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These Digests are issued in the interest of providing an early awareness of the research results emanating from projects in the NCHRP. By making these results known as they are developed and prior to publication of the project report in the regular NCHRP series, it is hoped that the potential users of the research findings will be encouraged toward their early implementation in operating practices. Persons wanting to pursue the project subject matter in greater depth may obtain, on a loan basis, an uncorrected draft copy of the agency's report by request to: NCHRP Program Director, Transportation Research Board, 2101 Constitution Ave., N.W., Washington, D.C. 20418

Bridge Deck Repairs

An NCHRP staff digest derived from quarterly progress reports on NCHRP Project 12-16, "Influence of Bridge Deck Repairs on Corrosion of Reinforcing Steel," by John E. Slater and David R. Lankard, Battelle Columbus Laboratories, Columbus, Ohio.

THE PROBLEM AND ITS SOLUTION

The cost of repair and replacement of deteriorated concrete bridge decks is a major expense for highway agencies. Damage usually results from corrosion of reinforcing steel caused by chloride ions in the concrete deck. Research indicates that the alkaline environment in concrete prevents the corrosion of steel that normally occurs in the presence of moisture and oxygen. The effect of chlorides is to cause a change in this alkaline environment, thus allowing the corrosion reaction to take place. Only a small amount of chloride is necessary to cause the reaction to start, but further addition of chlorides to the surface of concrete that has already shown distress may not be necessary for continued corrosion. Thus, application of a waterproof membrane and an overlay on a repaired bridge deck from which all chloride-contaminated concrete has not been removed may not solve the problem, and in some cases may actually aggravate the condition because it prevents processes such as flushing and drying that might help to remove chlorides and also because it prevents visual examination of the deck.

Numerous techniques are currently used to arrest and repair the damage caused by corroding reinforcing steel in otherwise structurally sound concrete bridge decks. Repair techniques include removal of the concrete to or below the level of the top mat of reinforcing steel, a variety of treatments of the steel, and use of various materials to replace the concrete removed. In addition to replacement of the damaged concrete, the repair often includes application of an overlay with or without a waterproofing membrane. The effect of these methods on subsequent corrosion has not been determined.

Accordingly, in September 1974 Battelle Columbus Laboratories began research on NCHRP Project 12-16, "Influence of Bridge Deck Repairs on Corrosion of Reinforcing Steel," a 30-month study with the objective of determining the relative effectiveness of the various repair methods in arresting corrosion of the reinforcing steel, and whether some of these methods actually aggravate the corrosion problem.

The research includes a preliminary field survey, laboratory evaluation, and field investigation of repair methods currently used throughout the United States. The laboratory evaluation phase constitutes the major part of this study. One hundred and sixty 28" x 26" x 8" slab specimens have been prepared, simulating various repair methods. The corrosion of steel reinforcement in the slabs will be monitored over a period of 18 months while they are subjected to a ponded chloride solution. The project is scheduled for completion by the end of February 1977.

The purpose of this digest is to provide early dissemination of the findings of the preliminary field survey stage. This stage has included personal and telephone contacts with numerous individuals and highway agencies, a mailed questionnaire (to all 50 states), and a search of available published information. The results indicate a great diversity in bridge deck repair practices. Although Digests are normally quite brief, it is believed that these findings could be useful immediately; therefore, segments of the agency's quarterly progress report are included in their entirety and *the statement in the heading regarding the availability of loan copies of uncorrected drafts does not apply to this Digest.*

FINDINGS

This Digest integrates the findings of the recently completed field survey with available published information concerned with the bridge deck spalling problem. The intent of this effort is to review the causes of deck deterioration, and to discuss and analyze the preventive and remedial solutions that have been applied to the problem. Primary attention was directed to the problem of delamination and spalling of concrete bridge decks due to salt-accelerated corrosion of the reinforcing steel. Information obtained in the field survey phase quided the selection of materials and techniques for the laboratory phase of the program. An extensive bibliography has been compiled covering research and field work concerned with these subjects and is available upon request to the NCHRP Program Director.

Overview of the Bridge Deck Deterioration Problem

Repairs and maintenance of portland cement concrete bridge decks are made necessary by the problems of spalling, scaling, cracking, and loss of skid resistance. The proper use of air entrainment in concrete has reduced the severity of scaling as a bridge deck maintenance problem. Cracking, which occurs in most decks, does not in itself usually constitute a need for maintenance, although it may contribute indirectly to the spalling problem. Loss of skid resistance has been a cause of extensive maintenance in only a few areas, but this problem may intensify as more states adopt a minimum skid number for pavements. Within at least the last 10 years, spalling has been the bridge deck deterioration phenomenon most responsible for the severity of the deck maintenance problem. It is to the spalling problem that NCHRP Project 12-16 is addressed.

It is well established that the delamination and spalling of PCC bridge decks is caused in the main by the corrosion of the top reinforcing steel, which in turn is related to the use of deicing salts on the deck surface. The salts promote corrosion of the steel by providing aggressive anions (chloride) that destroy the protective oxide film built up on the steel in the alkaline concrete.

It is not surprising, therefore, that surveys have revealed that states having the greatest "bridge deck problem" are those which routinely use large quantities of deicing salts. Extensive and comprehensive bridge deck condition surveys have been conducted in California, Kansas, Pennsylvania, Iowa, and Virginia. Ten states were involved in a comprehensive PCA/BPR study of the durability of concrete bridge decks over the period 1965 through 1970. Additionally, Kliethermes (3) recently provided a rating of the geographical nature of the bridge deck problem on the basis of the degree of corrosion of the reinforcing steel in highway structures.

These data indicate that states in the north, east, and midwest sectors of the U.S., as well as Texas and California, have, in the main, experienced the greatest difficulty with their bridge decks.

A major factor influencing the opinion of the various states regarding the severity of the deck maintenance problem is the actual number of bridges falling under state jurisdiction. The results of the field survey on this matter are given in Table 1. Pennsylvania and Texas have the largest number of bridges in their state highway systems (26,000). Other states responsible for a large number of bridges (>6000) are California, Illinois, Kentucky, Missouri, New York, North Carolina, Ohio, and South Carolina. Collectively, the states are responsible for more than 218,000 bridges, of which, as of January 1975, about 60 percent had concrete decks without overlays.

In those states where the number of bridges is large and the use of deicing salts is standard practice, the deck maintenance problem is usually judged to be severe.

Methods for Evaluating the Condition of Concrete Bridge Decks

The tools and procedures available to the bridge maintenance engineer for evaluating the current condition or the extent of deterioration of a bridge deck include:

1. Potential measurements of reinforcing steel.
2. Delamination detection.
3. Chloride analyses.
4. Nondestructive measurements of concrete and construction quality (acoustic velocity, Windsor probe, Schmidt hammer, pachometer, microseismic refraction).
5. Subjective visual assessments.

