Comparative Analysis of Dowel Placement in Portland-Cement Concrete Pavements

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No statistically valid proof has been found to indicate that dowel-bar alignment is better or worse by either the basket-assembly or the implanted-dowel-placement method. Also, no significant difference in the amount of joint-related distress in the basket-assembly projects compared with the implanted-dowel projects has been identified. There is no evidence that the joint-related distress on the projects studied can be directly linked with the type of dowel misalignment studied, because alignment error does not appear to be the sole determining factor of the distress. To provide the distress data for the study, visual surveys were conducted at selected concrete pavement locations constructed in the early 1960s in Alabama. Then an electronic metal detector was used to gather dowel alignment data from the same locations. Statistical tests and comparison procedures were employed to analyze the alignment data, and attempts were made to relate the alignment results to the distress data. Conclusions were drawn indicating that neither placement method appears to be superior, but statistical proof could not be established. Many uncontrollable variables, such as work crew difference, equipment difference, and inspection, may be as important to dowel alignment as the examined variables, e.g., contractor, form type, and dowel-placement method. Alignment data regarding dowel depth were unobtainable due to the electronic detection method of data collection employed and a prohibition against coring. Futher research should address this limitation.

Past practice of dowel installation in jointed plain portland-cement concrete (PCC) pavement has been to place the dowels either by a basket-assembly method or by mechanical implantation. Until recently most federal and state specifications have allowed the individual contractor performing the work the choice of dowel-placement method. Recent strict enforcement of tolerances for dowel alignment has virtually eliminated mechanical implanting. Some states, such as Georgia and Florida, have forbidden implanting and require basket assemblies. Dowels have been successfully implanted since the 1950s, but little is known of the actual bar position achieved by either the basket method or the implanting system.

Several recent studies by the Transportation Research Board (TRB) and others (1) have indicated that current dowel tolerance specifications are not realistic and that broader specifications can be tolerated. Due to the increased cost of approximately $30,000/Interstate mile for basket-assembly installation compared with that of the implanting method, it is important to investigate dowel alignment in existing pavements and the relationship of dowel location to joint distress. Little evidence linking distress to alignment error currently exists. These factors led to the initiation of this current study of dowel installation. After careful consideration, Alabama was deemed by TRB's Committee on Rigid Pavement Construction the most promising location for such a study because of the existence there of 67 miles of 20-yr-old PCC pavement. In this paper a description of the research effort and relevant findings are presented.

RESEARCH OBJECTIVES

The objectives of the study were

1. To determine from field investigations of existing pavements the alignment that had been achieved in the placement of dowel bars,
2. To determine the pavement distress that had developed at the joints, and
3. To determine whether a relationship exists between dowel-bar alignment and joint-related pavement distress.

In addition to the preceding objectives, other information was desired from the study. Also of interest was whether there is a significant difference in dowel alignment by using the implanting method compared with the basket procedure. Ultimately, an overall comparison of the basket-assembly method with the implanting method with respect to both distress and alignment was desired. Additional useful knowledge included the distress types present, their rates of occurrence, the severity, and the cause.

RESEARCH PROCEDURE

The overall research procedure consisted of four interrelated and progressive steps. The first step consisted of a thorough literature search; it was followed by the collection of initial background information on the pavement in question. The third step was a visual survey of distress; the final step consisted of actual field sampling of dowel alignment. This process was viewed as orderly and consistent with established procedures, because additional facts were gathered during each step.

Literature Review

A literature review was conducted to obtain pertinent background material related to pavement distress and dowel-bar alignment. The literature deemed beneficial was divided into the categories of distress, dowel alignment, and pavement surveys.

Past research has revealed several defects caused by load transfer, dowel alignment, and joint-forming problems. The most prominent defects caused are faulting, spalling, transverse cracking, restraint cracking, and raveling.

Joint-forming methods often lead to raveling and spalling when improperly performed (2). The three methods commonly employed to form joints are sawing, hand forming, and using inserts. Metal inserts that remain in place may fatigue or corrode (2), which can lead to spalling. Inserts may also tip from the vertical or be left above or below the riding surface. Defects in joints formed with inserts usually result from improper positioning of the insert (3).

Misaligned dowels can cause transverse cracking at midslab as well as spalling at the pavement surface above the dowels (2). Corrosion of dowels is a source of frozen joints; it can also cause transverse cracking (4). Faulting is related mainly to load-transfer problems. There are three major types of failure related to dowel misalignment (5, pp. 27-37): (a) transverse cracking at midslab, (b) local spalling at the joint, and (c) flexural cracks between the joint and midslab. Misaligned dowels can lock the joint (6). One research study (2) concluded that a 1-in. vertical misalignment can cause serious spalling. It was also determined that a 0.25-in. vertical misalignment or 0.75-in. horizontal misalignment was tolerable for a 0.50-in. joint opening. This is the basis for the dowel misalignment tolerance of 0.25 in./18-in. length now employed (2). Another study (5, pp.27-37), conducted in Alabama under laboratory conditions, concluded that alignment errors in the vertical plane were more critical than errors of equal magnitude in the horizontal plane. This same research also concluded that serious spalling failures could result from vertical alignment errors of 1 in. and horizontal errors of 3 in.

The final concern in the literature search was pavement surveys. The major objective of pavement surveys is to legitimately rate performance without biased opinions. Carey and Irick (7) state that rating consistency is important and that a replication of results is desired. The concrete-pavement-condition rating system developed by Majidzadeh and Ilves (8) consists of two steps: rating the pavement with a riding comfort index at highway speed and close inspection from the shoulder at predetermined random locations. This method does not require the closure of traffic lanes. The pavement-rating system used in the current study is a modification of the system of Majidzadeh and Ilves.

Collection of Background Information

The first step in organizing the field survey was a collection of all available pertinent information on the pavement in question.

