BRIDGE DECKS IN MICHIGAN:
A SUMMARY OF RESEARCH AND PERFORMANCE

Prepared for the Conference on a Federally Coordinated Program for Research and Development at Pennsylvania State University, September 20-24, 1976

C. J. Arnold
Physical Research Engineer
Supervisor, Structural Mechanics Group
Research Laboratory Section

Michigan State Highway Commission
Peter B. Fletcher, Chairman; Carl V. Pellonpaa,
Vice-Chairman, Hannes Meyers, Jr., Weston E. Vivian
John P. Woodford, Director
Lansing, August 1976

GENERAL OVERVIEW

A recent survey of the widened portions of 34 structures on I 94 in Michigan, showed that visible spalls comprised less than 10 percent of the measured hollow areas in the decks. Deck deterioration in some places is advancing at remarkable rates. Future costs for deck repair will be extremely high.

Coated rebars should provide an added margin of safety and increased length of service life to future bridge decks. However, we must be cautious, and resist the temptation to consider this factor as the primary solution to deck deterioration problems. It is one factor only, among many of considerable importance.

Information available to date from Michigan research seems to indicate that galvanizing bars has a beneficial effect on performance. The amount or significance of the effect and whether galvanizing is cost effective, are not clear at present. This is not hard, conclusive evidence, but rather a trend that seems to be emerging from preliminary data. Obviously, later developments may confirm or reverse this trend.

Initial experience with epoxy coated rebars indicates that significant improvements in quality control of the coating process are required.

Since the publication of the hypothesis of the formation of fracture plane deterioration by Missouri State Highway Researchers (1), in the mid-1960's, many people have accepted the fact that rebar corrosion is a major factor in deck deterioration. More recently, however, there seems to be less mention of the "failure plane," or "plane of weakness" along which fluids travel and failure progresses.

Recent improvements in mix design and quality control of concrete, have reduced the probability of formation of such planes in new decks. However, continued care and further improvements in these factors, as well as better construction techniques are required along with the coated rebars, if we are to achieve the goal of decks that perform well over the life of the bridge.

Another factor that is not widely mentioned is the following: The use of any finishing equipment on a deck surface generates a fluid wave in the concrete, so that it rises ahead of the float, depresses beneath the float, and rises again behind the float. If there are rebars near the surface, this action tends to segregate coarse aggregates from the area directly above the bar, leave the area above the bar slightly depressed, and increase the effective water/cement ratio of that small area so that shrinkage is higher than in the surrounding deck. These factors, along with the stress concentration caused by the presence of the bar, greatly increase the probability of vertical cracking directly above the bar. Bars buried more deeply below the surface, (perhaps 2-1/2 to 3 in.) do not cause this problem to occur to any great extent.

Therefore, in the newly proposed two-course construction, where cover over the rebars has been reduced in the first course, there will be an increased tendency for vertical cracking directly over the top rebars, in the first course.

With these factors in mind, the following excerpts from Research Report No. R-1008, just completed, are included below (2).

GENERAL SUMMARY OF BRIDGE DECK PROBLEMS AND PERFORMANCE

"The following is a summary of points that have been shown to be important; based on analysis of our own research, information from other states, observations made on numerous decks during construction, and evaluation of their performance over many years thereafter.

Concrete Quality

"Excess water in the mix appears to be the primary factor in deck deterioration, and along with concrete cover variations comprise the major variables determining the performance of otherwise identical decks. "Excess" in this case means simply a sufficient quantity to separate from the mix, and locally accumulate under the conditions of vibration that exist at the site. Tiny fountains of clear water were observed springing from the surface of one of the I 94 decks during widening under traffic. Vibration of the newly placed deck was severe due to truck traffic on adjacent lanes. This was merely an accelerated case of a phenomenon that also occurs in some new decks where localized accumulation of water, and deck "rippling," result from structural vibrations caused by construction activities. It is well known that relatively small increases in water/cement ratio in the mix can cause large increases in the average permeability of the concrete and the amount of chlorides that can penetrate the deck. (See for instance, "Durability of Concrete Bridge Decks, A Cooperative Study," by several State Highway Departments, FHWA and the Portland Cement Association, 1970.) However, average permeability is not the entire problem. Job conditions can cause extremely high water/cement ratios at selected layers in the decks, causing sieve-like porosity at those locations, and associated concrete strengths that approach zero. Evidence here in Michigan and in other states, shows that when decks delaminate at an early age, they fail along a built in plane-of-weakness. This "fracture plane" generally follows a horizontal, undulating pattern with the top rebars at the low points of the plane. Examination of fragments shows that the failure plane is porous and very weak, and is bounded above and below by higher quality concrete. A hollow area in an uncracked portion of one of the Berrien County structures was examined. Removal of a layer of high quality concrete above the fracture plane, revealed that the separation had occurred at a plane approximately 1/8-in. thick, that was composed of sandy rubble. This plane obviously was the remains of an area that had a very high localized concentration of water when the deck initially set. The tiny fountains of crystal-clear water, noted above, had to originate from a subsurface "lake." Subsequent evaportation of the "lake" would leave a lens, like the one found, so porous and weak it could not long survive the effects of weather and traffic.