Electrical Potential Measurements

The corrosion of reinforcing steel in concrete is believed to result from current flow between macroscopically separated anodes (steel corroding in the presence of chloride ions) and cathodes (noncorroding or passive steel) with oxygen reduction occurring on the passive surfaces. Because of the macroscopic separation and the flow of corrosion current, the differing electrode potentials of the anodic and cathodic areas can be determined using a reference half-cell placed on the surface of the concrete. In this way, the actively corroding (active potential) and passive (noble potentials) regions of the rebar may be determined by conducting a potential "scan" of the deck surface.

Some confusion exists regarding the presentation of the potential values exhibited by the rebar. The potential of the rebar is almost always active (negative) in relation to the $Cu/CuSO_4$ reference electrode, and thus should be reported as such (e.g., -0.35 V_{CSE}).* More active corrosion gives a more negative potential (e.g., -0.15 v). However, bridge maintenance engineers frequently disregard the sign of the potential, and in this convention a numerically larger value signifies a more active potential.

This nondestructive technique was developed primarily by California Department of Transportation researchers. When $Cu/CuSO_4$ is used as the reference cell, it has been established that steel reinforcement may be considered to be actively corroding when the measured potential is more active (negative) than -0.35v. If the measured voltage is more positive (noble) than -0.30 v, the steel is still in a passive state. Using this technique, it is possible to map a bridge deck showing equipotential contours and thus identify the active and passive areas of the steel in the deck. Electrical potentials must be measured using a high-input impedance voltmeter to overcome the high resistance of the concrete electrolyte.

The technique has recently been adopted as a standard test by ASTM. With respect to the interpretation of results, this standard reads:

(1) If potentials over an area are numerically less than -0.20 volts, there is a greater than 90 percent probability that no reinforcing steel corrosion is occurring in that area at the time of measurement.
(2) If potentials over an area are in the range of -0.20 to -0.35 volts, corrosion activity of the reinforcing steel in that area is uncertain.
(3) If potentials over an area are numerically greater than -0.35 volts, there is a greater than 90 percent probability that reinforcing steel corrosion is occurring in that area at the time of measurement.

The validity of electrical potential measurements as an indicator of the presence of active corrosion in concrete reinforcing steel has been verified by a number of researchers (4,8,17,18,25).

Although the half-cell potential is a valid indicator of corrosion activity of steel in concrete, it can not be used for a quantitative determination of corrosion rate. However, the numerical value of the potential increases with an increasing rate of corrosion (18,30).

The relationship between concrete cracking and steel potentials has also been studied (10). It was cautioned that:

1. The half-cell potential of steel can only be empirically related on a statistical basis to concrete cracking under specific conditions.
2. The half-cell potential does not measure the structural condition of concrete.
3. The cracking of concrete due to corrosion of steel is related to concrete strength, absorption, stresses, and thickness over the steel.

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* All electrical potentials referred to throughout this Digest are relative to a copper sulfate electrode (CSE).

Delamination Detection

The delamination or physical separation of concrete in a bridge deck has been detected through subjective judgments of the sound produced when the deck is struck with various devices such as hammers and steel rods, or when a chain device is dragged across the deck surface. Use of the chain drag to identify delaminated areas in a bridge deck has been discussed by Stewart (31) and by Carrier and Cady (20). Recently, an automated instrument has become available that has the advantages of more rapid analysis and elimination of some of the subjectiveness of the former techniques (32).

Chloride Analyses

Chloride analyses provide a quantitative measure of the chloride ion content of the concrete at various levels in the deck. At present, chloride analyses are obtained on cores or collected drill debris using the technique described by Berman (33), or other suitable analytical techniques. The Berman technique, which measures total chloride, involves digestion of the sample in dilute nitric acid and titration of the filtered extract with standard silver nitrate solution using a chloride-ion-specific electrode as an indicator.

Use of Evaluative Tools by Maintenance Personnel

As part of the field survey, the states were queried as to the availability and use of these various evaluative tools in their maintenance program. The results (see Table 1) indicate that 80 percent are equipped to perform chloride analyses, 75 percent can obtain electrical potential measurements, and 65 percent employ some method of delamination detection.

States that do not make use of any of the evaluative tools and techniques include Colorado, Georgia, Hawaii, Mississippi, North Dakota, and South Carolina. Not surprisingly, these are states where spalling is either minimal or nonexistent.

Although the majority of states are equipped to make these measurements (Table 1), this does not imply that such measurements are routinely used. In many cases data are obtained on a limited basis, whereas others have only recently begun to institute these procedures in their maintenance work.

Bridge Deck Repair and Rehabilitation Rationale

The responsibility for monitoring and maintaining the structural integrity and riding quality of bridge decks is usually in the hands of the Maintenance Division of the state highway agency. The bridge maintenance engineer is faced with an extremely challenging and complex situation. Within the constraints of budget, work force, traffic control, and weather, he must choose and schedule the most cost-effective treatment program in terms of maximization of the useful service life of the bridge deck. Fortunately, the bridge engineer today is considerably better equipped to face this challenge than he was five or ten years ago. Despite these advances (see previous section), however, it is evident in the literature and from discussions with maintenance personnel that the current status of evaluative procedures for determining maintenance requirements of bridge decks is considerably less advanced that those for pavements. Numerous excellent articles have been written concerning decision-making criteria in a pavement maintenance program. Unfortunately, few of these discussions devote specific attention to the bridge deck maintenance problem.

In arriving at his final decision, the bridge maintenance engineer must first become aware of the need for some action on a deck. The prompting is most usually an unacceptable degradation in the riding quality of the deck. The deck is then inspected and a decision is made as to treatment. The options are:

1. Temporary repair.
2. Permanent repair, partial restoration.
3. Permanent repair, total restoration.
4. Replacement.

In some cases, the optimum repair treatment may be obvious; usually it is not. Even after the decision is made as to the nature of the remedial treatment the engineer is still faced with a decision as to the actual materials and techniques to be used.

One of the most unfortunate aspects of this procedure is that it is simply a reaction to an unacceptable situation (riding quality). Thus, delaminated decks which still retain their riding quality are not routinely factored into the maintenance program, even though immediate preventive treatment might be significantly more cost-effective. Discussions with highway maintenance personnel revealed that most are keenly aware of the desirability and benefits of a systems approach to bridge deck maintenance. However, positive action in this area has emerged only recently.

