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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
SYNTHESIS OF HIGHWAY PRACTICE

4

CONCRETE BRIDGE DECK DURABILITY

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
SYNTHESIS OF HIGHWAY PRACTICE

4

CONCRETE BRIDGE DECK DURABILITY

RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION
OF STATE HIGHWAY OFFICIALS IN COOPERATION
WITH THE BUREAU OF PUBLIC ROADS

SUBJECT CLASSIFICATIONS:

BRIDGE DESIGN
BITUMINOUS MATERIALS AND MIXES
CEMENT AND CONCRETE
CONSTRUCTION
GENERAL MATERIALS
MAINTENANCE, GENERAL

HIGHWAY RESEARCH BOARD

DIVISION OF ENGINEERING

NATIONAL RESEARCH COUNCIL

NATIONAL ACADEMY OF SCIENCES—NATIONAL ACADEMY OF ENGINEERING

1970

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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.

In recognition of these needs, the highway administrators of the American Association of State Highway Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Bureau of Public Roads, United States Department of Transportation.

The Highway Research Board of the National Academy of Sciences-National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway departments and by committees of AASHO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Highway Research Board.

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.

NCHRP Synthesis 4

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This report was prepared by the contracting research agency. It has been reviewed by the appropriate Advisory Panel for clarity, documentation, and fulfillment of the contract. It has been accepted by the Highway Research Board and published in the interest of effective dissemination of findings and their application in the formulation of policies, procedures, and practices in the subject problem area.

The opinions and conclusions expressed or implied in these reports are those of the research agencies that performed the research. They are not necessarily those of the Highway Research Board, the National Academy of Sciences, the Bureau of Public Roads, the American Association of State Highway Officials, nor of the individual states participating in the Program.

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PREFACE

There exists a vast storehouse of information relating to nearly every subject of concern to highway administrators and engineers. Much of it resulted from research and much from successful application of the engineering ideas of men faced with problems in their day-to-day work. Because there has been a lack of systematic means for bringing such useful information together and making it available to the entire highway fraternity, the American Association of State Highway Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Highway Research Board to undertake a continuing project to search out and synthesize the useful knowledge from all possible sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series attempts to report on the various practices without in fact making specific recommendations as would be found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available concerning those measures found to be the most successful in resolving specific problems. The extent to which they are utilized in this fashion will quite logically be tempered by the breadth of the user's knowledge in the particular problem area.

Included with this document is a return card by which reader reaction is invited. The knowledge gained therefrom will be directed toward improvement of future issues in light of the express needs of the potential users. Further follow-up will be made to determine the usefulness of the syntheses in highway practice and to effect updating as appropriate.

FOREWORD

By Staff

Highway Research Board

Administrators, engineers, and researchers are faced continually with many highway problems on which much information already exists either in documented form or in terms of undocumented experience and practice. Unfortunately, this information is often fragmented, scattered, and unevaluated. As a consequence, full information on what has been learned about a problem is frequently not brought to bear on its solution, costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem. In an effort to resolve this situation, a continuing NCHRP project, carried out by the Highway Research Board as the research agency, has the objective of synthesizing and reporting on highway practices—a synthesis being defined as a composition or combination of separate parts or elements so as to form a whole. Reports from this endeavor constitute a new NCHRP series that collects and assembles the various forms of information into single, concise documents pertaining to specific highway problems or sets of closely related problems. This fourth report of this series treats the concrete bridge deck deterioration problem, considered by many highway departments to be one of the major maintenance problems they face. This report will be of special interest to bridge design, construction, and maintenance engineers, as well as engineers of materials and individuals concerned with the general problem of scaling and spalling of concrete.

There is much concern across the United States regarding the problem of deteriorating concrete bridge decks, the causes, prevention, and corrective measures that can be taken. Some reported repair costs to the bridge decks have approached the initial costs of the bridges. Although the true magnitude and extent of the bridge deck problem has not been fully determined, indications are that the concern is widespread for the 200,000 state highway bridges in the United States. There appears to be a similarity of bridge deck deterioration generally falling into three types of defects—spalling, scaling, and cracking. Spalling is generally recognized as the most troublesome defect, because the deck is weakened locally, reinforcement is exposed, riding quality is impaired, and repair work is difficult. Because highway personnel responsible for the design, construction, and maintenance of bridge decks have a perpetual need for the best “how-to-do-it” information, the Highway Research Board has attempted in this project to set down those solutions found to be most practical to minimize the problem.

To develop this synthesis in a comprehensive manner and to insure inclusion of most significant knowledge, the Board analyzed all information—for example, current practices, plans, specifications, manuals, and research recommendations—assembled from the knowledge of highway departments, toll road agencies, and other agencies responsible for highway and street design, construction, and maintenance. Furthermore, a thorough literature search of all pertinent publications was made, interviews were held with knowledgeable highway personnel, and a correspondence survey for pertinent information was conducted. A topic advisory panel of persons knowledgeable in the subject area was established to guide the researchers in organizing and evaluating the collected data, and for reviewing the final synthesis report.

As a follow-up, the Board will evaluate carefully the effectiveness of the synthesis after it has been in the hands of its users for a period of time. Meanwhile, the search for better methods is a continuing activity and should not be diminished. Hopefully, an early updating of this document will be made to reflect improvements that may be discovered through research or practice.

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Instrumental in the preparation of this synthesis were the members of the Advisory Panel, consisting of Russell H. Brink, Deputy Chief, Materials Division, Office of Research and Development, Bureau of Public Roads; Myron G. Brown, Chemical Engineer, Research Laboratory Division, Michigan Department of State Highways; Paul Klieger, Manager, Concrete Research Section, Portland Cement Association; Sanford P. LaHue, Chief, Construction Methods and Practices Branch, Office of Engineering and Operations, Bureau of Public Roads; Howard H. Newlon, Jr., Assistant State Highway Research Engineer, Virginia Highway Research Council; W. M. Stingley, Assistant Engineer of Planning and Development, State Highway Commission of Kansas; and Richard F. Stratfull, Corrosion Specialist, Materials and Research Department, California Division of Highways. Ray E. Bollen, Engineer of Materials and Construction; Adrian G. Clary, Engineer of Maintenance; and

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CONCRETE BRIDGE DECK DURABILITY

SUMMARY

Bridge deck deterioration continues to be a major maintenance problem. Although the true magnitude and extent of the problem has not been fully determined, indications are that concern is widespread.

The most commonly reported conditions are cracking, scaling, and spalling. Cracking, of itself, is not considered to be serious. Also, scaling can be virtually eliminated by the use of high-quality air-entrained concrete, assisted when necessary by periodic linseed oil applications. However, spalling, the most serious defect, has proved to be the most difficult to control.

Spalling, in the main, is caused by the corrosion of reinforcing steel, requiring the presence of moisture and a chloride salt. Cracks provide ready access for moisture and salt to reach the steel, although porous concrete without cracks is also susceptible to moisture and salt intrusion.

Various waterproof barriers protected by a wearing course are currently in vogue as a preventive measure. In addition, greater cover over reinforcing steel, increased efforts at crack control, and less porous concrete are urged as essential improvements.

Meanwhile, research is under way to discover alternate methods for deicing, evaluate coatings for reinforcing steel, consider quality improvements inherent in precast construction, and develop reliable waterproof membranes.

CHAPTER ONE

INTRODUCTION

EXTENT OF THE PROBLEM

In a survey made in 1955 for the Highway Research Board (1) to ascertain the principal problems faced by bridge maintenance engineers, concrete deterioration rated only fourth in the order of frequency of appearance. In a similar survey made in 1967 (2), in answer to the question, "What type of structure maintenance requires the greatest effort?", concrete bridge decks had become first in the order of frequency of appearance. In a highway engineering handbook published in 1960 (3), a leading engineer states, "The satisfactory maintenance of a concrete bridge floor has become one of the major bridge maintenance problems." Also, the opening words of a Highway Re-

search Board Symposium in 1962 (4) were, "The rate of deterioration of portland cement concrete bridge decks is far more severe than previously noted." The report goes on to state flatly that "the matter is serious." Clearly, then, sometime in the late 1950's engineers became acutely aware of mounting bridge deck distress.

Thus far the literature has not clearly pictured the whole extent of the problem nor has the broad corrective effort in design, construction, and maintenance been thoroughly documented. An article in a principal trade journal in 1967 (5) indicates concern across the country and quotes several sources as to their thoughts on causes, prevention, and correction. However, the costs quoted (\$150,000 per year for

one entire state, \$300,000 for another) (5) are deceptively low when compared with reported repair costs of \$400,000 for one bridge in New York (6), \$600,000 for one viaduct in a Midwestern state (5), and \$1,200,000 for a bridge deck in New Jersey (7). The Cooperative Bridge Deck Study (8) of the Bureau of Public Roads, ten state highway departments, and the Portland Cement Association, a landmark study relied on heavily elsewhere in this report, is nevertheless restricted to selected areas by its own mandate. An unpublished market survey (9) covering 10,000 bridges in 30 states by a private industry source indicates 800 old bridges resurfaced with a waterproof membrane and overlay in the past three years, and 900 old bridges and 850 new ones planned to be so treated in the next three. Yet the motive for providing an overlay is not always known and bridge inventories are widely variable among the states.

The President's Task Force on Bridge Safety, Committee 3, in its published guidelines (10) requested that each state institute a program of bridge inspection to be completed by January 1, 1970. Included in this guide is a recommendation that all bridge decks be inspected for deterioration by all states as some states now do. Collection and analysis of this information for the 200,000 state highway bridges in the United States should give a definitive picture of the bridge deck problem. For example, the Committee learned that for many years the toll roads in the United States have made such periodic reports, generally by outside consultants, as standard procedure (10). A review of several such reports indicates that bridge deck deterioration is a major concern of toll facilities in Maine, Massachusetts, New York, New Jersey, Pennsylvania, West Virginia, Virginia, Ohio, Kansas, Texas, and California.

Although the extent of the bridge deck deterioration problem has not yet been carefully documented, the intensity has. A significant number of thoughtful and well-prepared reports has begun to enrich the literature from a broad spectrum of sources. Among these are the aforementioned Cooperative Bridge Deck Study, the 1962 Highway Research Board Symposium summarized in *HRB Bulletin 323*, and such excellent statewide studies as the Kentucky report by Hughes and Scott (11) and the Pennsylvania State University reports by Larson, Cady, and Price (12). Figure 1 shows the states that have looked into the bridge deck problem and generated at least one published report since 1960.

* Definitions

- CLEAR COVER**—The vertical distance measured from the topmost projection of reinforcement steel to the top concrete surface.
- CORROSION**—Destruction of a metal by chemical or electrochemical reaction with its environment.
- MEMBRANE**—A thin waterproof barrier either prefabricated or applied as a liquid.
- SCALING**—Local flaking or peeling away of the surface mortar portion of concrete.
- SPALL**—A depression caused by a separation and removal of the surface concrete.
- TRANSVERSE CRACKING**—Reasonably straight cracks perpendicular to

the centerline of the roadway and generally occurring over primary slab reinforcement.

WATERPROOF

BARRIER—Any material placed on the surface of concrete to prevent the passage of water into the concrete.

NATURE OF THE PROBLEM

A reading of several reports shows an apparent similarity in the types of defects noted. The Cooperative Bridge Deck Study, Report 5 (13), provides a good overview of the occurrence of defects on 813 bridges summarized from surveys in eight states. The following is calculated from Table 2A of that study:

TYPE OF DEFECT	BRIDGES EXHIBITING DEFECT (%)
Spalling	12
Scaling	34
Cracking	76

Among bridges that exhibited cracking 78 percent showed transverse cracking. This cracking, of itself, is not considered a serious defect structurally. However, it permits easy access to the underlying reinforcing steel by deicing salts. This, in turn, induces corrosion and, eventually, spalling (7, 12, 13, 14, 15).

Thirty-four percent of the bridges surveyed exhibited scaling, but these were predominantly in states that were slow to adopt air entrainment or on structures where documentation is lacking as to the actual amount of entrained air obtained (13).

Spalling is generally recognized as the most troublesome defect because the deck is weakened locally, reinforcement is exposed, riding quality is impaired, and repair work is difficult. Eventually, if left unattended, spalls may grow into total deck failures and require the most urgent attention (7). However, such failures rarely occur without prior warning as evidenced by spall development. One example of such evidence is the common experience of noting hollow-sounding areas in decks exhibiting spalls.

Slipperiness is another serious concern, on bridge decks as on all roadway surfaces. A recent survey indicated that only three states currently specify a minimum coefficient of friction for pavements, but 18 contemplate such a requirement. Factors influencing the skid resistance of pavement surfaces obviously are applicable to wearing surfaces of bridges. In one of the three states that currently specify a minimum coefficient of friction (Virginia), loss of skid resistance has been the cause of extensive bridge deck resurfacing (16).