Contacts with the Alabama Highway Department and the dowel supplier for the paving projects in question provided initial facts. After the old specifications and plans had been reviewed, the many variables of each project were studied, and the actual screening process to determine representative projects was performed. The screening process consisted of visually inspecting each project, recording outstanding characteristics, and analyzing the results. After close examination of the visual data, projects were labeled as either potentially beneficial or not applicable. This initial stage was followed by a more exact visual survey of selected projects.

Visual Surveys

The actual field visual surveys consisted of a preliminary visual survey, a detailed visual survey, and a visual survey of the joints actually tested for alignment. Each type was intended to garner progressively more definite results. This process was used to first generalize then to specify details.

The preliminary visual survey consisted of completing a rating form on the project in question. This form was used to record the distress type, rate of occurrence, severity, location of distress, general condition of the pavement, and any relevant comments. The survey was carried out in a car traveling 55 mph. The projects were divided into 0.5-mile segments. After each segment, the rater would stop and complete the section of the form coinciding with the appropriate location. The entire project was covered. The distress was estimated for the right and left traffic lanes for both directions.

The detailed visual survey was a much closer view of the projects that had been visually inspected by the preliminary method. It also encompassed both directional lanes and the right and left traffic lanes. The projects were divided into 0.5-mile segments. Each segment was further separated into 132 sections, consisting of the 20-ft slabs between the joints. Ten consecutive joints from the 132 were surveyed. The precise location of the detailed section was selected by a random process. This procedure stratified the projects, ensuring that at least one 200-ft section out of each 0.5-mile segment would receive close scrutiny.

Forms were prepared to record the actual project location, the distress type, the general condition, any unusual distress, and pertinent comments. Within each distress type, the severity, actual joint or slab location, quantity, and type of repair were recorded. The distress was estimated by actually walking the 200-ft section and by analyzing it from the shoulder. Each inspection location was randomly predetermined and marked at the shoulder before the actual inspection.

The sampled-joint visual survey consisted of inspecting the joints that were tested for dowel alignment. This survey did not cover all of the projects surveyed by the detailed and preliminary visual surveys. Also, only one directional lane was examined but both right and left traffic lanes were examined. The joints were inspected from the shoulder and the estimated distress was recorded on prepared forms. The forms were devised to account for the project surveyed, location, joint number, distress type, severity, general condition, and relevant comments.

Dowel Alignment Testing

The overall procedure for actual alignment testing consisted of randomly selecting the joints and dowels and then measuring the alignment with an electronic metal detector. According to Gary Fowler of the Georgia Department of Transportation, similar procedures have been used in studies performed in Georgia with the same detector model.

Several methods were considered for the alignment testing. After discussion with Georgia Department of Transportation officials, it was concluded that the metal detector was the most suitable method without actually coring the pavement. Coring was specifically ruled out by the Alabama Highway Department. The detector was considered accurate for horizontal measurements, but vertical (depth) measurements could not be determined.

The field measurement process consisted of marking the ends of the dowel bar on the pavement and then measuring the distance from the right-hand pavement edge to the end marks. This established the lateral positioning of the bar across the joint. Next, a measurement from the joint to the front dowel mark was made to determine the longitudinal position of the bar with respect to the joint.

The field sampling performed in Alabama was executed on the most representative projects from the visual surveys. One directional lane was tested; only the right traffic lane was used. Each project was divided into segments consisting of 20 joints. One randomly selected joint of the 20 was sampled. This was equivalent to a 5 percent sample stratified in 20 joint segments. The joints were marked at the right shoulder before the actual sampling. Because only the right lane was tested, there were 12 possible dowel bars to examine. The first and last bars, i.e., the bar closest to the pavement edge and the bar closest to the left lane, were omitted. This was done for several reasons. It reduced electronic interference, was safer, and simplified numerical calculations. Of the 10 available dowels, only 4 were inspected. These were selected by a random process. For each joint sampled, the joint location, grade, bar measurements, and relevant comments were recorded.

ANALYSIS OF DATA

Distress-related data were gathered from the three visual surveys, whereas dowel-alignment data were collected by using the electronic metal detector. Each data type was analyzed differently.

The preliminary visual survey, the detailed visual survey, and the sampled-joint visual survey were all analyzed similarly. The raw data were separated into categories by project, type of dowel installation, contractor, location, and grade. The distress types were categorized as spalling, faulting, transverse cracking, restraint cracking, and other distress. The results were summarized into tables, and brief descriptions were made.

The data collected from actual field testing were analyzed in more detail than the distress data because quantitative measurements rather than subjective ratings were obtained. Before a statistical analysis technique could be devised, the raw numerical measurements were converted into the desired variable characteristics.

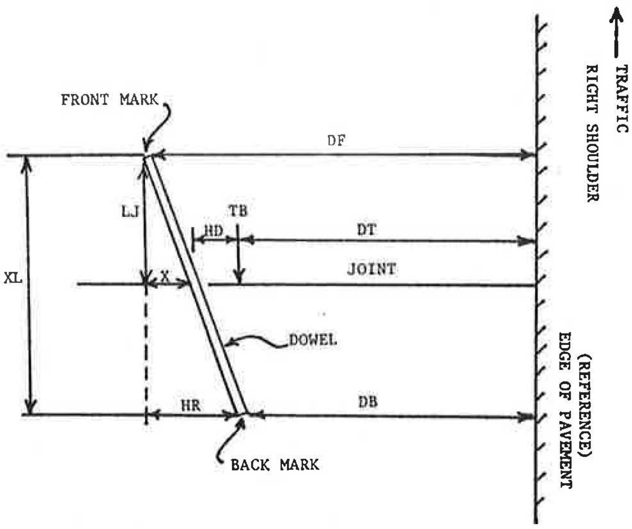
Calculation of Variable Characteristics

As previously noted, three measurements--distance from the pavement edge to the front mark of the dowel (DF), distance from the pavement edge to the back mark of the dowel (DB), and distance from the joint to the front mark of the dowel (LJ)--were made for each dowel. These measurements were used to calculate the three desired variables: horizontal rotation (HR), horizontal displacement (HD), and longitudinal displacement (LD). Each measurement was to the nearest 0.125 in. In Figure 1 the following theoretical, measured, and calculated variables are given:

1. TB = theoretical horizontal position of the dowel at the joint,
2. DT = distance from the edge of the pavement to TB,
3. $HR = DF - DB$,
4. $XL = (16^2 - HR^2)^{1/2}$,
5. $X = HR(LJ)/XL$,
6. $HD = (DF - X) - DT$, and
7. $LD = LJ - 8$.

