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CONSTRUCTION PRODUCTIVITY ADVANCEMENT RESEARCH (CPAR) PROGRAM

APPLICATION OF ROLLER-COMPACTED CONCRETE (RCC) TECHNOLOGY TO ROADWAY PAVING

by

Dennis Ludwig, Antonio Nanni, James E. Shoenberger

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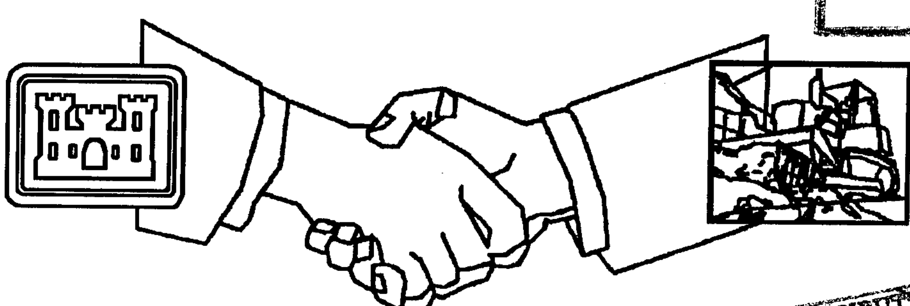

A Corps/Industry Partnership to Advance Construction Productivity and Reduce Costs

Construction Productivity Advancement Research (CPAR) Program

Technical Report
CPAR-GL-94-1
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Application of Roller-Compacted Concrete (RCC) Technology to Roadway Paving

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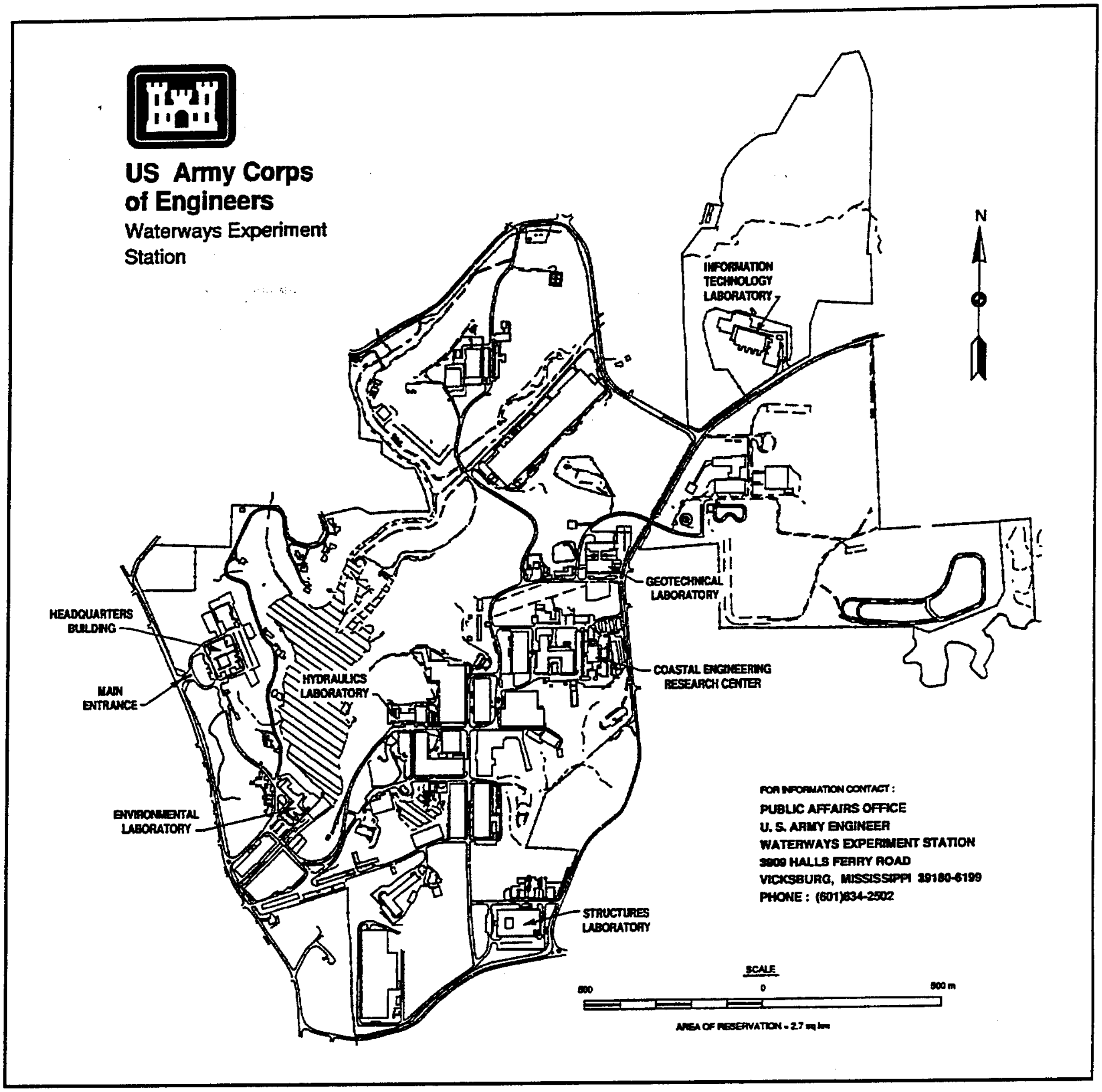

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Preface

Section 7 of the Water Resources Development Act of 1988, P.L. 100-676, 33 U.S.C. 2313, and the Stevenson-Wydler Technology Innovation Act of 1980, as amended, 15 U.S.C. 37102a, provide the legislative authority for the Construction Productivity Advancement Research (CPAR) Program. The CPAR Program allows the U.S. Army Corps of Engineers (USACE) to enter into cooperative research and development agreements with construction industry partners to conduct cost-shared, collaborative efforts with the goal of improving construction productivity.

The CPAR project "Application of Roller-Compacted Concrete (RCC) Technology to Roadway Paving" was a collaborative effort of the Geotechnical Laboratory (GL) of the U.S. Army Engineer Waterways Experiment Station (WES) and the Pennsylvania State University (PSU), doing business as the Pennsylvania Transportation Institute. The work was conducted from October 1989 to March 1993. The USACE Technical Monitor was Mr. Gregory Hughes.

The project was conducted under the general supervision of Dr. W. F. Marcuson III, Director, GL, WES, and under the direct supervision of Mr. H. H. Ulery, Jr., former Chief, Pavement Systems Division (PSD), GL; Dr. G. M. Hammitt II, Chief, PSD; Dr. R. S. Rollings, former Chief, Materials Research and Construction Technology Branch (MRCTB), PSD; and Mr. T. W. Vollor, Chief, MRCTB. The WES Principal Investigator was Mr. James E. Shoenberger, MRCTB, and the PSU Principal Investigator was Dr. Antonio Nanni. The report was prepared by Mr. Dennis Ludwig, PSU; Dr. Nanni; and Mr. Shoenberger.

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At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

1 Description of Research and Development Partnership

In September 1990, the U. S. Army Engineer Waterways Experiment Station (WES), Pennsylvania Department of Transportation (PADOT), and Pennsylvania Transportation Institute (PTI) entered into a Cooperative Research and Development Agreement (CRDA). This agreement was a part of the U.S. Army Corps of Engineers' Construction Productivity Advancement Research (CPAR) Program. The purpose of the research under this agreement was to investigate the performance of a roller-compacted concrete (RCC) pavement for use as a roadway pavement.

The PADOT intended to supply an RCC paving project as a major part of their contribution to the partnership. The RCC test section was to have been placed on several miles of a four-lane divided state highway in southwestern Pennsylvania. Failure to have a contractor bid the planned paving project at an acceptable price caused PADOT to have to withdraw from participation in the program. All contractor bids on the project were at least 30 percent over the estimated construction cost. Bid costs for the RCC portion of the project were not greatly above the estimate; however, a separate item for drainage was greatly above estimated costs. PADOT personnel felt that concerns over meeting RCC specified requirements caused the bidding contractors to overprice the drainage work as a hedge against pay reductions for non-compliance on the RCC portion of the project. This project was later rebid with conventional portland cement concrete (PCC) as an option; due to the aforementioned conditions, a contractor using conventional PCC paving supplied the low bid. In June 1992, an amendment to the existing CRDA was signed between WES and PTI, whereby PTI would provide an acceptable test pavement through Construction Technology Laboratories, Inc. (CTL).

CPAR is a cost-shared research and development partnership between the Corps and the U.S. construction industry, academic institutions, or other public or private entities who are interested in construction productivity and competitiveness. CPAR is designed to promote and assist in the advancement of ideas and technologies that will have a direct positive impact on construction productivity and project costs and on Corps mission accomplishment. The CPAR Program has received strong support from the

U.S. construction industry, and numerous projects have been funded since the program was initiated in 1989.