"Admittedly, the conditions on the widened structures were harsh. The evidence is clear, however, that on construction sites throughout the State similar weakened planes have been formed, though not generally of the severity noted on the widened structures. Typical fracture plane delamination on hundreds of structures testifies to the presence of a weak high water content zone sufficient to eventually precipitate failure.

"Coated rebar cannot be expected to completely solve deck failure problems that result from severe planes of weakness, although such decks should last longer than those using bare steel, because the expansive pressures associated with corrosion at the bar would be delayed, reduced, or prevented. However, the deleterious effects of salt, frost, and traffic can be expected to take their toll, if the severely weakened plane exists. Prevention of such action requires the limitation of water content in the mix, insofar as possible. Water reducers and water-reducing retarders should be beneficial in this respect, and it appears that the improved mix designs of recent years should be better than those used in the older structures now decaying.

"Michigan specifications, at the time the widened portions of the Berrien County decks were built, called for approximately six sacks of cement/cu yd. Water/cement ratios ranged about 6 gal/sack. More recent specifications require seven sacks of cement/cu yd, 3-1/2 in. maximum slump, water/cement ratios are limited to 5-1/2 gal/sack maximum, and typical values have been 5 to 5-1/4 gal/sack. Water reducers and water-reducing retarders have been used extensively and are now required, and specified cover over rebars has been increased. New specifications call for coated bars, with 3 in. of cover on some decks or 1-1/2 in. of cover plus 1-1/2 in. of low permeability bonded overlay in areas of heavy traffic. These changes should go a long way in improving deck performance."

Research on Galvanized Reinforcement

In 1969, the Research Laboratory Section of the Michigan Department of State Highways, in cooperation with the Federal Highway Administration, initiated a Highway Planning and Research project to determine the effectiveness of galvanizing the top reinforcing bars as a means to prevent fracture-plane deterioration of bridge decks. Previous research at various institutions had shown improved performance of small laboratory specimens, when the reinforcement was galvanized.

Twenty-nine 3 ft by 4 ft by 7-1/2 in. field exposure slabs were cast in the laboratory. One-half of the steel in the top mat of each specimen was galvanized with a nominal 1-1/2 oz per sq ft coating. Concrete mixes consisted of 6AA aggregate with 6 and 7 sacks/cu yd of cement, and 4-1/2, 5-1/4, and 6 gal of water/sack of cement. Concrete cover over the bars varied from 1/2 to 2 in. Specimens were cured with polyethylene for 7 days, then air cured for a minimum of 21 days before placement in the field. The slabs are exposed to natural climatic conditions, plus weekly applications of water and salt during cold weather.

Along with these slabs, a simulated composite deck section, 30 ft long, 5 ft wide, and 7-1/2 in. thick was cast on a 36-in. wide-flange beam in the field. Galvanized and ungalvanized bars were used in the top mat with the coating thickness as noted above; concrete cover varies from 1/2 to 3-1/2 in. The beam specimen was cast with a wet mix, subjected to surface drying, delayed application of curing, and early application of salt, to promote shrinkage cracking and early deterioration of the slab. Again, weekly applications of water and salt are made during winter weather.

Annual evaluations of the slabs include inspection for visible indications of deterioration, such as vertical cracking over the reinforcement, and rust staining, along with soundings for delamination. Corrosion cell readings also have been made.