HR, HD, and LD could result in either positive or negative values; absolute horizontal rotation (ABSHR), absolute horizontal displacement (ABSHD), and absolute longitudinal displacement (ABSLD) were defined as the absolute values for these variables, respectively. The horizontal rotation is a measure of the skewness of the bar in the horizontal plane. The longitudinal displacement measures the distance the bar is off center longitudinally. The horizontal displacement is a measure of the distance the dowel is left or right of the theoretical horizontal position at the joint. After the six computations had been performed, the analyses followed.

Figure 1. Measured and calculated variables for each dowel tested.



Methods of Analysis

Two approaches, labeled preliminary and final, were considered in the analysis of the alignment data. The preliminary method of analysis treated each dowel from a project as an independent observation and ignored probable within-joint as well as possible within-position dependencies. In the final method of analysis, the dowels within a joint were treated as subsamples and averaged to provide a single observation per joint.

The most important comparisons performed by means of the preliminary method of analysis were project, dowel installation type, form type, and contractor comparisons. The comparisons were made by a t-test procedure. The average values of the six characteristics of one category were compared with those of another category. Three additional factors were also analyzed by employing the preliminary analysis concept: the effect of dowel position on alignment, the effect of grade on alignment, and the interrelationship of dowels within a joint. These conditions were examined to illustrate possible additional causes of dowel alignment errors.

The final method of analysis was similar to the preliminary method except that it regarded the dowels within joints as more closely related to each other than to the dowels contained in other joints. The characteristics of the four dowels within each joint were averaged, and then the joints were averaged. Thus, each joint rather than each dowel was considered as a single observation. This reduced the sample size to one-fourth the size of the preliminary method. The same comparison procedure that was performed in the preliminary method of analysis was also employed in this final method.

RESULTS OF ANALYSIS

The projects considered were labeled with letters of the alphabet; the letters ranged from A to S. Of the 29 projects, 10 were labeled with both letters and numbers, as shown in Table 1. For project G-2 the G means that this project was constructed by the same contractor who built project G and during the same time span as project G; 2 means that this project was located adjacent to project G and differed only by federal contract number. The actual contractor identities were changed to fictitious names. The various geographic locations of the projects within the state were designated 1-4. In Table 1 the types of variables that affect both dowel alignment and joint-related distress are defined and the values of these variables are given for each project. After the initial background material had been prepared, the visual surveys were conducted.

Visual Survey Results

The results of all three visual surveys for the three major distress types (faulting, spalling, and transverse cracking) are summarized in Table 2.

The results of the preliminary visual survey were used as a barometer for the general condition of each project. Each was classified as being in poor, fair, or good general condition. The distress in all three visual surveys was subjectively rated as being very minor, minor, moderate, or severe. Also, the significant types of distress were recorded for each project.

Table 1. Variables affecting dowel alignment and joint-related distress.

Project	Contractor[a,b]	Type of Dowel Installation[a,b]	Type of Form[a,b]	Year Constructed[b]	Type of Base[b]	Joint-Forming Method[b]	Location[b]	1980 ADT[b]	Thickness[b] (in.)
A	Barnes	Implant	Rigid	1962	CTB	Unitube	1	7,620	9
B	Barnes	Basket	Rigid	1967, 1968	CTB	Saw	1	8,500	9
C	Nelson	Implant	Slip	1968, 1969	CTB	Unitube	1	9,130	9
D	Jones	Implant	Slip	1967	CTB	Unitube	1	9,130	9
D-2	Jones	Implant	Slip	1967, 1968	CTB	Unitube	1	9,130	9
E	Barnes	Basket	Rigid	1959, 1960	CTB	Saw	2	14,500	10
E-2	Barnes	Basket	Rigid	1959	LMST	Saw	2	14,500	10
F	Finley	Implant	Rigid	1960	CTB	Saw	2	14,500	10
G	Barnes	Implant	Rigid	1965	LMST	Saw	2	12,460	10
G-2	Barnes	Implant	Rigid	1965	LMST	Saw	2	12,460	10
G-3	Barnes	Implant	Rigid	1966	LMST	Saw	2	12,460	10
H	Barnes	Basket	Rigid	1960	LMST	Saw	2	13,150	10
I	Collins	Basket	Rigid	1958, 1959	LMST	Saw	2	16,000	10
I-2	Collins	Basket	Rigid	1958, 1959	LMST	Saw	2	16,000	10
J	Barnes	Implant	Rigid	1967	LMST	Saw	3	7,300	10
K	Barnes	Implant	Rigid	1961	LMST	Saw	3	7,300	10
L	Finley	Implant	Rigid	1964, 1965	LMST	Saw	3	6,000	10
L-2	Finley	Implant	Rigid	1964, 1965	LMST	Saw	3	6,000	10
L-3	Finley	Implant	Rigid	1964	LMST	Saw	3	6,000	10
M	Barnes	Implant	Rigid	1964	LMST	Saw	3	6,000	10
N	Rogers	Implant	Rigid	1965	LMST	Saw	3	7,000	10
N-2	Rogers	Implant	Rigid	1965	LMST	Saw	3	7,000	10
O	Finley	Implant	Rigid	1960, 1961	LMST	Saw	3	5,700	10
P	Smith	Implant	Rigid	1961	LMST	Saw	3	5,500	10
P-2	Smith	Implant	Rigid	1961	LMST	Saw	3	5,500	10
Q	Smith	Implant	Rigid	1966	LMST	N/A	4	11,000	10
Q-2	Smith	Implant	Rigid	1968	LMST	N/A	4	11,000	10
R	Barnes	Implant	Rigid	1963	LMST	N/A	4	12,000	10
S	Finley	Implant	Rigid	1961	LMST	N/A	4	13,500	10

Note: ADT, average daily traffic; CTB, cement-treated base course; LMST, limestone; rigid, rigid-formed; slip, slipformed; N/A = not available.