This research was conducted jointly between WES and PTI. PTI contracted through CTL with Peltz Companies, the paving contractor, and with Granite Rock, the pavement owner. WES and PTI also developed a plan of test that was compatible with the paving project. WES provided technical support during the construction and assisted in evaluation after construction. PTI, CTL, and the pavement owners' laboratory provided materials testing during and after construction.

2 Introduction

Background

High-speed roadway pavements require smooth, waterproof, and load-bearing wearing surfaces. In the past, there were two basic options for this wearing surface: PCC or asphalt concrete (AC). In the last 10 to 15 years, another option has become more widely used for low-speed applications: RCC. Through the use of high-quality aggregates with gradations typical of those used for AC and improved equipment and procedures, RCC construction practices can provide concrete pavements that are functionally the equivalent of conventional PCC pavements. RCC pavements behave and therefore are designed as rigid or PCC pavements.

RCC pavement is a construction procedure in which PCC is placed with asphalt paving construction methods and equipment. RCC is a very stiff (zero-slump) concrete mixture that is placed with an asphalt paver or other similar equipment such as that used for stabilized base placement and then rolled with vibratory and pneumatic-tire rollers. The consistency of fresh RCC mixture, with its cohesive nature, can be described as a wet dirty or wet cohesive gravel. RCC pavements have been placed with reported cost savings of 10 to 30 percent over conventional concrete pavements (Pittman 1986, Shoenberger et al. 1994). The cost savings are normally achieved through the elimination of forms or large slipform pavers, surface texturing, and in initial RCC construction, saw cutting for contraction joints. Current procedures are to use sawed construction joints at locations where a crack is expected.

There are two applications of RCC being used today: dams and pavements. This research project dealt exclusively with RCC pavements, so only a brief discussion of RCC dams is included in the following section. The rest of the report will then discuss the RCC pavement technology.

Objective

The objective of this project was to demonstrate the feasibility of using RCC as a high-speed pavement surface. To meet the objective of building a pavement surface suitable for high-speed applications requires satisfactory skid resistance and surface-smoothness or rideability.

Scope

An RCC test section was constructed. The test section included a small parking lot and a two-lane roadway. During the construction of these sections, three major parameters were varied: paver speed, rolling amount, and joint spacing. The paver speed was varied to determine what effect, if any, this has on the following properties: average lay-down density, average final density, rideability, skid resistance, load transfer, and density profiles. The load transfer was determined at transverse joints and transverse cracks by using falling weight deflectometer (FWD) data. The average lay-down and final densities of the RCC pavement were determined using a nuclear density device, which determined the density of various depths throughout the pavement. The density profiles show how the density varied from top to bottom of an RCC section. The rolling amount was varied to determine its effect on all of the same properties as paver speed except lay-down density because only the paver speed affects the lay-down density. The joint spacing was varied to examine an optimum spacing which would not develop intermediate cracking and would provide the desired rideability and load transfer.

Lay-down density, final density, aggregate interlock, and density profiles are measures of the RCC's physical properties. On the other hand, rideability, skid resistance, aggregate interlock, and cracking are measures of how well RCC would work under high-speed traffic conditions.

3 Use of RCC

Dams

RCC has been used for building dams in the United States since 1982. In that year, the first RCC dam was completed -- the Willow Creek Dam near Heppner, OR (Lawrence 1988). RCC placed for dams is similar to that of RCC for pavements except that bulldozers, graders, or spreading boxes are customarily used to place the RCC instead of pavers and the mixtures are generally leaner than pavement mixtures. Another major difference between the two technologies is the fact that the dams use a maximum aggregate size of 1-1/2 in. (3.8 cm) while maximum aggregate size of the pavement is generally 3/4 to 1 in. (1.91 to 2.54 cm). RCC has been used for constructing dams for many of the same reasons that it is being considered for use as a paving material. These reasons include the advantages of a quicker, simplified, and more economical construction process.

Pavements

RCC has been used as a paving material since the early 1930's. It was being used at that time in both Sweden and Australia. The first United States' RCC pavement was at an airfield in Yakima, WA, in 1942 (American Concrete Institute (ACI) 1991).

In the mid-1970's, WES evaluated RCC as a construction method to use substandard or marginal quality materials. These studies included applications for the military and commercial users (Burns 1976, Grau 1979).

Starting in the mid-1980's, there was an increase in the number of RCC pavement projects constructed.

In 1984, an 18,150-yd^2 (15,180-m^2) by 10-in.- (25.0-cm-) thick RCC pavement was constructed at Fort Hood, TX. The RCC pavement was a tracked vehicle hardstand (Hutchinson, Ragan, and Pittman 1987; and Ragan 1988).

In 1986, an RCC pavement was constructed at Burlington Northern's internodal hub facility in Houston, TX. The pavement was a loading apron that enabled the rail freight cars to be loaded and/or unloaded by large, heavy, slow-moving vehicles such as forklifts, trucks, and other such equipment. The RCC was placed in a single 18-in. (45.7-cm) lift. The total area for the pavement was 53,666 yd^2 (44,871 m^2), and it was the largest RCC project undertaken in the United States at that time. RCC was chosen for this project because it was the least expensive option available (*Highway and Heavy Construction* 1986). Also in 1986, a 17,000 yd^2 (14,200 m^2) by 7-in.- (18.0-cm-) thick RCC pavement was constructed at Harvey Barracks, West Germany. This RCC pavement was used as a secure parking area for rubber-tire and tracked vehicles (Ragan 1988, Pittman 1989).

In 1988 and 1989, 400,000 yd^2 (334,450 m^2) of RCC pavement were placed at the Fort Drum Army Base near Watertown, NY. The pavement, which was placed at vehicle maintenance facilities, was 10 in. (25.4 cm) thick (Munn 1989).

In 1989, at a Saturn Corporation automobile factory near Spring Hill, TN, more than 650,000 yd^2 (543,483 m^2) of 7-in.- (17.9-cm-) thick RCC pavement were placed. The pavement was used for constructing parking lots throughout the facility. RCC was chosen because it was the most economical alternative (Munn 1989). Also in 1989, RCC was used in a hangar for two of the Presidential Air Force One Jets at Andrews Air Force Base, near Washington, DC. The project used 14-in.- (35.6-cm-) thick RCC surfacings in the following areas: 140,000 ft^2 (13,006 m^2) hangar; 64,000 yd^2 (53,512 m^2) apron, and 20,000 yd^2 (16,723 m^2) parking areas (Munn 1989).

In 1992, Safeway Stores Inc. used RCC at their large warehouse site just outside Tracy, CA. This was the first major application of RCC in California as a pavement surfacing. The total pavement area was 270,000 yd^2 (225,754 m^2). Approximately 220,000 yd^2 (183,947 m^2) of this pavement had an 8-in.- (20.3-cm-) thick RCC surfacing. The remaining 50,000 yd^2 (41,806 m^2) had a 7-in.- (17.9-cm-) thick RCC surfacing. RCC was used in this warehouse project for the following reasons: low initial cost, rapid constructability, durability under heavy wheel loads in all weather conditions, and long-lasting performance with low maintenance (*Concrete Construction* 1992). However, since being opened to traffic, distresses such as pumping and cracking have occurred in the RCC, especially in areas of channelized traffic.[1]

In all of the above mentioned projects, there was one thing in common: the pavements supported heavy loads and slow-moving traffic. This common factor was due to the fact that RCC has typically not had sufficient surface smoothness (rough) for use with conventional high-speed traffic. The surface

[1] Personal Communication, 23 February 1994, Dennis McClanahan, Granite Rock, Redwood City, CA.

smoothness of a pavement affects the rideability, which is judged by the people driving on the surface. A smooth pavement is more rideable than a rough one. Since RCC pavements have typically been rough, drivers would feel that they were not getting a comfortable ride. That is why RCC has traditionally been used where the rideability of the pavement is not of major concern, i.e. train yards, tank stands, warehouses, etc.

Advantages and Disadvantages

Advantages and disadvantages to RCC pavements are given in Borges (1987). The advantages included the following:

a. Low construction cost.

b. Wide range of usable aggregates.

c. Shorter haul distance.

d. Less used cement than PCC.

e. Rapid placement.

f. Small construction crew.

g. No form work or paving trains required.

h. Hand finishing not required.

i. Long-term durability.

j. Lower maintenance cost.

k. Negligible rutting or creep under long-term loads.

l. Potential for use of asphalt construction equipment.