Among the first efforts to provide a more rational basis for bridge deck condition assessment were the PCA-BRP survey reports covering 1965 through 1970(36). In the PCA-BRP survey, data were obtained on total deterioration, including scaling, spalling, cracking, rusting, and popouts(29). In this survey, scaling was identified as light, medium, heavy or severe, depending on the area of the deck affected. Spalling was recorded as the number of large or small spalls on a span (small being <1 ft in diameter). Cracking was identified by type (transverse, pattern, etc.) and severity (light, medium, heavy). No data were obtained on delamination, steel corrosion activity, or chloride content of the concrete. The random survey technique used in the study proved that reasonably reliable and reproducible data could be obtained in a survey of bridge deck conditions.

With the advent of the potential measurement technique and increased use of chloride analyses, additional advances were made, particularly in terms of quantifying the various types of manifest deterioration and in providing a basis for predicting future problems.

Following a demonstration of the corrosion detection device (potential measurement) to 46 states in November 1971, FHWA(3) proposed a deck classification system that defined the type and extent of repairs to be made. The FHWA technique places strong emphasis on data obtained using the corrosion detection device. It is claimed that by using the classification system several decisions can be made; namely,

1. The limits of concrete to be removed beyond the spalled area can be determined. Removal of all concrete in areas with a potential reading more negative than -0.3 v was recommended. This requires an analysis of the readings obtained, which isolates the hot spots and calculates the area to be removed.
2. A decision can be made as to the type of patch and patch material to use.
3. It can be decided whether or not a membrane is to be placed on the deck after patching.

4. An administrative decision can be made that reflects the number and types of decks that can be repaired or rehabilitated as related to the available resources. On some decks it may be economically sound to repair a deck temporarily with minimum traffic interference until resources become available for complete rehabilitation.

The FHWA classification includes three categories that reflect the deck condition, as follows:

Classification 1—pertains to decks in an advanced state of deterioration with the following characteristics:

1. Corrosion readings indicate that active areas exist in from 50 to 100 percent of the deck area.
2. Concrete cover is variable.
3. Core samples indicate that chloride has impregnated a large percentage of the deck area.

Classification 2

1. Corrosion readings indicate that active areas are 20 to 60 percent of the deck area. The cells can be isolated into hot spots and are surrounded by a substantial area of less than 0.3v readings (more positive than -0.3v).
2. Concrete cover is reasonably uniform.
3. Core samples indicate that chloride is largely found only in spalling areas.

Classification 3

1. Corrosion detection readings indicate active areas ranging up to 25 percent of the deck area. These active hot spots can be isolated and are surrounded by a sizeable area of less than 0.3v (more positive than -0.3v) readings.
2. The cover is adequate for current design.
3. Deck core samples indicate a minor amount of chloride at isolated hot spots.

Bridge decks in Classification 1 are considered more or less beyond help. Low-cost maintenance (cold-mix patching) of riding quality is suggested prior to scheduling a complete rehabilitation.

Bridge decks in Classification 2 are considered appropriate for further evaluation with permanent partial restoration recommended, followed by periodic monitoring with the corrosion potential device.

Decks in Classification 3 are recommended for a more elaborate patching program. It is decks in this category that Kliethermes(3) feels will benefit most from a rational maintenance program in terms of extending service life.

Clear(7) also presented an interpretation of corrosion potential data relative to maintenance decision-making that also incorporates chloride analysis data. His findings:

Category 1—40 percent or more potentials greater than 0.35 V_{SCE} (more negative than -0.35v).

If a large percentage of the deck steel is actively corroding, it is possible that complete deck removal and reconstruction is economically warranted. To substantiate the deck condition prior to recommending reconstruction, it is suggested that five or ten chloride samples be obtained from the rebar level at intervals across the deck. Areas of sound concrete with potentials less than 0.35 V_{CSE} should be chosen for sampling. If a majority of these cores contain chlorides in excess of the threshold, reconstruction is probably warranted. An economic analysis should then be performed to determine the relative cost of complete deck removal and replacement versus further delineation and removal of contaminated concrete, patching and overlay (including disposal and environmental considerations). If reconstruction is chosen, no further chloride analyses are necessary. However, if repair is chosen or if a significant number of the cores show low chloride, additional analysis along the lines presented in deck category 2 should be performed.

Category 2—5 to 40 percent of the potentials are greater than 0.35 V_{CSE} (more active than -0.35 v).

If only a portion of the deck steel is actively corroding, it is possible that complete removal is unwarranted. Thus, the areas of unsound and contaminated concrete should be located and this concrete removed. The following procedures are suggested for this type of deck:

(a) Delineate the areas with potentials greater than 0.35 volts CSE. Assume the rebar in this concrete is corroding and the concrete must be removed below the top mat of reinforcing steel. Chloride samples can be obtained from these areas if the engineer doubts the validity of the potential readings.
(b) Define the structurally unsound areas that fall outside the greater than 0.35 volt area delineated under (a) above using chain drags, sounding rods, or the delamination detector. Remove the concrete in these areas below the top rebar mat in addition to that removed under (a) above. (This step is essential, as demonstrated by recent work by Boulware and Stewart (13), which showed that the greater than 0.35-volt potential contour will not encompass all unsound concrete.)
(c) The remaining concrete is structurally sound concrete with electrical potentials less than 0.35 volts. As shown in recent work by the author (Clear), it may be chloride-contaminated or uncontaminated and may contain passive or active reinforcing steel. To determine the portions of this concrete which must be removed, it is suggested that samples for the determination of rebar-level chlorides be obtained on a 5-ft grid pattern in these low electrical potential areas. The selection of a 5-ft grid pattern is based on the limited field data presently available. It may be necessary to modify this pattern as additional data are obtained. Chloride content corrosion threshold contours can be plotted to determine the areas of concrete removal. Obviously, after analysis of these initial samples, additional samples may be required for further delineation or a reanalysis of the advisability of deck removal may become necessary.

Category 3—Less than 5 percent of potentials greater than 0.35 V_{CSE} (more active than -0.35v) and no spalls.

A check for delaminated concrete should be made and the unbonded areas defined. Following the check it is suggested that about 10 samples be obtained from sound concrete across the deck and the chloride content of these samples determined prior to additional in-depth analysis. Several of these samples should be taken from the sound concrete areas with potentials greater (more active than) 0.35 volts CSE. If all of these samples contain chlorides at the rebar level which are below the lower limit of the corrosion threshold and no delaminations are present, there is a high probability that a waterproof membrane can be placed over the deck with safety. However, if high chlorides are encountered at some core locations or if delaminations are found, the contaminated areas should be defined by additional chloride analyses and removed prior to placement of a membrane or other permanent repair.