A COMPARISON OF SCALING AND SPALLING

Among the many anomalies that plague the study of deck deterioration none is more puzzling than the fact that, although scaling and spalling are unrelated to each other (13, 17), they nevertheless arise from the same root cause—increasing use of chlorides. The fundamental differences

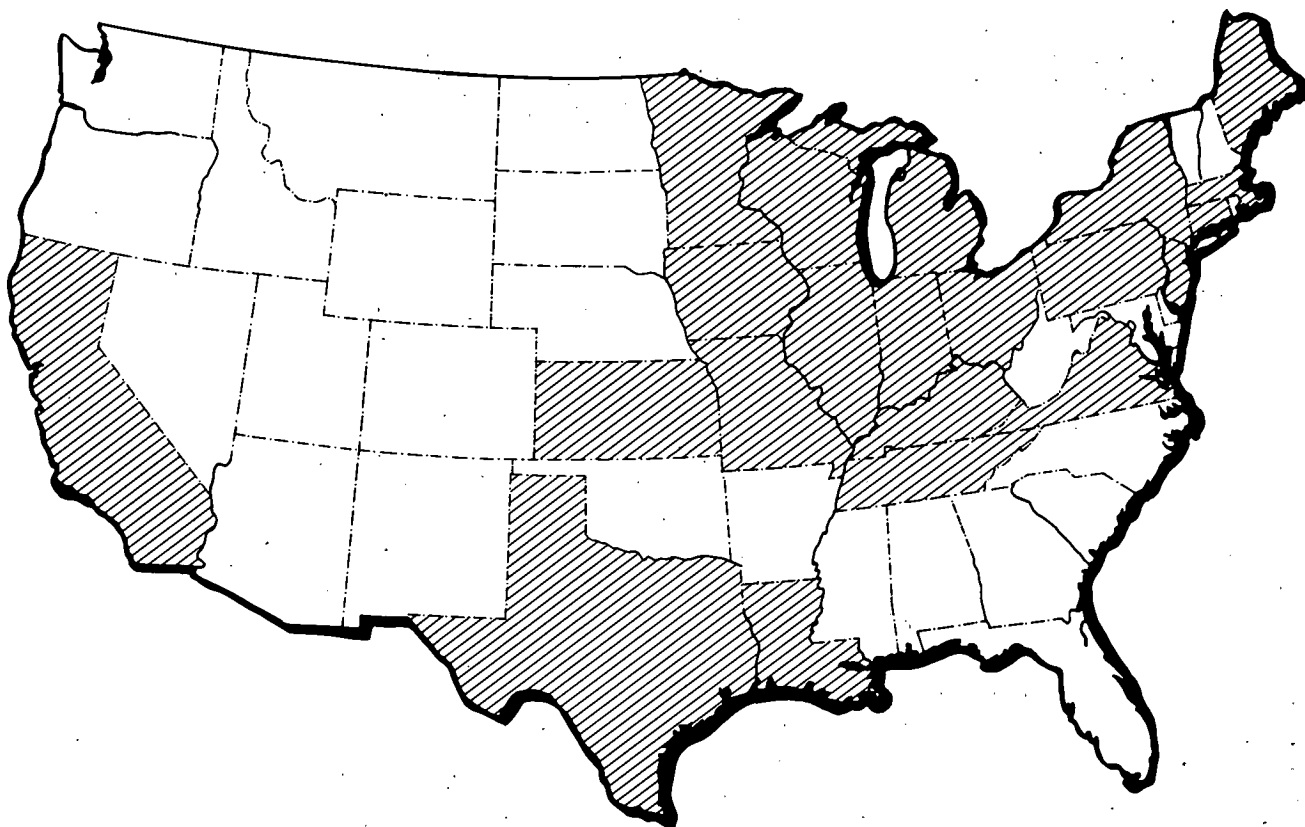


Figure 1. States that have conducted research on bridge deck durability.

are: (a) in scaling, freeze-thaw action in the presence of salt affects the concrete (18), whereas in spalling the salt affects the reinforcing steel (19, 20, 21); (b) in scaling the cracks are very fine and very shallow surface cracks (15), whereas in spalling the cracks are long, wide, and deep enough to provide access to the steel (20, 22, 23); and (c) for scaling young concrete is the most vulnerable (24), whereas for spalling age in years is essential. Thus it might be said that scaling and spalling are different species of the same genus.

In the foregoing it must be understood that salt is not the *sole* cause of scaling and spalling. It is entirely possible to create scaling by freeze-thaw action without salt and for under-surface fracturing to create spalling without salt. However, in contemporary bridge deck experience the preponderant amount of deterioration is caused by deicing salts in the form of either sodium chloride or calcium chloride.

MECHANICS OF SPALLING

From a synthesis of the literature an empirical picture of the spalling phenomenon is now possible.

Fresh concrete is cast in the deck, vibrated and screeded, and continues to consolidate. Aggregate particles settle to the bottom. Water is displaced and bleeds to the top surface. Meanwhile, the deck continues to deflect and vibrate

as concrete is placed to complete the span, and the concrete subsides. Twin mats of reinforcement disrupt this subsidence, causing differential consolidation—more settlement occurs between the bars than over them. The wetter the concrete the more pronounced will be the difference.

Over a given bar, concrete is caused to separate as particles tend to flow to one side or the other to the lower settled areas between bars. Plastic shrinkage, drying shrinkage, and thermal stresses find relief in this area and cause a crack—particularly if the steel is close to the surface and particularly if the concrete is very wet and thus subject to more shrinkage.

This crack over the topmost reinforcing bar, which is usually transverse to the traveled roadway, is very common in bridge decks. The concrete over the bar is, in accordance with accepted design procedures, considered to be cracked and is not used in design calculations. As years go by, however, water, dirt, and salt wash into the cracks. This action is increased by the flexing action of the bridge superstructure (Fig. 2).

Bleed water that is trapped under a surface crust creates planes of weakness that may cause early spalling.

Even if there are no cracks, water can permeate porous concrete—even air-entrained concrete—and so can salt. This permeability is especially great in high-water-content concrete.

Different concentrations of salt, or different concentra-

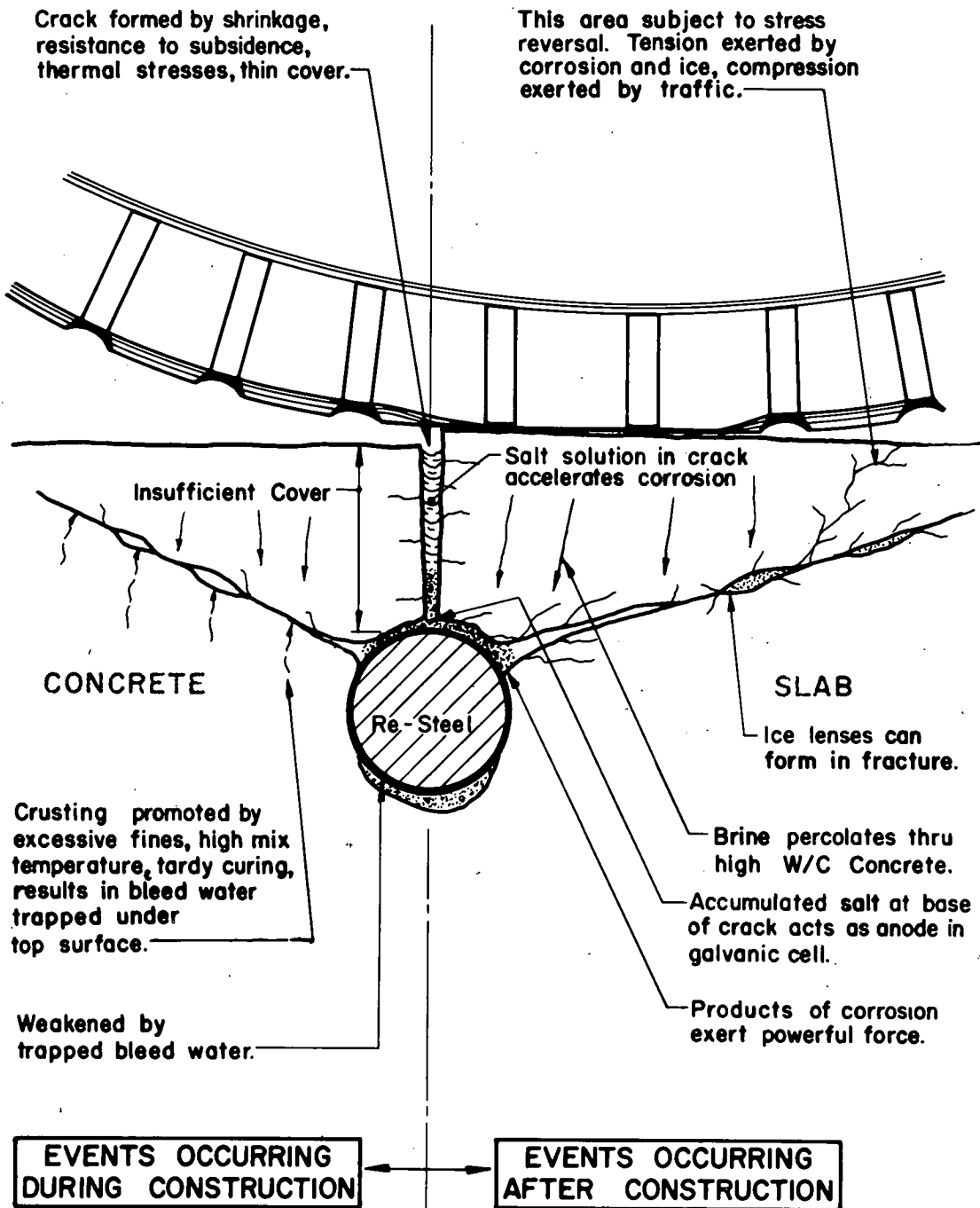


Figure 2. Genesis of a spall.

tions of moisture, are sufficient to set up anodic and cathodic areas in a macrogalvanic electrochemical cell and actually cause a flow of current. Salt in solution provides an electrolyte and oxygen in the water provides the oxidizing agent. An ideal environment is now established for the corrosion of the reinforcing steel, which involves the metamorphosis of iron into rust.

The products of this corrosion occupy considerably more volume than the parent metal and result in a tensile

force many times the strength of concrete. When the cracks fill with water and freezing occurs, even greater pressures are exerted. Passing traffic creates significant compressive stresses, thereby inducing stress reversals and fatigue characteristics.

Eventually certain random combinations of surface shrinkage cracks, cracked paste-aggregate bond, pressure from corrosion, and thermal stresses link to create a critical section that cracks to the surface. Ice pressure and the

shear stress linked with bending moments soon extend this crack to form a complete fracture plane and a spall is created.

MECHANICS OF SCALING

The preceding summary on spalling, although sufficiently conclusive, is nevertheless entirely empirical. Experimental verification of fundamental scaling mechanisms is also elusive. Nevertheless, the following discussions by eminent researchers answer the basic questions:

1. How does freeze-thaw action cause scaling?

When concrete dries, voids, called capillary cavities, are left by the evaporating water. When a water-saturated cavity is frozen either the volume must be expanded by 9%, or the excess water forced out.

In any system of voids, moisture tends to move from larger voids to smaller ones. Since the entrained air voids are far larger than the capillary voids, they remain essentially free of moisture. They are available as points of pressure relief. After thawing, the moisture is drawn from the entrained air voids to the capillary cavities by capillary action. If enough unfilled entrained air voids are present, disruptive hydraulic pressures will not develop. A low water/cement ratio paste will have smaller and fewer potentially vulnerable capillary cavities and will therefore be more resistant to frost action.

(From Ch. I, "Durability of Concrete in Service," by ACI Committee 201; *ACI Jour. Proc.*, Vol. 59, 1962)

2. How does salt aggravate scaling?

Placing salt on pavements for ice removal will increase the concentration of salt in the capillary voids near the surface of the pavement. As the salt solution freezes, a greater concentration of salt results and osmotic pressure is built up in the capillary cavities. This increase in pressure may be sufficient to cause a rupture of the cement gel near the surface of the pavement and consequently cause scaling.

Deicing salts not only create additional forces through osmosis, but also provide an additional source of surface moisture in freezing weather by melting the ice and snow. As snow and ice are melted by deicing salts, the temperature immediately below the surface is reduced significantly because of the comparatively large heat of fusion of ice. This may cause a damaging temperature drop in the saturated zone immediately beneath the surface.

Thus deicing salts may cause concrete to scale by any combination of the following:

1. By providing moisture from the melting of ice and snow in freezing weather.
2. By causing additional freezing through lowering the temperature in the subsurface zone (ice cream freezer principle).
3. By creating a system which develops osmotic pressures.
4. By a buildup of salt crystals in subsurface voids. (p. 44)

(From Ch. 4, "Freezing and Thawing of Concrete—Mechanisms and Control," *ACI Monograph No. 3*, by W. A. Cordon)

THE PHENOMENON OF SCALING

Scaling can be caused by freeze-thaw action in the absence of deicers. It also can be caused by chlorides without freezing. *But scaling is especially severe when concrete is subject to freeze-thaw action in the presence of deicers.*

Scaling can be markedly reduced by air entrainment. It also can be markedly reduced by linseed oil treatment. *But scaling can be virtually eliminated by the proper use of air entrainment plus, when required, linseed oil treatment.*

Although all of these maxims have been accepted by practically all highway agencies, the use of linseed oil treatment has been questioned by a few.

Other factors accepted by most engineers are that scaling is *increased* by high water/cement ratios, improper finishing, and improper curing, but is *not related* to spalling, deep cracking, or concrete strength.

ROADWAYS VERSUS BRIDGES

Another puzzle noted by careful observers (25) is that roadway slabs made with essentially the same materials, at the same time, carrying the same loads, and receiving the same salt application, are more durable than contiguous deck slabs. Such disparate performance can be accounted for almost entirely by differences in design, methods of construction, and environment.

To begin with, spalling requires that the reinforcing steel be attacked by salts. Where steel is used in road slabs it is of a smaller size, generally free to subside, and has greater cover. Therefore, spalling, the most serious deterioration found in bridge decks, is less likely to occur in roadway slabs.

Scaling, on the other hand, can and does occur in roadway slabs, but much less frequently than in bridge slabs. This is so because, for one thing, construction practices have a significant effect on scaling. Bridge decks are a one-at-a-time specialty item not conducive to the development of day-by-day improved techniques as used on long roadway slabs. Finishing machines on roadways are heavier and help to densify the surface. Poor hand finishing is often the cause of bridge deck scaling (11, 13, 26, 27).

Furthermore, the masses of reinforcing steel (Fig. 3) in bridge decks invite the use of higher slump. High water/cement ratios and lack of proper air entrainment are perhaps the greatest causes of bridge deck scaling (20, 28, 29). A contributing factor in this regard is that nearly all bridge decks are cast from transit-mix concrete, whereas central-mix concrete is normally used for road slabs. The number of different mixers involved in a transit-mix operation leads to greater variability in the concrete and makes it particularly difficult to control air and water contents.

These factors, plus the typical use of smaller coarse aggregate and the use of retarders, lead many observers to conclude that the concrete material in a deck is, after all, really not the same as that in a roadway slab.

Furthermore, there are significant environmental differences, such as more freeze-thaw cycles on bridge decks.

All of these items point toward the recent greater concern for bridge deck durability as compared with roadway durability.