[a] Variable affecting alignment.

[b] Variable affecting distress.

Table 2. Distress results from all visual surveys.

		Avg Faulting[a] (in.)			
Project	Survey Type	Right Lane	Left Lane	Spalling[b] (%)	Transverse Cracking[b] (%)
A	Preliminary	0.15	0.08	3.3	6.6
	Detailed	NP	NP	NP	NP
	Sampled	0.13	0.07	19.5	13.8
B	Preliminary	0.19	0.06	0.0	0.5
	Detailed	0.16	0.08	1.2	4.6
	Sampled	0.15	0.07	0.0	2.3
C	Preliminary	0.03	0.08	2.4	0.0
	Detailed	0.14	0.07	4.8	0.0
	Sampled	0.07	0.02	6.0	1.0
D	Preliminary	0.14	0.06	8.1	0.4
	Detailed	0.14	0.06	8.4	1.1
	Sampled	0.12	0.05	7.5	7.5
E	Preliminary	0.06	0.00	0.8	1.0
	Detailed	0.03	0.00	0.0	2.5
	Sampled	0.07	0.00	1.3	5.2
E-2	Preliminary	0.05	0.03	1.8	1.4
	Detailed	0.05	0.01	0.8	4.4
	Sampled	NP	NP	NP	NP
F	Preliminary	0.06	0.00	2.6	1.8
	Detailed	0.03	0.00	0.8	0.0
	Sampled	0.07	0.00	2.6	0.0
G	Preliminary	–[c]	0.06	3.6	26.5
	Detailed	–[c]	0.06	1.0	22.0
	Sampled	–[c]	0.06	0.0	44.0
G-2	Preliminary	–[c]	0.06	0.8	8.5
	Detailed	–[c]	0.06	0.0	3.3
	Sampled	–[c]	NP	NP	NP
G-3	Preliminary	0.15	0.06	0.0	0.0
	Detailed	0.13	0.06	0.0	0.0
	Sampled	NP	NP	NP	NP
H	Preliminary	0.15	0.06	1.4	0.8
	Detailed	0.13	0.03	7.5	0.0
	Sampled	NP	NP	NP	NP
J	Preliminary	0.03	0.00	0.2	0.0
	Detailed	NP	NP	NP	NP
	Sampled	NP	NP	NP	NP
K	Preliminary	0.10	0.03	0.0	0.2
	Detailed	NP	NP	NP	NP
	Sampled	NP	NP	NP	NP
A-G[d]	Preliminary	0.11	0.05	3.0	5.3
	Detailed	0.10	0.05	2.7	5.0
	Sampled	0.11	0.05	5.1	9.8
A-G	Average (all types)	0.11	0.05	3.6	6.7

Note: NP = survey type not performed.

[a] Faulting estimated to nearest 0.062 in.

[b] Actual number of joints distressed per 100 joints (distressed and nondistressed) in each project.

[c] Ground.

[d] Projects tested for dowel alignment.

Table 3. Average alignment values for all projects sampled.

		Alignment Value (in.)					
Project	Placement Method	ABSHR (in.)	HR (in.)	ABSLD (in.)	LD (in.)	ABSHD (in.)	HD (in.)
A	Implanted	0.431	-0.180	1.689	-1.391	0.375	0.109
B	Basket	0.391	0.100	1.493	0.195	1.432	0.371
C	Implanted	0.389	0.140	0.612	-0.356	0.540	-0.473
D	Implanted	0.402	-0.213	0.523	0.311	1.162	-0.543
E	Basket	0.373	0.043	1.178	0.413	0.880	-0.720
F	Implanted	0.360	-0.106	1.401	-1.158	0.580	-0.095
G	Implanted	0.344	0.170	2.862	2.555	1.177	-0.851
All							
Avg	Basket	0.388	0.079	1.371	0.275	1.226	-0.028
Avg	Implanted	0.386	-0.021	1.084	-0.330	0.696	-0.355
Avg	Both	0.387	0.019	1.200	-0.086	0.910	-0.224
Minimum	Both	0.344	-0.213	0.523	-1.391	0.375	-0.851
Maximum	Both	0.431	0.170	2.862	2.555	1.432	0.371
Range	Both	0.087	0.383	2.339	3.946	1.057	1.222

Note: ABSHR, absolute horizontal rotation; HR, horizontal rotation; ABSLD, absolute longitudinal displacement; LD, longitudinal displacement; ABSHD, absolute horizontal displacement; and HD, horizontal displacement.

Projects J and K, both implanted projects, were clearly superior to the remaining projects, but projects A, G, and G-2, also implanted projects, were the worst. The reason for this was identified during the alignment sampling. It was discovered that these projects possessed numerous joints in which the dowels had been omitted altogether. The remaining projects were generally rated as being in good overall condition.

The detailed visual survey produced the most extensive results of the three types of visual surveys. Only projects B, C, D, E, E-2, and H were included. These projects were considered to be the most representative projects that could be tested during the allotted sampling time span. On projects B, C, and D, all at location 1, faulting was measured. This was not possible at the other sites because of high traffic volumes. On these projects, faulting was estimated.