Stratfull et al.(37) and Stewart(31) in California also have reported on the use of corrosion potential measurements and chloride analyses in the formulation of maintenance decisions.

Clear(7) has presented an example of the use of chloride content data as regards deck repair as follows:

- ° Less than 1.0 lb Cl^-/yd^3—leave concrete intact.
- ° Greater than 2.0 lb Cl^-/yd^3—remove concrete to a level below the top mat of rebars or replace the entire deck.
- ° 1.0 to 2.0 lb Cl^-/yd^3—questionable area. The decision as to whether or not to remove concrete with chloride content in this range will depend on the engineer's willingness to accept the risk and cost of future corrosion problems.

Stratfull and other researchers have cautioned that none of the condition assessment tools alone can be used to establish needed repair area boundaries of a bridge deck. This result, however, can be reasonably well achieved through collective use of the various available tools and procedures.

Inasmuch as most of these recommendations are of relatively recent origin, it is not surprising that only a few states have made significant progress in incorporating these advances into their decision-making policy. However, as pointed out in the previous section, a majority of the states are now equipped to use the new available technology.

A good example is the flow chart for bridge deck treatment currently used by the Pennsylvania DOT (Fig. 1). This assessment/action statement is based on deck status, percent of spalled deck area, and chloride content of the deck concrete. Based on this input, action can range from patching with bituminous mix to complete replacement of the deck.

The groundwork has been laid for a rational systems approach to bridge deck maintenance. Time and budget restraints will govern the rate at which the new technology is adopted and used by the various state highway agencies. Meanwhile, engineering judgment based primarily on visual observations of a deck will continue to provide the basis for most of the decision-making routine regarding bridge deck maintenance.

Materials and Methods for Bridge Deck Repair and Rehabilitation

Remedial treatment to restore riding quality of structural adequacy to a delaminated or spalled deck can take several forms. The treatment prescribed may also be influenced by deck scaling or other surface mortar deterioration and cracking.

As might be expected, the materials and techniques used by the various state highway departments in deck restoration vary widely. It is also not uncommon for the practice to vary within the various districts of a given state. Despite this situation, several aspects of bridge deck maintenance are reasonably uniform from state to state, as follows:

1. Temporary Repairs — Temporary repairs are made in situations where a rapid restoration of the riding quality of the deck is required or where available funds or weather conditions preclude the use of other treatments. Temporary repairs usually involve filling of the spalled areas with a repair material with no significant preparation of the spall area prior to placement.

Discussions with maintenance engineers indicate that the practice of temporary repair is much more widespread than is generally acknowledged. Cold-mix asphalt is the material used most commonly for this type of repair. Significantly, it was learned that many of these so-called temporary repairs become in fact permanent repairs if they stay in place.

2. Permanent Repairs — In this situation, it is intended that the repair of the spalled area be reasonably permanent. The repair may take the form of partial or total restoration.

In partial restoration, only a portion of the deck is physically removed and replaced. The areas to be treated may be defined subjectively by the maintenance personnel or with the aid of delamination measurements, spall manifestation, corrosion potential measurements, and, in some cases, the chloride content of the concrete. Currently, the extent of the area treated is based primarily on visual observations of manifest spalling and delamination measurements.

The basic steps involved in the permanent repair of spalls are reasonably uniform from state to state and are:

(a) A saw cut is made to a depth of 1 or 2 in. around the spall.
(b) The deteriorated concrete within the saw cut is removed by chipping or air hammer.
(c) Corrosion product is removed from the exposed reinforcing steel.
(d) A bonding agent is applied to the cleaned spall area.
(e) The repair material is placed and cured.

In practice, the existing concrete is usually removed to at least the level of the top reinforcing steel. Frequently, the concrete is removed to an inch or so below the top reinforcing steel and, on occasion, full-depth removal is attained. It is not uncommon, however, for some of the top reinforcing steel to be still embedded in existing concrete in the repair area. Thus, the depth of removal of old concrete is by and large an uncontrolled field variable.

Cleaning of the corrosion product from the exposed reinforcing steel, usually by sandblasting or wire brushing, is common practice in a majority of states, as is the application of a cement paste or epoxy bonding agent.

For total restoration a certain depth of the entire deck is removed and replaced with new concrete. Frequently, all salt-laden concrete is removed to below the level of the top reinforcing steel.

Following either partial or total restoration, the repaired deck may be overlaid with asphaltic concrete or portland cement concrete. In some cases, a membrane moisture barrier may be placed between the deck and the overlay. When portland cement concrete is used as an overlay, the entire deck surface is scarified to a depth of at least 1/4 in.

3. Replacement — In extreme cases, the old bridge deck may be replaced with a completely new deck. In this case, the procedures for new deck construction are generally applied.

Current Maintenance Practice

The variance in current maintenance practice in the United States is reflected in the survey data given in Table 1. The majority of the states (58 percent) have no written specifications regarding maintenance practice to be used for bridge deck spall repair and overlays. However, a majority of the states (60 percent) do have written specifications regarding overlays on existing decks.

Typically the specifications cover:

1. Depth of concrete removal.
2. Areas of repair.
3. Removal of existing overlays.
4. Treatment of repair area (sandblasting, etc.).
5. Splicing and treatment of exposed rebar.
6. Equipment used for surface preparation, mixing, placing, and finishing.
7. Forming on full-depth repairs.
8. Use of bonding agents.
9. Curing procedures.

Bridge Deck Maintenance Materials

The materials used in bridge deck maintenance programs include those used for spall repair and those used for overlays. There is wide variation in the materials used for spall repair, whereas only a few materials are used routinely for overlays.

Spall Repair Materials

The wide variety of materials used for spall repair is understandable on the basis of data presented in Table 1, which show that 56 percent of the states do not have any written specifications in this area. The material specifications, when available, most frequently are of a performance nature based on setting time, compressive or flexural strength, freeze/thaw and scaling resistance, and, infrequently, chemical analysis, shrinkage, and soundness.

The materials used by state highway agencies (both historically and currently) for spall repair are identified in Table 2. The survey data indicate that the material used most frequently in the past and currently for spall repair is a portland cement mortar or concrete. Typically, these concretes have a high cement factor (6 to 8 sacks per cubic yard) and not infrequently contain calcium chloride as an accelerator. Commercial set accelerating admixtures also are used.

