**Zeitschrift:** IABSE reports of the working commissions = Rapports des commissions de travail AIPC = IVBH Berichte der Arbeitskommissionen

**Band:** 2 (1968)

**Artikel:** Laboratory and field evaluations of thin wearing surfaces for orthotropic steel deck bridges

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**DOI:** https://doi.org/10.5169/seals-3989

# LABORATORY AND FIELD EVALUATIONS OF THIN WEARING SURFACES FOR ORTHOTROPIC STEEL DECK BRIDGES

Essais de laboratoire et sur place de revêtements minces pour dalles orthotropes

Laboratoriums- und Feldversuche dünner Fahrbahnbeläge auf orthotropen Brücken

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## INTRODUCTION

With few exceptions, all of the orthotropic steel deck bridges in Europe and elsewhere have been paved with asphaltic compositions applied in thicknesses of 1-1/2 inches (3.7 cm) or more. The use of these materials have been more or less dictated by general familiarity and proven performance histories. The application of thin wearing surfaces applied in thicknesses of 1 inch (2.5 cm) or less has generally been limited to moveable or demountable bridges where excess weight is highly undesirable. In long span continuous bridges, the dead load of thick wearing surfaces may also be undesirable because the pavement does not contribute to the overall stiffness of the bridge. In keeping with the design philosophy of light weight steel deck bridges, a thin light weight wearing surface also is highly desirable provided the known pavement requirements may be met.

The history of thick wearing surfaces has shown that considerable time and study is needed before the suitability of a paving system may be fully assessed. The process can be accelerated with the help of laboratory studies. With this in mind, an experimental program at the Columbus Laboratories of the Battelle Memorial Institute was devised by the author under the sponsorship of the American Iron and Steel Institute to investigate a variety of materials which showed some promise as thin light weight paving materials for steel deck bridges. The objective of this program was to develop a number of test methods and procedures for measuring specific material properties which have been shown by experience to be important to the performance of suitable wearing surfaces. It was reasoned that the experimental data could hopefully be correlated with field performance to establish realistic design criteria and to provide a means to quickly evaluate new and improved materials as they become available.

## EXPERIMENTAL PROGRAM

In selecting the materials to be used in this study it was realized that numerous compositions might be suitable as worthy of consideration but as in any program of this kind, there is a practical limit to the number that can be handled. In order to confine the program to a manageable number of materials, the selection was limited to a few basic materials which were readily available on a commercial basis and with some performance history in reference to bridge deck reparis. With these considerations, the following thermosetting materials, in whole or in part, were selected for this investigation:

1. Coal tar epoxy
2. Oil extended epoxy
3. Polyester
4. Polyamide modified epoxy
5. Polyurethane
6. Epoxy asphalt.

Because of the relatively high cost of resinous binders, economics dictate that as high a filler content as practical be used. To investigate these practical limits, a portion of the program was devoted to determining the effects of different filler contents on the properties of the first four materials listed above. The remaining two were proportioned according to recommendations of the material suppliers.

## Material Property Determinations

The specific properties of the experimental materials determined were as follows:

1. Flexural strength
2. Modulus of elasticity
3. Fatigue resistance
4. Shear and tension bond strength
5. Abrasion resistance.

Most of the evaluations were conducted at room temperature; where applicable, they were made also at temperatures of $0^{o}$ and $140^{o}F$ ($-18^{o}$ and $60^{o}C$). These values are representative of the temperature limits which might be encountered in service.

## Flexural Strength and Modulus of Elasticity

The flexural strength of the resin mortar materials was determined from 1 x 1 x 10-inch (2.5 x 2.5 x 25 cm) specimens under three point loading over an 8-inch (20 cm) span. The elastic modulus of these materials was calculated from the deflections of the flexural specimens measured at the center of the span. The rate of loading was fixed at a loading head travel of 0.20 in/min. (5 mm/min).

The results of these measurements are given in Table 1. It is evident that the strength and the modulus of all the epoxy-resin materials decrease as the sand/resin ratio increases. Values of both also decrease with an increase in temperature with the exception of the polyamide/epoxy mortar. Heating these specimens to the test temperature of $140^{o}F$ ($60^{o}C$) apparently caused some slight additional curing of the binder, resulting in a higher strength.