The sampled-joint visual survey was performed on the seven projects tested for dowel alignment. Projects C and D revealed more spalling than other projects. The faulting severity of location 1 compared with that of location 2 was also similar to the detailed survey results.

Of the 469 joints surveyed, only 7.9 percent were found to be distressed. Furthermore, 2.9 percent of the joints were classified as very minor in distress, 2.5 percent were listed in the minor category, 1.9 percent of the joints were moderately distressed, and 0.6 percent of the joints were categorized as severely distressed.

Dowel-Alignment Results

A total of seven projects was sampled for dowel alignment: projects A, B, C, D, E, F, and G. Projects A and G, those lacking dowels, were tested less extensively than were the remaining five projects. A total of 511 joints and 2,035 dowels was included in the analysis. Six characteristics were analyzed: ABSHR, HR, ABSLD, LD, ABSHD, and HD.

The results of each project along with the overall results are given in Table 3. In addition, the average results of the basket and implanted projects are shown. The ABSHR values were virtually the same for both the implanted and the basket projects, but the ABSLD and ABSHD characteristics were noticeably better in the implanted projects.

Statistical Comparison Procedure of Dowel-Alignment Results

In an effort to evaluate the data statistically, t-tests, analysis of variance (ANOVA), and pairwise comparisons of means (averages) were performed. To compare the means between two variables, t-tests were used; the ANOVA was used when more than two variables were compared, and pairwise comparisons of means were used to determine category differences when ANOVA indicated significant differences. The variables compared were project, contractor, type of dowel installation, type of form, grade, location, and joint-forming method. The level of significance employed was 0.05 (5 percent).

Table 4. Summary of alignment variables for all projects sampled.

Project	Location	Placement Method	Type of Form	Joint-Forming Method	Base	Thickness (in.)
A	1	Implanted	Rigid	Unitube	CTB	9
B	1	Basket	Rigid	Saw	CTB	9
C	1	Implanted	Slip	Unitube	CTB	9
D	1	Implanted	Slip	Unitube	CTB	9
E	2	Basket	Rigid	Saw	CTB	10
F	2	Implanted	Rigid	Saw	CTB	10
G	2	Implanted	Rigid	Saw	CTB	10

Note: CTB, cement-treated base course.

Before the statistical comparison procedure was executed, Table 4 was devised to summarize the similar and dissimilar variables of each project. These variables and the contractor variable were used to establish groupings, and the statistical tests were employed to analyze the groupings.

The actual comparison procedure was an orderly process; each level, or step, was dependent on the preceding step or steps. Each step produced one of two results: (a) a statistically significant difference between the compared variables, which indicated that the process should not progress further, or (b) no statistically significant difference between the compared variables, which indicated that the comparison analysis should proceed. Table 5 should help clarify the process. The desired overall objective was a statistically valid comparison between the basket and implanted projects.

Results of Preliminary Analysis Techniques

The comparison process described in Table 5 was performed by using the preliminary analysis technique. A summary of the results is presented in Table 6. For the variables compared in the respective steps to be classified as similar for grouping, it was required that there be no difference between them with regard to any of the three characteristics (ABSHR, ABSLD, and ABSHD). If any one characteristic produced a difference, this would indicate that the compared variables were not similar for grouping, and the comparison procedure could be stopped at that step. Once the three base steps (steps 1, 2, and 4, as shown in Table 6) had produced a difference between the compared variables, the remaining steps were automatically rendered invalid. Thus, a statistically legitimate comparison between basket projects and implanted projects never materialized when the preliminary analysis concept was used. Other conditions, however, were examined by this technique.

Table 5. Comparison procedure employed by preliminary and final analyses.

Step	Projects Compared	Variable Compared	Similar Variables
1	B versus E	Project	Basket installation, rigid-formed, contractor
2	A versus G	Project	Implanted installation, rigid-formed, contractor
3[a]	B, E versus A, G	Implanted versus basket	Contractor, rigid-formed
4	C versus D	Contractor	Implanted installation, slipformed
5[b]	A, G versus F	Contractor	Implanted installation, rigid-formed
6[c]	C, D versus A, G, F	Rigid-formed versus slipformed	Implanted installation
7[d]	C, D, A, G, F versus B, E	Implanted versus basket	None

[a] Based on steps 1 and 2.
[b] Based on step 2.
[c] Based on steps 2, 4, and 5.
[d] Based on steps 1, 2, 4, 5, and 6.

Table 6. Results of preliminary analysis technique.

Step	Projects Compared	Variable	Project Results (in.) by Characteristic Compared		
			ABSHR	ABSLD	ABSHD
1	B versus E	B	0.391	1.493	1.432
		E	0.382	1.160	0.869
		Difference[a]	No	Yes	Yes
		Conclusion[b]	Dissimilar	Dissimilar	Dissimilar
2	A versus G	G	0.344	2.862	1.177
		A	0.427	1.798	0.387
		Difference	No	Yes	Yes
		Conclusion	Dissimilar	Dissimilar	Dissimilar
3	B, E versus A, G	B, E	0.388	1.371	1.226
		A, G	0.395	2.203	0.688
		Difference	No	Yes	Yes
		Conclusion	Dissimilar	Dissimilar	Dissimilar
4	C versus D	C	0.389	0.612	0.540
		D	0.402	0.523	1.162
		Difference	No	Yes	Yes
		Conclusion	Dissimilar	Dissimilar	Dissimilar
5	F versus A, G	A, G	0.395	2.203	0.688
		F	0.360	1.401	0.580
		Difference	No	Yes	Yes
		Conclusion	Dissimilar	Dissimilar	Dissimilar
6	C, D versus A, G, F	C, D	0.393	0.582	0.747
		A, G, F	0.376	1.758	0.628
		Difference	No	Yes	Yes
		Conclusion	Dissimilar	Dissimilar	Dissimilar
7	C, D, A, G, F versus B, E	C, D, A, G, F	0.386	1.084	0.696
		B, E	0.388	1.371	1.225
		Difference	No	Yes	Yes
		Conclusion	Dissimilar	Dissimilar	Dissimilar

Note: ABSHR, absolute horizontal rotation; ABSLD, absolute longitudinal displacement; ABSHD, absolute horizontal displacement.