The second most widely used class of repair materials are packaged, proprietary formulations sold commercially. Many of these have the feature of rapid hardening and are referred to as "quick-set" materials. The products identified to date which are used by various state agencies are given in Table 3. There are literally dozens of these products, many of which are marketed on a local or regional basis. The products marketed on a nationwide basis include Duracal, Darex 240, Speed-Crete, and Embeco. Table 2 indicates a trend toward more widespread use of these materials. Based on the survey results, the most widely used of the quick-set materials are Duracal and Speed-Crete. Almost all of the states have experimented to some degree with quick-set materials, with opinions varying as to their cost-effectiveness.

The interest in epoxy and polyester resin formulations as spall repair materials appears to be waning somewhat as the high cost of these materials has not always been justified by significant improvements in performance. In all cases, the resins are combined with aggregates on site to form the repair material. There does not appear to be a significant use of polyester resins as a binder for repair materials at present. A number of epoxies are furnished as proprietary commercial materials, such as GuardKote 250 (a coal tar epoxy); Radgrout; Steel Coat Epoxy; Metaseal Epoxy SinMast; Sika LoMod; Albitol; Concressive #1178; and Colma-Dur. Several states obtain epoxies tailored to meet specific performance specifications.

The data given in Table 2 which indicate that asphaltic concrete is not used routinely for spall repair do not represent the true situation. Many states use AC for so-called "temporary" repairs which, if they stay in place, become, in fact, permanent repairs. Asphaltic concretes are used quite extensively for spall repairs where initial cost, expediency, or inclement weather rule out the use of the other types of materials.

Overlay Materials

Overlays refer to those situations where the entire bridge deck has been covered with a new wearing course. Approximately 40 percent of the 218,000 bridge decks under state jurisdiction are covered with some type of overlay.

Overlays of existing bridges fall into four main categories:

1. Asphaltic concrete overlay without a membrane.
2. Asphaltic concrete overlay with a membrane.
3. Latex-modified concrete.
4. Low-slump PCC.

As indicated in Table 1, a majority of the states (64 percent) have written specifications concerning the materials used for construction of overlays on existing bridge decks.

The major type of overlay used has been asphaltic concrete without a membrane. This has resulted, in part, from pavement overlay situations in which the bridges on the highway were simply overlaid at the same time as the pavement. Most of the bridges overlaid with AC had spall repairs prior to the overlay, with a variety of repair materials being used.

Latex-modified concrete (LMC) has been used as an overlay on more than 200 bridges in 24 states since 1959 (typically 1-1/4 to 2 in. thick). In overlaying with

LMC, the deck is usually scarified to a depth of at least 1/4 in. prior to application of the LMC. No membrane is used in this system, as the latex is expected to provide an integral waterproofing function. To date most of the LMC overlays have been installed by the supplier of the latex material. All of the states using LMC as an overlay have written specifications for its use. These specifications basically reflect the experiences of the developer(38).

Mix designs for LMC vary somewhat from state to state although cement factors are usually in the range of 7 to 8 sacks per cubic yard. In many cases, a mortar mix is prescribed.

Thin, bonded, low-slump PCC overlays have been used in several states, notably Iowa and Kansas (39). This technique also requires the whole deck to be scarified to a depth of at least 1/4 inch. Exposed reinforcing steel is sandblasted and a portland cement mortar (1:1) grout is applied to the deck prior to the overlay. The 1/2-in.-slump concrete is consolidated and finished by hand or machine tamping (Kelly vibration compactor).

The recommended concrete contains 1,394 lb of coarse and fine aggregate and 823 lb of cement per cubic yard. A water-reducing admixture is required and an air content of 6 ± 1 percent is recommended.

The Iowa specification defines the surface preparation required for three classes of repairs using the technique. In all cases, loose, disintegrated, or unsound concrete must be removed from those portions of the bridge floor shown on the plans or designated by the engineer.

Class 1 Repair — All areas designated for Class 1 repair shall be uniformly scarified or prepared to the depth specified but in all cases at least 1/4 inch deep and deeper as required. That portion of the curb against which new concrete is to be placed shall be sandblasted. Surfaces of reinforcement exposed by scarification shall also be sandblasted.

Class 2 Repair — A saw cut approximately 3/4 inch deep shall be made along all boundaries of Class 2 repair areas adjacent to areas of no repair, except those boundaries adjacent to the face of a curb. The loose and unsound material shall be removed by chipping and by the use of hand tools. All exposed reinforcing bars and newly exposed concrete shall be throughly cleaned by sandblasting. Where the bond between existing concrete and reinforcing steel has been destroyed, the concrete adjacent to the bar shall be removed to a depth that will permit new concrete to bond to the entire periphery of the bar so exposed. A minimum of 3/4 inch clearance shall be required. Care shall be exercised to prevent cutting, stretching, or damaging any exposed reinforcing steel. The engineer may require enlarging a designated portion of the area to be repaired should inspection indicate deterioration of concrete beyond the limits previously designated. In this event, a new saw cut with a "dry" blade shall be made around the extended area before additional removal is begun.

Class 3 Repair — Within all areas designated for Class 3 repair and any designated areas of Class 2 repair in which the depth of remaining sound concrete is less than 50 percent of the original depth of the bridge floor, all concrete shall be removed. Designated Class 2 repair areas shall be measured as Class 3 bridge floor repair when full-depth removal is required. At the discretion of the engineer, limited areas of removal greater than 50 percent of the floor thickness, such as beneath reinforcing, may be allowed; these limited areas of excess depth will be measured as Class 2 bridge floor repair. A saw cut approximately 3/4 inch deep shall be made along all boundaries of Class 3 repair areas adjacent to areas of no repair except those boundaries adjacent to the face of a curb. The material shall be removed by chipping and by the use of hand tools. All exposed reinforcing bars and newly exposed concrete shall be throughly cleaned by sandblasting. Care shall be exercised to prevent cutting, stretching, or damaging any exposed reinforcing steel. Final removal at the periphery of Class 3 areas shall be accomplished by 15-lb chipping hammers or hand tools. Forms shall be provided to enable placement of new concrete in the full-depth opening. These forms shall preferably be suspended from existing reinforcing bars by wire ties. Forms may, in the case of large-area openings, be supported by blocking from the beam flanges. Forms will in all cases be supported by elements of the existing superstructure unless specifically noted or shown otherwise on the plans.

The Iowa specifications also spell out in detail the requirements for surface preparation equipment, proportioning, mixing equipment and techniques, placing and finishing equipment and techniques, and curing materials and procedures.

As a matter of interest, the Iowa researchers (39) rated the low-slump PCC and LMC technique comparable in a number of areas and have approved both for use. A majority of states contacted in the survey rated the Iowa technique very highly as a superior bridge deck rehabilitation technique.

Furr and Ingram(40) have also presented a case for cement-rich, bonded-concrete overlays.

