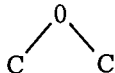


The name, origin, history, and development of epoxy resins over the last 20 years are described. While early developments made use of the properties as adhesives, electrical insulation, and protective coatings, these resins are now used extensively in the building industry. In order to use the epoxy, the components of the resin and hardener must be well mixed and then the resulting liquid gradually gets warm, solidifies, and cools to form a hard, infusible solid.

Epoxy Resins

By G. M. SCALES

□ "Epoxyes" are a group of synthetic resins ranging from low-viscosity solventless liquids to high-melting-point solids. The name for this group--"epoxy"--has its origin in the Greek description of the chemical symbol for the epoxy group which is



Thus "epoxy" is derived from the word "epi" meaning "on the outside of" and oxygen which, when the words are combined, describes the portion of the oxygen atom in the molecular structure.

Epoxy resins were known for a long time before practical ways of using them were discovered by P. Castan in Switzerland in 1938 and similar work was in progress by S. Greenlee in the United States.

These functional epoxy groups can be designed as part of other chemical groups in many ways, but the most usual way is to make the epoxy from intermediates derived from oil. These intermediates, known as Epichlorhydrin and Bisphenol, are "cooked" together in a long and complicated process, at the end of which an epoxy resin results (Fig. 1-1). The ratio of Epichlorhydrin to Bisphenol largely controls the type of resin produced. For example, the higher the ratio of Epi to Bis the lower the viscosity of the final resin and the lower its molecular weight. An epoxy resin made this way would be described as a "condensation product of Epichlorhydrin and Bisphenol A."¹

G. M. SCALES was born and educated in England. In 1942 he was graduated from the R. A. F. Officers Engineering College. At the end of World War II he joined CIBA and worked for them in various countries in adhesive development. He emigrated to the United States in 1953. He is now Manager of Applications Development, CIBA Products Company, Toms River, New Jersey.

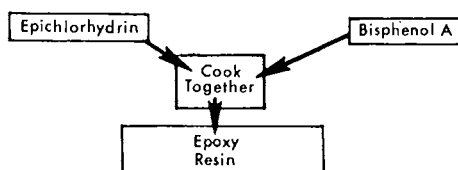


FIG. 1-1 THE MAKING OF AN EPOXY RESIN

The basic epoxy resin most often used in the construction industry is a light amber-colored liquid about the viscosity of heavy motor oil. This liquid will remain a liquid almost indefinitely. To use it as an adhesive, a hardener must be added. This hardener combines with the epoxy resin and changes it from a liquid to a solid. This change is due to a chemical reaction when the hardener combines with the epoxy resin. To accomplish this reaction effectively, the hardener must be adequately dispersed in the epoxy. This is why so much attention² is paid to thorough mixing. Just casual mixing is not enough because every particle of hardener has to connect and join with its epoxy counterpart. A perfect mixture will harden into a solid with each molecule firmly attached to the next. If the mixing is not perfect, there will be weak spots where the molecules are not firmly attached to each other; the result is somewhat like a chain-link fence with some of the links cut (Fig. 1-2). These spots are weaknesses where failure can begin. Correct mixing is therefore vital to the success of using an epoxy.

The process of setting, together with the terminology most often used, is illustrated in Fig. 1-3.

The principal properties and characteristics of epoxy resins are:

- (1) High strength adhesion to almost every material
- (2) Very low shrinkage during cure

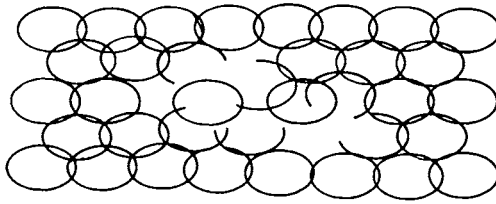


FIG. 1-2 WEAK SPOTS DEVELOP WITHIN THE MOLECULES WHEN THERE IS INADEQUATE MIXING

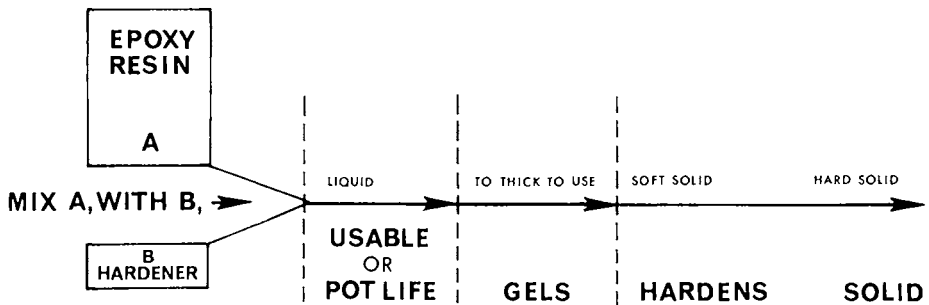


FIG. 1-3 THE PROCESS OF SETTING

- (3) Exceptional dimensional stability after cure
- (4) Natural "gap filling" qualities
- (5) Thermosetting (it will not melt)
- (6) Resistance to most chemicals
- (7) Good electrical insulation.

There are other properties such as fatigue resistance, creep resistance, and the ability to withstand thermocycling that also are of great interest to engineers.

A good example of what an epoxy can be made to do is shown by its use in the construction of the present supersonic bomber fleet. The composite construction of the aircraft is made possible by the extensive use of an (epoxy) adhesive. It is not difficult to imagine the extremes of temperature, high and low, as well as fatigue and other factors which this adhesive must withstand both on the ground and in the air. Epoxies are in everyday use in the construction of television sets, radios, and other

electronic equipment; epoxy primers are used for automobile and appliance finishes. The new one-piece automotive battery is put together with an epoxy. Thirty percent of the stained-glass windows made in the United States are of glass embedded in epoxy. Even solvent-resistant paint rollers are epoxy bonded. It is hard to find an item that does not have an epoxy somewhere in it.

Use of epoxies in building and construction began in the mid-1950's when epoxy was first used as a concrete bonding adhesive. Since then it has served many functions but most of the volume goes into concrete bonding, patching, floor toppings, crack sealing, and bridge-deck sealing.

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This article describes the work done by the Materials and Research Department of the California Division of Highways, since 1954, in adapting epoxy resins to the maintenance and repair of concrete highways and bridge decks. It discusses how the high coefficient of thermal expansion of cured epoxy mortars, which causes portland-cement concrete over which the epoxy mortars are applied to rupture in tension, may be neutralized by the formulation of epoxy mortars having high creep values at sub-zero temperatures. The first use of adhesives of the epoxy-resin type to bond new portland-cement concrete to old portland-cement concrete was made by the Materials and Research Department in 1954 and is described in this article.

Epoxies in Concrete Construction and Maintenance

By H. A. ROONEY

□ As early as 1954 the California Division of Highways, Materials and Research Department, became interested in the use of epoxy resins as an adhesive for the cementing of raised traffic-line markers to highway surfaces. At that time the Department initiated a research program for better delineation of traffic-lane lines at night in wet weather. It had long been observed by motorists that during periods of moderate to heavy rainfall at night, water tends to accumulate on the pavement to a depth sufficient to cover and obscure the beaded-painted center-line traffic stripe.

As an approach to solving this problem, the Department installed raised reflectorized white "buttons," made of epoxy resin, 4 in. in diameter and 3/4 in. high, the shape corresponding to the outer segment of a sphere. These markers were cemented to the highway surface in the gap in the painted stripe with an epoxy adhesive.

The excellent adhesion of these markers to portland-cement concrete prompted the Department to investigate the possible adoption of epoxy resins to the maintenance and repair of concrete highways and bridges. Accelerated tests initiated in September 1954 indicated that the life and adhesion of these markers would be about 20 years if they were installed in lane lines on portland-cement concrete pavements. It was realized

HERBERT A. ROONEY is a native of California. He obtained his AB degree in Chemistry from San Jose State College in 1935, and did post-graduate work in chemistry at Stanford University in 1936-1937. He has been employed by the State of California for twenty-seven years and is currently a Senior Chemical Testing Engineer for the California Division of Highways, Materials and Research Department, in Sacramento. He heads the Chemical Unit of the Materials and Research Department and is responsible for research and specification development on paints and adhesives.

early that the epoxy resins, because of their high cost, could not be considered as a primary construction material in competition with portland-cement or asphaltic concrete. Their important function concerns repair work on concrete structures where no known cheaper material will give the desired performance.

In highway and bridge repair work, epoxy resins are used in two different ways. In some applications aggregate and epoxy are mixed and the epoxy mortar is used as a patching material. In other applications the epoxy is used as a bonding agent for the welding of new or old concrete to old concrete.

Epoxy mortars are normally used where the volume of material is not large and where rapid curing can be obtained, even when the mortar is troweled to a feather edge. The repair of potholes and spalled joints on portland-cement concrete highways and bridge decks is an excellent example for the use of epoxy mortar especially where a lane cannot be closed to traffic for more than a few hours. The rate of curing of the epoxy mortar is directly dependent on the ambient temperature. In cold weather, small patches of mortar can be easily heated artificially to provide a rapid cure.