The validity of this list varies with the design and application of the RCC pavement. Letters *a* through *h* generally are advantages when RCC is compared with PCC. The first advantage, the lower construction cost of RCC as compared with PCC, comes from several of the other advantages (*b-h*). Initial uses of RCC involve a wider range of aggregates; and marginal materials can be used with RCC because the constituents are dry mixed and the consolidation is done by compaction. However, construction practices since the mid-1980's have been to use an aggregate gradation curve more stringent than that used for PCC. RCC must have a gradation that allows for stability under the rollers. Initial experiences with RCC surface texture led to limiting the nominal maximum aggregate size to 3/4 in. (1.91 cm).

Advantages *c* through *e* are questionable when compared with PCC placement with slipform placement. The use of less cement should be viable due to the low water/cement (w/c) ratios possible with RCC. However, experience has shown that, due to the variability in placement and density profiles obtained throughout the RCC, the mixture is normally proportioned for strengths greater than those used for PCC.

Advantages *f* through *h* are usually viable for RCC paving. RCC generally requires a smaller construction crew because there is no hand finishing required, as there is with PCC. The elimination of form work or large paving trains and finishing work provides the largest advantage of RCC.

Of the remaining advantages (*i-l*), three (*i-k*) are viable advantages over AC, especially where load applications are from heavy or tracked vehicle traffic. The last advantage (*l*) of RCC is that, even though it is a new technology, it utilizes equipment which already exists and is being used by the construction industry, such as asphalt pavers and rollers.

Some of the disadvantages of RCC given by Borges (1987) are as follows.

a. Smoothness difficult to achieve.

b. Raveling of cracks.

c. Contractor education required.

d. New technology.

The fact that an adequate smoothness is difficult to achieve makes RCC difficult to use for high-speed pavements; as a result, nearly all of the existing RCC pavements are used in areas such as factories, military bases, freight yards, and warehouses. Initially, the RCC was allowed to crack (was not saw cut), and ravelling occurred at these cracks. This condition decreased the smoothness and therefore the rideability of the RCC pavements. To prevent the raveling, contraction joints need to be saw cut, a procedure that increases the cost of RCC. The last two disadvantages -- contractor education required, and new technology -- go hand in hand.

4 Construction

As was found in various reports on RCC (Pittman 1986; White 1986; Piggott 1986; ACI 1991), several factors have affected the production of a quality RCC pavement. These factors include subgrade preparation, concrete mixture, placement, compaction, joints, and curing. For this project, several parameters related to those factors were varied and include mix design/composition, paver speed, section thickness, lift number, rolling amount, rolling type (static versus vibratory), joint spacing, joint cutting method, and curing method.

Site Description

Photos showing the general site conditions are given in Appendix A. Photos A1 through A4 show the completed roadway; Photo A5 shows the completed parking lot; and Photo A6 shows the typical truck traffic. Photos A7 through A10 are of both transverse and longitudinal joints.

The site for this RCC project was a Granite Rock, Inc., quarry located south of Hollister, CA. Hollister is located approximately 65 miles (104.61 km) south of San Jose. Granite Rock is a major supplier of aggregates for both PCC and AC in California.

There were two construction areas on this project, a roadway and a parking lot. The roadway was located adjacent to California Route 29. It was divided into two 14-ft- (4.3-m-) wide lanes for a total roadway width of 28 ft (8.5 m); each lane was 1,525 ft (465 m) long. From Route 29, there were approximately 100 ft (30 m) of AC pavement before the RCC roadway started. The RCC began with station (sta) 0+00. There was a nearly 90-deg curve starting near sta 8+50 and ending approximately 200 ft (60 m) from the end of the roadway test section. The parking lot was 100 ft (30 m) by 39 ft (12 m). Three 13-ft- (4.0-m-) wide by 100-ft- (30-m-) long sections were placed to make a total area of 100 ft (30 m) by 39 ft (12 m). The parking lot was adjacent to an existing building.

Since the roadway was the only way into and out of the quarry and ran through agricultural fields, there was no way to construct a temporary entry and exit for the quarry. This meant the roadway had to be opened 3 days after construction had taken place. The typical traffic loads placed on the roadway are from trucks with double bottom-dump trailers and an average weight of 40,000 lb (18,144 kg). From 19 April 1992 to 3 December 1992, the roadway was subjected to 9,400 truck-load applications for a total load of approximately 188,000 tons.

For the detailed layout of the varied parameters for Lane I, Lane II, and the parking lot, see Appendix B. Lane I was constructed on 15 and 16 April 1992; Lane II was constructed on 24 April 1992; and the parking lot was constructed on 15 April 1992.

RCC Mixture

A concrete mixture for RCC has constituent materials similar to conventional PCC. Those ingredients are aggregates (both coarse and fine), cementitious materials, water, and possibly admixtures. For this project, the only constituent materials that were varied from mixture to mixture were the relative amounts of fine and coarse aggregates. All of the other constituent materials were held constant for each of the four mixes. A description of each constituent as it applies to RCC follows. See Appendix C for the exact amount of each constituent for the mixes used in this project.

Materials

Aggregates

The aggregate gradation recommended by the Corps for RCC pavement is similar to that used for AC mixtures. Some of the initial RCC mixtures used gradations found in American Society for Testing and Materials (ASTM) C 33, Concrete Aggregates; however, more recently, satisfactory performance has been obtained with gradations similar to those used for AC. RCC paving mixtures used initially in the United States contained nominal maximum aggregate sizes up to 1.5 in. (38 mm); however, the majority of RCC pavement placed today has a nominal maximum aggregate size of 3/4 in. (19 mm). The Corps limits the percentage of aggregate passing the No. 200 sieve from 2 to 8 percent. In Australia, a gradation similar to that selected by the Corps is used, except that 1.5 in. (38 mm) is allowed as the maximum size aggregate and 5 to 10 percent passing the No. 200 sieve (Murphy 1987). In Canada, a well-graded aggregate is used with limits of 3/4 in. (19 mm) as the maximum size aggregate and 2 to 14 percent passing the No. 200 sieve (Piggott 1986). To prevent segregation and provide satisfactory surface quality, the maximum size aggregate used in Spain is limited to 1 in. (25 mm), with 3/4 in. (19 mm) used most frequently, and 10 to 20 percent of the aggregate by weight passes the No. 200 sieve (Jofre, Fernandez, and Molina 1988). Crushed aggregates have been used in most instances for RCC pavement mixtures. Natural sands have sometimes been blended into these mixtures to meet gradation requirements. Crushed aggregates compared to uncrushed aggregates in an RCC pavements mixtures are normally more difficult to compact; however, they are less likely to segregate during transport and placement (Ragan 1988). RCC composed of uncrushed aggregate usually needs less water to reach a given consistency than an RCC mixture that uses crushed aggregate. Crushed aggregate is also generally more stable during compaction, and a mixture using crushed aggregate usually achieves a higher flexural strength than a mixture using uncrushed aggregate (ACI 1991). When properly mixed, transported, and placed, no RCC pavement constructed with 3/4 nominal maximum size aggregate in a well-graded blend of aggregates has had problems with segregation or an open-textured surface (Ragan 1988). The major gradation variation between RCC and conventional PCC occurs in the RCC having more material passing the No. 4 sieve and succeeding sieves, through the No. 200 sieve. This additional final material provides for an acceptable surface texture and assists in presenting segregation. The final material, if non-plastic, can reduce the amount of cementitious material required (Hutchinson, Ragan, and Pittman 1987). The material passing the No. 40 sieve should have a liquid limit and plasticity index not exceeding 20 and 4, respectively (Hutchinston, Ragan, Pittman 1987). Plastic fines have been shown to greatly reduce the strength of zero-slump concrete mixtures (Hague 1981). The use of plastic fines has also lowered the skid resistance of the pavement surface when it is wet (Grau 1979).

Typical aggregate gradation curves for RCC and PCC mixtures are given in Figures 1 and 2 respectively.

The aggregate material used for this project was 100-percent crushed granite supplied by Granite Rock. The overall gradation of each of the four mixes was slightly different. (See Appendix C for the gradations of each mix as they compare to the typical aggregate gradation envelope for RCC mixture.) The aggregates were washed prior to mixing. The specific gravity of the aggregate was 2.80. The amount of each aggregate in each of the four mixes is listed in Table 1.

