetrant procedure. A fluid containing fluorescent particles was applied to the concrete surface The fluid penetrated the concrete through voids and cracks When illuminated with a fluorescent light the cracks became visible due to the fluorescent particles that were retained in the cracks. Photographs were taken, and the cracks detected in this way were marked on the negatives to increase their visibility. Typical examples of such photographs are shown in Figures G-3 and G-4. The left side of Figure G-3 shows the rounded surface of a revibrated half core with a section through a reinforcing bar. The plane surface parallel to the reinforcing bar which was generated by slicing the core in half is shown on the right side of Figure G-3. Figure G-4 shows a similar, nonrevibrated core. Radial cracks starting from the surface of the reinforcing bar and several cracks on the plane concrete surface parallel to the reinforcing bar can be seen in Figure G-3. In Figure G-4 an air void above the reinforcing bar as well as cracks along the steel-concrete interface are visible. The core broke in halves along the reinforcing bar either during coring, or during shipping of the core from Kansas to Illinois.

Microcracks around reinforcing bars might have been caused by revibration of the section from which the core was taken, or might have resulted from transmission of vibration energy through reinforcing bars into otherwise nonrevibrated sections. To further investigate this hypothesis, cores were taken from remaining test specimens in the laboratory which were not exposed to any significant vibration energy, direct or transmitted, other than initial compaction. The cores showed similar crack patterns. Thus, it is likely that the microcracks observed in the cores are due to shrinkage of the concrete which is restrained by the reinforcing bars. However, it cannot be determined whether the cracks developed already in the bridge deck or whether they were caused by drying and subsequent shrinkage of the cores after they were taken from the bridge deck and sliced in halves.

TABLE G-1

DIMENSIONS OF TEST CORES FROM BRIDGE DECKS NEAR NEWTON, KANSAS

CORE NO	LENGTH (IN)	DISTANCE FROM TOP: UPPER STEEL (IN)	DISTANCE FROM TOP: LOWER STEEL (IN)
Br No 35W-40-2 00			
1	5 5/8	3 1/16	5 1/2
2	6 5/8	2 7/8	6 9/16
3	5 1/2	3 1/8	—
4	5 5/16	—	5 1/4
5	5 1/8	2 5/8	—
6	5 7/8	—	5 13/16
Br No 35W 40-5 00			
1	7 1/4	—	—
2	4	2 15/16	—
3	6	2 3/8	6
4	6 1/4	2 5/8	6 1/16
5	6 1/8	—	—
6	5 7/8	—	—
7	5 1/2	—	—
8	5 3/4	3 1/8	—
9	5 7/8	2 1/8	5 9/16