Epoxy mortars, when fully cured, have compressive and tensile strengths far in excess of that of portland-cement concrete. Their coefficients of thermal expansion are more than five times that of portland-cement concrete, the ultimate value being determined by the ratio of aggregate to binder. This excessive linear thermal expansion is detrimental unless it is compensated by sufficient creep (plastic flow) at low temperatures to offset the internal strains resulting when the epoxy mortar is used as an overlay on concrete. With insufficient creep at low temperatures, the epoxy mortar will rupture the underlying concrete in tension, failure not occurring at the bond line but in the underlying concrete. The Materials and Research Department observed these phenomena a few years ago when an epoxy bridge-deck patch placed in the high Sierra Nevada mountains, where the winter temperatures sometimes are -10 F, ruptured the underlying

concrete about one in. below the bond line. This condition was subsequently duplicated in the laboratory with various epoxy mortars placed as overlays on concrete blocks and, after curing, subjected to freeze-thaw cycles between 77 F and -10 F. The epoxy binder mixes which were designed to have sufficient creep at low temperature did not rupture the concrete. Modified coal-tar epoxies and aromatic high-boiling petroleum-oil modified epoxies exhibit adequate creep when sufficient plasticization is used. In the summer of 1964 California placed epoxy overlays on 34 bridge decks in the high Sierra Nevada mountains on Interstate Highway 80. The object was to restore the top surface of the badly eroded concrete bridge decks in an area where tire-chain and snow-plow action is very severe and where salt is used for de-icing. The epoxy material used on these bridges was a gray petroleum-oil modified system conforming to a performance specification. It was applied at a rate of 3 lb per sq yd by means of a Broyhill machine, and sand in excess was manually applied to the binder immediately following the application of the binder. The Materials and Research Department has since developed a compositional specification for a petroleum-oil modified epoxy which is currently being tested on sections of portland-cement concrete highway in the mountain and valley areas to determine its durability under various climatic and traffic conditions.

Aromatic-oil modified epoxies which are pigmented gray to match the color of concrete darken on exposure to sunlight. This is a characteristic of these materials which, although not detrimental to the performance of the overlay, might be somewhat objectionable from the aesthetic standpoint. The compositional specification binder material has a tensile strength of 1,000 psi minimum, a tensile elongation of 75 percent minimum, a Shore D hardness of 50 minimum, and when mixed with 4 parts by volume of ASTM C-190 Ottawa sand has a compressive strength of 2,000 psi. The creep characteristics at low temperatures are sufficient to prevent rupture of the underlying concrete. Creep on the epoxy is measured by standard laboratory test methods, both in the unfilled state and when combined with aggregate as an overlay on concrete. Current investigation is being directed toward the use of non-discoloring alkyl benzene hydrocarbons used in conjunction with coupling agents to provide compatibility with the epoxy resins.

In 1954, the late Dr. E. D. Botts, former Senior Chemical Testing Engineer for the California Division of Highways, Research Laboratory, discovered that certain epoxy adhesives would bond new portland-cement concrete to old portland-cement concrete. A formulation developed by the author containing an epoxy-polysulfide polymer cured with tris (dimethylaminomethyl) phenol has been used nation-wide since 1957 for this purpose. The old concrete is first thoroughly cleaned by sandblasting or

jackhammering, and the new concrete having a slump not greater than 2 in. is placed at a minimum thickness of one in. over the epoxy bond layer. The epoxy is applied at a rate of 25 to 40 sq ft per gal. The new concrete must be placed immediately over the applied epoxy before the latter has achieved an initial set. This technique not only is less costly than the use of epoxy mortar or epoxy concrete but also the surface presents a better appearance in that it blends in with the rest of the portland-cement concrete structure. The new portland-cement concrete should, of course, be thoroughly moist-cured. In cases where a traffic lane cannot be closed for more than a few hours, the use of an epoxy mortar or epoxy concrete would be required for surface patches.

Severely spalled expansion joints on the San Francisco-Oakland Bay Bridge were repaired in 1957 with epoxy concrete and have to this date been successful. The repair work was started about 10 o'clock each morning and the lanes had to be opened to traffic by 3 o'clock that afternoon. Prevailing low temperatures (55 F to 60 F) on the bridge necessitated the application of external heat to hasten the curing of the epoxy concrete. This heating was accomplished by placing channel irons over the repaired joints and heating the channel irons with propane torches. The hollow air space in the channel irons heated the epoxy mortar by convection with no danger of burning the mortar.

It must be emphasized that epoxy resins must be judiciously used in the repair of concrete structures. They are not intended to be a "cure-all" and should not be used where cheaper satisfactory conventional materials can be employed. When the correct epoxy-resin system is used and properly applied, results are usually very satisfactory.

Widespread acceptance of epoxy surface treatments for pavements has been limited in part by problems associated with pinholing, poor surface appearance, and sheet detachment. Recent laboratory and field investigations promise to improve this situation markedly by use of 20 to 40-mesh rounded aggregates to stop pinholing, development of mechanical sand-spreading equipment to improve appearance, and improved techniques for deck preparation to obtain better adhesion. In addition, new application techniques permit one-step placement of pre-mixed epoxy mortars in 3/8-in. lifts, which offer numerous advantages in increased wear, improved wetting of both deck and aggregate, and greater structural integrity of the overlay treatment. These new techniques appear to be adaptable to even very large contracts. Despite existing problems, the protection afforded by epoxy treatments, together with the combination of thin courses and long life, continue to indicate a permanent place for these treatments in the highway industry.

Epoxy Surface Treatments for Portland Cement Concrete Pavements

By W. R. McCONNELL

□ In the past 10 years the use of epoxy-resin binders in surface treatments for portland-cement concrete pavements has grown from a gleam in the epoxy producers' eye to a multi-million dollar highway maintenance program. This paper describes successes and failures in this program and explores the future for these unique materials in light of some recent research on application technology.

WHY EPOXY BINDERS

Highway agencies first became interested in epoxy resins back in 1954. At that stage the idea was to use their well-known adhesive properties and high strength characteristics to bond small, sharp aggregates to slick roadway surfaces for the purpose of improving skid resistance.^{1,2} During field evaluations, other useful properties of the epoxy binders were quickly recognized,

ACI member W. R. MCCONNELL received his BS degree in Chemical Engineering from the University of Tennessee in 1951. He joined Shell Chemical as a chemist in the Technical Service Laboratory, Union, New Jersey. His initial duties encompassed all end uses for the relatively new epoxy resins, but were soon concentrated in the construction and maintenance fields. In 1960 he took charge of the firm's national epoxy-resin highway program becoming involved with both the marketing and technical aspects. He has since returned to Shell Chemical as District Manager, Western District, Industrial Chemical Division, Shell Chemical Company, Downey, California. In addition to his assignment in the Industrial Advisory Group to the American Concrete Institute's Committee 503, Mr. McConnell also served on the Highway Research Board Committee "Maintenance of Structures," on Task Force 1, American Road Builders Association and American Association of State Highway Officials preparing specifications for epoxy-resin binders; on International Bridge, Tunnel, and Turnpike Association research and engineering committees.

namely: (1) excellent film-forming properties; (2) low moisture and moisture-vapor transmission; and (3) good chemical resistance. Investigating the practicality of utilizing these properties to solve the increasingly serious problem of portland-cement concrete deterioration, particularly in bridge decks,³ then took preference over de-slicking.⁴ By 1958 most state highway agencies in this country were evaluating epoxy seal coats as protective sealing surfaces on bridge decks.

In spite of the highway industry's keen interest in solving the problem of concrete deterioration, these new products still had difficulties to overcome. Material costs of the epoxy binders were sufficiently higher than conventional portland-cement or bitumen binders to require special attention to the economics of their use. Not only was it important that the surface treatment incorporating epoxy resins perform better than those with conventional products but also they had to perform far better to justify their expense.

This economic hurdle, however, was crossed during the field testing period, not only because epoxy seal coats out-performed useful conventional products but also because in many cases conventional surface treatments are not considered adequate. For instance, on bridge decks and in toll booths which have an abnormally high traffic count conventional seal coats, slurries, and thin sand asphalt treatments wear rapidly and must be replaced frequently. Here the cost of replacement and the inconvenience to the public of lane closings limit their usefulness. Thick asphalt pavements require raising of expansion joints, drains, and curbs and increase the dead load by a significant amount.⁵ In addition to these structural, elevation, and longevity problems, with thick asphalt overlays highway engineers at this time were beginning to

realize that de-icing chemicals and water trapped at the interface with the concrete pavement were accelerating pavement deterioration. Therefore, in the opinion of many highway engineers, the new epoxy surface treatments were not competing with conventional materials but were offering something not currently available in the way of protection from freeze-thaw and salt damage and of long lasting skid-resistant wearing surfaces.