[a] Determination of whether there was or was not a statistically significant (at 0.05 level of significance) difference.
[b] "Dissimilar" means that compared projects should not be grouped.

The effect of dowel position on alignment was not a major objective of the study, but an analysis of this effect did produce interesting results. It was desired to determine whether the actual position of the individual dowel influenced alignment. The primary interest concentrated on the slipformed implanted projects. It was hypothesized that these projects would be more readily influenced by dowel position than the other types of projects. The reasoning was that the dowels closest to the pavement edge (or farthest away from the centerline) would tend to become more easily misaligned than the dowels near the centerline. With no rigid forms anchoring the edge of the pavement and no basket connections between the dowels, it was believed that the edge dowels might move or slip. Nevertheless, all projects were analyzed, and groupings were classified into three categories: rigid-formed basket projects, rigid-formed implanted projects, and slipformed implanted projects. Table 7 provides a summary of the alignment results for the individual dowel positions. The results indicated no substantial evidence that individual dowel position had an effect on the alignment achieved.

Results of Final Analysis Technique

The step-by-step comparison procedure employed for the preliminary method was also used for the final analysis technique. The identical steps, comparisons, and statistical tests were performed. Although there were minor changes in results between the final and preliminary methods with respect to the individual characteristics, the overall conclusions for each of the comparisons, and ultimately

Table 7. Results of alignment for individual dowel positions.

Dowel Position	ABSHR (in.)	ABSLD (in.)	ABSHD (in.)
Rigid-Formed Basket Projects			
2	0.402	1.174	0.964
3	0.385	1.344	0.993
4	0.358	1.161	0.812
5	0.422	1.189	0.967
6	0.405	1.181	0.896
7	0.368	1.233	0.889
8	0.429	1.160	0.899
9	0.317	1.178	0.917
10	0.369	1.093	0.917
11	0.412	1.295	0.830
Rigid-Formed Implanted Projects			
2	0.400	1.680	0.825
3	0.277	1.910	0.744
4	0.341	1.595	0.700
5	0.373	2.061	0.622
6	0.373	2.028	0.522
7	0.357	1.841	0.548
8	0.554	1.679	0.625
9	0.314	1.683	0.696
10	0.344	1.450	0.562
11	0.424	1.569	0.446
Slipformed Implanted Projects			
2	0.502	0.748	0.630
3	0.438	0.636	0.792
4	0.380	0.647	0.604
5	0.442	0.532	0.798
6	0.409	0.539	0.874
7	0.365	0.577	0.647
8	0.399	0.589	0.804
9	0.262	0.564	0.955
10	0.350	0.507	0.671
11	0.395	0.484	0.654

Note: ABSHR, absolute horizontal rotation; ABSLD, absolute longitudinal displacement; ABSHD, absolute horizontal displacement.

Table 8. Results of final analysis technique.

Step	Projects Compared	Variable	Project Results (in.) by Characteristic Compared		
			ABSHR	ABSLD	ABSHD
1	B versus E	B	0.391	1.493	1.432
		E	0.373	1.178	0.880
		Difference[a]	No	No	Yes
		Conclusion[b]	Dissimilar	Dissimilar	Dissimilar
2	A versus G	A	0.432	1.689	0.375
		G	0.344	2.862	1.177
		Difference	No	Yes	Yes
		Conclusion	Dissimilar	Dissimilar	Dissimilar
3	B, E versus A, G	A, G	0.395	2.203	0.688
		B, E	0.388	1.371	1.225
		Difference	No	Yes	Yes
		Conclusion	Dissimilar	Dissimilar	Dissimilar
4	C versus D	C	0.389	0.612	0.540
		D	0.402	0.523	1.162
		Difference	No	No	Yes
		Conclusion	Dissimilar	Dissimilar	Dissimilar
5	F versus A, G	A, G	0.395	2.203	0.688
		F	0.360	1.101	0.580
		Difference	No	Yes	No
		Conclusion	Dissimilar	Dissimilar	Dissimilar
6	C, D versus A, G, F	C, D	0.393	0.582	0.747
		A, G, F	0.376	1.758	0.628
		Difference	No	Yes	No
		Conclusion	Dissimilar	Dissimilar	Dissimilar
7	C, D, A, G, F versus B, E	B, E	0.388	1.371	1.225
		C, D, A, G, F	0.386	1.084	0.696
		Difference	No	Yes	Yes
		Conclusion	Dissimilar	Dissimilar	Dissimilar

Note: ABSHR, absolute horizontal rotation; ABSLD, absolute longitudinal displacement; ABSHD, absolute horizontal displacement.

[a] Determination of whether there was or was not a statistically significant (at 0.05 level of significance) difference.

[b] "Dissimilar" means that compared projects should not be grouped.

the entire study, were not affected. The results of the final method are summarized in Table 8.

The final step, the overall comparison between the basket projects and the implanted projects, showed that the implanted dowels were better aligned than the basket-assembly dowels with respect to ABSLD and ABSHD. In ABSHR, the implanting system and the basket method gave virtually identical results. Thus, the overall result was that the implanted projects were superior to the basket projects. Because of contractor inconsistencies and contractor differences, however, this conclusion must be taken with some degree of skepticism. The most interesting trait emerging from the results involved ABSHR. Neither form type, contractor, project, nor type of dowel installation generated a significant effect on ABSHR.