Materials

The cementitious materials used in RCC pavements often include Type I portland cement with 15- to 20-percent Class C or Class F fly ash. The fly ash is added to provide additional fine material needed to improve compactability (ACI 1991). Class F fly ash has only pozzolonic properties and has a minimum requirement of 70.0-percent silicon dioxide, aluminum oxide, and iron oxide. Class C, on the other hand, may have some cementing abilities and has a minimum requirement of 50.0-percent silicon dioxide, aluminum oxide, and iron oxide. This lower requirement allows for more calcium oxide to be in the Class C fly ash; because of the calcium oxide,

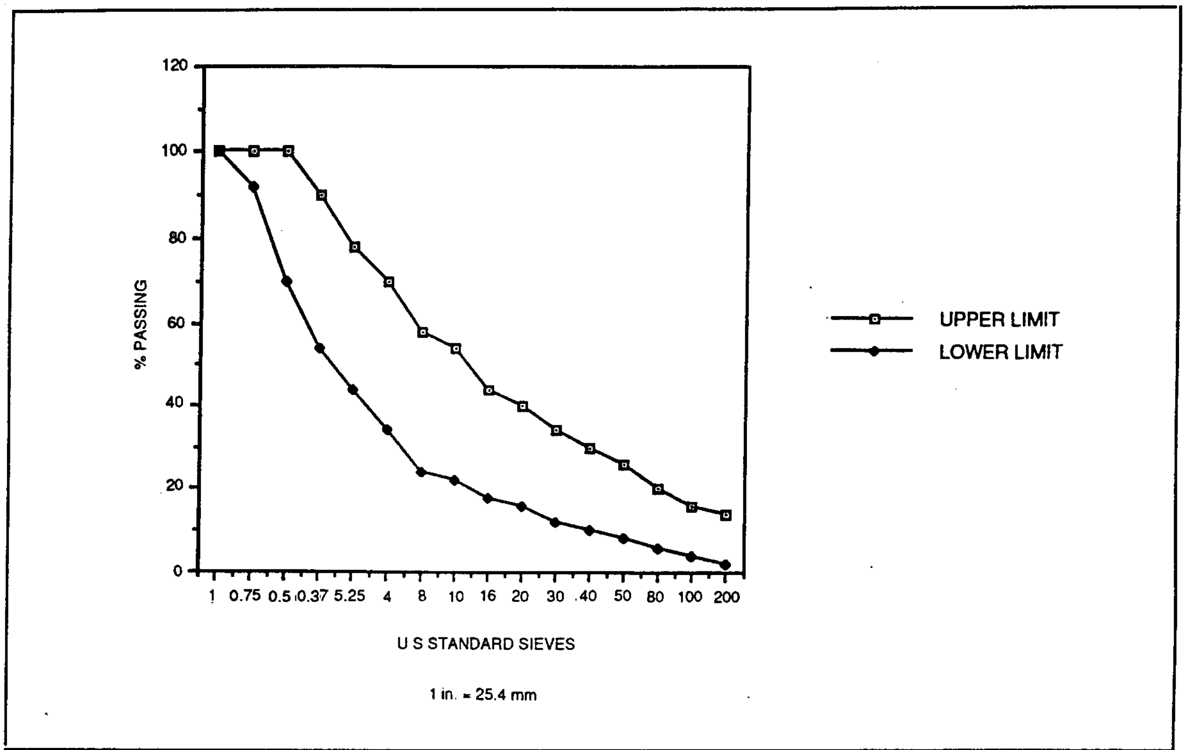

Figure 1. RCC aggregate gradation curve

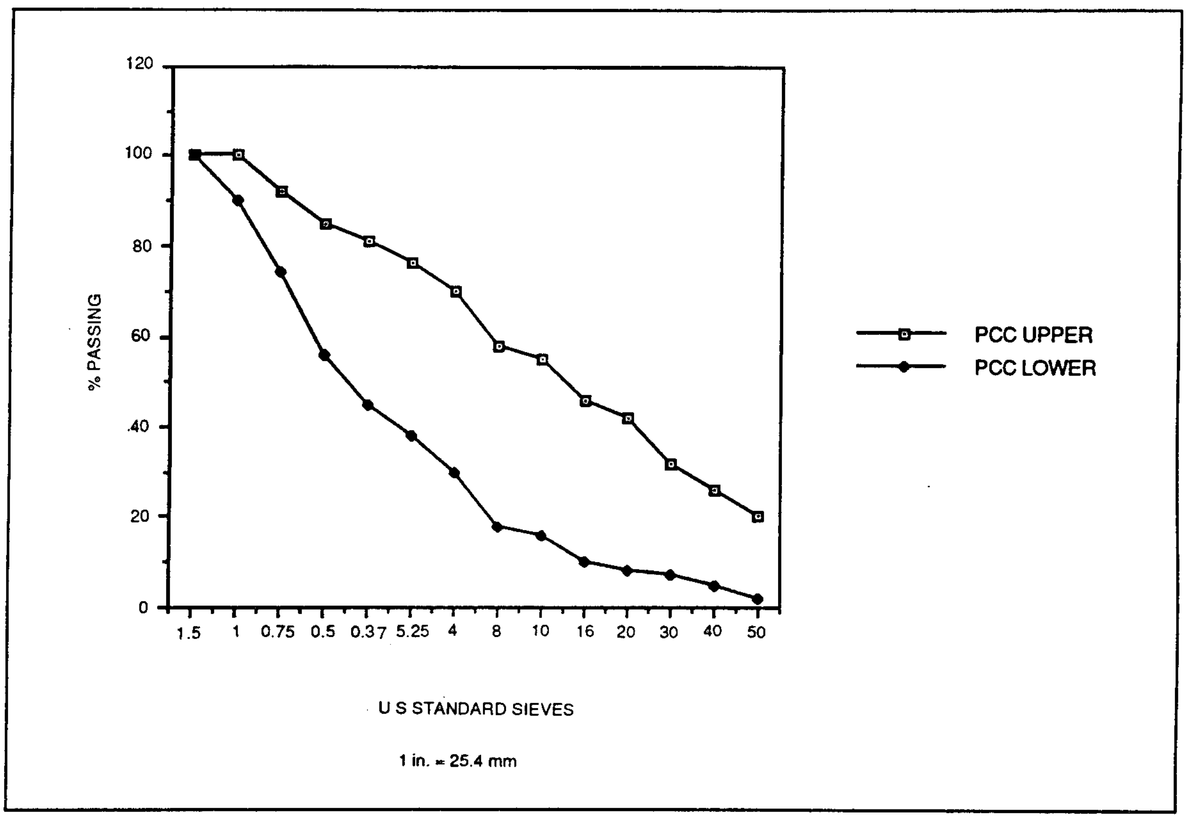

Figure 2. PCC aggregate gradation curve

Table 1
Amount of Fine and Coarse Aggregates per Mix

Mix	Fine Aggregate lb/yd^3 (kg/m^3)	Coarse Aggregate lb/yd^3 (kg/m^3)	Fine to Coarse Aggregate Ratio
A-1	1,687 (995)	2,016 (1,189)	0.84
A-2	1,734 (1,023)	2,000 (1,180)	0.87
B-1	1,838 (1,084)	1,860 (1,097)	0.99
B-2	1,787 (1,054)	1,960 (1,156)	0.91

Class C has some cementitious properties (Helmuth 1987). Fly ash can be used in RCC both for its pozzolonic and cementitious properties. The pozzolonic properties and the cementitious properties are used in an attempt to reduce the amount of portland cement used resulting in lowered costs. RCC mixtures with fly ash versus those without should provide RCC of equal long-term strength with lower shrinkage and improved workability. The use of fly ash is mandated for Federal Government construction unless it can be proved to be undesirable.

For this project, the cementitious material used was a blended portland Type I cement known as Type IP. The binder consisted of 82-percent portland Type I and 18-percent Class F fly ash. Each of the four mixes used 500 lb/yd^3 (296 kg/m^3) of this Type IP cement.

Water

Water requirements for RCC are similar to those of PCC. Water in an RCC mixture serves the following main purposes, which are the same that it serves in PCC: (a) it reacts with the cementitious materials to produce hydration, (b) it acts as a lubricant to contribute to the workability of the mixture, and (c) it secures the space necessary to allow the development of hydration products (Popovics 1979).

An RCC mix is very stiff (little to no slump) because of the relatively low amount of water in the mix compared to conventional PCC mixtures. This results in low water-cement ratio or water-cementitious materials ratio (w/c) for RCC. As an example, the w/c for all of the mixes in the project was 0.33. Due to the low w/c of RCC, there is no large excess of free water available for hydrating the cement; it should therefore not be allowed to dry, or scaling of the surface could result (Piggott 1986). The minimum w/c required for complete hydration is approximately 0.22 to 0.25 (Kosmatka and Panarese 1988). However, most conventional theories on hydration state that the minimum w/c should be 0.38 for complete hydration and required physical properties of the PCC (Philleo 1986). Such a low w/c is possible because

RCC is consolidated by compaction -- a force plus vibration applied onto the concrete -- whereas PCC is consolidated by vibration alone -- free movement of the concrete particles. Vibration alone needs more water to allow the unrestricted free movement of the particles. Slipform pavers have placed PCC mixtures with gradations containing fewer fines than comparable RCC mixtures with w/c approaching 0.38 or lower with water-reducing admixtures. Each mixture used during this project used 167 lb of water per cubic yard (99 kg/m^3).