THE MARKET

Although the situation varied among highway agencies, full-fledged commercial usage of epoxy surface treatments did not begin until 1962. Since then many large construction contracts have been awarded, and as an indication of the current importance of this maintenance tool I will describe the experiences of two highway agencies, the details of which are available in the literature. Probably the best example of the maturity of epoxy seal coats is the fact that the California Toll Bridge Authority, 1963 and 1964, invested almost \$1,000,000 in an epoxy coal-tar surface treatment on both decks of the San Francisco-Oakland Bay Bridge.^{6,7} The more than 50 lane-miles are reported by the Authority to be performing "very satisfactorily."⁸ The New Jersey Turnpike, with the concurrence of their consultants, are in the process of sealing all existing decks with an epoxy coal-tar binder, and specify this type of seal in all new bridge-deck construction.⁹⁻¹² This project began in 1963. Total investment to date is over \$1,000,000, and the Turnpike Authority reports satisfactory results. These two examples were picked because of their size and cost. Highway engineers do not spend this kind of money before they have conducted exhaustive tests to establish the usefulness of products proposed by suppliers. Therefore, it should be safe to say that surface treatments and sealers utilizing epoxy binders are no longer laboratory curiosities but are thoroughly tested materials with well-understood advantages.

In the past 5 years an estimated \$10,000,000 has been spent by highway authorities on the placement of epoxy surface treatments. Not all of this work has been successful. The predominance of successful work can be held as proof of the over-all usefulness of epoxy surface treatments, but the highway engineer does not always see the situation in that light. He looks at it this way: "I have just spent X dollars for an epoxy surface treatment, which is considerably more than I normally spend for similar work, to provide my pavement with a new, skid-resistant surface with good riding qualities and protect my bridge from the effects of freezing water and de-icing chemical for X years. X percent of this work is not performing properly for reasons which I do not completely understand, and I have no idea how much

more distress I will see in this job as time goes by. Further, I have no assurance that future work of this type will even be as satisfactory as this. Therefore, I cannot justify taking money for epoxy surface treatment from our limited budget when I cannot accurately predict my chances of success."

This legitimate point of view has retarded universal acceptance of epoxy binder by the highway industry for bridge-deck maintenance, and it will continue to do so until the engineering aspects of the performance and application of these materials are thoroughly understood by all concerned. In the last 2 years, much progress has been made along these lines by suppliers and users alike.

EPOXY BINDERS

Epoxy binders are supplied as two-component, low-viscosity liquids. One component contains the epoxy resin while the second contains a chemical which cures the resin. These two components must be accurately proportioned and thoroughly blended, in order to obtain optimum properties of the cured binder. After they are blended they are usually combined at one stage or another with graded aggregates. In seal coats the binders are distributed on the pavement and are followed by distribution of appropriate cover stone. Overlay pavements and slurries are placed after premixing the two components of the epoxy binder with the graded sand.

It should be emphasized that the epoxy resin and its curing agent, which form the basic ingredient in epoxy binders, prove to be useless without suitable additives. The high strength of these materials, coupled with their high thermal coefficient of expansion, create stresses at the interface (between the surface treatment and the portland-cement concrete) during fluctuating temperatures. These stresses are often in excess of the ultimate strength of the concrete. It is necessary to modify the resins to provide enough flexibility or stress-relaxation properties to absorb the stresses in the binder rather than transfer them to the concrete. The problem is further complicated by the fact that other performance characteristics such as wear resistance require a high tensile strength. The proper balance between flexibility, stress-relaxation properties, and tensile strength must be achieved.

PROBLEMS AND SOLUTIONS

There is nothing unusual to the casual observer about the process of applying epoxy surface treatments. There are, however, important differences some of which were not completely

understood until a few years ago. These differences when overlooked can cause distress, sooner or later, in the finished work. Distress in epoxy surface treatments are classified in order of importance as follows:

- (1) Pinholes or pinhole clusters in seal coats, which are manifest in poor wear resistance and inadequate protection for the concrete pavement
- (2) Poor appearance and riding qualities
- (3) Poor adhesion or loss of adhesion and resultant lifting (sheeting or peeling) of the surface treatment.

PINHOLES AND PINHOLE CLUSTERS

The ability of the epoxy binder to wet a pavement surface, which contributes to the excellent adhesion of these materials, complicates the selection of cover stone for a surface treatment. Sharp, relatively large stone, which is often selected because it is believed to provide better skid resistance, nests in the binder on the surface of the road in such a way as to form capillaries which pull the binder from its original position on the roadway and thus leave voids or "pinholes" and often pinhole clusters $3/4$ in. in diameter in the seal. This phenomenon has been recognized since 1963, but laboratory studies just being completed are supplying quantitative data. Relatively small (20 to 40-mesh) rounded aggregates do not form capillaries when they are broadcast, and thus they produce a dense (void-free with high aggregate content) seal. The cover stone receives better lateral support because of the improved density, which in turn gives improved wear resistance and eliminates pinholes in the surface treatment. The surface treatment then lasts longer and provides better protection for the underlying pavement.

POOR APPEARANCE AND RIDING QUALITIES

Other peculiarities of the epoxy binder require special attention to the distribution of cover stone. The short pot life and relatively fast set of the epoxy binders require that the cover stone be broadcast within 5 to 10 min. The low viscosity of the binder requires that care be exercised in broadcasting the sand to preclude shoving of the binder and the resulting rough, discontinuous surface. Also, binder applied to a grade or on a super-elevated pavement may flow because of its low viscosity unless sand is distributed promptly. These considerations are particularly important because the thermoset nature of the epoxy binder does not allow for smoothing out or healing of surface imperfections by traffic during hot weather.

Although many epoxy seal coats with excellent appearance and riding qualities contain cover stone which was broadcast by hand, properly designed sand spreaders would vastly improve the over-all situation. Conventional spreaders are not acceptable because they travel over the epoxy surface treatment after sand application. Before it is cured, the seal coat will not support traffic without tracking. A contractor in the New York City area* has solved this problem by designing his own equipment.

POOR ADHESION; LOSS OF ADHESION

The pavement over which the seal coat is placed must be perfectly clean and reasonably sound. The importance of surface preparation is better understood when it is recognized that the seal coat is applied in very thin layers (approximately 1/8 in.) and depends on the pavement for support just as a paint film depends on its substrate. This support is not available to the epoxy seal coat unless the epoxy binder is well bonded to the pavement. The bond, in turn will not develop unless the binder thoroughly wets the portland-cement concrete roadway surface. Therefore any oil, water, grease, dirt, traffic paint, or any other foreign material on the pavement to be sealed which prevents the epoxy binder from wetting the deck will prevent bonding of the seal coat. Again, because of the thermoset nature of the binder, it does not soften and rebond to the pavement in warm weather.

Preparing a portland-cement concrete bridge deck by sand-blasting is now believed to give more dependable results than acid etching, and agencies specifying this type of cleaning appear to have practically eliminated adhesion problems.

At the risk of overemphasizing the difficulties encountered in using epoxy surface treatments, this subject has been covered in some detail. Careful attention to these matters will improve significantly the over-all performance of epoxy surface treatment.

NEW DEVELOPMENTS

There has been encouraging evidence that improved wear resistance and better sealing properties can be obtained with epoxy surface treatments if the binder is thoroughly mixed with graded aggregate prior to application on the roadway, as opposed to the two-step seal-coat process described earlier. Field tests have demonstrated that at least twice the wear expected from a regular seal coat is available with the same amount of binder.

*Railroad Waterproofing, Inc., Port Washington, N.Y.

By adding to the total thickness to provide $1/4$ to $3/8$ in., at least five times the life can be reasonably expected.

Improved wear of premixes is attributed (1) to the prolonged intimate contact of the binder and aggregate during mixing, which contact improves adhesion between the two; and (2) to the graded aggregate which provides better lateral support for the surface particles exposed to traffic. Also the extra thickness of the overlay provides integrity, not available in seal coats, to keep the overlay in place even though there may be small areas of sub-standard base or adhesion to the base. In addition, the premix allows for designing a dense mortar which will provide improved protection of the substratum from water and de-icing chemicals.

The idea of premixing is not new; highway engineers have proposed this approach ever since epoxy binders were introduced. A major question however stood in the way of its adoption: How can large volumes of a mortar utilizing a binder with a short pot life and less than ideal troweling characteristics be handled on a production basis? During the past year an effort has been made to solve this problem. A vibrating screed has been commercially developed by Shell Oil Company which will lay a $3/8$ -in. layer of epoxy-mortar pavement 12 ft wide at the rate of 5 to 10 ft per min. This seems to be the best way to overlay an entire concrete bridge pavement with an epoxy-mortar mix.

Since mortars utilizing well-engineered epoxy binders have performed well under service conditions for about 10 years, there is little question about the ability of these products to perform well. The processing techniques which have been developed have already proved successful for small contracts. Many engineers believe that significantly larger contracts can be handled with the same equipment. At any rate, the development of large-scale production equipment is simply a mechanical problem and is already underway.