Correlation of Alignment to Distress

After the distress and alignment results had been reviewed, an attempt was made to relate the types of distress (spalling, faulting, and transverse cracking) to the alignment characteristics (ABSHR, ABSLD, and ABSHD). Only projects B, C, D, E, and F were included. Projects A and G were omitted due to the missing dowels. Table 9 presents a comparison of the distress results and the alignment results, and Table 10 gives the ranking of projects B-F according to results for distress and alignment.

The ABSHR results produced an extremely small range, only 0.087 in. Thus, it was concluded that no valid correlation could be demonstrated with ABSHR. Nevertheless, an attempt was made to relate ABSLD and ABSHD with the different types of distress. It was theorized that the higher (worse) the alignment value, the more frequent or severe should be the distress, but no consistent trend was discovered. In summary, no characteristic was directly linked with a specific type of distress.

Another subjective trial was attempted in an effort to relate alignment with distress. All distressed joints from the sampled-joint visual survey were compared with the nondistressed joints. As is clearly shown in Table 11, the alignment results of the distressed joints were not any worse or any better than those of the nondistressed joints. With this under consideration, it was subjectively determined that the alignment results could not be directly linked with the distress.

Table 9. Comparison of alignment and distress results.

Project	Distress Results			Alignment Results (in.)		
	Faulting[a] (in.)	Spalling[b] (%)	Transverse Cracking[b] (%)	ABSHR	ABSLD	ABSHD
A	0.14	9.2	8.2	0.431	1.689	0.375
B	0.17	0.4	1.9	0.391	1.493	1.432
C	0.11	4.2	0.3	0.389	0.612	0.540
D	0.13	7.0	3.0	0.402	0.523	1.162
E	0.06	1.2	3.6	0.373	1.178	0.880
F	0.05	0.3	0.5	0.360	1.401	0.580
G	—[c]	1.3	28.5	0.344	2.862	1.177

Note: ABSHR, absolute horizontal rotation; ABSLD, absolute longitudinal displacement; ABSHD, absolute horizontal displacement.

[a] Faulting estimated to the nearest 0.062 in.

[b] Actual number of distressed joints per 100 joints (distressed and nondistressed) in each project.

[c] Ground.

Table 10. Ranking of projects B-F by distress and alignment results.

Rank	Project by Distress Type			Project by Alignment Characteristic		
	Faulting	Spalling	Transverse Cracking	ABSHR	ABSLD	ABSHD
1	F	F	C	F	D	C
2	E	B	F	E	C	F
3	C	E	B	C	E	E
4	D	C	D	B	F	D
5	B	D	E	D	B	B

Table 11. Alignment results from distressed and nondistressed joints.

Project	Joint Condition	No. of Joints	Alignment Results[a] (in.)		
			ABSHR	ABSLD	ABSHD
B	Distressed	3	0.333	0.688	0.973
	Nondistressed	127	0.392	1.512	1.443
	Both	130	0.391	1.493	1.432
C	Distressed	7	0.322	0.594	0.830
	Nondistressed	109	0.393	0.613	0.521
	Both	116	0.389	0.612	0.540
D	Distressed	10	0.381	0.400	1.281
	Nondistressed	48	0.406	0.549	1.137
	Both	58	0.402	0.523	1.162
E	Distressed	4	0.352	0.633	0.878
	Nondistressed	72	0.384	1.189	0.870
	Both	76	0.382	1.160	0.870
F	Distressed	10	0.400	1.434	0.655
	Nondistressed	62	0.354	1.396	0.568
	Both	72	0.360	1.401	0.580
B, C, D, E, F	Distressed	34	0.367	0.797	0.929
	Nondistressed	418	0.387	1.094	0.939
	Both	452	0.385	1.072	0.938

Note: ABSHR, absolute horizontal rotation; ABSLD, absolute longitudinal displacement; ABSHD, absolute horizontal displacement.

[a] Average values.

CONCLUSIONS

After the data that were obtained from the three visual surveys and the dowel alignment measurements had been analyzed, the following results and conclusions were reached:

1. There was no significant difference between basket-assembly and implanted projects with respect to joint-related distress. Neither method was clearly superior to the other.

2. Although faulting was not severe, the pavement 10 in. thick exhibited less faulting than did the 9-in. pavement.

3. Spalling was only noticeable on the metal-insert projects. The metal-insert joints appeared to be the cause of the spalling, because there was much evidence of corroded insert segments. Raveling was also attributed to the metal inserts.

4. The results of the visual surveys revealed minor distress in all projects except for two special cases, projects A and G. Transverse cracking was not a problem on any project except those two. Both projects A and G were severely distressed. The reason for this distress was probably the high percentage of joints that contained no dowels. The omission of these dowels is the likely cause of the widespread transverse cracking and severe faulting encountered on these projects.

5. The results of the analyses on the alignment data indicated that no valid statistical conclusion could be reached for the comparison between the implanting and basket-assembly dowel-placement methods. The overall results, which must be viewed with some skepticism, showed that the dowels in the implanted projects, on the average, were better aligned than were the dowels in the basket projects. It could not be shown statistically, however, that this difference could be attributed strictly to the dowel-placement method (implanted versus basket) and that other factors, such as contractor difference and contractor inconsistency, did not also contribute to the difference.

6. The alignment error of the dowel in the horizontal plane, or skewness, averaged approximately 0.375 in. for both basket and implanted projects.

7. With respect to the longitudinal position of the dowel at the joint, the implanted projects produced an average error of approximately 1 in., or about 0.375 in. better than the results of the basket projects.

8. Regarding the horizontal position of the dowel at the joint, the error for the implanted projects, averaging approximately 0.75 in., was 0.50 in. better than the average error found on the basket projects.

9. The position of the dowel, whether it was the second, third, fourth, and so on, from the edge of the pavement, did not have an effect on the alignment results for the dowels.

10. There was also no effect from pavement grade--uphill, level, or downhill--on the dowel alignment or joint-distress results.