Admixtures

Air-entraining admixtures have had limited use with mixed results in RCC pavements. The main reason for this lack of use of air-entraining admixtures for RCC is the way that RCC is generally batched. It is usually batched in a pugmill mixer, and effectively placing air-entraining admixtures into this type of mixer and getting even distribution has proved to be very difficult, but not impossible (Shoenberger et al. 1994). Up until this point, the most effective means of producing an RCC pavement that is resistant to frost damage is for the mix to have a low w/c. This low w/c will yield a paste that has a low permeability so that once the concrete has cured, it becomes more difficult for the concrete to be critically saturated by outside moisture (ACI 1991). Chemical admixtures, such as water-reducing and retarding admixtures, have not seen widespread use either. Since RCC is compacted and not vibrated, the need for water reducers is questionable. It is supposed, though, that retarding agents may be advantageous in extending the setting time so that there is more time available for compaction. Also, retarding agents may be used to help improve the bond between adjacent lanes and succeeding lifts by permitting more time between placements. Plasticizers may also have some ability to be used in RCC to improve compactability (ACI 1991).

In this project, WR Grace supplied a chemical admixture Daracem 55, a midrange water reducer, to be used in the mixes. The Daracem 55 was used to see what effects it would have on the finishing of the parking lot. Daracem 55 was added to the concrete mixture at a rate of 6 oz/100 lb (0.17 L/45.4 kg) of cement.

Mixing

The concrete for RCC needs a vigorous mixing action to ensure that the relatively small amount of water gets distributed throughout the entire matrix and the constituents are homogeneously spread. The most commonly used mixer type for this vigorous mixing is a twin-shaft pugmill mixer that is also widely used for mixing AC (Pittman 1986). The pugmill mixer is also widely used for RCC pavements because it can be easily transported to the site and is easily set up. It also has a relatively large output capacity.

The mixer used during this project was an Aran ASR-280E twin-shaft continuous pugmill mixer with an output capacity of 365 yd^3/hr (279 m^3/hr). The ingredients were metered by means of hydraulically driven, volumetric feeders.

Subgrade/Base Preparation

The preparation of the subgrade/base for RCC is no different than for any other rigid pavement structure type (Piggott 1986). These preparations include ensuring a uniform subgrade; not allowing water into possible freezing zones; removing soft materials; and removing any fine-grained, frost susceptible materials. The subgrade for an RCC pavement must be well compacted because a soft subgrade would prevent proper compaction of the RCC. In addition, the subgrade must be sufficiently smooth to ensure that the RCC wearing surface is smooth.

The 6-in.-thick base course placed for the RCC pavement and for the parking area consisted of 100-percent crushed granite. The aggregate was compacted to a minimum of 95 percent of maximum density as specified in ASTM C 33. The subbase material was a class 4 aggregate subbase placed 6 in. thick. The base and the subbase used a 3/4-in. (19 mm) maximum aggregate particle size.

Placement

Photos of the paver and the paving operation are found in Appendix D (Photos D1 through D7). These photos show the paver, grade control with a stringline, the loading of the paver, and the freshly placed RCC.

The reason that RCC is faster to construct and therefore potentially more cost effective than PCC is the way that RCC is placed. RCC is placed with the use of a modified asphalt paver as opposed to the slipform pavers that are used in PCC construction. Slipforms take setup and preparation time for each section, whereas the RCC paver can move quickly from section to section with very little setup and preparation time (White 1986).

Originally, RCC was placed either with graders or similar equipment or with asphalt pavers equipped with only vibrating screeds (Keifer 1987). Now the pavers used to place RCC are also equipped with tamping bars that compact the RCC as it is being placed. Another modification made to standard asphalt pavers is that the hopper openings had to be enlarged to allow for the stiffer material (RCC) to pass through (ACI 1991). Since 1985, both a German company and an American company have made pavers specifically designed for RCC paving. Both pavers are equipped with vibrating screeds and tamping bars. Because of the tamping bars, these pavers produce a higher level of lay-down compaction than could be achieved by the original pavers, which had only the vibrating screeds (Keifer 1987). The disadvantage to this increased compaction is that a bridging or arching effect is created in the RCC layer of the pavement. That is, the top portion of the pavement section is more densely compacted than the bottom portion. In order to achieve a more uniform density, several roller passes must be made to destroy the arching effect and compact the entire layer uniformly.

The RCC mixture is loaded into the paver the same way that AC is loaded into an asphalt paver. A dump truck filled with concrete is backed up to the hopper of the paver. The truck then slowly empties its concrete into the hopper. Once the truck is emptied, it returns to the mixing plant for more RCC. While the trucks continually empty concrete into the paver's hopper, the paver moves along placing the RCC.

The total thickness of the RCC pavement section to be placed will have a great effect on the construction procedures used. Past construction has shown that as the thickness of the RCC pavement increases, achieving adequate density at the bottom of the lift becomes more difficult. It is suggested that for pavements thicker than 10 in. (25 cm), the concrete should be placed in two or more lifts (ACI 1991). Total thicknesses of 18 in. (46 cm) of RCC have been constructed in several lifts. When multilift construction is placed, a good bond must be achieved between the lifts for the pavement to be considered monolithic.

To ensure that the paver places the concrete at the correct thickness, two devices can be used. Those devices are an electronic string line and a traveling ski (Pittman 1986). Generally, the first lane or section is placed with electronic string lines on both sides of the paver. Each adjacent lane or section is placed with an electronic string line on the outside and a traveling ski running on the previously placed lane or section.

The width of each paving lane or section can vary from 12 to 28 ft (3.7 to 8.5 m), depending on the paver screed width. It has been shown that widths of 12 to 14 ft (3.7 to 4.3 m) work well with most pavers (Pittman 1986). Wider sections will normally require larger pavers than those are currently available. At the present state of the art, tamping bars and vibrating screeds have only a certain limited amount of energy that they can impart to the concrete. Therefore, as the screed width increases, the amount of compaction energy per unit area usually decreases. In contrast, with a small width screed, there is usually a larger amount of energy per unit area.

Currently, most pavers employ a restraining device on the free edge side of the paver. This device is designed to hold the concrete from the side, acting similarly to a slip form or a side form. This device accomplishes two tasks: it creates a more vertical edge and it holds the edges in place during screed compaction to improve the density of the RCC at the edge or joint.

The speed at which the paver moves is also very important to the construction process as the paver speed has an effect on lay-down density. For a given vibration frequency, a high paver speed should produce a lower lay-down density while a low paver speed should produce a higher lay-down density. As it affects lay-down density, the paver speed would also affect the in situ strength and possibly the rideability and skid resistance of the RCC. A lower density (higher paver speed) should give lower in situ strength and possibly better skid resistance and worse rideability, whereas a higher density (lower paver speed) should give a higher strength and possibly better rideability and worse skid resistance.

The paver used for this project was a German made ABG Titan 280 paver/finisher. This ABG paver is equipped with two sets of tamping bars. The first, or preliminary, set of bars precompact the RCC; then the second set, or main bars, provide additional compaction. For this project, the drop height for each stroke of the preliminary bars was 0.47 in. (1.2 cm). The drop height for the main tampers was 0.20 in. (0.5 cm). Each bar for both the preliminary and main tampers operated at 1,470 strokes per minute. This paver was also equipped with vibrating screeds which operated, when in use, at 3,900 revolutions per minute. The paving was done by Peltz Companies of Alliance, NE. The grade was controlled at various locations and in different situations by using the electronic string line, traveling ski, or joint matcher either separately or in combination. For the construction of the parking lot, electronic string lines were used on the first lane, and then the traveling ski was used on the fresh longitudinal construction joints. For the construction of the inbound roadway lanes, an electronic string line was used on the outside edge along with a traveling ski on the interior edge. The outbound lane was placed using a joint matcher on the interior edge and maintaining a constant 2-deg slope on the screed. The layout of how the paver speed was varied is detailed in Table 2.

For the parking lot, the medium paver speed of 8 ft/min (2.4 mpm) was the pass next to the existing building; 12 fpm (3.7 mpm) was used in the middle strip, while 4 fpm (1.2 mpm) was used in the outside strip from the building. The thickness of the concrete and the number of lifts for the two lanes were varied, as noted in Table 3.

Lift #1 refers to the lower of the two lifts. The portion of each lane from sta 10+80 to 11+50 with a lift thickness of 4 in. (10.1 cm) is where an existing concrete culvert went under the roadway (Appendix B, Figure B1).

In the multilift construction portion of Lane I, three different methods were used as interface treatments (binders). They are listed in Table 4.