LIMITATIONS AND ADVANTAGES

Let us conclude with a frank discussion of the limitations of epoxy surface treatments and a final review of the advantages.

Limitations

Weather limitations restrict the times of construction for epoxy binders, but these restrictions are not greatly different from those associated with regular construction materials. Because of the versatility of epoxy binders it is likely that this situation will be improved with time, but commercial epoxy binders with sufficient successful field experience to be considered

for regular maintenance work are limited to temperatures of 60 F and higher. Some successful work has been accomplished at 50 F; but extra care must be taken to assure good performance.

I hesitate to mention costs under "limitations," since costs are not strictly a limitation. Highway engineers are paid to construct the vehicular riding surfaces at the lowest cost to the public. The widespread acceptance of epoxy surface treatments today is evidence enough that the costs are not an over-all limitation. However, when it is recognized that epoxy seal coats cost about \$3, membrane treatments about \$2, and overlay pavements in the range of \$4 to \$6 per sq yd in place, the reluctance of highway engineers to accept this maintenance tool on an over-all basis with a comprehensive understanding of the performance properties can be appreciated. This understanding is usually developed through a combination of literature searches, discussions with material suppliers and other highway engineers familiar with the materials, and finally through field trials. But the catch is, if the field trials do not live up to expectations, the engineer often becomes unsure of his ground and declines to invest additional time and money in similar projects. Since we cannot criticize the engineer in this regard, the only answer to the dilemma is come up with sufficient engineering information on epoxy binders and surface treatments so that all involved will understand the causes of small distressed areas in epoxy surface treatments and not fear them as the first signs of total failure. The limitation is fast being overcome by the cooperative efforts of highway agencies, industry, and contractors to improve the over-all understanding of the products and processes.

Advantages

Epoxy surface treatments have demonstrated their effectiveness as an economical method for protecting portland-cement concrete bridge decks from the ravages of freeze-thaw damage, de-icing chemicals, and heavy traffic wear. The excellent adhesion of the binder (which is usually greater than the tensile strength of the portland-cement concrete) permits surface treatment to be applied in very thin layers (1/8 in.) without being dislodged by traffic. The same quality firmly bonds the cover stone into the seal coat to provide maximum wear resistance. Final surface treatment, consisting of sand-epoxy binder, is tough enough to withstand heavy traffic, is an excellent water and water-vapor barrier, and is unaffected by gasoline, oil, and other chemicals normally found on a roadway. Because of the thermoset nature of the binder, epoxy seal coats do not flow, bleed, or undergo substantial changes in physical properties over the temperature range normally found in the United States. Surface treatments will cure in approximately two hours during normal summer temperatures.

From the highway engineer's point of view, these properties suggest several advantages. Protective wearing courses can be applied quickly with a minimum of traffic delay. The life is many times that of equal thicknesses of conventional treatments, and the protection afforded is superior to that of conventional products. No water or de-icing materials can be trapped under the surface treatment.

Because of these advantages, and in spite of the limitations, none of which are considered serious, epoxy binders continue to promise unique advantages over conventional materials in bridge-deck maintenance programs.

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The history of epoxy-resin adhesives for bonding concrete and other materials to concrete is reviewed. During the short history of commercial use, epoxy-resin adhesives have evolved into two basic types: those capable of bonding plastic or hardened concrete to concrete, and faster-curing systems developed for bonding hardened concrete or other rigid structural materials to concrete. Experience has shown that proper surface preparation determines the success of concrete bonding. Mechanical abrading has proven the most reliable method of surface preparation; acid washing may lead to variable results. Although little difficulty has been experienced in the field, epoxy-resin adhesives may cause sensitization of individuals coming in contact with them. Precautions and toxicological details are covered. At present, there are no standard test methods for evaluating epoxy-resin adhesives for use with concrete although the diagonal-tension test has proven reproducible. The writing of standard specifications for these adhesives awaits the acceptance of standard test procedures.

Epoxy Resin Adhesives for Bonding Concrete to Concrete

By R. J. SCHUTZ

□ Ever since concrete has been used as a construction material there has been need for reliable methods of bonding plastic concrete, hardened concrete, or other materials to hardened concrete. Many methods and techniques have been tried over the years but until recently none had proven satisfactory or reliable. Historically, almost any adhesive system which showed merit in other applications was tried in the concrete field. Not until commercial production of epoxy resins began did a successful solution to this problem appear. Probably the first work in this area was carried out by the California Highway Department in 1953, and shortly thereafter work was conducted on the east coast by the Maryland Highway Department. Commercial production of epoxy-resin systems formulated specifically for concrete appeared on the American market in 1956. These adhesives fall basically in two classes: those developed for bonding plastic concrete to hardened concrete, and those developed for bonding hardened concrete to hardened concrete or to other solid materials such as steel, glass, and tile.

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SURFACE PREPARATION

As in any adhesive bonding, preparation of the surface is very important and will quite often determine the success of the particular installation. The surface to be bonded must be clean and sound. Tests have shown that a formed concrete surface may have a strength in direct tension as low as 75 psi. The tensile strength of a steel-troweled floor may vary between 50 and 120 psi. Removing the surface of such concrete will increase these values to the true tensile strength of the concrete.

Experience has shown definitely that the best manner of preparing a concrete surface for bonding is by mechanical abrading. This abrading can be accomplished by sandblasting, grinding, or chipping the surface layer of dirt and laitance from the concrete.

Acid washing, although economical, has not proven reliable. The presence of oil, grease, or wax will generally prevent good bond of epoxy-resin adhesives to concrete. Since most curing compounds are based on waxes or petroleum resins these must be removed prior to bonding.

BONDING PLASTIC CONCRETE TO HARDENED CONCRETE

The first successful epoxy adhesives for this purpose were based on epoxy-resin polysulfide polymer mixtures, and to this day products based on these systems have proven the most reliable. Early adhesive systems were very viscous; quite often solvents were added on the job site or included in the original formulation. The use of solvents required that the adhesive be applied some time prior to the placing of concrete in order to allow the solvent to evaporate. If concrete was placed on the adhesive before evaporation of the solvent, the solvent sometimes became entrapped and acted as a plasticizer, and the strength of the adhesive was impaired. Under early field conditions the time for evaporation of solvents varied, and even experienced workmen could not determine the proper time for placing of concrete.

As the state of the art improved, the viscosity of epoxy-resin bonding compounds was lowered without the use of solvents, thus increasing the safety factor in their use. Proper viscosity is important in the formulation of these adhesives. Viscosities as low as 1500 cps have been successfully used. If the compound is too viscous, mixing of the components becomes difficult and incomplete mixing is common, application is difficult, and coverage is poor. If the viscosity of the system is too low the adhesive may be absorbed by the substrate, especially in the case of lightweight concrete. The result will be a starved glue line and poor bonding qualities.

Adhesives for this purpose must of necessity be slow-curing systems. If the adhesive cures before the new concrete has hardened it will act as a bond-breaker rather than an adhesive. Such systems generally will have a working life (pot life) of approximately 20 to 30 min and a contact time after application of 45 min to 3 hr depending on the particular system employed. Upon spreading the adhesive the heat generated by the chemical reaction will be absorbed by the substrate and dissipated to the atmosphere. Once spread thin, these systems allow ample time for placing concrete.

The curing rate of all epoxy-resin systems will be affected by temperature. Below 50 F, slow-curing systems will have an extremely long curing time; however, if ACI Committee 306 recommendations for winter concrete are employed these systems can be used throughout the year. During hot weather, in order to have a usable working time the adhesives may be precooled before using the components. This procedure may be recommended for all installations where the ambient temperature is 95 F or higher.

APPLICATION

The ideal epoxy-resin bonding compound would be formulated to have a volumetric ratio between the curing agent and the epoxy resin of 1:1. In this manner small quantities can be batched in the field. Mixing can best be accomplished by use of mixing paddles attached to a low-speed electric hand drill (Fig. 4-1). After being mixed, the compound should be applied as soon as possible since the heat of reaction cannot be dissipated in a container, and the subsequent heat which is built up will accelerate reaction and shorten pot life.

Epoxy adhesives may be applied by brush, spray, or roller. Spray applications have not proven as satisfactory as application by brush or roller (Fig. 4-2). Spraying the adhesive will not necessarily wet down any dust present on the surface. Application by brush or roller will combine any dust present into the adhesive



FIG. 4-1 APPARATUS FOR MIXING BONDING COMPOUND

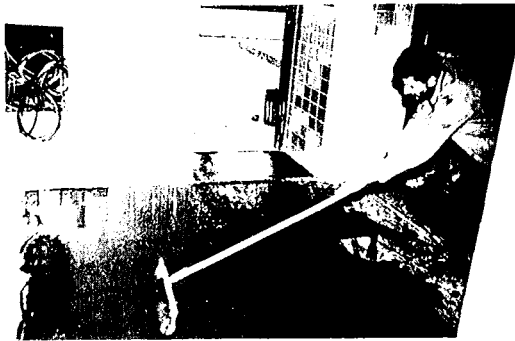


FIG. 4-2 APPLICATION OF ADHESIVE WITH ROLLER

system where it acts as an inert filler. In general, spray application should only be used in areas inaccessible by brush or roller. Where large areas are to be covered with a mortar topping terrazzo or overlay, aggregate may be sprinkled on the freshly applied bonding compound to allow workmen to walk on the area without slipping or sticking (Fig. 4-3 and 4-4).