Specifications for galvanizing on the field exposure specimens called for 1-1/2 oz/sq ft average, with a minimum of 1 oz/sq ft. Measurements were made on the bars before and after galvanizing to check the actual thickness of coating applied. A total of 274 locations were checked. The average coating thickness was 2.6 oz/sq ft, with a range from 0.6 to 5.9 oz/sq ft.

Only one location measured 0.6 and the 5.9 reading occurred twice in the 274 points.

Early evaluations revealed that salt had penetrated to the top layer of steel and some rusting of ungalvanized bars had occurred during the first winter of treatment.

Table 1 shows a summary of the electrical potential measurements from the field exposure slabs. Such readings have been recorded periodically on these specimens, and also have been made on numerous bridge decks throughout the State. The values are noted for long-term trends in evaluation of experimental decks or specimens, but are not weighted heavily in conclusion, because of the wide variability in readings that occurs. These measurements no longer are made on bridge repair projects because of erratic results, and lack of correlation with conditions found in the decks. Delamination detectors, selective coring of solid areas, and chloride analysis are used on bridge repair projects.

Cores recently were cut from the field exposure slabs, after six winters of heavy salt treatment. These cores are now being processed through the laboratory for chloride analysis and some results may be available by the September meeting date. Performance information is limited to date, since many of the specimens are still in relatively good physical condition. Only limited spalling and isolated hollow areas have occurred. All specimens had extensive hairline cracking over the bars at the end of three years. Rust staining occurred early on the uncoated bars with 1/2-in. cover. Open cracks, evidently due to pressure from corrosion products, have occurred earlier and more extensively on the plain bars with 1/2-in. cover, but the galvanized sections opened earlier in the 2-in. cover. Hollow areas occurred first at four years of age in the 7-1/2 sack mix, plain bars, with 1/2-in. cover. The following year, a hollow area developed in the galvanized specimen with spliced bars, 6-sack mix and 1/2-in. cover. These areas have been cored, and bars are now being inspected, so further information should be available for the September meeting. It is evident from the information gathered thus far that the galvanized portions of the specimens are in considerably better condition on the average, than the uncoated portions. Some of the galvanized bars removed from the cores show white corrosion products on the surface, and in some cases the surface is so badly stained that it is difficult to determine the coated from the uncoated bars. However, a polished specimen shows that about 70 percent of the coating remains on the bar in the stained area. Note that the top mats of the field exposure specimens have three galvanized and three plain No. 6 rebars in the primary or "transverse" steel. Two galvanized No. 4 bars make up the "longitudinal" portion of the top mat and are placed below the larger bars. The bottom mat of six No. 6 "transverse" and four No. 5 longitudinal bars all are uncoated.

There has been controversy concerning the effect of mixing galvanized top mat with ungalvanized bottom mat in structural decks. The field exposure specimens on this project contained uncoated No. 6 bars in direct contact with the galvanized No. 4 bars underneath. Preliminary examination shows no visible penetration of the galvanized coating at the contact

TABLE 1
ELECTRICAL POTENTIAL MEASUREMENTS[1]

Galvanized Rebar Experimental Slabs

Concrete Cover	Sacks/ cu yd	W.C. Ratio (gal/sack)	Galvanized Bars (Average)						Plain Bars (Average)					
			6/71	7/72	8/73	8/74	9/75	8/76	6/71	7/72	8/73	8/74	9/75	8/76
1/2-in.	6	5-1/4	0.74		0.52	0.63	0.55	0.43	0.56		0.56	0.59	0.55	0.44
	6[2]	5-1/4	0.78		0.61	0.62	0.51	0.44	0.56		0.65	0.62	0.52	0.49
	6	6	0.78		0.56	0.60	0.55	0.52	0.58		0.58	0.56	0.53	0.54
	7-1/2	4-1/2	0.66		0.54	0.67	0.54	0.56	0.55		0.56	0.60	0.57	0.56
1-1/4-in.	6	5-1/4	0.56		0.54	0.59	0.55	0.47	0.50		0.50	0.43	0.52	0.51
	6[2]	5-1/4	0.71		0.56	0.58	0.54	0.46	0.50		0.48	0.51	0.55	0.46
	6	6	0.60		0.54	0.52	0.52	0.48	0.48		0.50	0.48	0.60	0.52
	7-1/2	4-1/2	0.45		0.50	0.45	0.36	0.44	0.38		0.46	0.41	0.46	0.52
2-in.	6	5-1/4	0.47		0.48	0.51	0.48	0.54	0.41		0.42	0.45	0.44	0.51
	6[2]	5-1/4	0.61		0.57	0.60	0.65	0.59	0.53		0.44	0.48	0.51	0.58
	6	6	0.55		0.47	0.49	0.51	0.46	0.49		0.42	0.47	0.52	0.49