The thickness of the RCC pavement placed on the parking lot varied from 7 to 9 in. (18 to 23 cm) along the length of the parking lot. The thicknesses were held constant across the 39-ft (11.9-m) side. The variation in thickness was achieved by varying the depth of the surface of the subgrade to the final grade by the final thickness desired.

Table 2
Variations of Paver Speed

Section	Speed ft/min	Speed mpm[1]	Begin	End	Surface Area, ft (m)
Lane I	7	2.1	0+00	4+00	--
	8-10	2.4-3.0	4+00	8+50	--
	12	3.7	8+50	10+65	--
	8	2.4	10+65	15+25	--
Lane II	8-9	2.4-2.7	0+00	8+50	--
	18	5.5	8+50	10+75	--
	8-9	2.4-2.7	10+75	15+25	--
Parking Lot	4	1.2	--	--	13 × 100 (3.96 × 48)
	12	3.7	--	--	13 × 100 (3.96 × 30.48)
	8	2.4	--	--	13 × 100 (3.96 × 30.48)

[1] mpm = meters per minute.

Table 3
Variation of Pavement Thickness and Number of Lifts

Lane	Number of Lifts	Thickness of Lift #1 in. (mm)	Thickness of Lift #2 in. (mm)	Total Thickness in. (mm)	Begin	End
I	1	7 (177)	--	7 (177)	0+00	10+80
	1	4 (101)	--	4 (101)	10+80	11+50
	2	4 (101)	4 (101)	8 (203)	11+50	12+75
	2	5 (127)	4 (101)	9 (228)	12+75	14+0
	2	6 (152)	4 (101)	10 (254)	14+00	15+25
II	1	7 (177)	--	7 (177)	0+00	10+80
	1	4 (101)	--	4 (101)	10+80	11+50
	1	7 (177)	--	7 (177)	11+50	15+25

Table 4 Interface Treatment Variation for Multilift Section of Lane I		
Binder	Begin	End
Water	11+50	12+75
None	12+75	14+00
Cement Slurry	14+00	15+25

Compaction

Photos of the rolling operation are found in Appendix D (Photos D8 and D9). The photos consist of general rolling photos and freshly rolled concrete photos.

One of the main differences between RCC and PCC is that RCC must be compacted by a vibratory roller after placement by the paver. The rollers that are used for the compaction can be static or vibratory steel-drum rollers, rubber-tire rollers, or more commonly, a combination of these. The final surface texture on a RCC pavement is that left by the rollers as opposed to conventional PCC pavement, which is textured by some method to obtain a desired surface texture.

Compaction by rolling is one of the most important, if not the most important, aspect of RCC construction. If it is not done correctly, a good pavement will not be produced. Experience of the Corps has shown that the following method provides good compaction (Pittman 1986). First, a dual-steel-drum roller (10 ton) makes two static passes to breakdown the RCC (initial compaction). After the static rolling, a dual-steel-drum vibratory roller makes several vibratory passes until the desired density is reached. Next, a 20-ton rubber-tire roller makes two or more passes to close up any surface micro-cracking caused by the steel-drum rollers. Finally, the 10-ton dual-steel-drum roller makes two or more static passes to smooth the surface and remove any tire marks. This last step is not always necessary (Pittman 1986). The rolling should commence within 10 min of the placing of the concrete and within 45 min from the time that the water is added at the mixing plant (ACI 1991).

The best rolling pattern is one in which the desired density is achieved in the fewest number of passes. The rolling patterns used are dependent on whether a fresh joint or a cold joint is to be made with the adjoining RCC paving lane. Fresh joints are defined as when the adjacent lane is placed within 45 min (ACI 1991) or up to 60 min or less (Pittman 1986), depending on weather conditions. Cold joints are defined as placing the adjacent lane at any time greater than that established for fresh joints.

For fresh joints, 12 to 18 in. (0.3 to 0.5 m) of RCC on the free or unconfined edge is left uncompacted until the following lane is placed (Figure 3). For cold joints, the fresh RCC is placed overlapping the existing RCC pavement and then pushed back with a rake to provide more mixture in the joint to achieve a higher density. This joint is then rolled with all but approximately 1 ft (0.3 m) of the roller width on the existing RCC pavement to provide a smooth joint (Figure 4).

The roller patterns for compaction are very similar for both types of joints except for the differences previously noted. First, two static passes with the vibratory steel-wheel roller are placed on the RCC pavement. Next, the vibratory steel-wheel roller in the vibrating mode normally makes four to six passes followed by several passes with a 20-ton rubber-tire roller. The static roller is then used to remove any marks left by the rubber-tire roller.

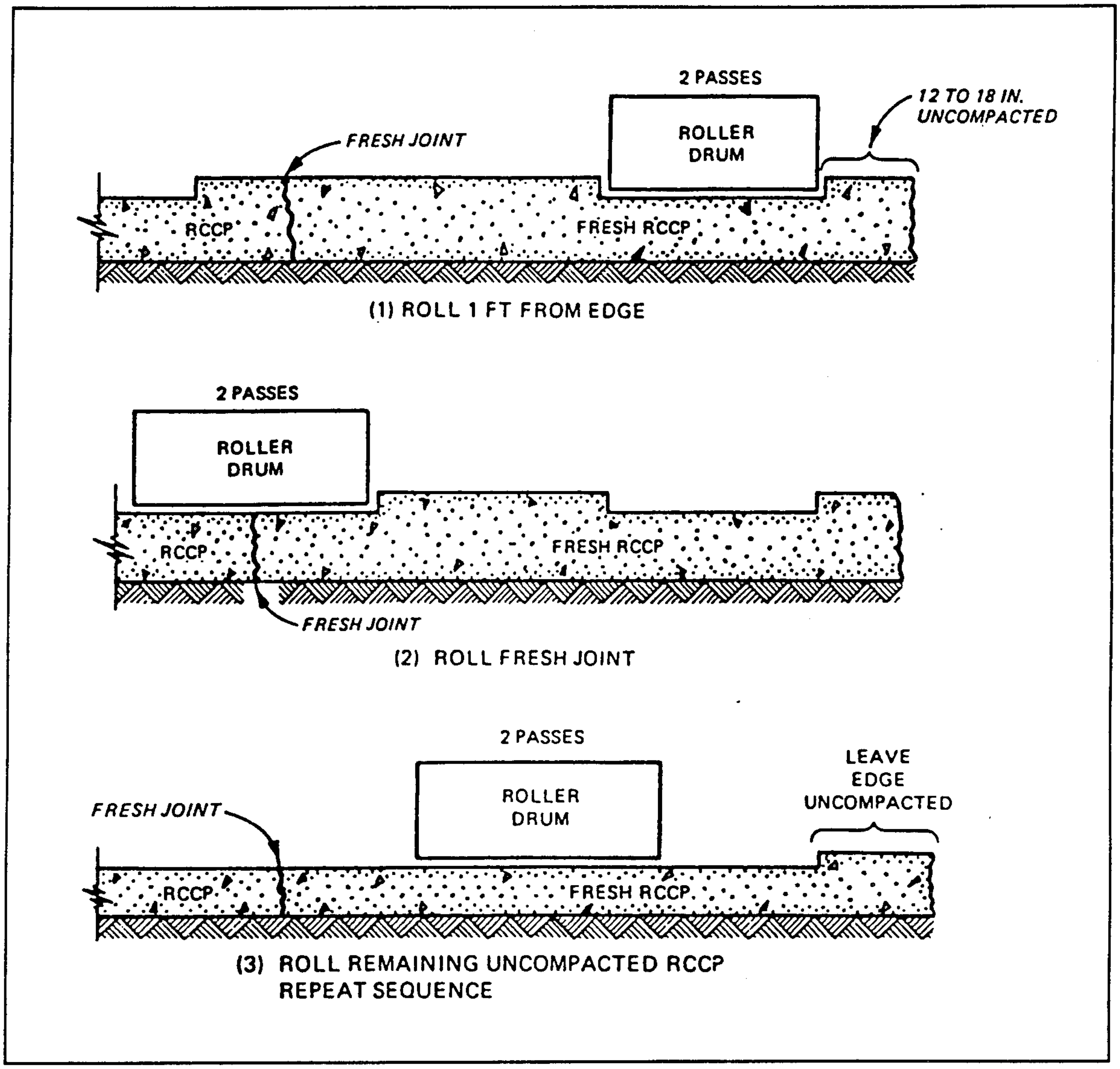

Figure 3. Roller pattern: fresh joint construction (from Pittman 1986)