ADHESIVE SYSTEMS FOR BONDING HARDENED CONCRETE TO HARDENED CONCRETE

Although hardened concrete can be bonded to hardened concrete by using adhesives developed for bonding plastic concrete, usually the curing rates for such systems are too slow to be practical. With such products, shoring or holding devices will need to be kept in position for several days. For bonding hardened concrete to hardened concrete, fast-curing systems may



FIG. 4-3 SPRINKLING AGGREGATE ON TERRAZZO TOPPING



FIG. 4-4 SPREADING MORTAR TOPPING

be employed (Fig. 4-5). These systems do not need to be insensitive to water although such a characteristic is desirable. For bonding mating surfaces together, low-viscosity adhesives can be used; they will represent economy in that mixing and application will be easy and fast. Where non-mating surfaces are involved, gap-filling adhesives should be employed. These systems will be similar in character to low-viscosity systems except that before curing they will be thixotropic and will fill the gap which may exist between solid members (Fig. 4-6). By use of such systems, a variety of materials such as steel, aluminum, glass, and ceramics can be bonded to concrete.

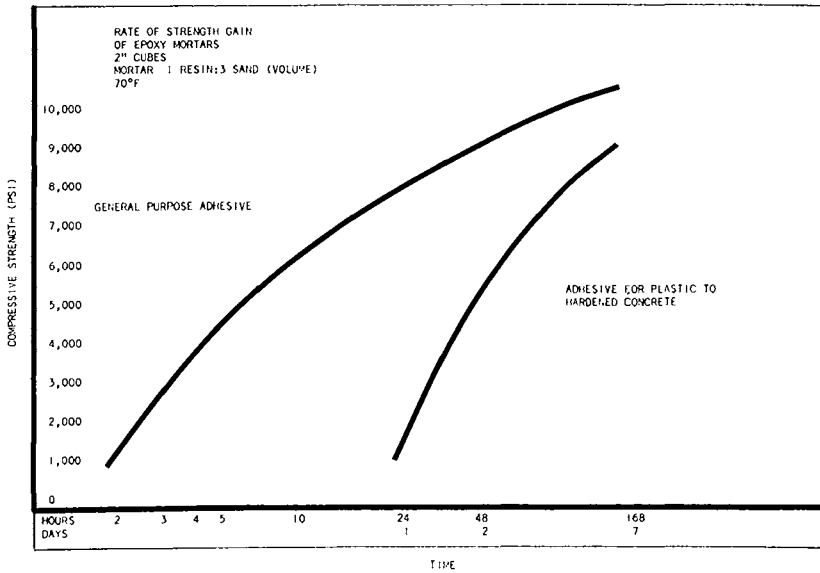


FIG. 4-5 RATE OF STRENGTH GAIN OF EPOXY MORTARS



FIG. 4-6 THIXOTROPIC GAP FILLING ADHESIVE APPLICATION

TEST METHODS

Many test methods have been proposed for testing the bond strength of epoxy-resin adhesives. The difficulty in the concrete industry is that the tensile strength of a good epoxy adhesive will be in the order of 10 to 20 times that of concrete. Most test procedures will not indicate the strength of the adhesive but will merely show the strength of the bonded concrete. The tests

presently used by the industry are the diagonal-tension test described in Appendix A, developed by Professor James Kriegh of the University of Arizona; the flexural or beam test, Appendix B; and the compressive double-shear test, Appendix C. The beam test has proven popular due to its simplicity and due to the fact that the equipment for this test will be available in any well-equipped concrete laboratory. The diagonal-tension test requires special molds but has proven reliable and probably reflects field conditions better than the other available test methods. The compressive-shear test indicates only the strength of the mortar to be bonded and can be used only when testing adhesives developed for bonding hardened concrete to hardened concrete.

DIFFICULTIES EXPERIENCED IN THE FIELD

When epoxy-resin adhesives were first introduced, incomplete mixing of the components presented a problem. However, as contractors and mechanics became used to two-component systems the problem of mixing disappeared. Most failures reported have been caused by the addition of solvents to the bonding compound in the field; experience has shown that the use of solvents should be forbidden.

Due to the high tensile strength of the adhesive, thin overlays can be applied and can be feather-edged where required. These adhesives are vapor barriers before and after curing; therefore, thin overlays will lose water only from the top surface which will tend to shrink on drying and thus cause the overlay to curl. Since drying may take place at a rather fast rate before the bonding compound has obtained strength, the bonding compound may cure without contact with the topping and thus result in a failure. The only method to prevent curling of the topping is to cure the topping thoroughly by the use of ponding, wet blankets, or application of a good concrete-curing compound.

Starved glue lines have resulted when bonding to lightweight or other porous concrete. The application of two coats of adhesive will prevent absorption of the second coat. A more economical method is to wet down the concrete to be bonded with water before application of the adhesive.

TOXICOLOGICAL PROPERTIES

Although epoxy resins themselves are not considered toxic, they are allergens and may cause dermatitis. The curing agents may be alkaline or toxic, therefore adequate protection should be employed. The best protection is the use of protective clothing such as rubber gloves or disposable polyethylene gloves. In



general, rubber gloves have not proven as efficient as polyethylene gloves; rubber gloves are expensive and cannot be discarded when dirty. When gloves are contaminated on the inside, the mechanics will rub the resin into their skin; disposable polyethylene gloves can be discarded when contaminated. When mixing with power-driven equipment, goggles should be worn. For applications involving spraying of epoxy-resin systems, barrier creams are available for application to the face to protect from overspray. When spraying these systems goggles should always be worn. Workmen should not be allowed to clean spilled curing agent or resin from the skin with solvents, as solvents will tend to dilute the resin and permit further penetration into the skin. The aromatic solvents used for cleaning equipment will tend to defat the skin and may by themselves cause dermatitis. In the event of contact with the skin, waterless skin cleaners or thorough washing with soap and water should be employed.

CLEAN-UP

Before curing, epoxy-resin systems are soluble in most aromatic solvents and ketones. Tools and equipment should be cleaned before curing. If the epoxy-resin systems are allowed to harden on tools, removal is generally too expensive to be practical.

CONCLUSION

The use of epoxy-resin bonding compounds for bonding plastic concrete, hardened concrete, or other materials to hardened concrete has proven successful in the field. The compounds are economical and relatively easy to use. Their use does not eliminate the need for good concrete practices since successful systems are based on modified epoxy-resin systems and an almost infinite variety of modified systems are available. There is a need for fast, easy-to-perform standard test methods for acceptance of materials.

APPENDIX A

THE ARIZONA COMPOSITE CYLINDER TEST (DIAGONAL TENSION)

To determine whether an epoxy resin can bond fresh concrete to old concrete, a composite cylinder test was devised. The cylinder is made by placing an elliptical insert into the standard 6 x 12-in. test cylinder and then casting a half-cylinder with a

30-deg slope from the vertical. After the half-cylinder is cured for 28 days, the surface of the beveled face is treated in the selected manner and then coated with a 10-mil thickness of epoxy resin. The half-cylinder is then placed back into the mold, and the rest of the cylinder is cast. This arrangement results in an epoxy bond line at 30 deg from the vertical.

After the completed cylinder has cured for a designated period, the ultimate compressive strength is determined. This compressive strength is compared to the ultimate strength of the weaker of the two concretes from which the cylinder is made.

APPENDIX B

BEAM TEST

The specimens shall be tested for flexural strength using the simple beam with third-point loading. The specimens shall be prepared and tested in accordance with the procedure outlined in ASTM C 78-49 except that the concrete shall be designed for 800 to 900 psi flexural strength and shall be prepared in 3 by 4 by 16-in. molds using an aggregate of maximum size not larger than one in. The beam shall be sawed transversely at midpoint, and the sawed edges shall be acid-etched and bonded with a 10-mil thickness of the epoxy adhesive under test. Hardened-concrete to hardened-concrete specimens shall be cured a minimum of 96 hr and then soaked in water 24 hr prior to breaking. Plastic-concrete to hardened-concrete specimens shall be burlap-cured for 24 hr and then placed in a moist room for the duration of the curing period. For each series of tests, an unsawed companion beam shall be broken as a reference.