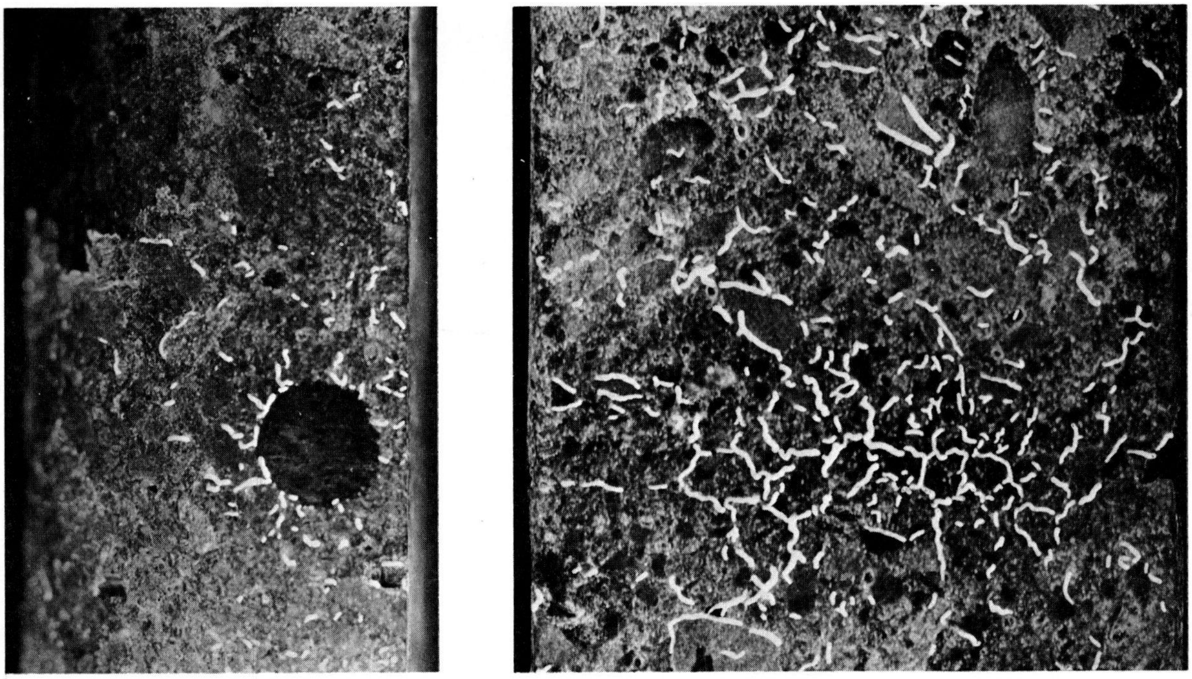


Figure G-3. Microcracks in revibrated core from Br. No. 35W-40-2.00 near Newton, Kan.

The results from studies of the air void characteristics of the cores are given in Tables G-2 and G-3 (State Highway Commission of Kansas) as well as Tables G-4 and G-5 (University of Illinois). The data determined by the State Highway Commission of Kansas are average values for the plane surfaces which were generated by longitudinally slicing the cores in halves. Therefore, they do not take into account variations of air void and cement paste

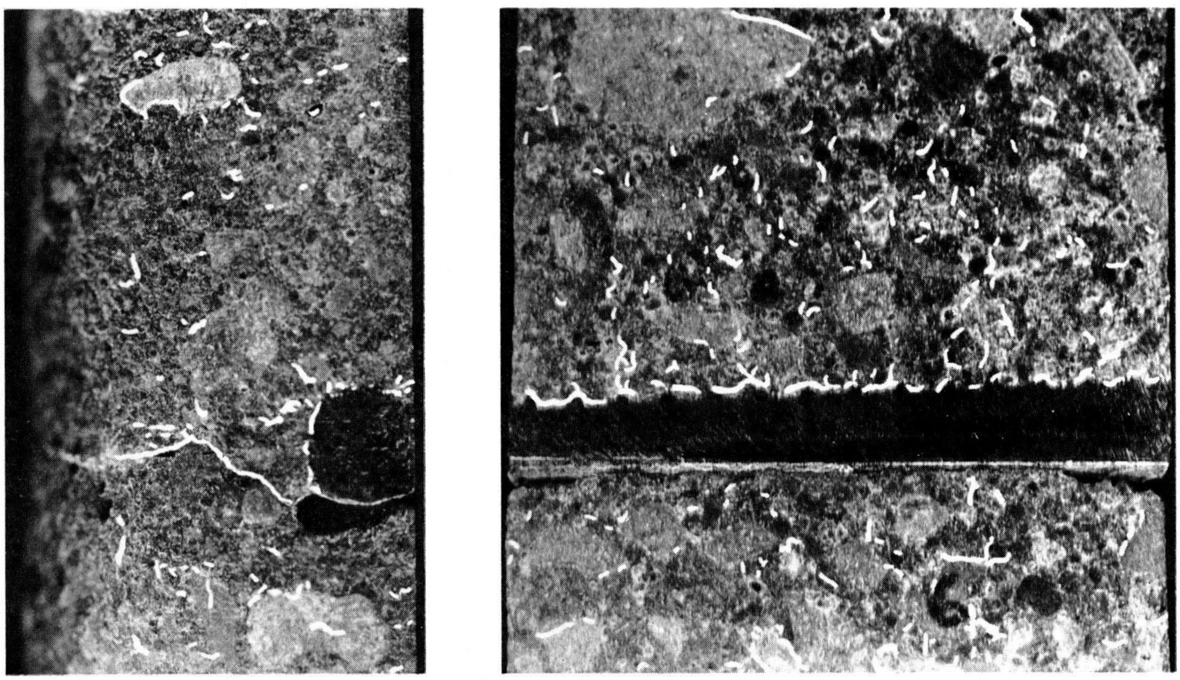


Figure G-4. Microcracks in nonrevibrated core from Br. No. 35W-40-2.00 near Newton, Kan.