The significance of these values is that many of these materials could increase the stiffness of a steel plate even at temperatures up to $140^{o}F$ ($60^{o}C$) and at sand/resin ratios as high as 8:1 under instantaneous loading. The magnitude of the increase would, of course, depend on the ratio of pavement thickness to plate thickness.

TABLE 1. FLEXURAL STRENGTH AND ELASTIC MODULUS OF EXPERIMENTAL PAVING MATERIALS UNDER VARIOUS CONDITIONS

| Material | Binder Content, w/o | Flexural Strength, psi | | | Flexural Modulus, psi | | |
|---|---|---|---|---|---|---|---|
| | | 0 F | 77 F | 140F | 0 F | 77 F | 140F |
| Coal Tar Epoxy | 18.7 | 3000 | 900 | 200 | 1,600,000 | 230,000 | 30,000 |
| | 12.1 | 2500 | 800 | 175 | 1,000,000 | 150,000 | 20,000 |
| | 8.2 | 1700 | 600 | 150 | 680,000 | 65,000 | 8,000 |
| Oil Extended Epoxy | 16.4 | 2350 | 1000 | 200 | 530,000 | 140,000 | 40,000 |
| | 10.6 | 2000 | 780 | 80 | 430,000 | 70,000 | 4,000 |
| | 7.0 | 1200 | 500 | 50 | 320,000 | 22,000 | 2,000 |
| Polyamide/Epoxy | 18.0 | 3650 | 3350 | 3500 | 1,050,000 | 900,000 | 700,000 |
| | 11.6 | 3300 | 2800 | 2950 | 950,000 | 850,000 | 650,000 |
| | 7.6 | 2800 | 1600 | 2850 | 800,000 | 740,000 | 600,000 |
| Polyester | 18.8 | 3100 | 1900 | 1000 | 900,000 | 320,000 | 35,000 |
| | 12.2 | 1700 | 850 | 300 | 800,000 | 220,000 | 32,000 |
| | 7.8 | 600 | 300 | 150 | 450,000 | 150,000 | 25,000 |
| Polyurethane | 20.0 | 3690 | 1800 | 1080 | 640,000 | 533,000 | 84,000 |
| Epoxy Asphalt | 7.25 | 3190 | 690 | 480 | 4,680,000 | 410,000 | 187,000 |

## Shear and Tensile Bond Strength

The shear bond specimens consisted of a 1/2 x 4 x 8-inch (1.3 x 10 x 20 cm) long steel specimen which was coated with 1/2 inch (1.3 cm) of the various epoxy mortars over one half of the plate (end half). The plate was grit blasted to white metal and primed with a 1/32 inch (0.8 mm) thick layer of the pure binder prior to placing the mortar. After curing, a similar sized plate was cemented to the top of the paving mix so that the unpaved sections of the plate extended in opposite directions. The specimens were then placed in a loading jig. The bottom specimen plate was bolted to the jig and the top plate pulled in a parallel plane by means of a threaded rod tightened against an angle bar attached to the jig. A set of rollers was used to insure that the top plate remained parallel to the bottom plate while the load was being applied. The load was measured by means of a load cell. The shear jig with a specimen mounted is shown in Figure 1.