OLD VERSUS NEW BRIDGES

Reports have been received that bridges prior to World War II have not scaled as noticeably as bridges built recently (30). First, it should be noted that with modern

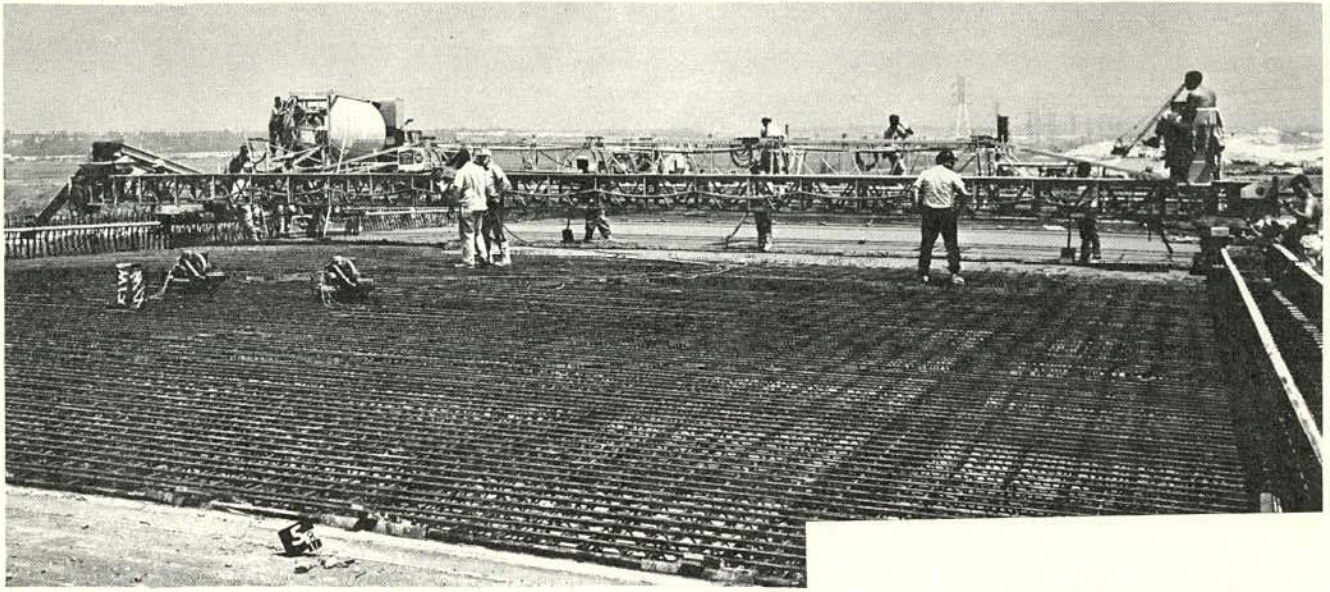


Figure 3. Constructing a concrete bridge deck.

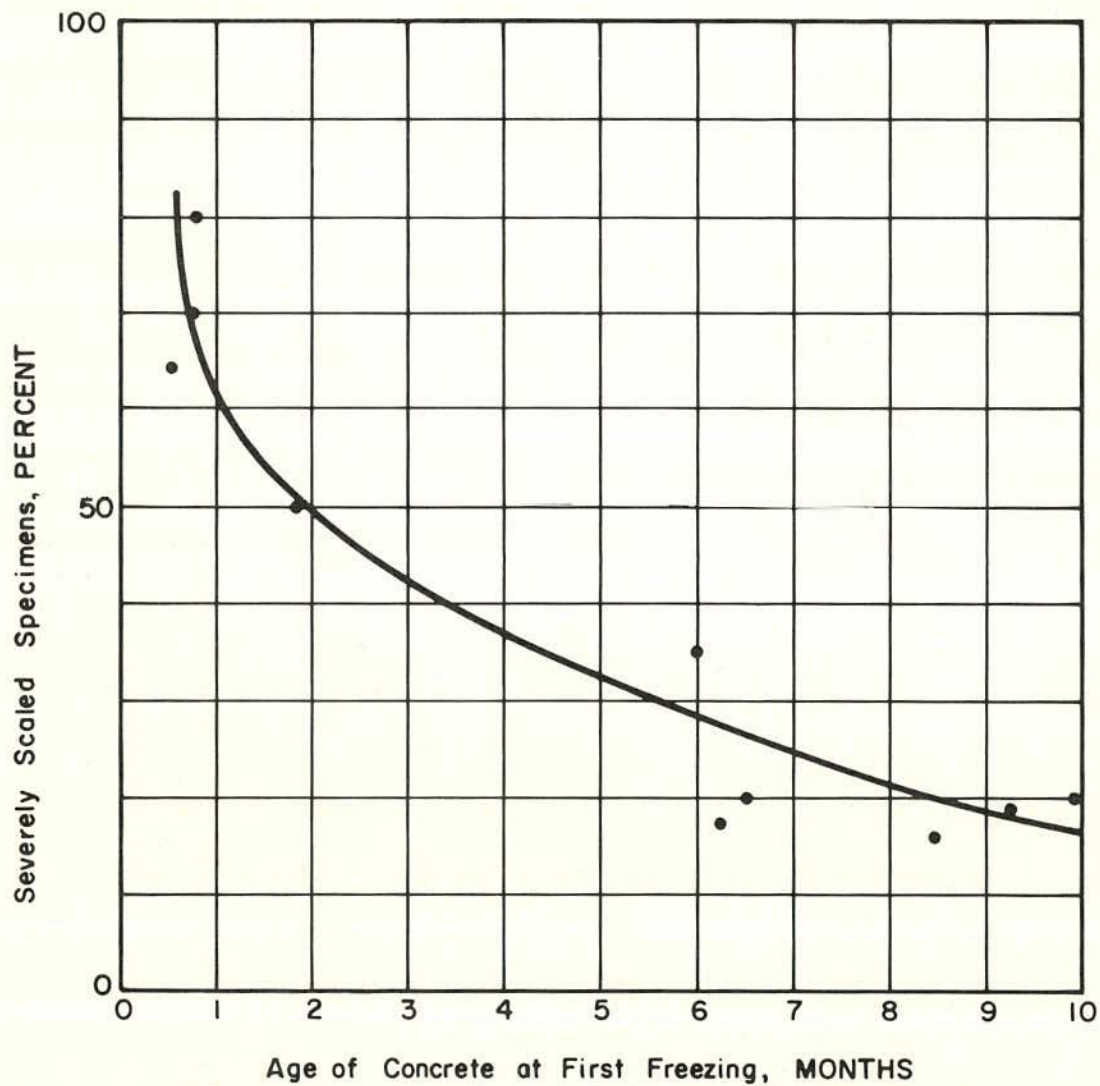


Figure 4. Relationship of scaling to concrete age. (Source: Grieb, Werner, and Woolf, HRB Bull. 323).

bridges the whole population is being observed, whereas with old bridges only the survivors—the better specimens—are being observed. Second, differences may be attributed to the fact that scaling is significantly affected by the age of the concrete at the first salt application (Fig. 4) (24). Because deicing salts were not commonly used until the 1950's, considerable resistance to salt attack had already been developed. However, for bridges built since the 1940's scaling does appear to increase with age (13).

DURABILITY VERSUS TESTING

Another anomaly sometimes encountered is the noticeable deterioration of a bridge deck even though the concrete "passed" all the tests. The problem here is two-fold; one of nomenclature and one of test method.

Durability is not properly defined. Some of the most prestigious organizations consider durability as the resistance to freeze-thaw cycles, which in a bridge deck generally takes the form of scaling, while acknowledging that spalling is unrelated and more serious. Durability of bridge decks should also include resistance to spalling, which, for con-

crete, is best exemplified by low permeability. Crack resistance is itself not yet well understood.

Beyond that the tests usually referred to are compression, slump, and air content. Reports have shown that compressive strength is not related to either spalling (17) or scaling (26, 29). Slump is, of course, a useful control of water/cement ratio; but it is only a control. Tests have shown that slump is diminished by as much as 1 percent per minute of mixing time (31). Therefore, a concrete with 6-in. slump mixed 50 min, a not uncommon time (22, 23, 32), might have a 3-in. slump at the job site. Consequently, the slump value alone could give a false indication of the quality of the concrete.

The volume of entrained air is not the most important parameter of an air-void system. It is the distance between air voids that is the most important (33). In fact, it is the uniform distribution of the air-void system in the *surface* of the deck that is significant, not the content in a random portion of the mass.

So it is that a batch of concrete may "pass" the usual tests (compression, slump, temperature, air volume) and still turn out to be unsuitable for use in a bridge deck.

CHAPTER TWO

IDENTIFYING CAUSES

RELATIONSHIP OF DETERIORATION TO DESIGN

Bridge deck deterioration problems are fundamentally related to construction methods and materials rather than to the bridge design criteria, except deflection. Nevertheless, some bridge design and detailing practice can contribute to bridge deck problems. And, conversely, many design decisions can greatly improve deck performance.

Certain empirical relationships have been demonstrated between the extent of bridge deck deterioration and the design system. For example, the incidence of transverse cracking is increased with span length (12, 13, 22, 34), increased with skew (11, 12), and increased on continuous spans (13, 22). Because the presence of a crack over a transverse bar greatly accelerates the corrosion process that leads to spalling (12, 20, 23), it can be surmised that a long, limber, continuous, and sharply skewed structure will have a much greater likelihood of developing spalling than a short, simple, normal, and massive superstructure.

However, by far the greatest cause of spalling related to design criteria is the depth of cover over the top reinforcement. Virtually all responsible researchers (11, 17, 18, 22, 35, 36) point to insufficient cover as a primary cause of spalling. Among the more persuasive of these is the

statistical correlation demonstrated in Missouri (14) and the excellent maps of bar depth prepared by Kansas (17). A plot developed from the Kansas study is shown in Figure 5.

Horizontal and vertical geometry also can be factors if care is not taken to provide for drainage runoff. Ponding of water in "bird-baths" (37) at curb lines, although often the result of poor construction and maintenance practices, can nevertheless be greatly aggravated by insufficient slopes and grades, which put too great a burden on precise construction controls. Such ponding can significantly contribute to scaling.

Some other design factors mentioned in the literature are: (a) the effect of corrugated metal forms in reducing cracking (38), (b) the appearance of longitudinal cracks on slab bridges (13), and (c) the role of dynamic stresses in accelerating spalling (39). One agency has experienced corrosion problems with stay-in-place forms.

RELATIONSHIP OF DETERIORATION TO MATERIALS

The literature abounds in both extensive and intensive investigations into the constituent materials of concrete. Many are discussed here where they seem to have some

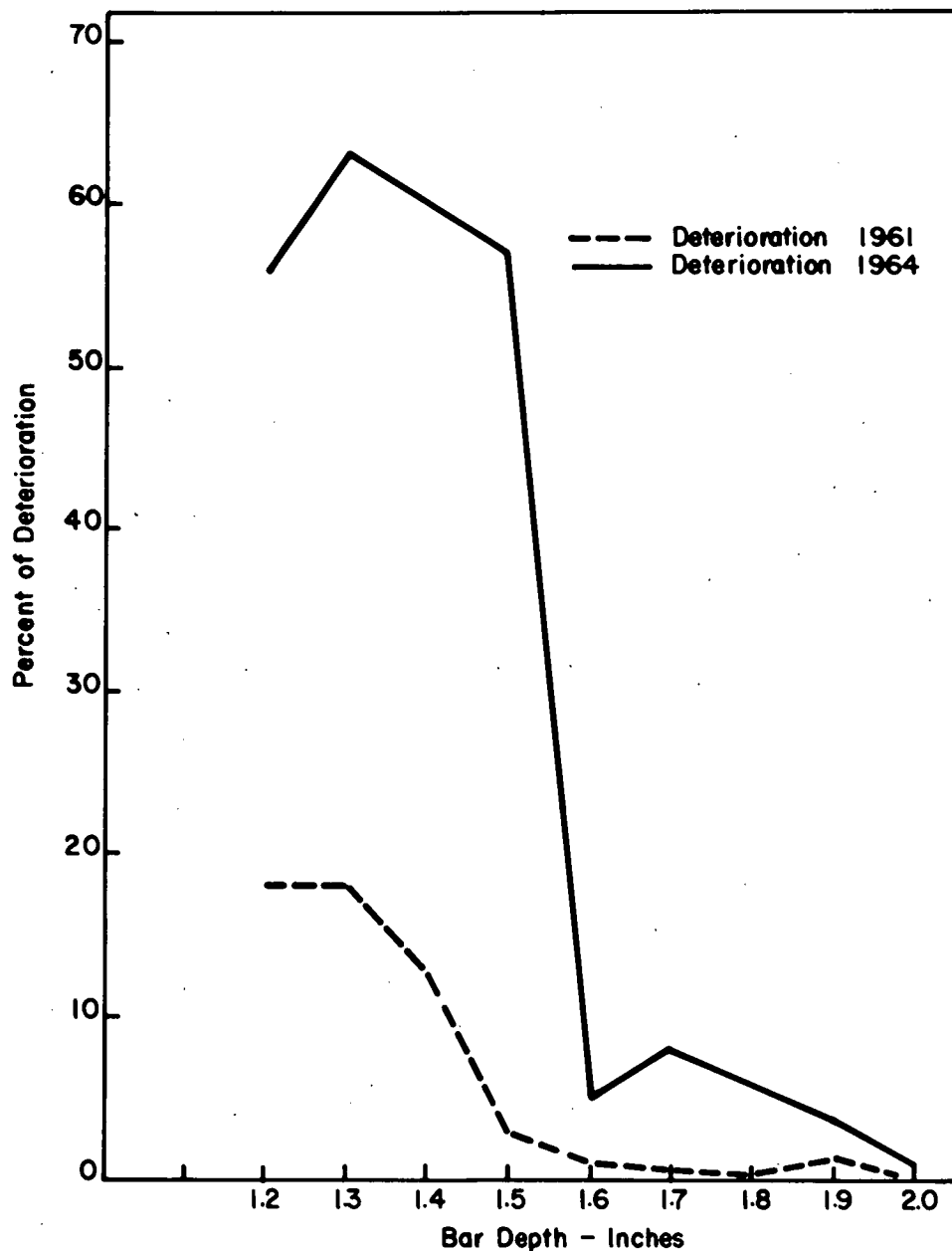


Figure 5. Relationship of amount of deterioration to average bar depth per 5-ft. increment. (Source: Bridge Deck Deterioration Study—Part 8, Kansas State Highway Comm., 1969).

relevance to scaling and spalling. However, it must be emphasized that, all things considered, none of the properties of properly specified concrete materials by themselves create deterioration in a properly proportioned, low water/cement ratio, air-entrained, adequately consolidated, cured slab. Some materials, though, if improperly used, can contribute to an imbalance in one or more of those characteristics of a good slab.