TABLE G-2

DETERMINATION OF AIR VOID CHARACTERISTICS, BR. NO. 35W-40-2.00 (STATE HIGHWAY COMM'N OF KANSAS)

ITEM	CORE NO. 1	CORE NO. 2	CORE NO. 3	CORE NO. 4	CORE NO. 5	CORE NO. 6
T = total traverse, in inches	95	90	90	95	95	95
N = total number of air voids intersected in the entire traverse	505	455	401	468	425	512
M = average chord intercept of the ten largest measured air voids	0.07110	0.10687	0.10955	0.09190	0.12797	0.07272
m = average chord intercept of the ten smallest measured air voids	0.00072	0.00064	0.00054	0.00054	0.00053	0.00057
t = total cumulative inches of voids measured in the traverse	4.56604	5.89821	4.11301	5.24166	5.97417	4.70746
$\bar{l}$ = average chord intercept of air voids in inches (t/N)	0.00908	0.01296	0.01026	0.01120	0.01410	0.00921
n = average number of air void sections intersected per inch (N/T)	5.32	5.06	4.46	4.93	4.47	5 39
p = the proportional volume of cement paste in concrete, expressed as a percentage of the volume of the hardened concrete; calculated as the simple summation of the proportional volumes of the cement and water included in the concrete mixture (paste content)	28.8	28.8	28 8	28.8	28.8	28.8
A = the proportional volume of air voids in concrete expressed as a percentage of the volume of the hardened concrete (air void content) ($100\, n\, \bar{l}$)	4.9	6.6	4.6	5.5	6.3	4.95
α = the surface area of the air voids in hardened concrete, expressed as square inches per cubic inch of air void volume (specific surface) ($4/\bar{l}$)	443.9	308.6	389.9	357.1	283.7	434.7
$\bar{L}$ = use index related to the maximum distance of any point in the cement paste from the periphery of an air void, in inches (spacing factor)	0.0114	0 0141	0.0132	0.0133	0.0157	0.0114

characteristics over the depth of the bridge deck. The data reported by the University of Illinois were obtained after slicing the half cores horizontally as described for the laboratory specimens ("Determination of Air Content," in Appendix C). The air void characteristics were determined for the finished surface and at distances of 0.5 in. and 3 in. from the top at the cores. Because of these differences in procedures, the data obtained in both laboratories are not directly comparable. According to the results from the Kansas laboratories, possible differences between the air void characteristics of the revibrated and the nonrevibrated concrete are overshadowed by batch to batch variations of the concrete, as exemplified by the differences between cores of each bridge that underwent similar treatment. The same conclusion has to be drawn from the Illinois data given in Tables G-4 and G-5. In addition, these results consistently show a decreased air content and an increased paste content of the surface layer of both revibrated and nonrevibrated concrete; however, there was little variation of the spacing factor over the depth of the cores. Similar results have been found in the laboratory experiments reported previously.

The following conclusions may be drawn from studies of the bridge deck cores:

1. More voids, particularly above reinforcing bars, were found in cores from nonrevibrated bridge decks than in cores from revibrated bridge decks. However, revibration did not completely eliminate large air inclusions. The number of cores taken was not sufficient to yield statistically significant results.
2. Both revibrated and nonrevibrated cores had microcracks, particularly around the reinforcing bars. These microcracks cannot be attributed to revibration; they may be caused by shrinkage after revibration either in the bridge deck from which the cores were taken or by shrinkage of the concrete after coring.
3. No significant differences between the air void characteristics of revibrated and nonrevibrated bridge deck concrete were found.

Observation of the long-time performance of all three experimental bridge decks will be continued throughout the following years. No damage of either the revibrated or the nonrevibrated decks was reported or found after the first winter.