Simulated Deck Section

Concrete Cover	Galvanized Bars (Average)						Plain Bars (Average)					
	6/71	7/72	8/73	8/74	9/75	8/76	6/71	7/72	8/73	8/74	9/75	8/76
1/2-in.	0.68	0.57	0.51	0.57	0.40	0.60	0.60	0.68	0.59	0.53	0.42	0.63
1/2-in.[2]	--	--	--	--	--	--	--	--	0.62	0.57	0.49	0.66
1-in.	0.59	0.62	0.52	0.50	0.48	0.48	0.51	0.57	0.54	0.52	0.39	0.54
1-1/2-in.	0.41	0.53	0.47	0.42	0.41	0.45	0.44	0.47	0.49	0.45	0.45	0.54
2-in.	0.27	0.36	0.40	0.34	0.35	0.38	0.31	0.42	0.41	0.36	0.36	0.40
2-1/2-in.	0.28	0.34	0.34	0.29	0.32	0.36	0.28	0.34	0.37	0.29	0.31	0.36
3-in.	0.30	0.37	0.38	0.30	0.31	0.37	0.27	0.34	0.34	0.29	0.31	0.36
3-1/2-in.	0.35	0.43	0.44	0.49	0.46	0.51	0.29	0.40	0.41	0.30	0.37	0.42

1 Average of six readings, two locations on each of three bars.

2 Lapped bars.

point, and no red rusting of the No. 4 bars. While it is obvious that galvanizing does not prevent the occurrence of cracking and hollow areas, serious deterioration is significantly less on the sections with galvanizing.

The second phase of the project involved the placement of galvanized rebar in the top mat only, on approximately one-half of each of five new bridges. These structures were placed in the Metropolitan (Detroit) District, in order to subject them to maximum traffic and deicing chemicals. The experimental bridges carry Hubbell, Schaefer, Grand River, Meyers, and Wyoming Streets over the new I 96 Freeway. Contracts for the five structures included 205,967 lb of galvanized rebar at $.30/lb and 769,754 lb of ungalvanized rebar at $.19 to $.22/lb. The jobs were let in 1971 and decks were built in 1972.

Specifications for coatings on the structures required galvanizing in accordance with ASTM A 123, with the exception that the weight of coating average no less than 1-1/2 oz/sq ft with no individual specimen less than 1 oz/sq ft. Test results from rebars checked, showed coating thicknesses ranging from 2.8 to 4.4 and averaging above 3 oz/sq ft.

Details of the construction are published in Research Report No. R-845 (3). Yearly surveys, including visual condition checks, corrosion cell readings and delamination-detector runs are made on the experimental decks. Corrosion cell readings have been generally low, (see Table 1-A) with a few isolated higher readings near steel expansion dams. The decks, now approximately four years old, show no signs of deterioration.