The surface of any material is a weak region compared with the interior because there are fewer bonds on the surface than within the mass (40). A concrete bridge slab is a bilayered system composed of the thinner, upper mortar

surface and the lower, larger aggregate mass (15). Also, cement paste is intrinsically porous because the solid content is limited to 72 percent of the apparent volume (41). Therefore, it can be anticipated that distress would first appear at the surface—precisely where any attack is concentrated.

Concrete may crack due to rapid evaporation of moisture during the early stages of hardening. If the evaporation rate is much greater than 0.1 lb of water per square foot per hour, such cracking will almost certainly occur unless precautions are taken (42).

Cement

Controversy continues to follow the effect of cement fineness. It seems clear that cements are generally finer now (43) and that this fineness has some effect on shrinkage (44), consistency, strength (45), and setting time (46). Because both consistency and time of set affect water requirement, at least in the eyes of field practitioners, it may be that greater fineness is essentially less desirable from durability considerations. However, long-time test results show no correlation between durability and fineness.

Aggregate

Aggregates play a multiple role in bridge deck concrete—the effect of their own durability, paste-aggregate bond, and concrete shrinkage. One laboratory study has shown no correlation between freeze-thaw resistance and sulfate soundness tests or abrasion tests (47). Other studies have shown no general effect of coarse aggregate on scaling (36). There is some correlation between percentage of deleterious particles and freeze-thaw resistance. (47). At least one researcher has found chert to play a role in deepening spalls below reinforcement (17). A number of highway departments have correlated sulfate soundness tests and service performance for certain aggregates. The significant property of aggregate is usually considered to be pore structure.

Aggregate shape and gradation contribute significantly to water requirement, hence to shrinkage (48). Also, in certain sections of the country alkali-silica reactive and alkali-carbonate reactive aggregates are known to produce differential expansion problems (49).

Aggregates also play an important role in skid resistance. Only non-polishing aggregates should be used on exposed bridge decks.

Water

The quality of water is not known to play a significant role in bridge deck deterioration, but the quantity of water certainly does. That subject is discussed elsewhere in this report.

Admixtures

There is general agreement now among researchers (12, 22, 50, 51) that there are no deleterious effects, per se, of chemical retarders, such as water-reducing retarders, on the freeze-thaw durability of concrete. In fact, such admixtures are generally helpful when properly used. They do not affect the nature of hydration, only the rate (46). However, chloride accelerators, because of the probability of corrosion, should not be used in bridge decks (52, 53).

The sequence of adding the various admixtures to the mix is important. This matter is discussed in the next section.

RELATIONSHIP OF DETERIORATION TO CONSTRUCTION

Surely no aspect of bridge deck technology has been the subject of more criticism than the construction process itself, for the process is a difficult one. A host of trained

investigators (11, 14, 32, 37, 54, 55, 56) all across the United States have pointed out construction practices that significantly affect bridge deck durability. The casting of a concrete slab takes only a few hours but requires many days of preparation. The cost of the freshly mixed concrete is only about 10 percent of the total slab cost. Yet the placing of that material at that time is an essentially irreversible act creating enormous pressures on those involved in the decision-making process.

Where the specifications are contradictory (cement content vs strength), arbitrary (single curing material), or irrelevant (height of broom handle), little is gained or lost by following them. Where specifications are silent (air-void spacing, the precise time to apply cure, acceptable humidity levels), great significance may be hidden.

Engineers, contractors, and the concrete industry have collectively "solved" concrete strength problems by simple and effective tests (slump, compressive strength) and statistical evaluation. There is good reason to believe that the same group can "solve" durability problems once they are adequately defined, effectively tested, and properly evaluated.

Dimensions

The two vertical dimensions of depth of cover and slab thickness are both enormously important to durability because of their contribution to cracking. Reports from several states (12, 17, 38) show a wide discrepancy between design cover and actual cover. Variability of thickness, sometimes brought on by excess camber (57), can, of course, greatly reduce the ability of the slab to carry design loads.

Concrete Mix

What depth of cover over the reinforcement is to the designer, what air entrainment is to the specification writer, so the amount of mix water is to the field engineer. For one thing, excessive water induces bleeding, which contributes to subsidence and thence to cracking (22). Porosity of the concrete, hence its permeability to brine, hence the corrosion of the steel, is strongly affected by the water/cement ratio (20, 22, 58).

Figure 6 clearly shows this relationship. Practically all researchers (20, 24, 28, 29, 36, 37, 50) note the significant effect of water/cement ratio on scaling.

A specification on the water/cement ratio, however, is not valid unless the mix consistency is also considered (59). Although the consistency of concrete has a pronounced effect on the corrosion rate, it is not governed only by the water/cement ratio or the cement content (60).

One factor influencing the use of more mixing water is the increased mixing time often observed with transit-mix trucks (14, 32, 38). Such grinding action tends to increase the fineness and surface area of the mix constituents (31). This accelerates hydration, increases the temperature (23), and requires more water for wetting, thereby decreasing the slump (31). Such prolonged mixing also tends to decrease the air content (29, 31). The notorious practice of retempering has been observed on many projects. Neverthe-

less, addition of water beyond that required by design to improve workability can only be made at the expense of durability.

There is growing evidence that chemical admixtures should not be added until after the initial mixing (46, 57) and not in the same stage as the air-entraining agent because a large and undesirable air-void spacing factor develops. Also some air-entraining and water-reducing admixtures are incompatible when added at the same time.

Another important factor involving set-retarding admixtures is that they are designed to increase the time to set as measured by the penetration resistance. However,

all such admixtures, although performing this function, also significantly increase the slump loss (61). Thus the construction team is sometimes faced with the demand to add water to restore workability—an opposite effect from what was anticipated.

The temperature of the mix is believed to have an important effect on its durability because differential air and concrete temperatures promote plastic shrinkage (62) and contribute to transverse cracks (39). Elevated mixing temperatures cause an increase in early strength but a loss in year-old strength (63), thus demonstrating profound lasting effects.

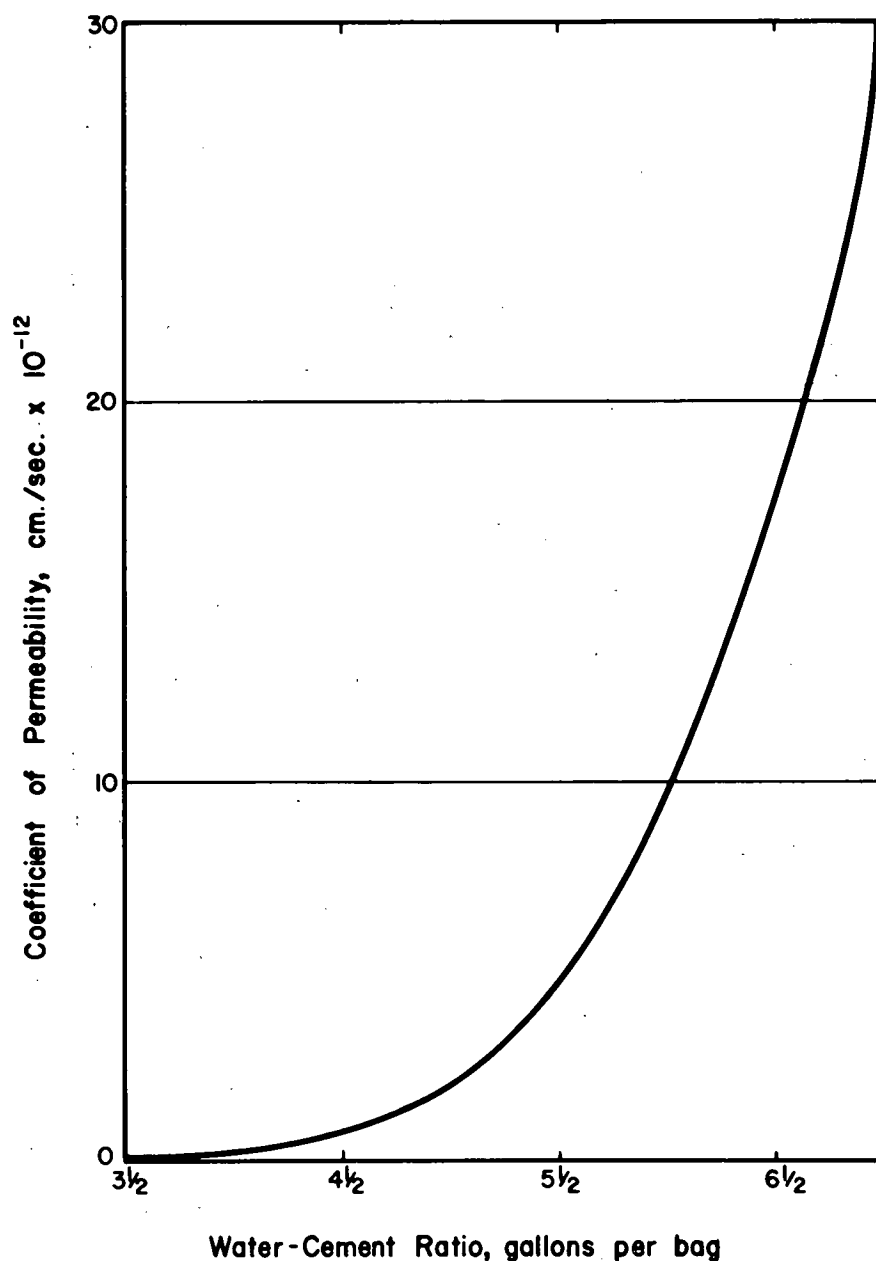


Figure 6. Relationship of permeability of cement paste to water-cement ratio. (Source: Portland Cement Assn.)

Air-Entraining Admixtures

The presence of adequate air entrainment is probably the greatest single factor in controlling concrete scaling (20, 22, 64, 65, 66) although not in controlling spalling. It is the magnitude of the air-void spacing factor (the distance between bubbles), rather than the total amount of air, that is the most important (67). This spacing factor is influenced mostly by the kind and amount of agent used (68).

Research has shown that a deficient air-void system was probably placed that way (29, 56); that is, the placing and finishing operations do not seem to alter good characteristics as much as do variations in the initial air content.

Placement

Concrete handling procedures are neither more nor less important in bridge decks than elsewhere. Concrete is deposited by bucket, buggy, pump, or conveyor. There is no evidence of a durability relationship in any method. One element of placement that can affect bridge deck durability is the capacity to move concrete from the mixer to the forms. If sufficient equipment is not on hand to insure steady delivery of concrete, extended holding times may result. Finishing of the concrete deck will then proceed at a slow, inefficient rate, thus leading to nonuniformity and difficulty in finishing.

Consolidation

Consolidation of the concrete is very important. Under-vibration is usually more serious than overvibration. The almost universal use of internal vibrators seems to have virtually eliminated complaints of honeycomb. Successful revibration of retarded concrete in bridge decks to minimize surface and interior cracks and the voids that are found under top resurfacing steel has been reported (69).

Finishing

All work done on the concrete between the time of vibration and the time of applying cure is often referred to as "finishing." This may include such steps as screeding, planing, floating, rubbing, smoothing, and texturing. All such steps are, to some degree, a durability risk; the more steps, the greater the risk.

Striking-off or screeding, must be done to meet prescribed elevations. But this should be done immediately (23, 27), and machines are better than hand screeds (39). Special studies at the University of Illinois have concluded that excessive surface manipulation lowers the surface scaling resistance of concrete, especially if the manipulation occurs during the bleeding period. Attempts to finish after the bleed water has evaporated from the surface often lead some finishers to sprinkle water on the surface (11, 12), which results in decreased scale resistance (29). One researcher (65) found that one light swish with a soaked calcimine brush increased the surface water/cement ratio by 0.12 by weight. Finally, other experiments have shown that concrete surfaces struck off immediately after casting with no further finishing manipulations during or after the bleeding period showed greater resistance to surface scaling than those given a second and final finish (27).

Overfinishing does not seem to affect air voids (29, 70, 71). It is apparently the creation of a weakened zone due to intermixing of bleed water or sprinkled water that results in poor durability rather than an alteration or "working out" of the air.

The result of all these subtleties may be summarized by the conclusions of two independent studies (54, 56)—that the contractor is the greatest single factor in the quality of bridge deck finishing.

Curing

After finishing comes curing—one serious concern following another. At least one study (39) believes poor curing to be a primary cause of deterioration and other investigators (12, 14) have looked to curing as an important factor in slab performance.

Wet curing methods are favored to reduce scaling (14) and to reduce cracking (39). This is so because moisture promotes hydration and the more cement that is hydrated, the less the concrete will deteriorate. Studies by the Portland Cement Association (58) show that the length of cure affects permeability; the longer the cure, the less permeable the concrete.

The time of applying curing material is clearly vital to guard against plastic shrinkage cracks. Observations of curing material in cracks (62) clearly indicate that cracking can occur at an early age. It is probable that more bridge decks suffer from late application than from early application of curing.

RELATIONSHIP OF DETERIORATION TO ENVIRONMENT

The environment of a concrete bridge slab is an unhappy combination of weather, chemicals, and loads. Consequently, it is very difficult to duplicate in the laboratory and serious researchers (14, 15) have thus far been frustrated in attempting to create spalling as a first step to isolating the more significant variables. Scaling, however, is easy to produce, hence environmental effects are positively demonstrated.

Weather

Hot weather during placement is especially difficult for concrete construction because of more rapid evaporation with higher temperatures. Conformance with the requirements of ACI Recommended Practice 305, "Hot Weather Concreting" can greatly reduce these difficulties.

Much attention has also been directed toward the problems of concreting in cold weather. Guidelines that minimize these problems are given in ACI Recommended Practice 306, "Cold Weather Concreting."

It is plainly evident that hardened concrete can be affected by freeze-thaw cycles. When concrete dries, voids, called capillary cavities, are left in the cement paste fraction by the evaporation of the water. When a saturated cavity is frozen, either the volume must expand by 9 percent or the excess water is forced out (20). Entrained air provides pockets for such water to flow to. Thus non-air-entrained concrete is highly susceptible to scaling, but air-entrained concrete is protected from scaling.

Ice lenses in bridge deck cracks can also be expected to exert pressure on the walls of such cracks, accelerating deterioration.