Membranes. The placement of membranes on existing decks was covered in the survey. The results are given in Table 2. A majority of states (78 percent) either require or permit the use of membranes on existing bridge decks. Not all states use chloride content as a factor in the decision regarding the use or nonuse of a membrane. In almost all cases where membranes are used, asphaltic concrete is the overlay material. Sheet-type membranes are preferred over liquid types by a majority of the states.

Special Treatments

Recently a number of new techniques have been suggested as preventive and remedial treatments for bridge decks and pavements, including polymer (4) impregnation, epoxy injection (43), and the use of precast slabs.

CONCLUSION

The results obtained from the preliminary field survey and a review of pertinent literature clearly show the magnitude of the bridge deck spalling problem. There is little doubt that the phenomenon is a direct result of the increased use of deicing salts on bridge decks in freeze-thaw areas.

The "life-cycle" of a spall now appears to be well understood. Deicing salts applied to the deck penetrate to the rebar and initiate corrosion; corrosion product builds up, exerts pressure, and eventually causes concrete splitting or delamination; the cracks reach the deck surface and the concrete pops out, producing a spall. Factors that affect the process include concrete composition and properties, construction variables, and environmental variables. Quality (permeability) of the concrete and depth of cover influence the initiation period for rebar corrosion, evidently by increasing the time necessary for a threshold quantity of chloride ion to penetrate to the level of the steel.

Because the spall is the ultimate result of chloride-induced corrosion in reinforcing steel with macroscopically separated anodes and cathodes, measurement of rebar potential in an as-yet undistressed area is the detecting instrument of choice for the earliest determination of incipient danger areas in a bridge deck. This technique has received much attention, and is currently the object of ASTM scrutiny. Chloride analyses to determine the existence of high Cl^- content, and therefore likely corrosion, are useful but time consuming, and at present can only be made destructively in selected areas. Delamination detection locates incipient damage at a much later stage, when subsurface cracks have initiated. Although these techniques for determining incipient damage are now available, the survey indicates that they are not yet in routine use.

The rationale for decision-making on bridge deck repair and rehabilitation procedures is in its infancy. Several flow charts for remedial action have been published, leaning heavily on potential readings and/or chloride analyses. As discussed earlier, current use of these techniques is limited. The major factor currently influencing decision-making appears to be financial constraints; this factor will continue to be important in the adoption of new techniques and rationales.

Methods and materials for deck repair and rehabilitation vary widely from state to state, and even within each state. Repairs involving placement of cold-mix AC in spall-holes is still probably the most widespread "repair" method, even though such a repair is frequently adjudged "temporary." More permanent repairs involve a number of factors, including removal of deteriorated concrete, removal of corrosion product, application of bonding agent, and placement of repair material plus any overlay or membrane.

The depth and extent of removal of unsound or chloride-contaminated concrete is variable between and within states. Most states remove corrosion product from exposed rebar, and apply either epoxy or cement paste bonding agent. The most common spall repair material is portland cement concrete, typically with a high cement factor. Commercial quick-set materials are gaining favor, whereas interest in epoxy or polyester formulations is varying.

Overlays are present on 40 percent of the bridges covered in the survey, although most are simply AC overlays acting as a wearing course. Waterproofing overlays are gaining favor. Latex-modified concrete and thin, bonded low-slump PCC are both being used in an attempt to prevent ingress of Cl^- ion. Waterproofing membranes with an AC wearing course are either permitted or required in a majority of states.

APPLICATION

In conclusion, the preliminary field survey provided an excellent foundation for the choice of repair techniques and materials for the laboratory investigation phase of the program and the results should be of interest to engineers responsible for the maintenance of bridge decks. The survey has also shown the large gap in knowledge regarding the relative efficiencies of the various technique/material combinations, and it is anticipated that the laboratory evaluation phase will aid in filling this void.