APPENDIX C

MMM-B-00350 ARMY (CE)

4.5.4 Compressive (double) shear strength.

4.5.4.1 Preparation of mortar prism specimens. - The mortar specimens used shall be sawed from 2- by 2- by approximately 12-in. prisms, prepared in accordance with the procedure outlined in method 2701 of Federal Test Method Standard No. 158. The length of the prisms may be increased, if desired, to facilitate quantity preparation of specimens. The portland cement used shall conform to the requirements of Federal Specification SS-C-192, type I. The curing period prior to sawing shall be 28 days and in accordance with method 2301, paragraph 5.2 of Federal Test Method Standard.

No. 158. At the end of the 28-day water curing period, the prisms shall be cut to 2.0-in. cubes with a diamond saw blade and a uniform distance shall be maintained between cut faces. On completion of the sawing operation, the cube faces shall be lightly scrubbed with a moderately stiff, fine-bristle brush while the cube

is held in a stream of water. After removal of surface fine particles caused by the sawing operation, the cubes shall be stored in a moist closet maintained at 90 percent relative humidity and 23 C plus or minus 1.7 C (73.4 F plus or minus 3 F) until used.

4.5.4.2 Preparation of shear-strength specimens. - The preparation of the compressive shear-strength specimens shall be accomplished by arranging the 2.0-in. cubes, temporary shims, and applying a 50-mil plus or minus 5-mil thickness of the epoxy binder in the necessary sequence to pyramid the bonded and unbonded cubes as shown in Fig. 4-7. Only the sawed faces of the 2-in. cubes shall be used as the contact areas of the epoxy binder and cubes. The number of specimens prepared for each test condition (see 3.4.3) shall be not less than three. The mixing of the epoxy component and the polysulfide curing-agent component shall be accomplished in accordance with the procedure recommended by the supplier. Hand-mixing shall not be permitted and the mechanical stirring device used shall operate at low speed.

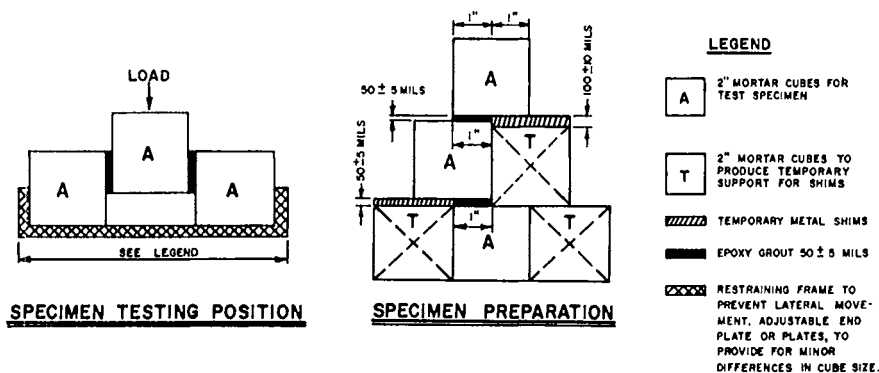


FIG 4-7 COMPRESSIVE SHEAR-STRENGTH SPECIMENS

4.5.4.3 Curing of shear-strength specimens. - The specimens prepared in accordance with the preceding procedure shall be cured in accordance with the conditions specified in Table III.

4.5.4.4 Determination of shear strength. - Prior to application of load, the test specimens shall be placed in a restraining frame which extends up 1 in. on the vertical exterior faces of the two base 2-in. cubes (see Fig. 4-7). Provision shall be made in the restraining frame to compensate for minor dimensional differences in the 2-in. cubes and to prohibit lateral movement of the 6-in. base dimension of test specimens. The rate of total load application shall be 700 lb plus or minus 25 lb per minute. The compressive shear strength in pounds per square inch shall be computed as follows:

$$\text{Compressive shear strength, psi} = \frac{\text{total load to failure of bond, lb}}{\text{total adhesive bonded area, sq in.}}$$

After reviewing briefly why cracks should be repaired, the authors discuss the feasibility of repair, how effective structural repair is accomplished, and limitations of repairs. Examples are given of typical applications of a method which consists in injecting an epoxy-resin adhesive into cracks to "weld" the concrete back together into monolithic form.

Effective and Practical Structural Repair of Cracked Concrete

By R. W. GAUL and E. D. SMITH

□ For the first time in the history of concrete construction a method of repairing cracks in concrete has been effected. During the past decade it has been used in numerous critical applications, with significant cost savings over alternative methods of repairing damaged concrete.

The method consists in injecting an epoxy-resin adhesive into cracks or voids in concrete, effectively "welding" the concrete back together into monolithic form.

This paper reports on the reasons why cracks should be repaired, the feasibility of repair as a function of crack causes, how effective structural repair is accomplished, and the limitations to repair; and it gives detailed examples of typical applications.

WHY CRACKS SHOULD BE REPAIRED

Since most cracked concrete has long been ignored because no effective method of repair was available, it is reasonable to ask if cracks are important enough to be of concern. The compelling answer that cracks should be repaired is dictated by these basic reasons:

- (1) For a structural member a loss of strength results from the cracked concrete being unable to transmit loads as it was initially designed to do.
- (2) Cracks in concrete are an occasion for serious spalling to occur in climates where water and freeze-thaw cycles combine to cause additional damage to concrete.

R. W. GAUL is Vice-President, Adhesive Engineering Company. After receiving his BSME degree from the University of Santa Clara he worked first as a product planning engineer. He became Technical Sales Manager and then Operations Manager at Adhesive Engineering. He has supervised the development and application of his company's process of structural repair of cracked concrete.

E. D. SMITH is project manager of the Construction Materials Development Department, U. S. S. Chemicals Division, of U. S. Steel Company. He holds a BS degree in chemistry from the University of Dubuque. He has long been active in the development and technical service of structural adhesives and protective coatings for concrete.

- (3) Corrosion of reinforcing and prestressing steel in concrete structures occurs in the area of the cracks.
- (4) Leakage of water and fluids which might be used such as in industrial processing causes contamination and damage to those objects such as equipment which are intended to be protected by the concrete structure.
- (5) In architectural concrete cracks are unsightly.

WHEN IT IS FEASIBLE TO REPAIR

While it is desirable to repair most cracked concrete, consideration should be given as to whether even the most effective method of repair now available is feasible in all cases. Certainly, the repair of cracked concrete by injection of epoxy-resin adhesive is not a panacea. Cracks are a result of over-stressing of the concrete. If the forces which caused the over-stressing have not been relieved when cracking occurred or are not subsequently eliminated, a concrete member which has been "welded" back together will only crack again as it did when it was initially over-stressed. Therefore, before proceeding with repair as complete a determination as possible must be made of the cause of the crack. If the cause has been or can be eliminated, the repair is then feasible.

The most frequent cause of cracks in concrete is shrinkage during curing, especially because the concrete has not developed its full strength. It cannot withstand the stress caused by the necessary change in dimension, or strain, which results from the curing of concrete. After the concrete has cured, cracking due to shrinkage will have been stabilized and repair is definitely in order.

A second major cause of the cracking of concrete is mechanical overload, either static or dynamic. These can be normal

overloads, such as an overweight truck on a bridge deck designed for light traffic, or abnormal overloads such as those caused by severe earthquakes. If steps can be taken to prevent future overloads, or if the overload is not expected again, repair is feasible.

A third cause for cracks, and a most common one, is that of temperature changes in the structure where no provision has been made for movement or controlled cracking, such as weakened-plane contraction joints. In these cases, repair should be started only after provision has been made in the structure to relieve the stresses which must necessarily occur with temperature changes.

Finally, settlement of the base or foundations can cause severe cracking of structures and pavements. Often settlement is limited and stops after a period of time. In these instances cracks can and should be repaired.

HOW CRACKS SHOULD BE REPAIRED

The method of structurally repairing concrete cracks by the injection of epoxy adhesive has evolved over the past 10 years. As it exists now in its advanced state of the art, the usual procedure is as follows:

First, a temporary surface seal is painted over the surface of the crack, after using mastic tape to provide uncoated spaces in the crack line to serve as entry ports. These entry ports are at positions along the crack which are at least as far apart as the depth of the concrete member. If the crack extends through the member, back sealing is necessary to prevent runoff.

Then two metering pumps drive the two components of a very fast-setting epoxy adhesive through a mixing head, and into the entry port on the face of the crack through a special gasket which prevents leakage of the adhesive on the face of the concrete. The two-component epoxy adhesive is pumped into the first entry port until the adhesive begins to show at the adjacent entry port. Experience has shown that because of the spacing of the entry ports, the operator can be assured that the adhesive material has traveled to the full depth of the concrete member when the show of material appears at the next port. At this time the first port is plugged, and injection is begun at the second port. This procedure is used until the entire crack or void in the concrete is filled. The procedure works the same on horizontal or vertical members. On vertical members the first port injected is always the lowest and the injection progresses upward. The equipment in use can develop pressures up to 300 psi, although pressures above 100 psi are seldom required. After the epoxy adhesive has cured, the temporary surface seal is scraped off leaving the

face of the concrete smooth and unmarred except for the trace outline of the crack. Sacking or painting can completely hide the crack.

An example of the method is illustrated progressively in Fig. 5-1, 5-2, and 5-3.