During the progress of the research project on galvanized reinforcement

TABLE 1-A

CORROSION CELL READINGS, EXPERIMENTAL DECKS

Structure / Year of Readings	Galvanized Sections, Distance From Curb: 1 ft Avg.	1 ft Std. Dev.	6 ft Avg.	6 ft Std. Dev.	11 ft Avg.	11 ft Std. Dev.	Non-Galvanized Sections, Distance From Curb: 1 ft Avg.	1 ft Std. Dev.	6 ft Avg.	6 ft Std. Dev.	11 ft Avg.	11 ft Std. Dev.
Hubbell St												
1973	0.03	0.040	0.03	0.027	0.03	0.030	-0.08	0.036	-0.08	0.031	-0.08	0.032
1974	0.08	0.040	0.11	0.058	0.15	0.042	0.05	0.043	0.08	0.058	0.11	0.044
1975	0.17	0.082	0.19	0.073	0.21	0.076	0.13	0.079	0.11	0.083	0.12	0.063
Schaefer Rd												
1972	0.15	0.040	0.15	0.033	0.20	0.047	0.23	0.039	0.21	0.033	0.26	0.054
1973	0.20	0.048	0.22	0.040	0.24	0.045	0.25	0.038	0.25	0.041	0.28	0.046
1974	0.21	0.048	0.26	0.042	0.26	0.037	0.25	0.062	0.28	0.057	0.29	0.059
1975	0.27	0.135	0.26	0.114	0.26	0.131	0.23	0.079	0.19	0.061	0.20	0.069
Meyers St												
1972	0.57	0.098	0.50	0.075	0.54	0.118	0.38	0.046	0.33	0.040	0.36	0.057
1973	0.23	0.047	0.25	0.053	0.26	0.041	0.31	0.035	0.31	0.023	0.33	0.028
1974	0.22	0.058	0.22	0.040	0.23	0.039	0.34	0.051	0.32	0.045	0.34	0.073
1975	0.20	0.084	0.20	0.072	0.20	0.074	0.23	0.049	0.21	0.035	0.21	0.042
Wyoming Ave												
1972	0.17	0.046	0.16	0.051	0.15	0.038	0.12	0.043	0.11	0.044	0.11	0.048
1973	0.12	0.047	0.14	0.052	0.13	0.043	0.11	0.068	0.14	0.071	0.15	0.062
1974	0.19	0.045	0.16	0.045	0.16	0.046	0.18	0.068	0.17	0.064	0.16	0.067
1975	0.19	0.040	0.16	0.056	0.14	0.059	0.18	0.081	0.15	0.074	0.13	0.088
	3 ft		8 ft		13 ft		3 ft		8 ft		13 ft	
Grand River Ave												
1972	0.45	0.148	0.41	0.093	0.47	0.126	0.31	0.064	0.31	0.051	0.33	0.053
1973	0.23	0.051	0.24	0.033	0.24	0.033	0.29	0.039	0.31	0.035	0.31	0.027
1974	0.29	0.062	0.24	0.044	0.25	0.039	0.40	0.089	0.32	0.058	0.40	0.089
1975	0.30	0.074	0.26	0.073	0.26	0.078	0.35	0.112	0.28	0.104	0.28	0.098

Note: First set of readings in each case is on the new deck. Readings made on 5 ft centers.

and prior to that project, many investigations have been made of bridge deck vibrations, deterioration, construction problems and techniques for analysis and repair.

An associated HP&R project, including both galvanized and epoxy coated rebars, was initiated in 1973. This project included 38 each, 3 ft x 4 ft x 7-1/2 in. specimens for outdoor exposure; 152 each, 4 in. x 4 in. x 14 in. specimens for laboratory salt immersion, each having an 18-in. long, No. 6 bar embedded 12-in.; and three experimental bridge decks, each having one span each of two different epoxy coatings on the rebar, one span with galvanized rebar and one span with plain rebar. Field exposure specimens were cast and erected during the summer of 1974 and have been treated for two winters. Laboratory specimens were prepared and treatment began in the spring of 1975. Contracts for the experimental structures were let in June 1975. All rebar has been coated for the experimental decks, and two of the three decks have been cast during the past month. Costs of the rebar for the structures were as follows:

For S13 of 81103 and S02 of 82102:

Epoxy Coated Rebar	168,000 lb	$.50/lb
Galvanized Rebar	36,300 lb	$.40/lb
Uncoated Rebar	877,300 lb	$.27/lb

Average cost of galvanizing $.13/lb

Average cost of epoxy coating $.23/lb

For S04 of 58152:

Epoxy Coated Rebar	99,000 lb	$.46/lb
Galvanized Rebar	19,900 lb	$.46/lb
Uncoated Rebar	201,200 lb	$.38/lb

Average cost of either coating $.08/lb

Coated rebars delivered to the experimental structures showed some problems with coating thickness, continuity and uniformity. Michigan now requires epoxy coated rebars in the top mat on all new structures. Steps are being taken to improve quality control on the coating process for future jobs.

Special Considerations for Bridge Deck Widening

An investigation of construction problems on the Rouge High Level Bridge (4) led to the conclusion that structural vibrations during deck placement caused deck surface rippling and a tendency for low spots and vertical cracks over rebars. Another project, begun in 1965, included evaluation of the widening of 110 spans of 34 structures on I 94 in Berrien County. The Department specified that traffic be maintained during widening on all except one structure, where traffic was diverted to the opposite roadway. Early in the construction program it became obvious that traffic on the bridges would subject the new deck sections to severe vibrations during placement and curing of the concrete. Based on the results of initial experimentation, it was decided that temporary shoring should be placed on 44 of 94 spans to be widened under traffic, and that information should be obtained concerning the long term performance of the decks in question. Some of the following information is taken from a report just published (2), concerning bridge deck problems in general and the 10-year performance of the Berrien County structures in particular.