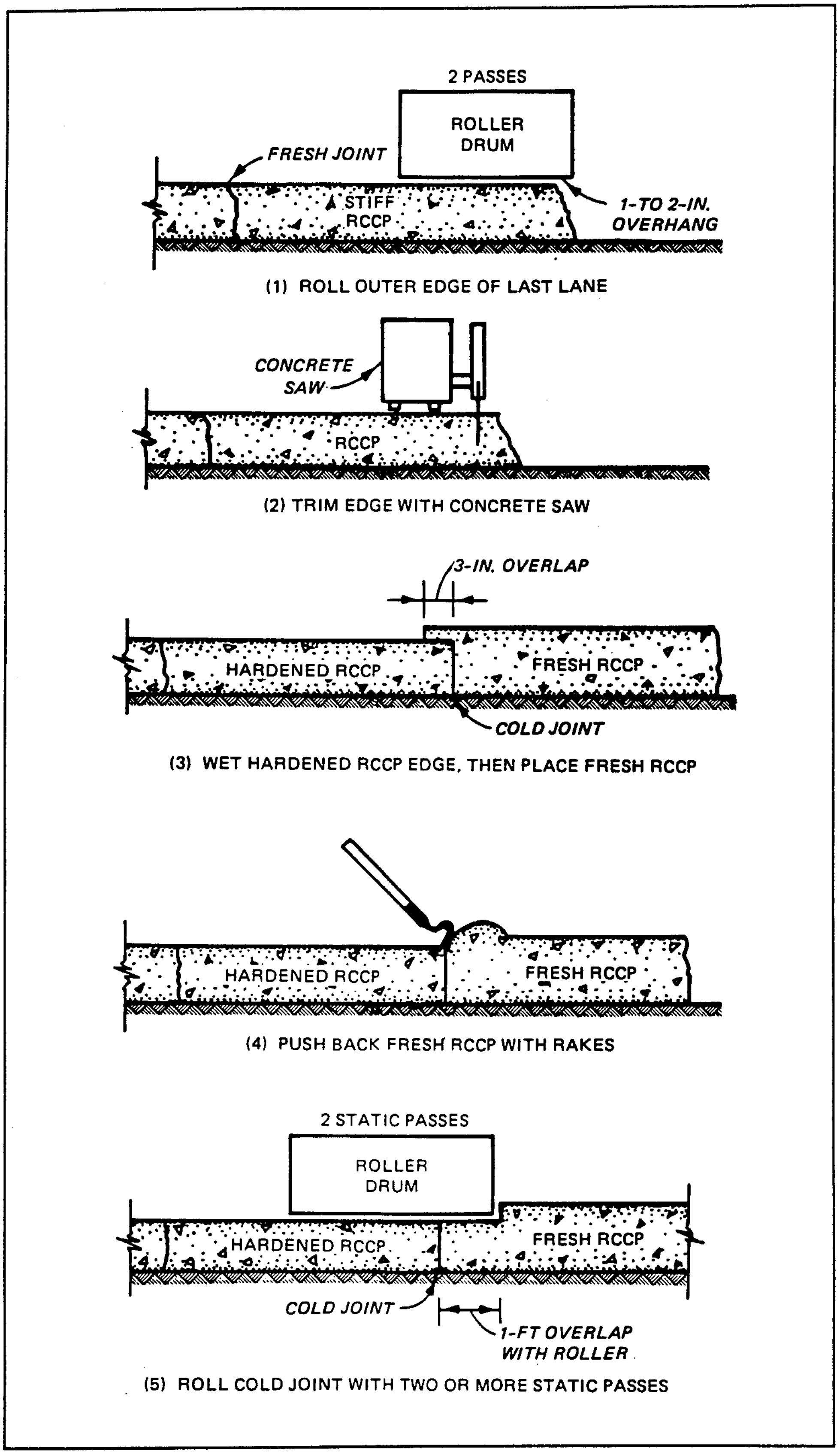

Figure 4. Roller pattern: cold joint construction (from Pittman 1986)

The steel-drum rollers should follow the patterns shown in Figures 3 and 4. The outside (unsupported) edge should be rolled first, then the joint, and then the remainder of the paving lane.

The vibratory roller should never stop on the concrete, and the rubber tire roller should follow immediately after the vibratory roller. Upon reaching the end of the lane, the roller rolls off the transverse edge. Rolling off this edge will ramp or round the concrete. This ramped concrete must be trimmed in order to place more concrete later (Pittman 1986).

The amount of rolling has a significant impact on the density; a lesser amount of rolling yields a lower density. The rolling for this project was done using an Ingersoll Rand, dual-drum steel roller with both vibratory and static capabilities. No rolling was done with a rubber-tired roller. The rolling pattern used for this project was similar to what was described previously except that there was no rubber-tired rolling. The rolling for the project was varied, as detailed in Table 5.

Table 5
Roller Pattern Variation

Section	Begin ft (m)	End ft (m)	Number of Lifts	Thickness in. (cm) of Lifts	Rolling	Area, ft (m)
Lane I	0+00	11+50 (3+51)	1	7 (18)	2 static passes	--
	11+50 (3+51)	15+25 (4+65)	2	4 (10)	2 static (top lift)	--
	--	--		Varied 3 to 6 (8 to 15)	3 static (bottom lift)	--
Lane II	0+00	4+00 (1+22)	1	7 (18)	4 static, 2 vibratory	--
	4+00 (1+22)	15+25 (4+65)	1	7 (18)	4 static	--
Parking lot	--	--	1	Varied 7 to 9 (18 to 23)	4 static, 2 vibratory	100 × 13 (30.48 × 3.96)
	--	--	1	Varied 7 to 9 (18 to 23)	4 static	100 × 13 (30.48 × 3.96)
	--	--	1	Varied 7 to 9 (18 to 23)	no rolling	100 ×13 (30.48 × 3.96)

For the parking lot, the portion with no rolling was the lane closest to the existing building.

The amount of rolling can have an effect on the surface smoothness of the RCC. Variations in the amount of volume change will recur with changes or variations in rolling and therefore compaction. These variable roller patterns can result in variations in density and in surface smoothness (just as with AC).

The amount of rolling should not have a major effect on skid resistance. Skid resistance depends on the surface texture of the RCC. The main factors affecting this should be the type of rolling equipment, mixture materials (aggregate properties), and mix design. The amount of rolling should have an effect only if the rolling worked a paste to the surface (not likely with RCC mixes) or the RCC surface was overstressed during rolling and extensive and deep cracking occurred.

Joints

Photographs of the joints appear in Appendix A. Photos A7 through A10 consist of both transverse and longitudinal joints. The transverse joints are sawcut, and the longitudinal joints are construction joints.

When an RCC pavement is constructed, two types of joints will be encountered: longitudinal and transverse. These joints can be classified as either fresh or cold. Fresh joints usually offer no problems and are handled as described in the section on compaction by rolling. After placement, the rollers compact the RCC to with 18 in. (45.7 cm) of the edge where an adjacent lane is to be placed. Once the adjacent lane is placed, the rollers either compact to within 18 in. (45.7 cm) of the next lane, or if this lane is to be the last one, the rollers compact up to the edge of the lane. Then the rollers compact the fresh joint region and then the rest of the most recently placed lane.

Cold joints in RCC pavements are more difficult to construct and require special care. A cold joint occurs when work stops for an extended period of time, such as at the end of the day. When this happens, the vertical face along the last paver pass should be cut back a minimum of 6 in. (15.2 cm) or until fully compacted RCC is found at a consistent depth away from the edge. When construction commences again, the hardened face should be sprayed with water directly ahead of the paver to promote bond between the lanes. In some projects, a cement slurry has been used instead of water to increase this bond strength. Experience has shown that the use of a cement slurry provides minimal bond between cold joints. Special care must also be taken to make sure that there is sufficient compaction in the cold joint area to ensure that the required density is achieved in this critical area (Piggot 1986).

In most of the early construction of RCC pavement, contraction joints were not sawcut or formed. Nearly all of the early construction with RCC was for military hardstands or industrial areas where the aesthetics of using sawed joints did not override the economic gain of letting the pavement crack. Saw cutting joints in the traditional wet-cut manner was also found to be difficult with some early RCC pavement construction (White 1986). However, recent experience has shown that this method of saw cutting can be accomplished successfully.

The practice of jointing RCC pavement has become more widespread and is normally employed during placement in areas where cracking is expected, such as around existing building structures, manholes, etc. Saw cutting joints also allows for a more effective application of joint sealant rather than sealing a meandering crack.

During this project, there were two cold construction joints on the roadway. A cold transverse joint exists at sta 6+50 of Lane I, and a cold longitudinal joint exists between Lanes I and II. The cold joints were handled by the procedure that was previously described in this section. To summarize, the edge was cut back, and then the next time that construction was to begin, the face was sprayed with water. There were also fresh joints in the parking lot. These fresh joints were handled as described in the compaction section. Transverse control joints were cut into both lanes. The joint spacings are listed in Table 6.