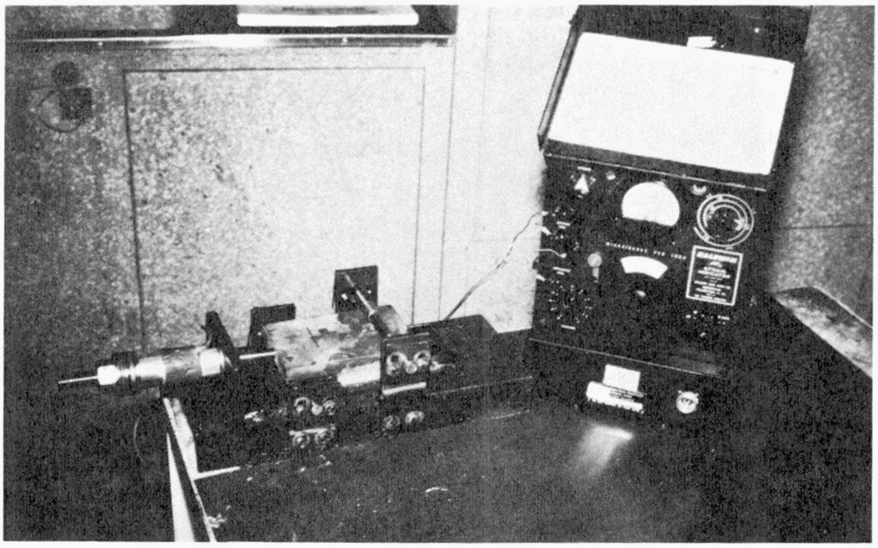

FIGURE 1. APPARATUS USED TO DETERMINE THE SHEAR BOND STRENGTH OF EXPERIMENTAL PAVING MATERIALS

The tension bond specimens were prepared by placing a 1 inch (2.5 cm) thick layer of epoxy mortar between two 2 inch (5 cm) diameter steel plates. The plates were grit blasted and primed with 1/32 inch (0.8 mm) of pure resin binder before placing the epoxy mortar. A load was then applied normal to the center of the plates through rods threaded into nuts welded to the back of the plates. A universal joint was fitted into each rod to compensate for any misalignment in the specimen. A tension bond specimen is shown in Figure 2.

In all cases the specimens were maintained at the desired test temperature for at least four hours prior to loading. In all but a few cases failure occurred by complete separation of the wearing surface at the steel plate interface. Occasionally a small portion of the wearing surface broke free and remained attached to the steel plate. In no case did the portion of the wearing surface which remained attached to the plate exceed 5 percent of the bond area. The results of the bond strength measurements are given in Table 2.

TABLE 2. SHEAR AND TENSILE BOND STRENGTH OF THE CANDIDATE PAVING MATERIALS TO A STEEL PLATE

| Material | Binder Content, w/o | Shear Bond Strength, psi | | | Tensile Bond Strength, psi | | |
|---|---|---|---|---|---|---|---|
| | | 0 F | 77 F | 140 F | 0 F | 77 F | 140 F |
| Coal Tar Epoxy | 18.7 | 900 | 640 | 75 | -- | -- | -- |
| | 12.1 | 680 | 380 | 55 | 700 | 475 | 155 |
| | 8.2 | 420 | 255 | 45 | 365 | 195 | 95 |
| Oil Extended Epoxy | 16.4 | 475 | 330 | 50 | -- | -- | -- |
| | 10.6 | 450 | 300 | 50 | 525 | 445 | 35 |
| | 7.0 | 385 | 250 | 20 | 460 | 175 | 30 |
| Polyamide/Epoxy | 11.6 | 900 | 830 | 950 | 2000+ | 1150 | 1300 |
| | 7.8 | 840 | 630 | 700 | 535 | 415 | 830 |
| Polyester | 18.8 | 715 | 450 | 180 | -- | -- | -- |
| | 12.2 | 470 | 425 | 100 | 730 | 575 | 80 |
| | 7.8 | 245 | 300 | 80 | 120 | 90 | 65 |
| Polyurethane | 2.0 | 830 | 645 | 275 | 1620 | 1420 | 340 |
| Epoxy Asphalt | 7.25 | 665 | 185 | 50 | 1650 | 220 | 110 |

## Fatigue Tests

The fatigue tests consisted of subjecting the experimental paving materials mounted on steel plates to continuous flexing at specified deflections to determine their tensile cracking susceptibility.

The materials were placed on 3/8 and 1/2 inch (1 and 1.3 cm) steel plates, 4 inches (10 cm) wide and 17 inches (42.5 cm) long. The paving materials were cast over the middle 14 inches (35 cm) of the plates in various thicknesses. The epoxy resin mortars were applied by hand painting a 1/32 inch (0.8 mm) primer of the resin binder on the grit blasted steel plate and casting the mortar directly on the prime coat. There were slight variations in the above procedure depending on the specific recommendations of the materials supplier.

The specimens were mounted in a specially-designed machine which tested two specimens simultaneously at different deflections and with separate controls. The specimens were enclosed in an insulated box and the required temperature was automatically maintained. Each specimen was deflected about its center point to simulate three point loading by applying a cyclic load at one of the end supports by means of an eccentric cam. The load was transmitted to the specimen through a heavy spring so that the load would remain constant during small variations in the deflection. The load applied was that required to deflect the bare steel plate to the desired span/deflection ratio. A slight preload was applied to the specimen to prevent it from bouncing on the supports. The paving materials were stressed in tension only.