Salt

During the 1950's more and more states instituted a "bare pavements" policy in response to public demand. That policy resulted in the extensive use of deicing chemicals—mostly sodium chloride—on all pavements, including bridge decks. Since then salt use has increased markedly (Fig. 7). Salt has a pronounced deleterious effect on concrete, both for scaling and for spalling. There is no significant difference between the effects of sodium chloride or calcium chloride.

The association of salt with scaling, although not clearly understood, has been noted by many researchers (20, 22, 72). Indeed, one report (18) notes that scaling can be caused in the presence of salt without freezing. There is also general agreement that salt concentrations of 2 to

4 percent are more likely to cause scaling during freezing and thawing than are higher concentrations (73, 74).

Chloride salts are of paramount importance in spalling. Investigation reveals corrosion of reinforcing steel to be the primary cause of spalling (13, 15, 22, 49). Two variables must be present simultaneously before steel can corrode in concrete: (1) sufficient moisture in the concrete and (2) sufficient chloride-salt in the concrete (75). The foregoing assumes a normal amount of concrete cover and a bridge-type concrete.

Once corrosion of the steel occurs, the corrosion products can occupy 2.2 times as much space as the original metal and may develop mechanical pressure as high as 4,700 psi, a force many times the tensile strength of concrete (76). The result of the disruptive pressures caused by rust is either the cracking and separation of concrete over the bar or the spalling of a layer of concrete that may extend over a distance of several reinforcing bars (15, 22, 75).

The appearance of a crack over a reinforcing bar obviously provides the salt ready access to the steel (20, 77).

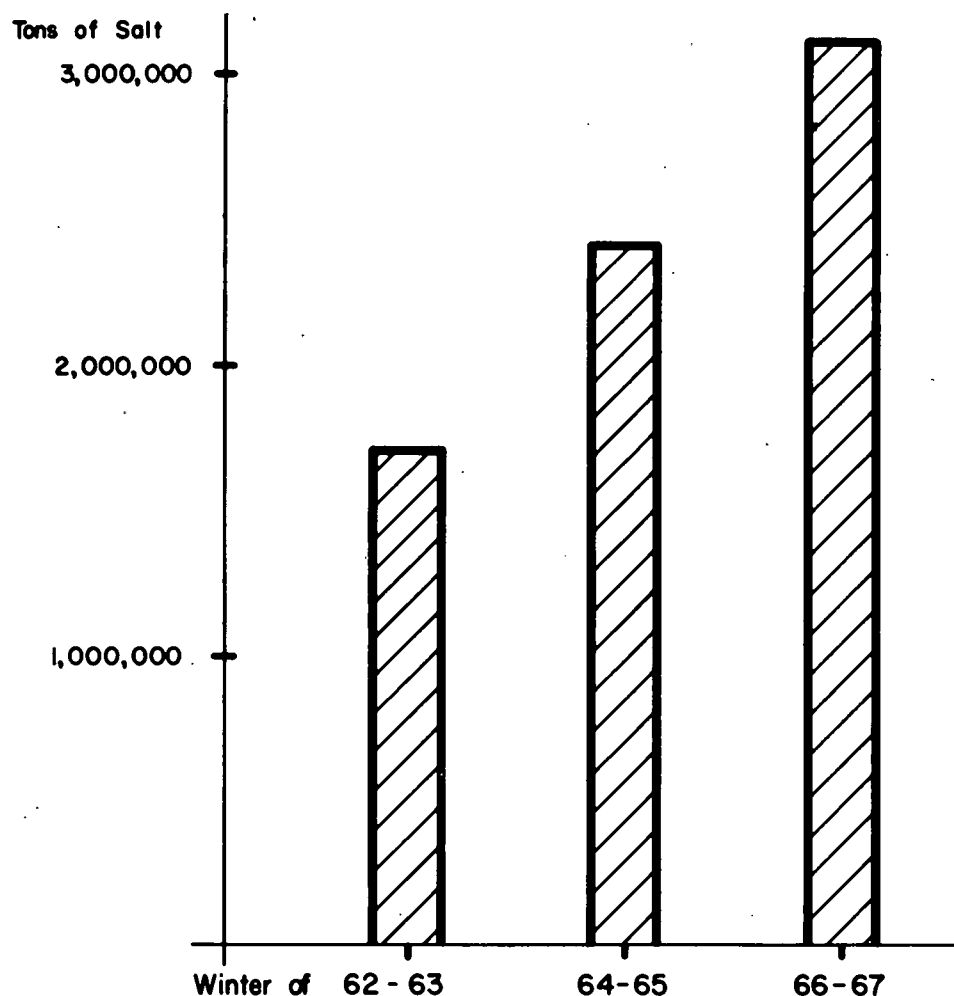


Figure 7. Use of salt for snow and ice control by state highway departments in the United States. (Source: Salt Institute).

One research report (78) states that "as the salt penetrates the concrete, the chloride concentration varies from point to point, a condition which can also result in a difference in potential. However, the most important effects of the salt are to increase the electrolytic conductivity within the steel-concrete composite, and to activate the metal surface, thus intensifying the corrosion."

However, salt can migrate several inches through concrete (79) without the presence of cracks, and penetration is largely dependent on depth and the permeability of the concrete (19, 80). Research in California has developed an ingenious nomograph relating water/cement ratio, depth of cover, and salt content to predict the time to corrosion of reinforced concrete piles (19). A similar graph could no doubt be prepared for bridge decks.

The distribution of chloride salt in non-visibly cracked concrete is related to depth (81). In rough terms, for each additional inch of depth, the chloride content of the concrete will reduce by about one-half. In comparing the influence of concrete cover as empirically derived and that observed, it appears that there is relatively close agreement

on the mathematical influence of depth of cover to the time to deterioration and also to chloride content. In effect, increasing the depth of cover from 1 in. to 2 in. should result in about doubling the time to observed deterioration.

Further evidence that salt of itself is sufficient to cause corrosion is shown by laboratory tests that produced cracks over reinforcing bars simply by applying salt to unloaded specimens, and by the appearance of spalling on the underside of bridge decks splashed by salt water over Biscayne Bay in Florida (no freeze-thaw cycles). The top surface of this bridge is remarkably free of deterioration.

Loads

Opinion is currently divided on the effect of loads, either in magnitude or frequency, on deterioration. Most engineers seem to agree that scaling is not related to traffic (13) and observers note scaling on bridges with no traffic. Shrinkage cracks, too, have been shown to grow appreciably in time with no traffic (32).

Spalling, on the other hand, is often observed to be more severe on heavily traveled bridge lanes (14, 39, 82). How-



Figure 8. A typical spall, with exposure of shallow top (transverse) reinforcing bars.

ever, cracking, which contributes to spalling, does not appear to be caused by loads (15, 22, 39), although cracks may be aggravated by loads (12, 34, 39) (Fig. 8).

Although traffic may not be the initial cause of cracking, there is no doubt that continued flexing will abrade the crack and tend to increase its dimensions. Also, a weak-

ened plane in a deck slab may only be fractured by very heavy loads creating the shear flow associated with bending moments. Heavily traveled lanes have a greater likelihood of experiencing exceptionally heavy loads.

Thus, traffic loads do not cause bridge deck deterioration, but they do contribute to its magnitude.

CHAPTER THREE

CURRENT SOLUTIONS IN PRACTICE

DESIGN-ORIENTED SOLUTIONS

- Provide waterproofing
- Design two-inch clear cover
- Specify air entrainment

Wearing Course

Foremost among design considerations is the question of whether or not to place an overlay or wearing course on the bridge deck. Properly proportioned and placed concrete itself is satisfactorily wear resistant. However, certain defects in construction, as discussed in Chapter Two, and repeated salt applications may cause serious deterioration. To protect the structural concrete from such attack, wearing courses and membranes are often used. In Canada thin bonded concrete overlays have been successfully used on new bridges (83) and in Kansas single-course thin bonded overlays are used in deck restoration work. Elsewhere in the United States waterproof membranes protected by bituminous overlays are more common. Five states and several toll authorities (9) now specify some type of membrane and eight other states use them in special situations such as bridges subject to heavy repair cost, heavy traffic, or heavy salt application.

Some controversy has been generated because of a common experience of discovering areas of slab deterioration concealed beneath old bituminous overlays. This deterioration has often advanced to a serious stage while being hidden from the view of maintenance observers. Such instances arise from a mistaken view of the function of the wearing course. Because the agents that cause destruction of the concrete are all waterborne (salt, dirt, ice), a successful membrane, by definition, must be a waterproof barrier. Most waterproof barriers used on bridge decks are not sufficiently wear resistant, especially under studded tires. Therefore, wherever a waterproofing membrane is specified a wearing surface should be applied over the membrane. Where a membrane is not used, the placement of a bituminous overlay is questionable because of its void characteristics. Bituminous pavement must be designed with a

void system to inhibit flushing (the migration of softened asphalt to the surface) during heavy traffic and high temperatures. Such a void system permits salts and water to reach the concrete surface and then prevents the removal of such brine from the concrete surface.

Consideration of these factors has led some designers to install small drains beneath the overlay to drain from the concrete surface through the deck slab (84), and others to develop essentially void-free pavements by adding asbestos (7). Such refinements would not be necessary in the presence of a truly impermeable membrane because the membrane would protect the concrete and the bituminous pavement itself is not damaged by salt. However, the construction of a truly impermeable membrane has proved elusive and safety factors are often welcome.

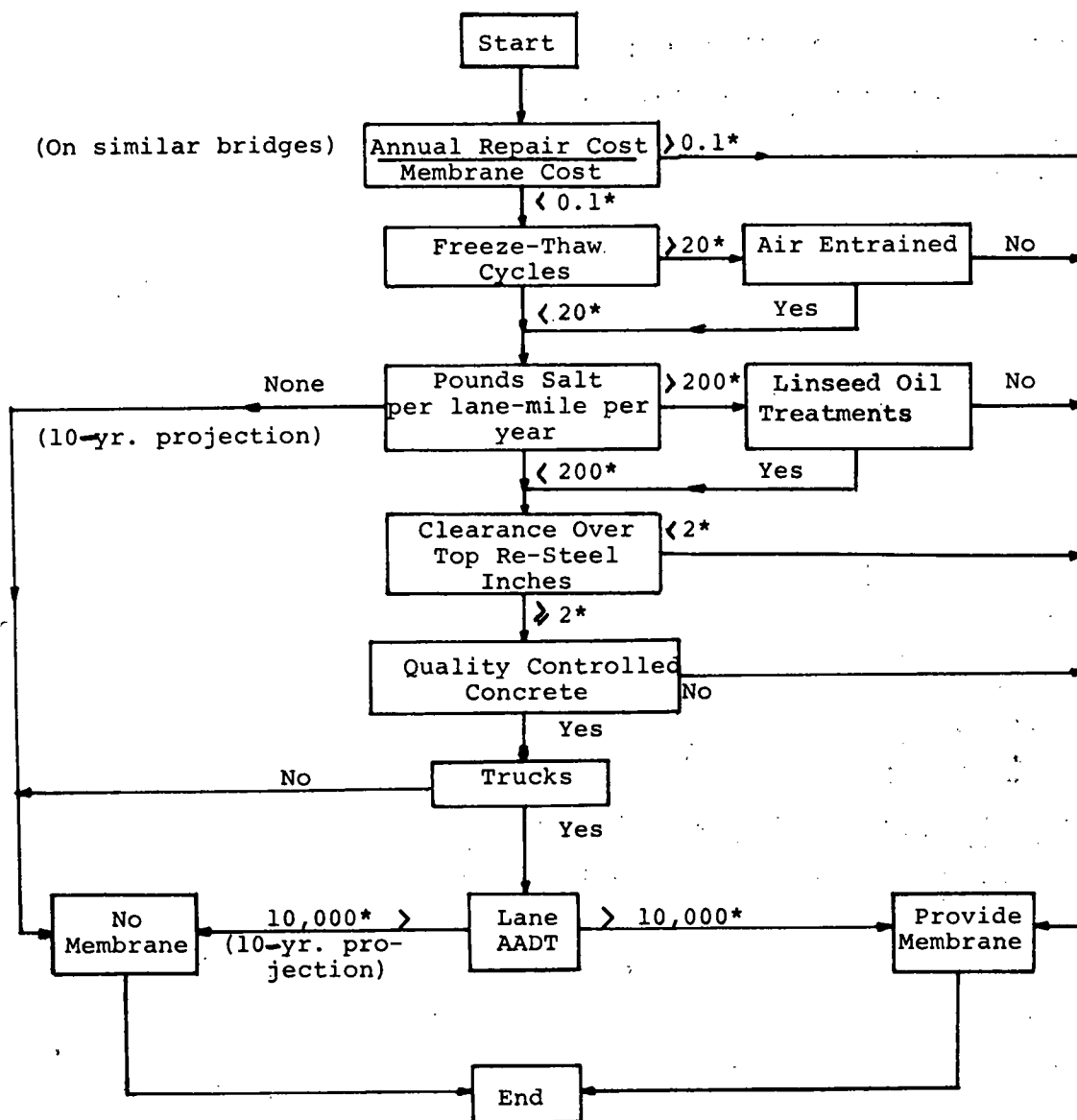
Therefore, the decision to design for a bituminous overlay is a concomitant of the decision to provide a waterproof membrane. The membrane protects the concrete and the overlay protects the membrane.

Combination products, which are intended to be both waterproof and wear resistant, are also currently being marketed.

Waterproof Membrane

The use of an impermeable interlayer membrane has won favor throughout the country. Maine, New Hampshire, Massachusetts, and Rhode Island now specify such an interlayer on all important bridges, and Tennessee, Ohio, Michigan, Illinois, and California, among others, specify such a membrane on selected bridges. The generally acceptable criterion pointing to the necessity for a membrane on new bridges has not as yet been developed. Obviously, costs, the frequency of freeze-thaw cycles, salt-use history, cracking characteristics of local concrete, and traffic are all factors. Illinois, for example, requires such a membrane on all major bridges. A suggested algorithm for a decision to use a membrane is shown in Figure 9.

Waterproof membranes fall into two general categories—reinforced and unreinforced systems. The most common



*All values are for illustrative purposes only.

Figure 9. Algorithm for bridge deck membrane.

type of reinforced barrier currently used is glass fabric mopped with several coats of coal-tar pitch emulsion. A schematic of such a system is shown in Figure 10. Costs of such systems range from \$0.40 to \$0.70 per square foot. Such systems have apparently been highly successful where extensively used. Disadvantages are the amount of time to cure the several layers and the amount of hand work involved.