TABLE G-3

DETERMINATION OF AIR VOID CHARACTERISTICS, BR. NO. 35W-40-5 00 (STATE HIGHWAY COMM'N OF KANSAS)

ITEM	CORE NO 1	CORE NO 2	CORE NO. 3	CORE NO. 4	CORE NO. 5	CORE NO 6	CORE NO. 7	CORE NO 8	CORE NO. 9
T = total traverse in inches	100	90	90	90	90	90	95	95	95
N = total number of air voids intersected in the entire traverse	467	416	402	—	—	—	393	451	394
M = average chord intercept of the ten largest measured air voids	0 08895	0.08917	0.22046	0.10250	0 12792	0.08899	0 10041	0 24403	0.08981
m = average chord intercept of the ten smallest measured air voids	0 00065	0 00060	0 00056	0 00054	0 00049	0 00046	0 00049	0 00046	0 00056
t = total cumulative inches of voids measured in the traverse	5 41146	4.66455	7 65115	5.21694	6 91349	4 15804	5 70117	7 90561	4 71475
l = average chord intercept of air voids in inches (t/N)	0 01159	0 01121	0.01903	0 01194	0.01462	0.01063	0 01451	0 01753	0 01197
n = average number of air void sections intersected per inch (N/T)	4 67	4 62	4 47	4 86	5.26	4 34	4.13684	4.74737	4.14737
p = the proportional volume of cement paste in concrete, expressed as a percentage of the volume of the hardened concrete; calculated as the simple summation of the proportional volumes of the cement and water included in the concrete mixture (paste content)	29 5	29 5	29.5	29.5	29 5	29.5	29.5	29.5	29 5
A = the proportional volume of air voids in concrete expressed as a percentage of the volume of the hardened concrete (air void content) ($100\ n\ \bar{l}$)	5.40	5.18	8.50	5 8	7.68	4 62	6.00	8 32	4 96
α = the surface area of the air voids in hardened concrete, expressed as square inches per cubic inch of air void volume (specific surface) ($4/\bar{l}$)	345.0	356.8	210 2	335 0	273.6	376.3	275.7	228.2	334.2
$\bar{L}$ = use index related to the maximum distance of any point in the cement paste from the periphery of an air void, in inches (spacing factor)	0.014	0.0137	0.0165	0.0139	0 014	0.0138	0.017	0.016	0.015

TABLE G-4

AIR VOID CHARACTERISTICS OF CORES FROM BRIDGE DECK, BR. NO. 35W-40-2.00 (UNIV. OF ILLINOIS)

CORE NO.	REVIBRATION	DISTANCE OF SECTION FROM TOP (IN.)	AIR CONTENT (%)	PASTE CONTENT (%)	SPACING FACTOR (IN.)
1	Yes	0	3.9	44.2	0.0092
		0.5	4.6	21.8	0.0103
		3	5.4	24.7	0.0111
3	Yes	0	3.2	41.7	0.0098
		0.5	4 9	23.4	0.0124
		3	5.1	22 6	0 0117
4	No	0	4.2	38.2	0.0107
		0 5	5.1	23.7	0.0132
		3	5.6	26.1	0 0118
6	No	0	4 5	39.7	0 0110
		0.5	5.1	27.2	0.0105
		3	4.8	25.7	0 0128

TABLE G-5

AIR VOID CHARACTERISTICS OF CORES FROM BRIDGE DECK, BR. NO. 35W-40-5.00 (UNIV. OF ILLINOIS)

CORE NO.	REVIBRATION	DISTANCE OF SECTION FROM TOP (IN.)	AIR CONTENT (%)	PASTE CONTENT (%)	SPACING FACTOR (IN.)
1	Yes	0	3.9	38.7	0 0121
		0.5	4.8	23.6	0 0112
		3	5.3	26.7	0.0121
3	Yes	0	4.4	41.9	0.0128
		0.5	6 1	19.9	0.0138
		3	6.4	23.9	0.0137
5	Yes	0	4.7	37.4	0.0137
		0.5	5.4	27 9	0.0129
		3	6.1	22.6	0.0141
7	No	0	4.8	38.9	0.0148
		0.5	5.4	27.9	0.0152
		3	6.3	24.9	0 0129
9	No	0	4.2	36 7	0.0120
		0.5	5 9	25.2	0.0139
		3	4.8	25.7	0.0124

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