FIGURE 1. FLOW CHART FOR BRIDGE DECK TREATMENT

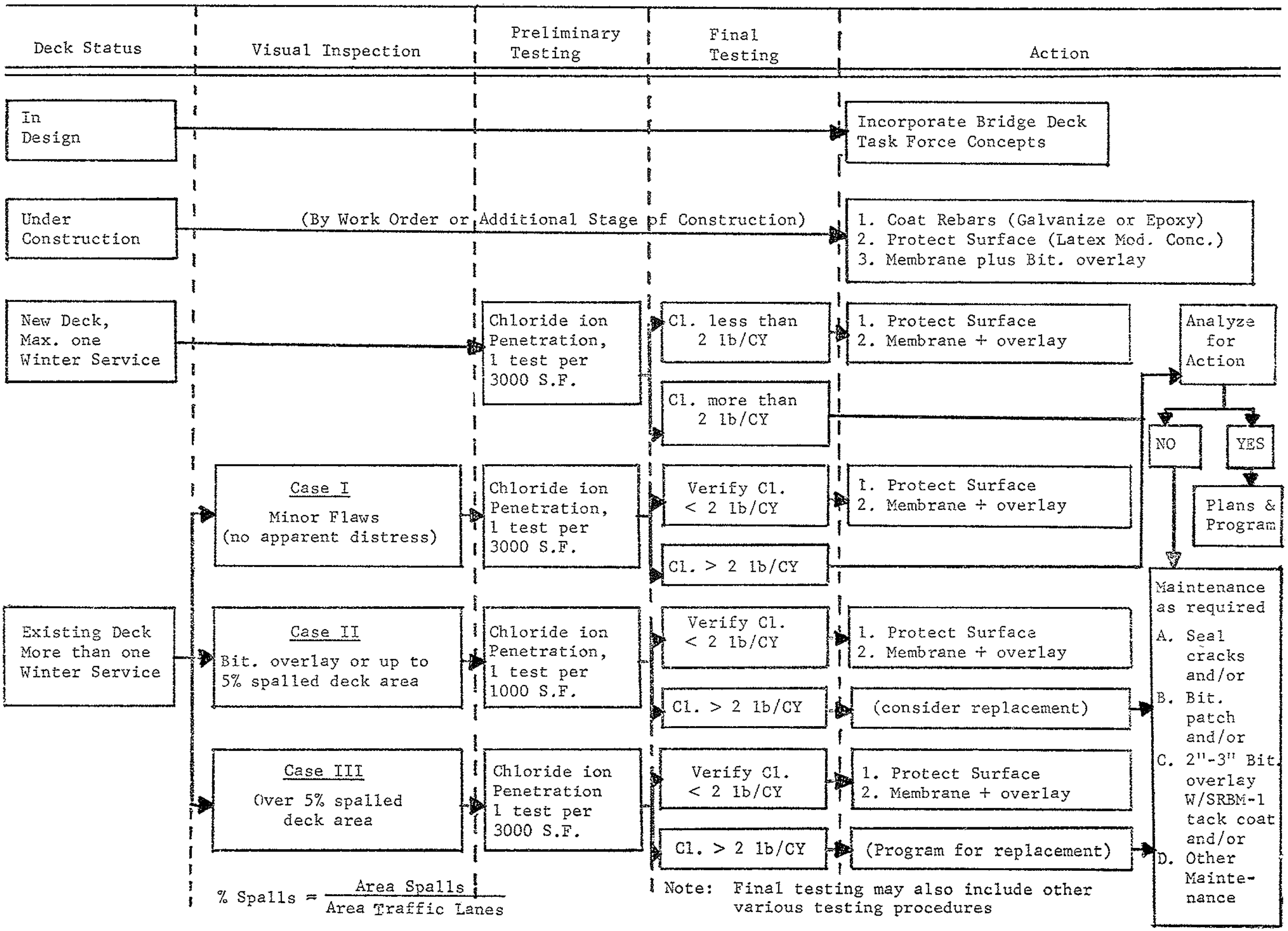

TABLE 1. RESULTS OF QUESTIONNAIRE SURVEY, BRIDGE DECK REPAIRS, AS OF DECEMBER 1974

State	Bridges in State Highway System			Use of Bridge Deck Condition-Evaluation Tools and Procedures			Written Specifications			
							Procedures		Materials	
	Total No.	Bare in Dec. '74 No.	Bare in Dec. '74 %	Chloride Analysis	Electrical Potential Meas.	Delamination Detection	Repair of Spalls	Overlay Existing Decks	Repair of Spalls	Overlay Existing Decks
Alabama	4,200	2,940	70	Yes[a]	Yes[a]	Yes[a]	No	No	No	No
Alaska	560	40	7	Yes[bc]	Yes[bc]	Yes[bc]	No	Yes	No	Yes
Arizona	1,350	1,012	75	Yes	Yes	Yes	Yes[q]	Yes[q]	Yes[q]	Yes[q]
Arkansas	4,800	3,120	65	Yes[d]	Yes[d]	No[d]	Yes	Yes	Yes	Yes
California*	11,400	11,286	99	Yes[e]	Yes[e]	Yes[e]	Yes	Yes	Yes	Yes
Colorado	2,500	1,200	50	No	No	No	No	No	No	No
Connecticut	3,000	1,200	40	Yes	No	Yes	Yes	Yes	Yes	Yes
Delaware	197	83	42	Yes	No	No	Yes	Yes	Yes	Yes
Florida	4,500	3,600	80	Yes[b]	Yes[b]	No	No	No	No	No
Georgia	4,200	2,520	60	No	No	No	No	No	No	No
Hawaii	507	456	90**	No	No	No	No	No	No	No
Idaho	1,033	620	60	Yes	Yes	Yes	Yes	Yes	Yes	
Illinois	8,000	4,800	60	Yes[b]	No	Yes	Yes	No	Yes	No
Indiana	4,637	2,550	55	Yes[b]	Yes[f]	Yes[g]	No	Yes	No	Yes
Iowa	4,000	2,400	60	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Kansas *	2,700	405	15	Yes[b]	Yes	Yes	No	Yes	No	Yes
Kentucky	6,800	3,400	50	Yes[b]	Yes[b]	Yes[b]	Yes	Yes	Yes[q]	Yes
Louisiana	3,270	1,635	50**	Yes[h]	Yes[h]	Yes[h]	No[r]	Yes	No[r]	Yes
Maine	2,600	1,820	70	No	Yes[i]	No	No	No	No	No
Maryland	1,700	476	28	Yes[bj]	Yes[bj]	No	No	No	No	No
Massachusetts	1,800	270	15	Yes	Yes		Yes	Yes	No	
Michigan	2,500	2,000	80	Yes[b]	Yes[b]	No	No	Yes	No	Yes
Minnesota	4,500	4,275	95	Yes	No	Yes	Yes	Yes	Yes	Yes
Mississippi	2,813	2,813	100	No	No	No	No	No	No	No
Missouri	6,400	3,840	60	Yes[k]	Yes[k]	Yes[k]	Yes	Yes	Yes	Yes
Montana	820	738	90	Yes[b]	Yes[b]	Yes[b]	No	No	No	No
Nebraska	2,000	2,000	100	Yes[l]	Yes[l]	Yes[l]	No	Yes	No	Yes
Nevada	453	86	19	Yes	Yes	Yes	No	No	No	No
New Hampshire	1,700	17	1	No	Yes[b]	No	No	No	No	No
New Jersey	2,000	1,800	90	--	--	--	No	Yes	No	Yes
New Mexico	1,500**	1,275	85	Yes	Yes	No	No	No	No	No
New York	6,300	1,575	25	Yes[m]	Yes[m]	Yes[m]	Yes	Yes	Yes	Yes
North Carolina	6,300	1,890	30	No[n]	No[n]	Yes	No	No	Yes	Yes
North Dakota	1,190	490	70	No	No	No	No	Yes	No	Yes
Ohio*	12,000	6,000	50	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Oklahoma	5,000	4,000	80	Yes[o]	Yes[o]	Yes[o]	No	No	No	No
Oregon	3,200	2,083	65	Yes	Yes	Yes	No	No	No	No
Pennsylvania*	26,000	10,400	40	Yes	Yes	Yes	No	Yes	Yes	Yes
Rhode Island	400	20	5	Yes	Yes	Yes	Yes	No	No	
South Carolina	9,000	8,550	95	No	No	No	No	No	No	No
South Dakota	1,900	1,520	80	Yes[b]	Yes[b]	No	No	Yes	No	Yes
Tennessee	5,000	4,000	80	Yes	Yes	Yes	No	No	No	No
Texas	26,000	18,200	70	No	No	Yes	Yes	Yes	Yes	Yes
Utah	1,000**	120	12	Yes	Yes	Yes	Yes[q]	Yes	Yes[q]	Yes
Vermont	2,800	28	1	Yes[b]	Yes[b]	No	No	No	Yes	Yes
Virginia *	5,500	2,200	40	Yes[b]	Yes[b]	Yes	Yes	Yes	Yes	Yes
Washington	2,200	1,980	90	Yes	Yes	Yes	Yes	Yes	Yes	Yes
West Virginia	4,000	2,400	60	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Wisconsin	1,475	781	53	Yes[o]	Yes[o]	Yes	Yes	Yes	Yes	Yes
Wyoming	800	720	90	Yes[p]	Yes[p]	Yes[p]	No	Yes	No	Yes
Total	218,015	131,634	60.4%	80%Yes	75%Yes	65%Yes	42%Yes	60%Yes	44%Yes	64%Yes

* Visited by Battelle Columbus Laboratories personnel.
** Estimated by Battelle Columbus Laboratories.

a) Used on major bridges.
b) Limited basis.
c) Not used routinely for all bridge inspections.
d) Very limited use.
e) Extensive use.
f) Potential measurements on new and reconstructed decks.
g) Only on decks to be repaired.
h) Limited information on 10 bridges only.
i) Data obtained by Research Division.
j) Only by specific request.
k) Data obtained only prior to surfacing.
l) On selected basis only.
m) Limited data collected by research personnel.
n) Recently started collecting data.
o) Work just beginning.
p) Used only on "problem" decks.
q) Contract repairs only.
r) Specifications currently being prepared.