Structural vibration problems were very severe during deck curing, due to heavy truck traffic on the adjacent portion of the decks. There were unusual construction problems due to this vibration. Also, there was strong evidence of water separating from the mix and ponding beneath the surface, as noted early in this report. Table 2 from that report is included here to give an indication of the rate of deterioration that was encountered on the decks under observation. The first use of a delamination detector in 1975, drastically increased the known fracture plane separation. Visible spalling represented less than 10 percent of the recorded hollow areas during the 1975 surveys. However, some of the decks built under these severe conditions are performing remarkably well. This appears to be due, primarily, to differences in concrete quality and local construction conditions.

Recommendations and conclusions from that report that relate to widening of freeway decks, are included below, for the information of any who may be facing the same task. Obviously they are not all-inclusive:

"Several problems arise and special considerations are required when widening structures, especially when traffic is not diverted. The following points were noted on the Berrien County jobs.

"1) The existing sidewalk, rail, and a portion of the deck must be removed from above the existing fascia beam. Since the fascia beam may have more camber than the other beams, and in general is not low enough to blend well with the new deck section, a thin slab can result and the reinforcement can extend too near the finished surface in this area. This can result in premature deterioration of the deck. Therefore, the existing fascia beam should be removed and used as the fascia for the widened section, or reseated lower to avoid the problem.

"2) When widening is done on an old structure, new bridge rail will generally be required to meet current specifications. This results in a strange appearance unless the opposite rail is reconstructed to match. Also, on widening the highway, there is good justification for bringing the opposite rail up to current standards. If this is done in the usual way, it requires careful demolition of the sidewalk to avoid damage to the reinforcement and the deck underneath and is a very expensive process. Several of the Berrien County structures were fitted with new parapet rail without the removal of the sidewalk. Epoxy grouts in drilled holes were used to anchor reinforcement into the existing sidewalk and deck. The process gave good results, and reportedly saved about $30,000 on the two projects.

"3) Traffic-induced vibration causes rippling of the new deck concrete. This condition is further complicated by grade or superelevation of a structure, and by close proximity of traffic to the freshly placed mix. In some cases it will be necessary to refloat the deck surface several times while the concrete is obtaining its initial set. The Berrien County structures show no ill effects from such refinishing.

"4) The face or edge of the existing slab should be coated with epoxy grout immediately prior to placement of the new concrete, to aid in bonding and sealing the construction joint.

"5) Steel reinforcement should be tied tightly in place. Steel for the Berrien County structures was tied at every intersection; and the mat was supported at many more locations than would be normal for new bridge construction.

"6) Depth of steel at the longitudinal construction joint is fixed by the location of the existing deck steel. Since many older decks have less cover than is presently specified, and low cover is a major factor in deck deterioration, the steel depth should be increased as quickly as possible, near the construction joint.

"7) The side-by-side bar splice detail has proven to be a problem in bridge deck performance throughout the state. If other factors are equal, the first location to spall away is directly above the splice. Once this concrete is gone, the net effect is about equivalent to a broken bar. Therefore, it is obvious that special care should be taken to provide extra cover in the region of the splice. Also, a vertical arrangement of the lapped bars should be used instead of the horizontal or side-by-side configuration. Since the splice is important to the structural integrity of the deck, and can also be a deleterious factor in performance of the deck, careful attention to this detail is of utmost importance.

"8) If other factors are equal, and bar splice areas are excluded, spalling generally occurs first where cover is least. Since there are plus and minus tolerances on both the beam seat elevations and the camber of beams, it would be wise to design the widened section with beam seats slightly lower than usual. This will help ensure adequate cover over the reinforcement, while maintaining proper slope for drainage of the deck. Construction personnel should set steel toward the lower end of tolerance to increase cover over the bars, especially at the splice.

"9) Since ease of placement is important to construction, and low water/cement ratio is required for durability, it would seem reasonable to specify a seven-sack mix with water reducing admixtures for future projects."