11. No correlation could be found between the alignment characteristics considered--absolute horizontal rotation (ABSHR), absolute longitudinal displacement (ABSLD), and absolute horizontal displacement (ABSHD)--and the various distress types (faulting, spalling, and transverse cracking).

12. There was no evidence to identify dowel-bar alignment errors as the cause of pavement distress. Of the distressed joints that were actually tested for dowel alignment, the alignment was neither better nor worse than was the alignment of the dowels in the joints that exhibited no distress. There was therefore no evidence to conclude that the distress was directly linked with the type of dowel misalignment that was measured in this study. It should be noted, however, that the literature search indicated that vertical dowel misalignment may be more significant than horizontal alignment errors in leading to joint-related distress. Because the limitation imposed on coring precluded the opportunity of measuring vertical alignment, there is no way of knowing from this study whether or not vertical dowel misalignment was the cause of the joint distress that was observed.

13. There is no statistical proof that either basket projects or implanted projects are superior. There are indications that dowel alignment and joint-related distress may be more influenced by factors other than dowel-placement method. Contractor difference and inconsistency by the same contractor appear to be major factors in dowel alignment. There was a wide variation in dowel alignment between projects, even when the identical type of dowel installation (basket versus implanted), form type (rigid form versus slipform), and contractor were present. Inspection, supervision, work-crew difference, and equipment difference may be important factors in determining dowel alignment. Also, the attitude of the contractor toward quality construction and the need to finish a project quickly may also influence alignment. The type of dowel installation does not appear to be the sole determining factor in dowel alignment.

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Effect of Hot Climate on Shear Strength of Concrete

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Many construction projects are being carried out in countries known to have a hot climate during the major part of the year. High-temperature conditions create problems in preparation, placement, and curing of concrete and adversely affect the properties of concrete. Results are presented of tests on reinforced-concrete beams of different sizes prepared and cured at various temperatures; the tests were performed under both natural atmospheric conditions and controlled laboratory conditions. Tests have shown that even if the concrete mix is so designed to give the required compressive strength of concrete in high-temperature conditions, the shear strength of the concrete is still reduced by 7 to 20 percent in the temperature range of 90 to 113°F.

It is generally known that special problems are created when concreting is done in hot climatic conditions and that the quality of the concrete is adversely affected by high temperature during mixing, placing, and curing. Rapid evaporation of water at the time the hot ingredients are mixed occurs at high temperatures; this results in lower slump, which is generally restored by adding more water. This increased demand for water is considered to be largely responsible for the reduced strength of the concrete (1,2).

Furthermore, under high-temperature conditions cement sets faster, and it becomes difficult to compact and finish the concrete (3). The American Concrete Institute (ACI) Manual of Concrete Practice (4) gives the harmful effects of concreting under high-temperature conditions, and the necessary precautions to be taken in advance to minimize these effects are also given in various books and publications (1-5). In the construction specifications for regions with hot climates, it is required that the concrete temperature not exceed 90°F; hence either ice is added to reduce the temperature of the concrete or concreting is done in the evening when the atmospheric temperature is low enough so that the concrete can be prepared and placed at a temperature not exceeding 90°F. Sometimes it is impossible to avoid concreting under high-temperature conditions; precautions are then required, which not only are difficult to follow but add to the cost of the concrete. Even if the temperature of the concrete is lowered to 90°F or less and the workability is restored by adding the proper amount of extra water, the curing problem remains, because the process is to be carried out in hot weather for at least 7 days, preferably longer.

The compressive strength of concrete is the most important property for designing concrete structures. The shear, tensile, and bond strengths of concrete are expressed in terms of its compressive strength (6), which in turn is greatly influenced by the effective water/cement ratio. Although the extra quantity of water required at high temperatures can be estimated by using the information given in the ACI Manual of Concrete Practice (4), it is difficult to do so accurately under changing atmospheric conditions; the result is that too much extra water is added, which yields a higher effective water/cement ratio and lower compressive strength.

Moreover, it must be emphasized that natural atmospheric conditions in a hot climate are different from controlled laboratory conditions, mainly because the atmospheric temperature does not remain constant throughout the day. The high-temperature conditions prevail for only a few hours during the middle of the day, whereas the temperature at night may even be lower than 86°F. Therefore, the test specimens must be cured at varying daily temperatures. This is perhaps one of the main reasons for the conflicting results obtained about the effect of high temperature on the compressive strength of concrete (3,5,7-11).

Tests conducted at the University of Petroleum and Minerals, Dhahran, Saudi Arabia (12), have shown that if just sufficient extra water is added to compensate for the loss caused by evaporation in high-temperature conditions, which keeps the effective water/cement ratio unchanged, and if curing of the concrete is done properly at varying daily temperatures, the compressive strength of the concrete is unaffected even at concrete temperatures as high as 113°F. On the other hand, even if the concrete temperature is lowered by taking necessary precautions, improper curing in hot climatic conditions results in lower concrete compressive strength.

Therefore, if a concrete mix could be so designed to give the specified compressive strength when the mix is prepared at the prevailing high temperature and in the curing conditions of the natural atmosphere, the other properties of concrete that are known to depend on the compressive strength, such as bond strength (development length), shear strength, modulus of rupture, and tensile (split-cylinder) strength, should remain unaffected. Tests on reinforced-concrete beams with varying lengths of embedment (13) have shown that when beams are prepared and cured in hot weather, a reduction in the bond between steel and concrete results. This reduced bond causes a reduction in the moment capacity of these beams compared with that of beams prepared and cured under normal laboratory conditions even if the moment capacity is computed by using the actual compressive strength of the concrete prepared under both conditions, which eliminates the effect of hot weather. Consequently, the following test program was carried out to determine the effect of hot weather on the shear strength of concrete.

TEST PROGRAM

Two series of specimens were prepared at different