Chemical compounds include coal-tar epoxies (New Jersey, New York) and synthetic rubber (Ohio, Michigan). Experience records on these systems run from two to six years. Users generally express satisfaction, although experience is limited. Costs run from \$0.30 to \$0.90 per square foot and vary widely because of specification restrictions,

the magnitude of the area to be covered, and the experience of the contractors. Disadvantages are weather sensitivity and deck preparation requirements.

One advantage common to all overlays is that their use reduces the need for close concrete finishing tolerances.

Reinforcement

Designers must make several important decisions with regard to reinforcement. First is the type to be used. Some toll authorities now specify welded trussed joists for added rigidity and dimensional stability. However, care must be taken to avoid fatigue characteristics when designing welded members for live-load areas.

As mentioned previously, the clear cover over the top

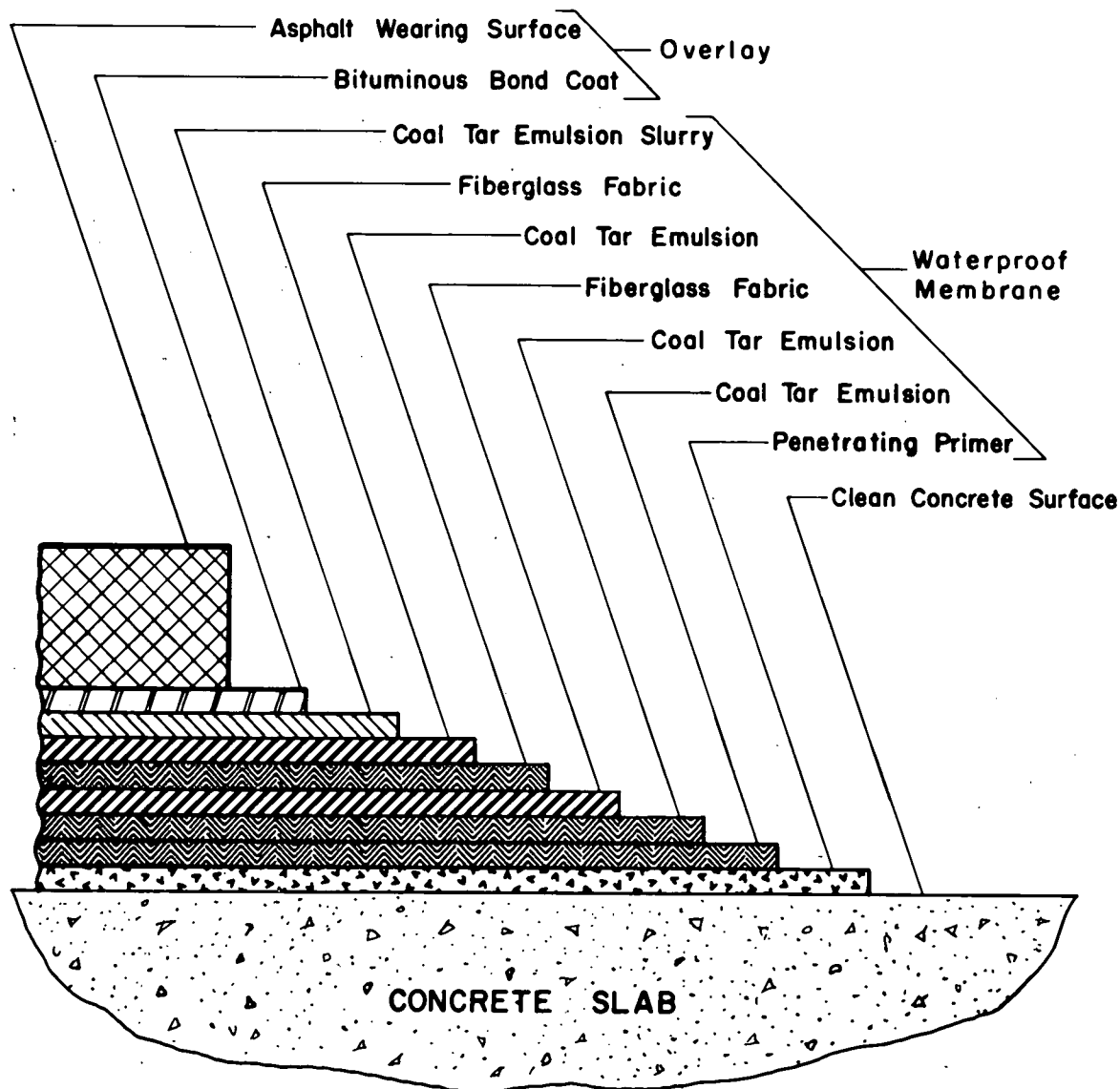


Figure 10. Typical bridge deck protective system.

reinforcing bar is of paramount importance. Virtually all organizations prominent in concrete technology now recommend a minimum of 2 in. of clear cover over the topmost steel. To achieve this, and in view of the inherent variability in the construction process, one researcher (14) has found it necessary to specify an average clear-cover depth of 2½ in. The Portland Cement Association suggests placing lighter (No. 3), more widely spaced (9 in.), longitudinal temperature reinforcement on top of the transverse bar rather than just beneath it as is common in current practice. This has the dual beneficial effect of lowering the transverse steel while providing reinforcement to keep closed the cracks that often develop over transverse bars.

Positive anchoring of the reinforcing steel to prevent displacement during concreting is also necessary. Carrying bars are sometimes welded to the shear connectors to provide a continuous reference for tying the transverse bars.

The coating of reinforcing bars has also been the subject of some study. Recent reports (78, 85) suggested that nickel, hot-dip galvanizing, and asphalt-epoxy coatings might give good protection.

Another researcher (86) has suggested placing a priming coat of pure portland cement slurry over the reinforcement.

Air Entrainment

The designer's responsibilities to prevent scaling include (a) providing careful profile geometry for good drainage characteristics, and (b) the use of air-entrained concrete.

An enormous amount of literature has been assembled (20) on the unique ability of entrained air to resist the destructive effect of freeze-thaw cycles. Air entrainment is now recognized as an essential ingredient in bridge deck concrete in freeze-thaw areas. About 9 percent (by volume) of the mortar should be entrained air. This translates

to about 6 percent (by volume) of the concrete for the ¾-in. size aggregate commonly used in bridge decks. Smaller aggregates require more mortar and hence more total air, such as 7 percent for ½-in. size (87).

CONSTRUCTION-ORIENTED SOLUTIONS

- Keep the water low
- Keep the slump low
- Keep the temperature mild
- Use screeding machines
- Use wet cure

The primary and proper emphasis in the literature for improved bridge deck construction practice is a vigorous re-statement of the need for instituting good construction practice. The absolute requirement for generous cement factors (at least 6 sacks), low water/cement ratio (5 gal per sack), low slump (never more than 3 in.), and carefully controlled mixing, placing, finishing, and curing cannot be overemphasized and must be scrupulously enforced.

Inspectors

Most agencies now recognize that at least three inspectors are required to insure good construction practice and to keep good records of materials and procedures. There should be one inspector at the point of batching, one inspector at the point of mixing, one inspector at the point of placing. Their more important duties are given in Table 1.

A thorough discussion of good construction practice is contained in "ACI Manual of Concrete Inspection," *Publication SP-2*, of the American Concrete Institute. Each inspector should be provided with a copy of this pocket-size book.

Slump, air, and temperature tests must, of course, be taken on each batch, or from statistically reliable random samples.

Concrete Temperature

Many agencies have expressed increasing concern with the problem of concrete placement during hot weather. Elevated mix temperatures (80 to 90 F) are believed to play a major role in crack development, high water requirement, and strength loss. The Portland Cement Association recommends the use of ice to cool the mix (23) as was successfully used on New York's Verrazano Narrows Bridge (88). Some states recommend night work because commercial ice is seldom readily available.

Engineers in Ontario have found that their best decks are built during the winter. This is so because the concrete is cast under complete tents covering the whole work area and the inside climate is controlled to gain optimum temperature and humidity.

Admixtures

Accelerating admixtures should never be used on bridge decks because most of them include salts and increase temperature rise.

Set-retarding admixtures are useful, particularly on long

TABLE 1

DUTIES OF CONCRETE CONSTRUCTION INSPECTORS

BATCHING	MIXING	PLACING
Verify the use of approved materials	Receive batch certificates	Check clearance of reinforcement
↓	↓	↓
Monitor aggregate moisture	Monitor mixing time	Insure adequate vibration
↓	↓	↓
Check batch weights	Add retarders as required	Time finishing to guard against drying
↓	↓	↓
Prepare batch certificates	Conduct tests on slump, air, temperatures	Apply cure at proper time

spans, to reduce deflection cracks. However, retarders are best added after some initial mixing, although it is undesirable to mix retarders in the same stage with air-entraining admixtures. Retempering water should never be added to a mix. However, according to one report (89) workability of stiff mixes may be improved by adding lignosulfonate retarders.

Screeding Machines

Machines for screeding and planing are recommended instead of hand finishing (39) because they provide a more uniform surface, avoid the need for wading through the concrete, and provide a reference line for pretesting clearance over reinforcing steel.

Curing

Wet curing (with burlap, cotton mats, etc.) is more desirable on bridge decks than are sprayed-on membranes (39), *provided the burlap is kept constantly wet*. Polyethylene sheets have also been used successfully. However, a fundamental factor in all curing is the importance of expeditiously applying the cure as soon as the visible bleed water has evaporated. There may be a need during hot weather to use a membrane cure to protect the surface during the time that wet curing cannot be applied without marring the surface. Probably no area of concrete construction technology is more demanding of training, experience, and forthright action than the timely application of curing.

Curing is especially vital in the prevention of plastic shrinkage cracks. Such cracks are the result of rapid drying which, in turn, is affected by atmospheric conditions. Figure 11 shows the interrelationship of several variables with evaporation.

MAINTENANCE-ORIENTED SOLUTIONS

- Apply linseed oil
- Make repairs expeditiously

Maintenance traditionally encompasses two distinct categories—prevention and repair. The first is naturally pre-

ferred. But the maintenance organization cannot be expected to prevent deterioration if design considerations (such as suitable surface drainage) and proper construction procedures (such as the use of high-quality concrete) have been overlooked.

Nevertheless, there are important steps that the maintenance organization can take to prevent or retard deterioration regardless of design and construction. Foremost among these is the application of surface treatments such as linseed oil to the concrete surface. Probably no product in recent

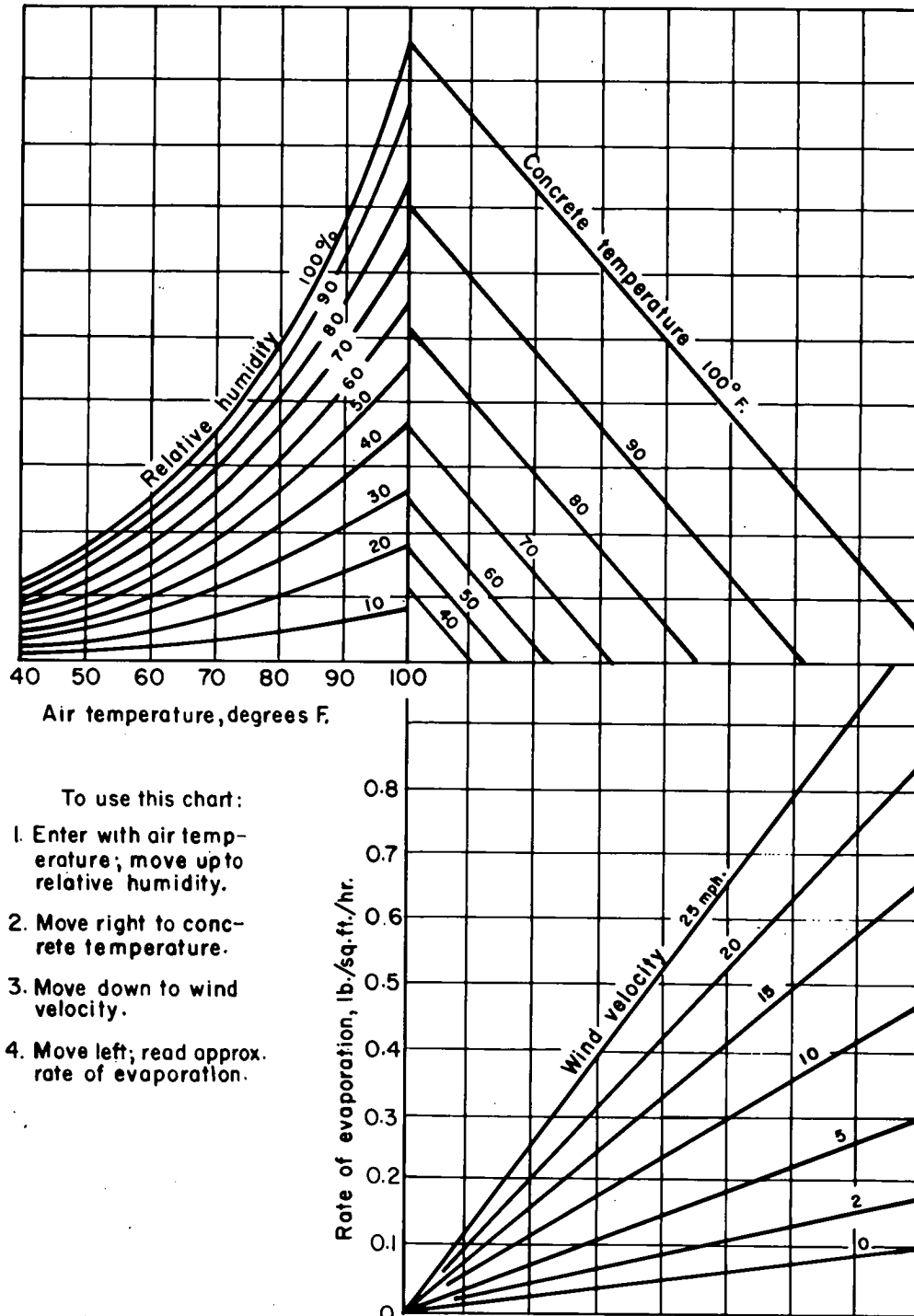


Figure 11. Effect of concrete and air temperatures, relative humidity, and wind velocity on the rate of surface moisture from concrete. (Source: Design and Control of Concrete Mixtures, Portland Cement Assn.)

years has been so widely tested and thoroughly evaluated (11, 20, 23, 35, 51, 55, 77, 90, 91, 92, 93). The beneficial anti-scaling characteristics of linseed oil treatments are widely accepted. Two coats of boiled linseed oil in solution have generally given the best results. Figure 12, from a Bureau of Public Roads study, is a good example of the effect of various linseed oil treatments. It should be noted that modest durability benefits can be gained even on undesirable high-slump, low-air concrete—an important maintenance consideration.