After the specimen reached the desired test temperature, the machin started automatically and applied the load at a frequency of 1750 cycles/min. A stripe of electrically conductive material was painted on the paving material the full length of the specimen and wired into a circuit breaking mechanism. When a surface crack occurred the circuit was broken and the machine was automatically shut down.

The specimens were run at various span/deflection ratios down to 300 as representing the maximum value used in design. It was intended to determine the maximum deflection (lowest span/deflection ratio) the paving material could withstand over a period of 5 million cycles. The results of these experiments are given in Table 3. No attempt was made to determine the minimum allowable span/deflection ratio when it was less than 300 and in the table of results the value is merely given as something less than 300. No values are given for tests performed at 140°F (60°C) as in no case did failures occur at this temperature for span/deflection ratios of 300.

TABLE 3. SPAN/DEFLECTION RATIOS SUSTAINED WITHOUT FAILURE FOR FIVE MILLION CYCLES

| Binder Material | Binder Content w/o | Pavement Thickness inch | 3/8-inch Steel Plate 0 F | 3/8-inch Steel Plate 77 F | 1/2-inch Steel Plate 0 F | 1/2-inch Steel Plate 77 F |
|---|---|---|---|---|---|---|
| Coal Tar Epoxy | 12.1 | 5/8 | < 300 | < 300 | < 300 | < 300 |
| | 8.2 | 5/8 | " | " | " | " |
| Oil Extended Epoxy | 10.6 | 5/8 | " | " | " | " |
| | 7.0 | 5/8 | " | " | " | " |
| Polyamide/Epoxy | 7.6 | 5/8 | " | " | " | " |
| | 7.6 | 1 | " | " | " | " |
| Polyester | 18.8 | 1 | 400 | -- | 350* | -- |
| | 11.6 | 5/8 | < 300 | < 300 | < 300 | < 300 |
| | 7.8 | 1/2 | 600 | 400 | 530 | -- |
| | 7.8 | 3/4 | 530 | -- | 670 | 560 |
| Polyurethane | 20.0 | 3/4 | < 300 | < 300 | < 300 | < 300 |
| Epoxy Asphalt | 6.5 | 3/4 | " | " | " | " |

* Estimated.

Abrasion Resistance

This evaluation was intended to determine the relative resistance to wear of the various paving materials examined. Since there is no standard laboratory method for evaluating wear rates, a scheme was devised whereby the wear rate of epoxy mortars could be compared with asphalt concrete. In this experiment, the various epoxy mortars were applied to 4 inch (10 cm) square steel plates in 1/2 inch (1.3 cm) thicknesses. The specimens then were placed in a drill press and the surface ground with a cone shaped grinding wheel rotated to 800 rpm with a force of 15 pounds (6.8 kg). The grinding operation was continued for 1 to 3 minutes and the wear rate calculated from the weight loss per unit of time. The specimens were immersed in water during the grinding operation to prevent heat buildup. The setup used is shown in Figure 3. The results of these experiments are given in Table 4.