LIMITATIONS TO EFFECTIVE REPAIR

The structural-concrete bonding process is applicable to all cracks wider than 0.005 in. that are clean or can be cleaned. In actual practice cracks as narrow as 0.002 in. have been successfully injected with 100 percent penetration to depths of 60 in. for lengths exceeding 100 ft. Success in these extremely small cracks is entirely dependent on the specific conditions encountered, and in general it is impossible to say whether or not injection will be successful unless an actual field test is performed. Even in cracks wider than 0.005 in. it is possible to encounter severe contamination or deposits that prevent effective injection.

DEFICIENCIES OF ALTERNATIVE METHODS

In the past repairs were attempted using techniques which were not fully effective even though for a short time a crack had



FIG. 5-1 CRACKED CONCRETE SEAT BEAM PRIOR TO REPAIR

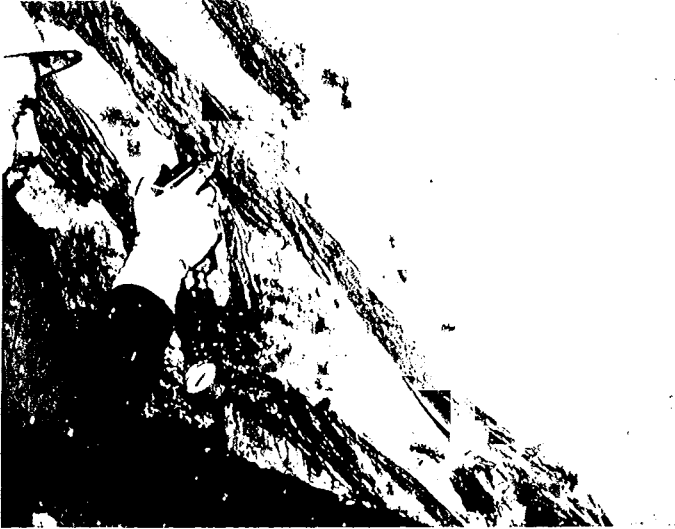


FIG. 5-2 OPERATOR PREPARING TO INJECT EPOXY ADHESIVE INTO CRACK. SURFACE SEAL HAS BEEN APPLIED TO CRACK FACES AND OPEN PORTS LEFT FOR INJECTION AT REGULAR INTERVALS



FIG. 5-3 CRACK INJECTION COMPLETED AND SURFACE SEAL REMOVED

apparently been repaired. A brief resume of these alternatives follows.

Routing and Sealing

The technique is simply to rout a "V" 1/4 to 1 in. deep, for the length of the crack and to fill it with a rigid or flexible grouting material. This approach will usually seal a crack that does not move (of these, however, there are very few). It will not be effective on a working crack. If a rigid grout is used another crack will appear in the grout when the concrete changes temperature because it is a weakened plane. If a flexible grout is used it will seal the crack as long as the grout, usually an elastomeric sealant, retains its properties when exposed to the elements. In neither case is there a structural repair.

Stitching

This involves the drilling of holes on both sides of the crack and grouting-in stitching dogs which span the crack. While stitching can restore the tensile strength of the concrete member parallel to the stitches, it cannot seal the crack from water penetration unless it is combined with some other sealing procedure. It is expensive and usually not esthetically acceptable.

Cement Slurry Grouting

The cement paste shrinks and provides a very poor bond.

Routing and Sealing with Batched Epoxy Injection Through Fittings

This method is the father of today's best methods. It is time-consuming, does not provide clean and easy entry into the crack, and requires the use of slow-curing epoxy adhesive systems which sometimes do not resist movement either from temperature changes or from other causes of stressing prior to curing of the adhesive. The repair can suffer permanent damage if movement takes place while the epoxy adhesive is not adequately cured.

As stated, the method is extremely time-consuming. Time must be taken to rout out the crack, to drill holes, to insert fittings, to mix and apply the epoxy sealant material, and to allow the sealant to cure. Then and only then can the actual injection begin. In addition, after the crack injection is complete there is the long, tedious process of removing fittings, repairing spalled areas, and grinding down the epoxy sealing compound. It also follows that, because of the time-consuming nature of the application and the technical difficulties inherent in properly routing and placing fittings, the method is costly.

TYPICAL APPLICATIONS

Typical of some jobs which have been performed are the following:

Overloading had cracked a reinforced-concrete craneway at the Richmond refinery of the Standard Oil of California. Repairs were effected by epoxy-adhesive injection without dismantling the crane or shutting down plant operations. This approach saved \$16,000 over the alternative method of dismantling the entire system and completely replacing the concrete.

Monolithic construction of the two-mile monolithic tunnel for the Stanford linear accelerator near Palo Alto, California, was made possible by epoxy-adhesive injection. This structure was cast in alternate 80-ft sections. After the concrete had cured, all joints and shrinkage cracks were injected with epoxy-resin adhesive.

At the Columbia, Geneva Division of the U.S. Steel plant at Pittsburg, California, a falling 7-ton steel coil shattered a 12-in. double-reinforced floor slab located over an air plenum. The floor was repaired in place by means of epoxy injection for approximately one-tenth the cost of removing and replacing the damaged floor area.

A good illustration of an engineered application developed at the International Harvester truck assembly plant at San Leandro, California. It was recognized by the company when this plant was purchased that the second-floor slab was badly deteriorated because of overloading. It had been reduced to approximately 40 percent of its original load capacity. Practically all of the second-floor area could be used only for storage of light materials, spaced carefully throughout the area to prevent overloading in any one section. Replacement was initially considered but this would have entailed not only tearing out and replacing the existing slab but also shutting down the entire production facility.

The floor was divided into 18 bays, 20 x 8 ft each. It was decided to test the effectiveness of repair by epoxy injection with a deflection load test. Two bays having approximately the same condition of cracking were chosen for the test. Loading was done by point loading with forklift trucks.

Fig. 5-4 illustrates the loads required to develop deflections in a calculated uncracked slab, the epoxy-repaired slab, and an unrepaired slab. The calculated over-all effectiveness of repair was 86 percent. With an allowance for safety the repair was considered to be 80 percent effective.

A total of 30,008 lin ft was injected during 4 months at a total cost of less than \$100,000. In addition there was no shut-down of plant operation at any time during the repair operation.

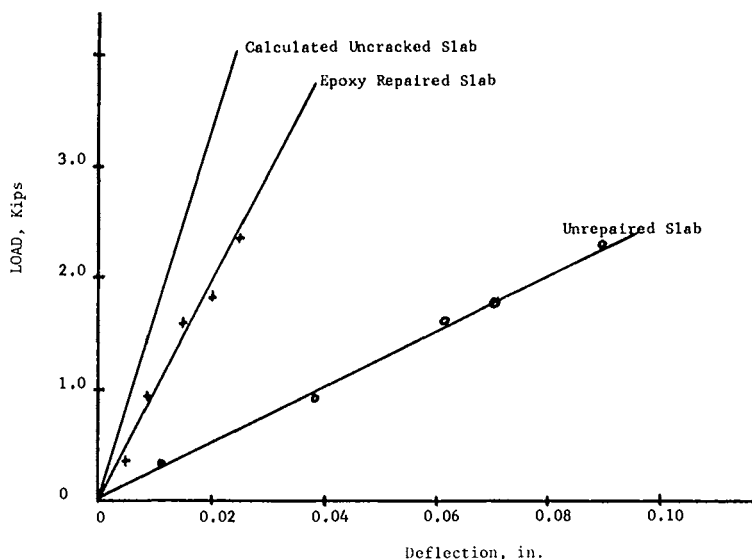


FIG. 5-4 DEFLECTION UNDER LOAD OF INTERNATIONAL HARVESTER FLOOR BEFORE AND AFTER REPAIR

and the second-floor area was open to full production immediately after each area had been repaired. The alternative method would have required complete replacement of the second-floor slab at a total estimated cost of over \$250,000. The savings on the repair alone were augmented by allowing production to continue while the repair was in progress and the floor has been in service for approximately two years since the repair and is 100 percent satisfactory.

CONCLUSION

The foregoing examples demonstrate that cracks in concrete structures should no longer be ignored because of failure to find an effective method of repair. Most cracks can and should be effectively repaired with a structural concrete bonding process which effectively "welds" the concrete together again.

The general aspects of the use of epoxy compounds and of epoxy curing agents for patching and grouting concrete are discussed. The successful use of epoxy materials requires that certain material criteria are met and that proper surface-preparation procedures are followed. Basic information on both these subjects is presented. This paper describes the application of epoxies for repair of freeze-thaw damage, chert pop-out failures, damage to precast pieces, and floor deterioration affected by steel-wheel vehicles. Also discussed are prevention of dusting, cavitation, cold joints, and chemical attack.