TABLE 2. RESULTS OF QUESTIONNAIRE SURVEY, BRIDGE DECK REPAIRS, AS OF DECEMBER 1974

State	Materials Used on Spall Repairs[a]								Use of Membranes on Existing Bridge Decks			
	Portland Cement Mortar or Concrete		Asphaltic Concrete		Organic Binder-Based Compositions		Proprietary (Quick Set) Materials				Allowable Chloride Content	
	Past	Present	Past	Present	Past	Present	Past	Present	Required	Permitted	Specified	Value
Alabama	1	1								Yes	No	
Alaska	1	1							Yes		No	
Arizona	2	1			3	2	1		Yes[g]		Yes	2.3 lb/cu yd
Arkansas	3				1	1	2			Yes	No	
California	1	1			2	2				Yes	No	
Colorado			1				2	1		Yes	Yes	
Connecticut							1	1	Yes		Yes[h]	250 ppm
Delaware	1	1								No[i]		
Florida					1	1		2		Yes	No	
Georgia		1[e]			1		2			Yes	No	
Hawaii	b	b								No		
Idaho	3				2		1	1		Yes	Yes	2.0 lb/cu yd
Illinois	1	1							Yes		No	
Indiana	3				1	1	2	2	Yes		No	
Iowa	1	1								No[i]		
Kansas	1	1	2	2						No		
Kentucky		1[f]					1	2	Yes		No[j]	
Louisiana					2	2	1	1		Yes	Yes	
Maine	1	1						2		Yes	No	
Maryland	1[c]	1[c]								Yes	Yes	1.3 lb/cu yd
Massachusetts							1	1	Yes		Yes	2.0 lb/cu yd[m]
Michigan	1	1			2					Yes	No	
Minnesota	1	1								Yes	No	
Mississippi					2	2	1	1		No[i]		
Missouri	1	1							Yes		Yes[h]	2.0 lb/cu yd
Montana	1	1								No		
Nebraska	1			1						Yes	Yes	2.0 lb/cu yd
Nevada	1					1				Yes	Yes[h]	2.0 lb/cu yd
New Hampshire	1	1							Yes		No	
New Jersey							1	1		Yes	No	
New Mexico					1	1	2			Yes	Yes	1.5 lb/cu yd
New York	2	2			3		1	1	Yes[k]		No	
North Carolina	1	1								No		
North Dakota							1	1		No		
Ohio	1	2					2	1	Yes		No	
Oklahoma							1	1	Yes		Yes	2.0 lb/cu yd
Oregon					1	1				Yes	No	
Pennsylvania	1	2	2	1						Yes	Yes	2.0 lb/cu yd
Rhode Island	2						1	1	Yes		Yes[n]	<0.3 volts
South Carolina					1			1	Yes		No	
South Dakota	1	1								No		
Tennessee	1	1					2	2	Yes		Yes	2.0 lb/cu yd
Texas	1	1							Yes		No	
Utah	1	1					2		Yes		Yes[j]	
Vermont					2		1	1		Yes	No	
Virginia	1	1						2		Yes	No	
Washington	1	2					2	1		Yes	No	
West Virginia	1	1[f]								No		
Wisconsin	1	1					2			No		
Wyoming							1	1	Yes		No	
Total	55%[d]	51%[d]	2%[d]	4%[d]	14%[d]	12%[d]	29%[d]	33%[d]	37%Yes	22%No	34%Yes	

a) Rating reflects frequency of use of a given material, with 1 being the highest.
b) No spall repair materials have been used by the state.
c) Shotcrete applied.
d) No. 1 rating.
e) Epoxy-modified PCC.
f) Latex-modified PCC.
g) Use of membrane required if deck is salted.
h) On Federal-aid projects only.
i) No experience.
j) Still under study.
k) On work done by Maintenance Division.
m) If 35 percent of deck is <2.0 lb/cu yd.
n) Corrosion potential measurements.

TABLE 3. PROPRIETARY QUICK-SET COMMERCIAL MATERIALS USED FOR BRIDGE DECK SPALL REPAIRS

Trade Name	Supplier	Type of Material	Remarks
Duracal	U.S. Gypsum Co.	Gypsum/portland cement binder	
AllCrete	Allied Construction Supply Corporation, Dallas, Texas	Portland cement based	
Darex 240	W.R. Grace Co.	Complex magnesium phosphate binder with aggregate	Two components
Speed-Crete	Speed-Crete of Louisiana, Metarie, La.	Quick-setting cement	
Tiger Crete			
Embeco	Master Builders Co. Cleveland, Ohio	Shrink-resistant mortar with metallic aggregate	
Zip-Crete	Texas Industry, Inc. Arlington, Texas	Portland cement based	
Bonsal	W.R. Bonsal Co.		
Express Repair			
Rapid Set			
Bostik 275	Upco Co. Cleveland, Ohio	Magnesium phosphate binder with aggregate	Two components
Minute Patch			
Fast Fix			
Fondu	Lone Star LaFarge Co. Norfolk, Virginia	Calcium aluminate cement	Combined with aggregate at site
Sika Set	Sika Chemical Co. Lyndhurst, N.J.	Portland cement based	No calcium chloride
Piecrete	Pocono Fabricators E. Stroudsburg, Pa.	Portland cement based	
Octucete	Penn Cete Products Co., Inc., Pa.		
Mavacrete	Exide Co.		
Pavement Repair	Standard Drywall		
Lumnile	Universal Atlas Cement Co., Pittsburg, Pa.	Calcium aluminate cement	Combined with aggregate at site
Set 45	Set Products Macedonia, Ohio	Magnesium phosphate binder	One component
Supor Rok			
Sta-Fill			
Cone Crete			
Frigid Patch	Randustrial Corp. Cleveland, Ohio		
VHE	U.S. Gypsum Co. Chicago, Ill.	Quick-setting cement	Available only recently

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