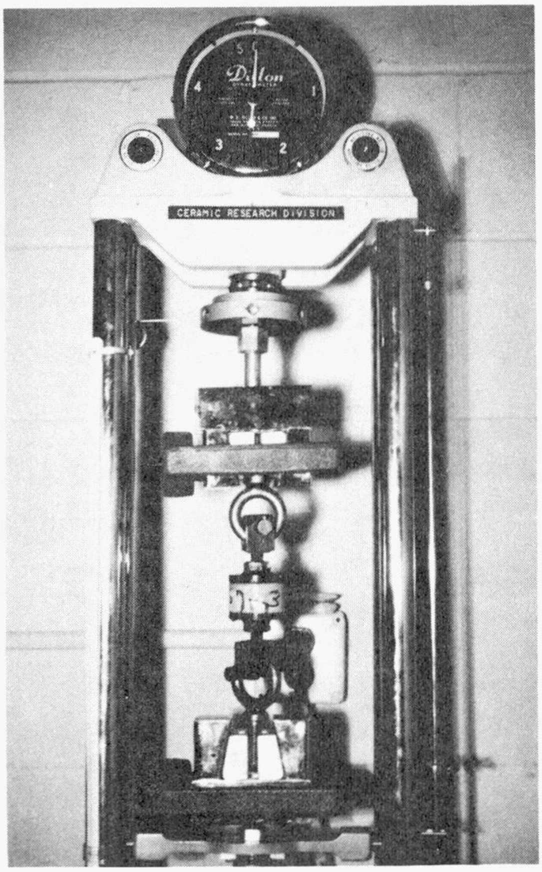


FIGURE 2. APPARATUS AND PROCEDURE FOR DETERMINING TENSION BOND STRENGTH OF EXPERIMENTAL PAVING MATERIALS

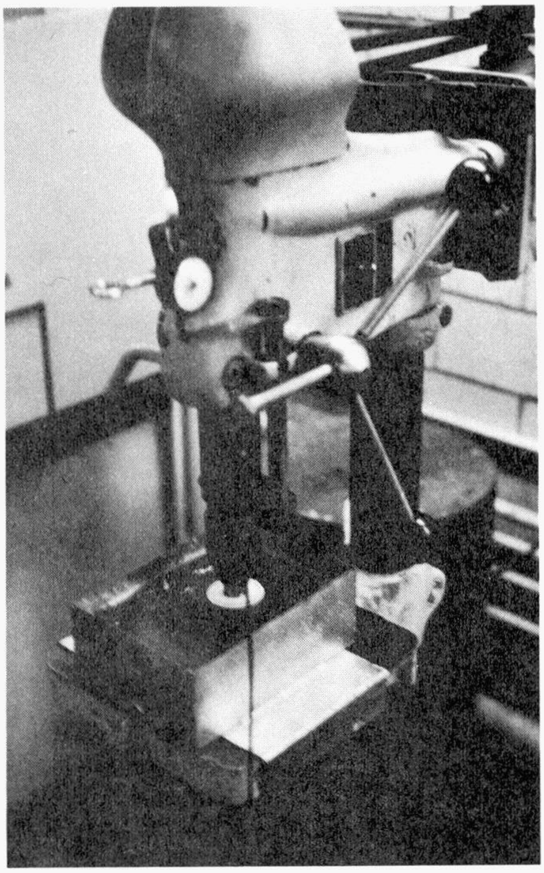

FIGURE 3. EXPERIMENTAL SETUP FOR DETERMINING RELATIVE WEAR RESISTANCE OF THIN PAVING MATERIALS

TABLE 4. RELATIVE WEAR RESISTANCE OF EXPERIMENTAL PAVING MATERIALS

| Material | Binder Content, w/o | Wear Rate Weight Loss, gms/min |
|---|---|---|
| Coal Tar Epoxy | 18.7 | 0.33 |
| | 12.1 | 2.50 |
| | 8.2 | 4.33 |
| Oil Extended Epoxy | 16.4 | 4.17 |
| | 10.6 | 7.0 |
| | 7.0 | 22.6 |
| Polyamide/Epoxy | 18.0 | 0.33 |
| | 11.6 | 0.83 |
| | 7.6 | 3.83 |
| Polyester | 18.8 | 0.67 |
| | 12.2 | 2.33 |
| | 7.8 | 14.63 |
| Polyurethane | 20.0 | 0.25 |
| Epoxy Asphalt | 7.25 | 1.33 |
| Asphalt Concrete | 6.5 | 1.97 |

## FIELD EXPERIENCE

Laboratory data have little meaning unless they can be related to field performance. Unfortunately, there is a limited amount of field data on these wearing surfaces available at the present time. There are, however, four American bridges wholly or partially paved with thin epoxy based surfacing materials. The following is a brief description of the paving materials used on these bridges and their field performance.

### Ulatis Creek Bridge*

In September of 1965, one lane of this bridge was paved with five different paving materials. Three sections were paved with epoxy mortar containing 11.25 weight percent of oil extended epoxy (three different suppliers) 1-1/4 inches (3.2 cm) in thickness. Another section was paved with epoxy asphalt. A tack coat of the pure resin binder was used for each material. The steel deck was first primed with three mils of inorganic zinc.

After approximately three years in service, all of the above mentioned materials are performing quite well. The only problem has been near the joints between the different pavements where a small angle was tack welded to the deck plate to serve as a divider. Several of these angles have broken loose and the pumping action has chipped away the pavements within

* For a complete description of the paving procedures, see Bulletin No. 6, Paving Practices for Wearing Surfaces On Orthotropic Steel Bridge Decks, January, 1968, American Iron & Steel Institute.

a few inches of the joint. With these exceptions, no cracking, rutting, excessive wear or other defects are noticeable. Test cores in the epoxy asphalt and one of the epoxy mortar sections yielded tension bond strengths of approximately 210 and 425 psi (15 and 30 kg/cm$^2$), respectively.