Reports indicate that linseed oil is inexpensive. Costs across the United States are on the order of \$0.05 to \$0.06 per square foot of application.

There are four important considerations to observe with any linseed oil treatment, as follows:

1. A period of drying should be allowed for the concrete before applying the linseed oil (90).
2. Linseed oil can be slippery (94, 95) when first applied and slipperiness is not easily corrected by sand (96).
3. Linseed oil must be renewed to maintain its benefits.

4. Linseed oil is not effective against spalling or cracking—only against scaling.

Several other surface treatments, both penetrating sealants and surface coatings, have been evaluated in an effort to offset the disadvantages of slipperiness and the need for renewal found with linseed oil. Sealants such as silicone treatments (50) and petroleum distillates (97) have not always proved effective. Coatings such as epoxy resins and chlorinated rubber compounds, and a tar-based penetrating sealing compound, give conflicting results in resistance to scaling. Costs of epoxy resins are high, ranging from \$0.40 to \$1.00 per square foot. All coatings are subject to wear, particularly by tire chains or studded tires; therefore, renewal costs persists. Thus, as noted under "Design-Oriented Solutions," the more expensive coatings are ordinarily overlaid with a wearing course. Epoxy coatings are useful to correct slipperiness on bridges, regardless of other durability considerations. Skid resistance, of course, is a vital property on any roadway surface.

Research has now been published (73) on the effective-

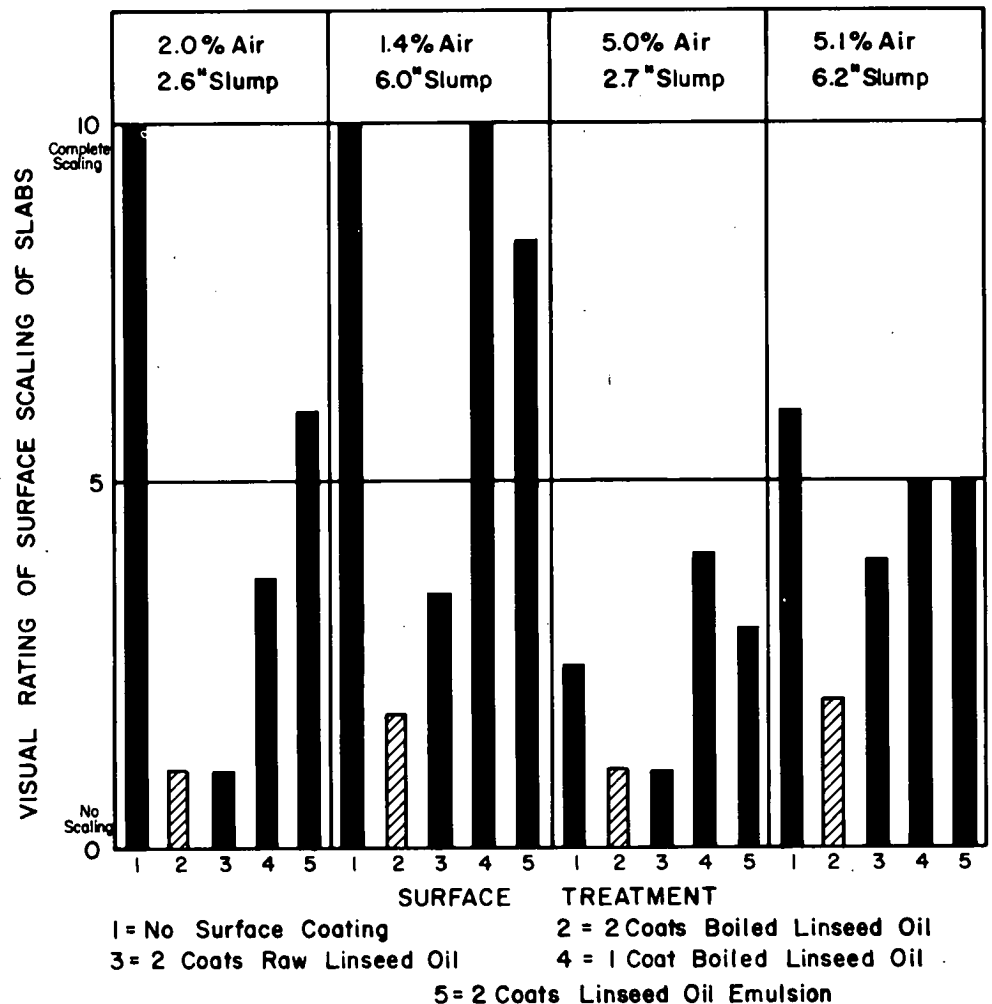


Figure 12. Interrelationship of slump, entrained air, and linseed oil with scaling of slabs. (Source: Grieb and Appleton, Hwy. Res. Record No. 62)

ness of non-corrosive chemicals as deicing agents. Urea and calcium formate have been found to be efficient in lowering the melting point of ice so as to provide bare pavements. However, both compounds (a) are considerably more expensive than salt, (b) must be used on a considerable length of approach to avoid tracking salt onto the deck, and (c) create water pollution problems. Furthermore, urea, in high concentrations, may be more corrosive than salt.

Of greater promise is the addition of inhibitors as a mixture with the salt. Corrosion inhibitors are reactive or surface-active substances and can be absorbed by the dirt before they get to the surface (73). Thus they need only be applied directly to the deck and not to the approach. The addition of polyphosphate in the amount of 1 lb per 100 lb of salt in a 5 percent salt solution reduced corrosion by 50 percent (73, 98).

The use of such inhibitors should be seriously considered on badly cracked bridges where, for whatever reason, a membrane and wearing course cannot be installed.

Repair

The repair of deteriorated decks has brought into play a whole array of proprietary products and maintenance techniques. Many have been reported in the literature (99, 100).

A conclusion of one study (100) underlines a fundamental truth: "This study revealed no special material or shortcut method to substitute for proper construction practices to obtain consistently good results."

TABLE 2

COST COMPARISON FOR BRIDGE DECK PATCHING

PATCH TYPE	ADVANTAGES	DISADVANTAGES	COST (\$/SQ FT)
Regular portland cement	Ease of handling; low cost	Slow cure; edge cracks	1.00-6.00
High early strength cement	Reduced cure; low cost	Shrinkage	1.00-6.00
Metallic aggregates	Reduce shrinkage	High cost; may contain salt	5.00-10.00
Latex additives	Increase bond	High cost	5.00-20.00
Epoxy resin	Fast cure; good bond	High cost; edge cracks	4.50-20.00

Repair of badly deteriorated decks requires complete slab replacement (82). According to the Bureau of Public Roads, the cost of replacing a concrete deck in service commonly runs to twice the cost of constructing the original deck (101). This emphasizes once again the importance of careful attention to bridge deck problems.

Top surface deterioration, as distinguished from full-depth destruction, is generally repaired by thin, bonded replacement overlays (Fig. 13). Two special considerations in such work are the necessity of removing all bad concrete



Figure 13. Constructing an overlay on a bridge in service.

and the importance of a carefully applied grout on the old surface just before the new surface is constructed. All concrete containing appreciable amounts of chlorides should be removed from the periphery of the steel. Chloride content can be measured from cores.

Patching of concrete generally follows the two steps previously noted plus the casting of a wide range of specialized

concretes. These can be grouped as (a) portland cement type and (b) synthetic type. Table 2 summarizes pertinent aspects of the various products.

Perhaps the most important consideration in any maintenance program is the need for periodic inspection by trained observers and prompt attention to minor defects before they develop into major ones.

CHAPTER FOUR

CURRENT AND FUTURE RESEARCH

CURRENT RESEARCH

Several agencies are continuing research into the general problem of bridge deck durability. Among these the Highway Research Information Service of the Highway Research Board reports the following.

General

U.S. Bureau of Public Roads
California Division of Highways
Illinois Division of Highways
Kansas State Highway Commission
Missouri State Highway Commission
New York State Department of Transportation
Pennsylvania State University
Portland Cement Association
Texas Transportation Institute

Structure

The use of precast-prestressed concrete for bridge decks is under investigation at Purdue by the Indiana State Highway Commission.

An investigation of traffic-induced vibrations and their effects on concrete decks on steel girders is under way at the University of Alabama.

The British Road Research Laboratory is studying the effect of crack width, amount of concrete cover, and porosity of concrete on the corrosion of reinforcing bars. Bridge girder deflections as affected by thermal conditions and sequence of concrete placement during construction is under research by the Virginia Highway Research Council.

The Portland Cement Association is conducting research into the use of precast-prestressed concrete rods as reinforcement.

Detection

California is doing research into determining the corrosion activity of steel by means of electrical measurements.

The detection of distress or irregularities in bridge slabs

—particularly those under cover—has prompted further research.

The New Jersey Department of Transportation is investigating methods for nondestructive testing to determine integrity.

The New York State Department of Transportation is investigating wave pulse and nuclear methods of concrete distress detection.

The diagnosis of deteriorated bridge decks is being studied by Texas A & M University.

Evaluation

The Illinois Division of Highways is conducting a survey study of concrete bridge deck deterioration and the Texas Transportation Institute is investigating statistical evaluation of bridge deck condition surveys.

Both California and New York are evaluating bridge deck coatings.

Construction

The contribution of the finishing process to bridge deck deterioration is under study by the Virginia Highway Research Council and the Kentucky Department of Highways.

Revibration of retarded concrete for continuous bridge decks is being investigated by the University of Illinois.

The Ontario Department of Highways is conducting research into the air-void system near the surface of concrete bridge decks.

The effect of a silicone admixture on durability is being studied by Purdue University.

Overlay

Methods and materials for overlaying conventional bridge decks so as to prevent deterioration has motivated further research. The Ontario Department of Highways is among agencies involved in this investigation.

The Michigan Department of State Highways is evaluating methods for control and prevention of deterioration.

Both a plastic-modified portland cement mortar and a synthetic resin overlay are being investigated by the Pennsylvania Department of Highways.

Restoration

The problem of restoring deteriorated decks continues to promote its share of research.

The Minnesota Department of Highways is looking into the general problem of bridge floor restoration.

Purdue University is investigating major repairs and improvements of county bridges.

The British Columbia Department of Highways is evaluating both thin concrete overlays and epoxy resin overlays.

NEED FOR FURTHER WORK

Research

The development of suitable precast-prestressed slabs would eliminate many construction-oriented problems. One researcher, for example, has suggested that it would be most efficacious if slabs could be turned upside down after casting. Research in this area would be most helpful.

One researcher has suggested that a possible reason for cracking could be rolling of the concrete ahead of the tire in much the same way that soil humps up ahead of a compacting roller. This might help to explain the many transverse cracks as compared with the few longitudinal cracks in beam and girder bridges. Perhaps more longitudinal steel is necessary to resist these rolling stresses. A mathematical analysis of this hypothesis would lead to greater understanding.

Continued materials research, now well under way, into the mechanics of crack initiation and crack propagation may hopefully lead to chemical antidotes or mechanical restraints to eliminate cracking.

Recent investigations into polymer concrete (102) suggest that this development might lend itself to bridge deck applications. Field tests of this nature would be most welcome.

A surface admixture having an affinity for water (bleed water) and capable of forming an insoluble gel in the surface capillaries could be a remedy for many durability problems.

It has been noted that the two most vital parameters in field concrete control—water content and air-void spacing—cannot be easily measured. Quick, simple, and reliable tools for making such measurements are badly needed. Perhaps a nuclear device for correlating water content could be adapted. An inexpensive optical tool is probably necessary for air-void spacing.

A “drying danger” detector (such as a fugitive dye) that would change color to indicate the optimum time to apply curing materials would be extremely useful.

It would be very significant to undertake metallurgical studies of how the corrosion products of reinforcing steel might be modified.

Research studies are badly needed to uniformly analyze the cost of differences in bridge deck construction, maintenance, and repair. Preventive maintenance and temporary repairs made by departmental teams are costs rarely calculated, and even less often compared for different systems. Thus, the economical value of improved but more costly design cannot be measured.

Development

The importance of cooling concrete mixes for bridge decks is obvious. Because the number of commercial ice suppliers is dwindling, the development of means to reduce concrete temperature would be beneficial.

“Finishing” machines that could uniformly consolidate, truly plane, and suitably texture in one pass are still sought after.

The need for a suitable revibration device is still evident.

A reliable moisture detector placed beneath membranes would be of great help in evaluating those membranes. Beyond that, the properties and performance criteria for membranes have not been established as yet, and should be. Impermeability, adhesion, and resistance to shear under braking loads are obvious but undefined characteristics.

Evaluation

Information is needed as to whether it can be determined if a slab has already absorbed sufficient salt for the corrosion to continue in spite of impervious membranes. Also, the question of how much moisture is necessary to continue corrosion, and in the presence of what salt concentrations, remains unanswered. It might be profitable to research methods of predicting decks liable to spalling using information from surveys of deck salt concentrations and moisture content. The influence of temperature on corrosion rate is not understood. Do states with continuously frozen conditions have fewer corrosion problems for this reason? Also, does salting in winter in below-freezing conditions have less effect (on corrosion) than the same salting in fall or spring?

Infrared photography has been found to be reliable in detecting corrosion of steel in concrete. Many states would welcome a procedure whereby low-level flights, say, might make strip maps of bridge decks that could indicate areas of high corrosion activity by the infrared process.

There is considerable need to evaluate the much useful work already under way. The collecting, collating, analyzing, and standardizing of bridge deck condition surveys from states, counties, and toll agencies may help to uncover trends or factors heretofore unnoticed. Such a storehouse might also disclose a market to induce private interests to undertake further development.

Careful, periodic in-service evaluation reports of current practices and research findings over extended periods are vital. The published costs, successes or failures, and effects of various overlays, corrosion inhibitors, and deicers would be enormously useful.