"It should be emphasized here that the purpose of the seven-sack mix is to obtain lower water/cement ratios and workability, rather than additional strength. Use of water reducers seems to be the only reasonable way to sharply reduce water/cement ratios, while maintaining workability. This seems to be especially critical in deck widenings under traffic, where concrete is subjected to continuing severe vibration during cure, but is equally important for new decks if high durability and performance are to be obtained.

"Information gathered on this project and several others indicates that excess water in the mix is a primary cause of many of the problems that plague bridge decks. These problems include shrinkage and associated cracking over rebars, porosity, and formation of a plane-of-weakness that develops fracture plane separation. These conditions are exceptionally troublesome when associated with bar laps or insufficient cover over the reinforcement.

"CONCLUSIONS"

"Ten-year performance of the I 94 deck widenings have shown no advantage gained from temporary shoring. In fact, shored spans show more deterioration, on the average, than unsupported spans.

"It is not the intent to recommend prohibition of shoring on all future projects, but rather to indicate that shoring as a general practice to prevent vibration is not warranted by improved performance of the deck. Note that none of the bridges evaluated were of continuous design. Widening such a structure may present additional problems. Structures with girders continuous over piers may require shoring to prevent rotation over the piers. Shoring also may have construction advantages in predetermining the amount of girder deflection due to dead load and construction machinery.

"Recent evaluation of the widened portions of the decks with a delamination detector revealed that hollow areas were about 10 times as extensive as spalling.

"There is strong evidence of the formation of planes of extremely high water content within the decks, causing high porosity and very low strength at those locations, resulting in fracture plane separation or spalling of the surface.

"Hard evidence of the porous plane-of-weakness in bridge decks has existed for several years, but has not received broad acceptance or wide distribution in the highway field. However, it continues to point to the need for strong measures to ensure that excess water is not allowed in concrete for bridge decks. Considerable vibration due to construction activities exists even on new structures, and the countless bridges that suffer from fracture plane separation attest to the remarkable extent to which excess water has collected in the most unfortunate locations. Strong measures are needed to prevent this condition in new decks. Major improvements are possible and every effort should be expended to bring water/cement ratios to the lowest practical level. Our current seven sack mix, 3-1/2-in. maximum slump, and use of water reducers or water reducer-retarders, are certainly steps in the right direction."

TABLE 2
TOTAL DETERIORATION OF BRIDGE DECK WIDENINGS
(Based on 30 Deteriorating Structures)

Survey Date	Cracks, lin ft			Hollow Areas, sq ft			Fracture Plane Separations, sq ft		
	Total Increase	Percent Increase	Total Accumulation	Total Increase	Percent Increase	Total Accumulation	Total Increase	Percent Increase	Total Accumulation
1970	320	---	320	Hollow Areas Not Recorded			420	--	420
1971	920	290	1,240	1,700	---	1,700	200	50	620
1973	1,760	140	3,000	1,920	110	3,620	420	70	1,040
1974	570	20	3,570	1,560	40	5,180	250	20	1,290
1975	1,000	30	4,570	26,000*	500	31,180	1,110	90	2,400

* Delamination detector used.

Recommendation for Further Research

Since performance information requires such a long time to develop, and since a considerable backlog of unpublished data exists at any given time, it would seem most fruitful in the short run to initiate a nationwide project that would pull together and analyze the results from all of the various projects that are in progress. Analysis of all available information by an informed investigator, using the same guidelines throughout, should shed some additional light on the subject, and sort out the many variables that are included in the widely scattered experiments.

REFERENCES

1. "A Study of Deterioration in Concrete Bridge Decks," A Progress Report on Investigation 59-2A, HPR 1(4)-30. Missouri State Highway Department in cooperation with the Bureau of Public Roads, October 1965.

2. Arnold, C. J., Chiunti, M. A., and Bancroft, K. S., "A Review of Bridge Deck Problems, and a Final Report on the Performance of Several Berrien County Structures That Were Widened Under Traffic," MDSHT, Research Report No. R-1008, Research Laboratory Section, June 1976.

3. "Galvanized Steel Reinforced Concrete Bridge Decks, Construction Report," MDSHT, Research Report No. R-845, Research Laboratory Section, January 1973.

4. "Deck Rippling on Various Michigan Bridges," MDSHT, Research Report No. R-608, Research Laboratory Section, October 1966.