Patching and Grouting of Concrete with Epoxy Systems

By L. V. CORBETT and F. B. ALVEY

□ Cementitious materials traditionally have been and still are chosen as a prime construction material. They form strong, economical, durable products either from a plastic mass or by the assembling of precast pieces. Technological advances have been made that extend the use of concrete to new and diverse applications. Reinforcing steel, water reducers, air-entraining admixtures, scientific mix designs, and latex and asbestos additives are examples of successful advances made in improving concrete performance. Continuing work in these and other areas will create new uses and expanding markets for cementitious materials.

One of the present developments in concrete construction, protection, repair, and maintenance is the use of epoxy compounds with concrete. They enable rapid, economical repair; can impart property improvement; and serve to protect concrete from unfavorable physical and chemical environments.

Part of the utility and versatility of epoxies in concrete applications relates to the wide variety of available epoxy materials (liquid, resinous solid, solution, and tough thermoplastic) and the diverse hardening agents (amines, amides, catalysts, acids, etc.) that are used with epoxies. In addition, numerous modifiers can be incorporated in the epoxy systems such as diluents, extenders, and surface agents. These numerous material combinations and variations yield a spectrum of application and cured-state properties from epoxies, and have made epoxies

LEO V. CORBETT received his bachelor's degree from Syracuse University and attended graduate school at the University of Michigan and UCLA. For the last thirteen years he has been investigating the relationship between concrete and plastics. He was president of a small research and development company investigating these relationships; and later he was appointed vice-president and technical director of Great Western Research Corporation, a subsidiary of American Cement Company, where his work continued. This paper was written during his employment as market development specialist at Celanese Coatings Company. He is now employed as assistant to the president, Colonial Industries, Maple Shade, New Jersey. Mr. Corbett is a member of ACI Committee 503, NACE, Committee T-3K, and ASTM Committees D-1, D-14, C-3, and C-9.

FRANCIS B. ALVEY received the AB degree from Bellarmine College, Louisville, Kentucky, and then the PhD degree in physical organic chemistry from the University of Louisville in 1960. He conducted research in epoxide chemistry in the research laboratories of the Devoe & Reynolds Company (now Celanese Coatings Company) from 1960 to 1965. During the same period he taught at the University of Louisville. Since 1965 he has been Product Manager, Plastics, with Celanese Resins.

adaptable to many uses in conjunction with concrete. The need for the proper selection and utilization of materials from the variety available makes quite important the role of the epoxy formulator.

The information contained in this presentation is supplemental to that in the comprehensive guide¹ published by ACI Committee 403 and augments other papers in this symposium.

CONCRETE EPOXY CONSIDERATIONS

The successful utilization of epoxy compounds with portland-cement concrete results from their physical, chemical, and application compatibilities with concrete. Compatibility implies that epoxies have respectively adequate strength, adhesive, and temperature-response characteristics; chemical reactivity and resistance properties in the concrete environment; and properties facilitating their use in conjunction with concrete.

Material Criteria

Following are some general criteria useful in designing epoxy compounds for concrete uses:

1. The material should remain relatively stress-free during curing.

- (2) It should have a curing rate designed to give acceptable working characteristics and still cure to a satisfactory state under conditions of placement.
- (3) It should not contain volatiles or plasticizers which could migrate and cause stresses or brittleness with resulting bond failure.
- (4) It should be flexible enough to take up internal stresses.
- (5) It should be unaffected by its chemical environment.
- (6) It should be able to withstand heavy wear.
- (7) It should retain its flexibility and strength after long exposure.
- (8) It should be safe and easy to handle.
- (9) It need not be over-designed for the job it must perform.
- (10) And, related to "9", material costs should not be excessive on a basis of a unit of performance per unit of cost.

Surface Preparation

In addition to the foregoing desirable material properties, the successful employment of epoxy with concrete also calls for proper application techniques. Surface preparation is essential for success in many concrete-epoxy combinations. It is desirable to preface our primary concern, patching and grouting, with some consideration of surface preparation.

Before an epoxy material or any other material is applied to a surface, the concrete must be clean and sound. Removal of laitance is necessary.

The best method of removing surface weaknesses from concrete is by sandblasting using 20 to 40-mesh, clean, sharp, washed silica sand. Oil and water trays should be used. All sand should be removed from the surface prior to application. The sandblasting equipment and technique selected will greatly influence labor costs.

If the concrete surface is dirty, an excellent method for preparing the surface is to spall the surface with an air-operated tool.

Cleaning greasy concrete with a trisodium phosphate slurry with or without a surfactant is satisfactory only when repeated two or more times. Even then, this method should be limited to

preparing surfaces to be treated with epoxy materials having a viscosity less than 1,500 cps (epoxy solution coatings).

Acid etching with a 3:1 water solution of muriatic acid will clean a surface and remove laitance. However, there are some disadvantages to this method:

- (1) Chlorides resulting from acid-base reactions may reach the reinforcing steel. Under some circumstances, the acid solution itself may cause some corrosion of the reinforcing steel.
- (2) Neutralization and removal of the chloride solutions should be complete. Frequent rinsings are necessary.
- (3) Released gases may affect nearby appurtenances by causing corrosion.
- (4) Released gases developed in this process are irritating to nose and throat membranes.
- (5) Clothing and footgear may be attacked.
- (6) Acid etching will not clean areas coated with a deposit of hard-water salts or grease.

Other physical methods of removing a dirty or unsound concrete surface may be satisfactory. The important consideration is that concrete have a clean, sound surface prior to epoxy applications.

Related to surface preparation is the surface-wetting properties of the epoxy compound. Without a clean surface, good wetting is either impossible or ineffectual; without good wetting, a clean sound surface is not utilized in adhesion.

Because of the relative tensile properties of epoxies and concrete, epoxy materials must be in contact with as large a surface area as possible to prevent tensile breakdown of concrete surfaces. Epoxy resin must wet the entire concrete surface to develop high adhesion for good performance. The concrete surface includes pores, elevations, and depressions. Surface tension of the epoxy system determines the degree of wetting.

Bridging of depressions in concrete surfaces with epoxy materials reduces the effective area of the interface. Concrete surfaces are rough enough to cause a several-fold difference in effective bonding area between a high-viscosity material with high surface tension and low "wettability" and a low-viscosity material with low surface tension and high wettability.

Surface-tension properties of epoxies are important in applications where the epoxy must have good penetration of the concrete medium.

PATCHING AND GROUTING

A discussion of some areas where epoxy compounds have proved very useful follows. These are general patching and grouting applications.

Freeze-Thaw Damage

Although air-entraining agents have reduced this problem considerably, many areas still exist where epoxies serve a very useful purpose in restoring concrete to its original serviceability. Damaged surfaces may be patched with epoxy mortars or overlaid with epoxy toppings, or overlays may be firmly bonded to the substrate with an epoxy adhesive. Furthermore, epoxy-solution surface impregnants effectively prevent freeze-thaw damage.

Fig. 6-1 shows an area of freeze-thaw damage prepared for patching with epoxy compound. Fig. 6-2 was taken one year after the patch was completed, and Fig. 6-3 shows the patch

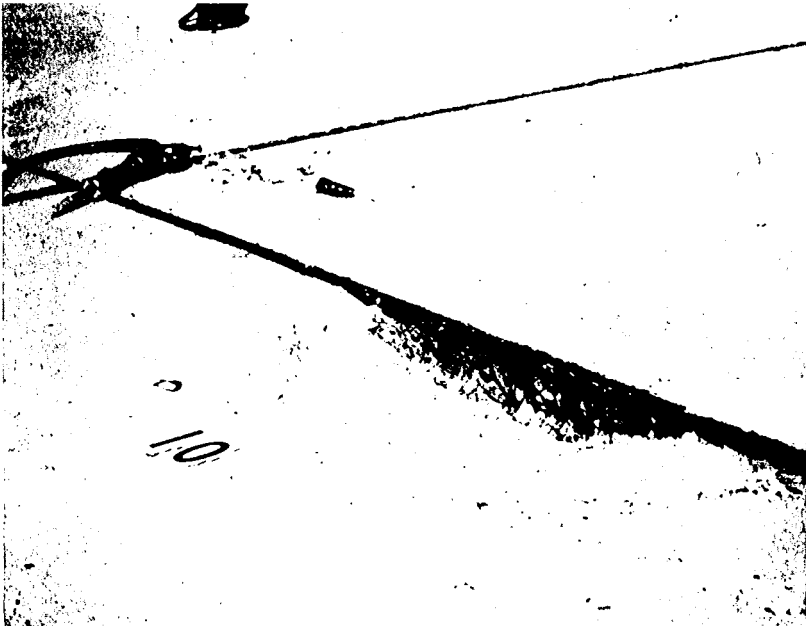


FIG. 6-1 AREA OF FREEZE-THAW DAMAGE



FIG. 6-2 FREEZE-THAW DAMAGED AREA ONE YEAR AFTER
REPAIR WITH EPOXY-SAND COMPOUND



FIG. 6-3 FREEZE-THAW DAMAGED AREA 3 YEARS AFTER
REPAIR WITH EPOXY-SAND COMPOUND