New Jersey Turnpike Bridge*

This bridge was paved in November, 1965, using the "Realgirt" and "Cybond" paving system, each over half the bridge. The "Realgrit" system involves tack welding an expanded mesh to the deck plate and then pouring an epoxy-grit slurry over the mesh to a depth of 1/4 to 3/8 inch (6 to 8 mm). This system is shop applied with a similar treatment given to the joints in the field. The Cybond system involves pouring polyester resin over the resin primed deck plate to a depth of approximately 1/8 inch (3 mm) and then scattering sand over the resin resulting in a finished thickness of 1/4 to 3/8 inch (6 to 8 mm). This system was applied in the field.

After 2-1/2 years in service, the epoxy grit of the "Realgrit" system has been worn away over the high points of the expanded mesh in the wheel paths. As yet there are no signs that moisture has penetrated at these points but the condition may be expected to get progressively worse.

The Cybond system has developed a fine crack over each of two longitudinal bolted joints in the deck. These cracks extend the full length of the joint and were apparently caused by relative movement of the adjoining plates at the joint. There was some evidence of water seepage through the crack and the joint. Except for these cracks, no other defects were noted.

Dublin Bridge*

Two spans of this four-span bridge were paved in December of 1965 with a coal tar epoxy-grit slurry. Prior to paving, the steel deck had been prepared by three methods: (1) sandblast only, (2) sandblast followed by 1 mil (.028 mm) of hot zinc metallizing, and (3) sandblast followed by 5 mils (0.14 mm) of hot zinc metallizing. After the deck preparation, the epoxy was sprayed over the deck at a rate of 6.6 lbs/yd$^2$ (3.6 kg/m$^2$) after which alumina grit was broadcast over the surface at a rate of approximately 27 lbs/yd$^2$ (15 kg/m$^2$). The finished thickness varied from 1/4 to 3/8 inch (6 to 8 mm).

* Ibid.

After one year of service the surfacing had failed over a large area leaving the steel deck exposed. There was evidence that the amine curing agent for the epoxy had reacted with the zinc metallizing to form hydrogen gas which in turn destroyed the bond. The pavement breakup was the most severe over the area which had been metallized. Much of the pavement placed on the bare sandblasted deck was still intact although there were some signs of wear.

During the summer of 1967, the failed sections were removed and the pavement replaced. The deck was sandblasted and primed with an inorganic zinc preparation. The new pavement was essentially the same as the old one. A subsequent inspection (November, 1967) indicated that the alumina grit had not been uniformly distributed as a few spots were found with little or no grit over the epoxy. A further inspection only a few months ago indicated than in these thin spots, the pavement had been worn down to the steel plate. Except for this wear, no other defects such as cracking were observed. The bond of the new pavement to the steel deck appears to be quite good.

Battle Creek Bridge*

One lane of this small three-span bridge was paved in May, 1967, with two types of epoxy mortar placed in a thickness of approximately 5/8 inch (1.6 cm). Half of this lane was paved using an oil-extended epoxy binder. The aggregate was a No. 7 Joplin grit having a binder content of approximately 9 percent by weight. The other half used a coal tar epoxy binder with a content of approximately 14 percent by weight. The same aggregate was used in this latter mix.

Within three months the wheel paths on the oil-extended epxoy mortar pavement was worn down to the steel plate almost over its full length. The coal tar epoxy mortar was still intact but from one half to two thirds of the pavement thickness had been worn away. In September, 1967, both pavements were repaired using the oil-extended epoxy mortar and No. 7 grit as before. In this case, however, the binder content was increased to approximately 20 percent and a hand roller was used to compact the mix in place. In making the repairs, the old material was not removed but merely brought up to grade.

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* Ibid.

To date, the repair material has performed quite well with no further signs of wear or any other defects.