TABLE 3

SUMMARY OF KNOWN RESEARCH ACTIVITIES RELATED TO CONCRETE BRIDGE DECK DURABILITY^a

RESEARCH PROJECT TITLE	RESEARCH AGENCY	HRIP NO. ^b
Design Analysis and Dynamic Lab Testing of a Composite Highway Pavement Consisting of Precast and Prestressed Concrete Panel Sections Covered with Asphaltic Concrete	South Dakota State University, Civil Engineering Dept.	25 012882
Continued Surveillance of Bridge Decks	Pennsylvania State University, Civil Engineering Dept.	26 007352
Bridge Deck Study	South Dakota Department of Highways	26 012881
Durability of Concrete Bridge Decks	New York State Dept. of Transportation, Bur. of Phys. Res.	26 016116
Durability of Structural Concrete—Bridge Decks	Bureau of Public Roads	26 017518
The Influence of De-Icing Salt on Concrete	Bridges & Hwys. Cen. & Reg. Labs. (France)	26 063030
Bridge Deck Deterioration Study	Kansas State Highway Commission	27 001310
Instrumentation and Testing of Concrete Bridges Reinforced with High-Strength Steel	New York State Dept. of Transportation, Bureau of Phys. Res.	27 003056
Finishing Methods—Concrete Bridge Decks	Virginia Highway Research Council	27 007125
Influence of Load and Environment History on Cracking in Reinforced Concrete	University of California, Berkeley	27 007652
Slab Bridge Deflection Study	California Division of Highways, Bridge Department	27 007657
Potential Accelerating Effects of Chemical Deicing Damage by Traffic and Other Environmental Induced Stresses in Concrete Bridge Decks	University of Illinois, Dept. of Civil Engineering	27 012340
Waterproofing Bridge Structures	Ontario Department of Highways, Research Branch	27 050130
The Air Void System Near the Surface of Concrete Bridge Decks	Ontario Department of Highways, Materials Testing Branch	27 050459
De-Icing of Bridge Decks	Road Research Laboratory (UK)	27 060253
Cracking of Concrete Bridges	Road Research Laboratory (UK)	27 060255
Waterproofing of Bridge Decks	Road Research Laboratory (UK)	27 060256
Stress Corrosion in Prestressing Steel	Newcastle-upon-Tyne University (UK)	27 060448
Crack Distribution in Reinforced Concrete	Cement and Concrete Assoc., London (UK)	27 060458
Design and Construction of Precast Composite Bridge Deck Slabs	Pisa Technical University (Italy), Inst. Science of Constr.	27 061072
Experimental Investigation of the Structural Behavior of Full Scale Pseudo-Slab Concrete Bridge Decks	Asian Institute of Technology (Thailand)	27 064120
Survey Study of Concrete Bridge Deck Deterioration	Illinois Division of Highways, Bur. of Res. and Devel.	27 082133
Use of Precast-Prestressed Concrete Rods as Reinforcement	Portland Cement Association	27 082209
Factors Affecting the Durability of Concrete Bridge Decks	California Division of Highways, Bridge Department	27 082716
Bridge Girder Deflections as Affected by Thermal Conditions and Sequence of Concrete Placement During Construction	Virginia Highway Research Council	27 086862
Investigation of Traffic-Induced Vibrations and Their Effects on the Concrete Decks of Steel Girder Bridges	University of Alabama, Dept. of Civil Engineering	27 086897
Use of Precast-Prestressed Concrete for Bridge Decks	Purdue and Indiana State Highway Comm. Joint Highway Res. Proj.	27 086960
Revibration of Retarded Concrete for Continuous Bridge Decks	University of Illinois	27 089543
An Evaluation of Bridge Vibration as Related to Bridge Deck Performance	University of Tennessee	27 207789
Investigate Resistance to Cracking of Concrete as Affected by Admixtures	California Division of Highways, Matls. & Res. Dept.	32 001287
Concrete Durability Studies	Virginia Highway Research Council	32 001301
Effect of Additive, Dow Corning 777, on Bridge Deck Durability	Purdue University	32 001874
Influence of Cement Composition on Effectiveness of Water-Reducing Admixtures	Virginia Highway Research Council	32 003084
Durability of Portland Cement Concrete	Iowa State Highway Commission	32 003136
Statistical Quality Control of Portland Cement Concrete Pavements	University of Oklahoma, School of Civil Engineering	32 003812
Corrosion of Steel in Concrete	Cement and Concrete Research Inst. (Sweden)	32 004073
Plastic Coatings for Concrete	Cement and Concrete Research Inst. (Sweden)	32 004074
Effect of Fine Aggregate on Concrete Mixing Water Requirements and Strength	National Sand and Gravel Assn., National Ready Mixed Concrete Assn.	32 004602

RESEARCH PROJECT TITLE	RESEARCH AGENCY	HRIP NO. ^b
Effect of Coarse Aggregate Characteristics on Shrinkage of Concrete	National Sand and Gravel Assn., National Ready Mixed Concrete Assn.	32 004612
Resin Study	Virginia Highway Research Council	32 007134
Linseed Oil as a Protective Coating for Concrete Exposed to Deicing salts Under Conditions of Freezing and Thawing	Kansas State University, Applied Mech. Dept.	32 007486
Fibrous Reinforced Concrete	Ohio River Div. Labs., Army Corps of Engineers	32 007503
Oil-Solvent Treatment to Control Salt-Scaling	Illinois Division of Highways, Bureau of Res. and Dev.	32 007614
Corrosion of Steel in Concrete	California Division of Highways, Materials and Res. Dept.	32 007791
Deterioration of Concrete Bridge Floors	Missouri State Highway Comm., Div. of Materials and Res.	32 012534
A Study of Air Entraining and Curing of Portland Cement Concrete Concrete Popouts	Ohio Department of Highways	32 012818
Means for Improving the Durability of Portland Cement Concrete	Iowa State University, Eng. Exp. Sta.	32 013621
The Control of Cracking of Concrete	University of Illinois	32 017710
Long Range Observations—Salt Water Concrete	University of Illinois	32 017711
Migration of Carbon Dioxide in Concrete	Naval Civil Eng. Lab., Port Hueneme	32 040750
Permeability of Concrete to Oxygen	Naval Civil Eng. Lab., Port Hueneme	32 040757
Curing Compound Investigations	Naval Civil Eng. Lab., Port Hueneme	32 040759
Durability of Concrete	Bureau of Reclamation	32 043341
Waterproofing of Concrete	Building Research Station (UK)	32 060392
Frost Damage to Concrete Structures	British Railways Board, Chem. Div. Civil Engineer. Res. Inst. HDB (Japan)	32 060432 32 061215
The Properties of Concrete Placed in Cold Weather	Nagoya Institute of Technology (Japan), Civil Engineering Dept.	32 061288
Testing Concrete Products for Frost and Deicing Salt Resistance	Building Research Inst. ATU (Germany)	32 061591
Protection of New Concrete Pavement Against Scaling Caused by Salt Influence of Fines on the Properties of Concrete	Stuttgart Tech. University (Germany)	32 061827
Influence of the Type of Cement on Corrosion of Concrete Reinforcement	Stuttgart Tech. University (Germany)	32 061828
A Study of Additives for Cements, Mortars and Concrete, Grinding and Plasticizing Agents, Air Entrainers, Waterproofing Compounds, Etc.	Ciments Lafarge (France)	32 063217
Effects of Admixtures on the Properties of Concrete	Ciments Lafarge (France)	32 063219
Physical Properties of Aggregates and Their Effect on Concrete Durability	Portland Cement Association	32 082212
Special Studies of Concrete Durability	Portland Cement Association	32 082213
An Investigation of Accelerated Curing Methods for Concrete	Portland Cement Association	32 082219
Effects of Delayed Mixing (on the Job) after Batching of Truck-Mixed Concrete	Virginia Highway Research Council	32 084773
Construction and Finishing Techniques—Concrete Bridge Decks	National Ready Mixed Concrete Assn.	32 201595
Compaction of Concrete	Kentucky Dept. of Highways	33 007047
Concrete Finish Affected by Mix and Placing Methods	Cement and Concrete Assoc., London (UK), Res. and Dev. Div.	33 060594
The Electro-Osmotic Dehydration of Fresh Concrete	Cement and Concrete Assoc., London (UK), Res. and Dev. Div.	33 060601
Shrinkage of Fresh Concrete	Constr. Mach. and Oper. Inst., ATU (Germany)	33 061607
Control of Concrete Manufacture	Bridges and Hwys. Cen. and Reg. Labs. (France)	33 063033
Synthetic Resins for Bridge Construction	Bridges and Hwys. Cen. and Reg. Labs. (France)	33 063079
Mixing Time Study, Phase I & II	Road Research Center (Poland)	33 064148
Composite Action of Stay-in-Place Steel Forms	Louisiana Department of Highways	33 080975
Bridge Floor Restoration	Pennsylvania State University, Dept. of Civil Engineering	33 082498
Galvanized Steel Reinforcement for Concrete	Minnesota Department of Highways	34 001076
Effects of Salts on Portland Cement Concrete	University of California, Berkeley	34 001262
Corrosion of Load Transfer Dowels in Concrete Pavements	Minnesota Department of Highways	34 001575
Linseed Oil as a Concrete Curing Agent	Connecticut State Highway Dept.	34 001844
Thin Resinous and Aggregate Overlays on Portland Cement Concrete on Highway and Bridge Decks	North Dakota State University, Coll. of Eng. Res. Branch	34 007528
Concrete Bonding Studies	California Division of Highways, Materials and Res. Department	34 007813
Investigation of Zinc Coating on Reinforcing Steel	Bureau of Reclamation	34 040212
Corrosion Evaluation and Processes	Naval Civil Eng. Lab., Port Hueneme	34 040758
Corrosion	Bureau of Reclamation	34 043342
Corrosion of Metal Reinforcement in Concrete due to the Action of Various Additives, with Particular Reference to Chlorinated Additives	Eduardo Torroja Inst. Constr. and Cem. (Spain)	34 060630
	Bldg. and Public Works Res. Centr. (France)	34 061458

RESEARCH PROJECT TITLE	RESEARCH AGENCY	HRIP NO. ^b
Corrosion Testing of Wires under Tension for Prestressed Concrete	Bldg. and Public Works Res. Centr. (France)	34 061459
Adhesives for Repairing Concrete	Bldg. and Public Works Res. Centr. (France)	34 061461
Corrosion of Steel Imbedded in Concrete	Munich Technical University (Germany), Research Inst. for Building Materials and Methods	34 061754
Bridge Sealing with Soft Mastics	S. Fed. Inst. Testing Matls. and Res. (Switzerland)	34 062154
Corrosion under Tension of High-Resistant Steels	Bridges and Hwys. Cen. and Reg. Labs. (France)	34 063043
An Epoxy-Tar Based Product for Thin Sealing Layers	Albert Cochery Co. (France)	34 063234
Crack Width—Corrosion Study	University of Texas, Arlington	34 089470
Concrete Distress Detection in Bridge Decks by Wave Pulse and Nuclear Methods	New York State Dept. of Transportation	34 089821
Deterioration of Concrete Aggregates	Memphis State University	35 019276
Corrosion Control of Steel in Concrete	California Division of Highways, Materials and Research Department	40 006373
Linseed-Oil Retreatments to Control Surface Deterioration of Concrete Bridge Structures	Illinois Division of Highways, Bur. of Res. and Development	40 007735
Deicing of Elevated Structures	Canadian Good Roads Association, Soils and Materials Committee	40 050011
Concrete Bridge Deck Resurfacing with Thin Concrete Overlays	British Columbia Dept. of Highways, Victoria (Canada)	40 050077
Concrete Bridge Deck Resurfacing and Repairs Using Epoxy Resins	British Columbia Dept. of Highways, Victoria (Canada)	40 050087
Heating of Roads	Road Research Laboratory (UK)	40 060304
Behavior of Prefabricated Prestressed Concrete Slabs for Road Repair and Traffic	Roadway, Earth, and Tunnel Construction Inst. (Germany)	40 061632
Impregnation of Concrete Surfacing with Synthetic Resin to Reduce At- trition and Damage due to Salt	Stuttgart Technical University (Germany)	40 061826
The Protection of Fresh Road Concrete against Damage by Deicing	Stuttgart Technical University (Germany)	40 061831
Prevention of Salt Damage to Concrete Roads	Austrian Cement Manufacturers' Assn.	40 062464
Protection of Concrete Structures against Deicing Chemicals	Cement and Concrete Res. Inst. (Sweden), Bridge Division	40 062593
A Study of Reinforced Concrete Bridge Deck Deterioration: Diagnosis, Treatment, and Repair	Texas Transportation Institute	40 086734
Bridge Deck Icing Study—Valley Environment	California Division of Highways	40 088919
Repair and Protection of Concrete Structures and Pavements	New York State Dept. of Transportation, Bureau of Physical Research	40 088928
Plastic Modified Portland Cement Mortar Overlay	Pennsylvania Department of Highways	40 202216
Synthetic Resin Overlay for Bridge Deck Surfaces	Pennsylvania Department of Highways	40 202217
Machine-Applied Epoxy Resin Overlay	Pennsylvania Department of Highways	40 202218
Galvanized Steel Reinforcing for Concrete Bridge Decks	Michigan Department of Highways	—

^a As of April 1970. ^b Acquisition number assigned by the Highway Research Information Service of the Highway Research Board; HRIP = publication entitled *Highway Research in Progress* (current issue).

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THE DIVISION OF ENGINEERING is one of the eight major Divisions into which the National Research Council is organized for the conduct of its work. Its membership includes representatives of the nation's leading technical societies as well as a number of members-at-large. Its Chairman is appointed by the Council of the Academy of Sciences upon nomination by the Council of the Academy of Engineering.

THE HIGHWAY RESEARCH BOARD, organized November 11, 1920, as an agency of the Division of Engineering, is a cooperative organization of the highway technologists of America operating under the auspices of the National Research Council and with the support of the several highway departments, the Bureau of Public Roads, and many other organizations interested in the development of transportation. The purpose of the Board is to advance knowledge concerning the nature and performance of transportation systems, through the stimulation of research and dissemination of information derived therefrom.

HIGHWAY RESEARCH BOARD

NATIONAL ACADEMY OF SCIENCES—NATIONAL RESEARCH COUNCIL
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