## CORRELATION BETWEEN LABORATORY AND FIELD DATA

On the basis of the field performance data, few if any problems may be expected with fatigue cracking for any of the epoxy materials when pavement thicknesses are one inch or less. Polyester resin is the only material investigated which has been found to be fatigue sensitive primarily owing to the fact that this material is more brittle than the others evaluated. For high resin content, however, i.e. in excess of 15 percent as is commonly used in field applications, fatigue is generally not a problem. The cracks observed on the New Jersey Turnpike Bridge are attributed to relative movement of the deck plates and not associated with the fatigue characteristics of the polyester resin.

As with any material, good bond to the deck plate is an absolute necessity. Once the bond is destroyed, as on the Dublin Bridge, any pavement will soon be destroyed. The improved bond of the new pavement on the Dublin Bridge has shown that better performance may be expected. The high bond values found for all the materials in the laboratory experiments indicate that no problems may be expected from this standpoint. The cores pulled from the paving materials on the Ulatis Creek Bridge indicate that equally high bond strengths may be obtained in the field if care is taken during installation. If not, some debonding and subsequent failure may be expected.

Wear has been found to be the most critical problem with thin epoxy based materials. The abrasion experiments carried out in the laboratory have shown that wear may become a problem when the binder content is below 10 percent by weight. In these experiments, a well graded aggregate was used so as to produce a dense pavement. The wear problem on the Battle Creek Bridge has borne out the need for a well graded aggregate. On this bridge, a single sized aggregate was used which produced a coarse, open textured material. It was apparent upon observation that much of the epoxy binder migrated to the bottom of the mix leaving a weak skeletal structure near the surface. This type of structure was easily broken down and worn away by traffic. A gap graded aggregate will have a high void ratio with large pores which cannot retain the binder especially when the binder content is not sufficient to fill all the voids in the aggregate. When the Battle Creek Bridge pavement was repaired, the binder content was doubled and gave the appearance of filling all the aggregate voids. No wear of this epoxy mortar was observed after several months in service.

The Ulatis Creek pavements contained a well graded aggregate with a binder content of 11.25 percent. These materials have shown essentially no signs of wear after three years of heavy service. All of these paving materials were premixed insuring that the aggregate will be fully wetted. In the case of epoxy-grit mixtures, where the aggregate is broadcast over the surface of the epoxy, equal wetting is not assured and the pavement may experience more rapid wear. This was found to be the case on the Dublin Bridge, particularly where the aggregate coverage is insufficient to completely impregnate the epoxy binder.

## CONCLUDING REMARKS

Taking into consideration both laboratory and field data, it appears that a suitable thin wearing surface of epoxy mortars may be designed to give a useful life. The use of 3/8 inch (8 mm) or less epoxy-grit mixtures appear questionable not only from the standpoint of excessive wear but also because no leveling of the deck plate may be accomplished. An epoxy mortar on the order of 1 inch (2.5 cm) thick, using a well graded aggregate and having a binder content of 10 to 12 percent should perform quite well if properly installed. As with asphaltic compositions, however, the quality of the field application can be critical in providing a durable pavement. At this time epoxy mortar pavements are hand placed in the field. Before an increase in use may be expected, a mechanized operation must be developed.

## SUMMARY

An extensive laboratory investigation was carried out on six different types of epoxy mortar to determine their suitability as lightweight pavements. The results of the laboratory study were compared with the observed field performance of four bridges paved with similar materials. The comparison shows that several epoxy mortars would be suitable for steel deck pavements if certain precautions are taken.

## RESUME

Des recherches de laboratoire importantes ont été faites sur six types de mortier d'époxy pour déterminer leur aptitude comme revêtement léger. Les résultats de cette étude de laboratoire ont été comparés avec les performances sur place observées sur quatre ponts traités de revêtements semblables. Il en résulte que plusieurs mortiers d'époxy conviennent au revêtement de tabliers en acier, à condition de prendre certaines précautions.

## ZUSAMMENFASSUNG

Weitgehende Laboratoriumsuntersuchungen sind an sechs verschiedenen Epoxydmörteln mit dem Zweck durchgeführt worden, um festzustellen, ob sie sich als Leichtbeläge eignen. Die Ergebnisse dieser Untersuchungen wurden mit den Beobachtungen an vier mit ähnlichen Belagsstoffen überdeckten Brücken verglichen. Der Vergleich zeigt, daß mehrere Epoxydmörtel als Fahrbahnbelag von Stahldecken in Frage kommen, sofern bestimmte Maßnahmen getroffen werden.