Contraction joints were placed at 20 ft (6.1 m) spacings to be comparable to conventional PCC practice at this RCC thickness. Also, larger spacings of 40, 60, 80, and 100 ft (12.2, 18.3, 24.4 and 30.5 m) and two uncut sections of 405 ft and 215 ft (123.4 and 65.2 m) were tried to ensure that cracking would develop between the sawed joints. The amount of load transfer across the joints and cracks was determined by means of a falling weight deflectometer.

The control joints for Lane I were cut with the traditional wet-cut saw. There were some spalling and raveling when attempts were made to cut the joints the same day as constructed. Wet cutting the joints in the RCC pavement the next day was successful. When Lane II was placed a week later, a dry-cut saw was used on the concrete within 3 hr of placement. The spalling and raveling were eliminated by using this dry-cut jointing method. To summarize, Lane I was cut by using a wet-cut saw, and Lane II was cut by using a dry-cut saw.

Curing

RCC has such a low w/c that there is a minimum amount of excess moisture. The RCC surface will dry quickly under normal circumstances; therefore, a combination of moist curing and/or membrane curing should be used when possible to prevent drying and scaling. For optimum curing, a

Table 6
Joint Spacings

Lane	Spacing ft (m)	Number	Begin	End
I	20 (6.1)	2	0+00	0+40
	40 (12.2)	6	0+40	2+80
	60 (18.3)	6	2+80	6+40
	100 (30.5)	4	6+40	10+40
	20 (6.1)	1	10+40	10+60
	60 (18.3)	1	10+60	11+20
	uncut	1	11+20	15+25
II	20 (6.1)	2	0+00	0+40
	40 (12.2)	6	0+40	2+80
	60 (18.3)	6	2+80	6+40
	80 (24.4)	1	6+40	7+20
	20 (6.1)	1	7+20	7+40
	100 (30.5)	1	7+40	8+40
	92.5 (28.2)	1	8+40	9+32.5
	7.5 (2.3)	1	9+32.5	9+40
	100 (30.5)	1	9+40	10+40
	20 (6.1)	1	10+40	10+60
	60 (18.3)	2	10+60	11+80
	50 (15.2)	1	11+80	12+30
	80 (24.4)	1	12+30	13+10
	uncut	1	13+10	15+25

water spray truck, fogging system, or a wet burlap system should be used continuously to keep the pavement moist within the first 24 hr after construction (Pittman 1986). After the first day, the RCC should be cured for 6 more days by using either water spray curing, burlap covering, or membrane forming material. The membrane material -- either a white pigmented material or an asphalt emulsion material -- must form a continuous void-free membrane. This condition should continue throughout the entire cure period. Spanish and Australian experience has shown that acceptable results can be achieved by placing a membrane material immediately after compaction is completed.

All of the surfaces for this project were white membrane cured except for the truck port, which was water spray cured. The curing compound was applied by hand with a pressurized spray wand. This method was used instead of a full-width spray bar due to the limited size of the pavement section. However, equipment utilizing a full-width spray bar would have provided a more uniform application of curing compound. The application rate was approximately 1 gal/100 ft^2 (3.8 L/9.3 m^2).

5 Site and Laboratory Testing

Several onsite and laboratory tests were conducted for this project to determine the suitability of RCC for high-speed traffic pavements. These tests include nuclear densities, moisture content, strength, California profilograph, skid resistance, crack mapping, FWD tests to determine load transfer, and density profiles.

Nuclear Density

Photos concerning the nuclear density tests appear in Appendix E (Photos E1 and E2). Achieving satisfactory density is critical to the performance of RCC pavement. Greater density results in higher strength and should improve freeze-thaw durability by making RCC more difficult to saturate. A dual probe nuclear density gage was used during construction to measure the RCC pavement densities. The gage was calibrated with calibration curves supplied by the gage manufacturer. The maximum theoretical density of the RCC mixture was calculated to be 159.7 lb/ft^3 (2,558 kg/m^3), and the densities obtained are a percentage of that amount. These were normally conducted at a probe depth of 6 in. (15.2 cm). The tests were performed by BSK and Associates of Pleasanton, CA. The tests were conducted on Lane I, Lane II, and the parking lot.

Two construction variables, the speed of the paver and the degree of compaction achieved during paving, were evaluated for this project. Tables 7 and 8 list the effect paver speed on the lay-down density for the two RCC roadway lanes. In Table 7, the density listed is the lay-down density, which means that it is the density taken just after the paver has placed the RCC. In general, these readings were taken at 50-ft (15.2-m) intervals. Table 8 also lists the paver speed versus the lay-down density; this table gives the average density and standard deviation for each paver speed.

The standard deviations in Table 8 are low, ranging from 1.0 to 2.9, which translates to coefficients of variation that are very low, ranging from 1.1 to 3.3 percent. These density variations would be considered reasonable for conventional slipform paving, although anything over 2 percent would be considered high. This means that each paver speed produces a reasonably

Table 7 Paver Speed Versus Lay-Down Density			
Lane[1]	Station	Paver Speed fpm (mpm)	Lay-Down Density % of max (POM)
I	0+25	7 (2.1)	89
	0+50	7 (2.1)	88
	1+00	7 (2.1)	87
	1+50	7 (2.1)	88
	2+00	7 (2.1)	89
	2+50	7 (2.1)	87
	3+00	7 (2.1)	90
	3+50	7 (2.1)	89
	4+00	7 (2.1)	88
	4+50	8-10 (2.4-3.0)	87
	5+00	8-10 (2.4-3.0)	89
	5+50	8-10 (2.4-3.0)	88
	6+00	8-10 (2.4-3.0)	90
	6+50	8-10 (2.4-3.0)	87
	7+00	8-10 (2.4-3.0)	87
	7+50	8-10 (2.4-3.0)	87
	8+00	8-10 (2.4-3.0)	87
	8+50	12 (3.7)	92
	9+00	12 (3.7)	90
	9+50	12 (3.7)	93
	10+00	12 (3.7)	90
	10+50	12 (3.7)	89
	11+00	8 (2.4)	88
	11+50	8 (2.4)	85
	12+00	8 (2.4)	85
	12+50	8 (2.4)	87
	13+00	8 (2.4)	86
	13+50	8 (2.4)	86
	14+00	8 (2.4)	89
	14+50	8 (2.4)	86
	15+00	8 (2.4)	84

(Continued)

[1] All RCC was placed 7 in. (17.8 cm) thick, except from 11+50 to 15+00 the top lift thickness was 4 in. (10 cm).

Table 7
(Concluded)

Lane	Station	Paver Speed fpm (mpm)	Lay-Down Density % of max (POM)
II	0+00	8-9 (2.4-2.7)	83
	0+17	8-9 (2.4-2.7)	92
	0+50	8-9 (2.4-2.7)	86
	1+00	8-9 (2.4-2.7)	87
	1+50	8-9 (2.4-2.7)	86
	2+50	8-9 (2.4-2.7)	84
	3+00	8-9 (2.4-2.7)	92
	3+50	8-9 (2.4-2.7)	88
	4+00	8-9 (2.4-2.7)	91
	4+50	8-9 (2.4-2.7)	91
	5+00	8-9 (2.4-2.7)	90
	5+50	8-9 (2.4-2.7)	88
	6+00	8-9 (2.4-2.7)	82
	6+50	8-9 (2.4-2.7)	85
	7+00	8-9 (2.4-2.7)	87
	7+50	8-9 (2.4-2.7)	87
	8+00	8-9 (2.4-2.7)	87
	8+50	8-9 (2.4-2.7)	88
	9+50	18 (5.5)	81
	11+00	8-9 (2.4-2.7)	85
	11+50	8-9 (2.4-2.7)	89
	12+25	8-9 (2.4-2.7)	91
	13+75	8-9 (2.4-2.7)	90

small range of densities. But when all of the densities are analyzed together, the mean is 87.7 percent of maximum (POM) with a standard deviation of 2.5 POM. This corresponds to a coefficient of variation of 2.9 percent. This coefficient of variation for all of the densities is slightly higher than that expected for conventional PCC; however, there are no clear trends.

The results of an analysis of variance test using MINITAB are given in Table 9.

The sources where variance could arise (listed in Table 9) are the paver speed and error (which is the actual density readings), and then the total of

Table 8
Paver Speed Versus Lay-Down Density

Lane	Paver Speed fpm (mpm)	Average Density % of max	Stand Dev. % of max	COV %
I	7 (2.1)	88.3	1.0	1.1
	8 (2.4)	86.3	1.6	1.9
	8-10 (2.4-3.0)	88.2	1.2	1.4
	12 (3.7)	90.5	1.6	1.7
II	8-9 (2.4-2.7)	87.7	2.9	3.3
	18 (5.4)	81.0	--	--
All	--	87.7	2.5	2.9

Table 9
Analysis of Variance for Paver Speed Versus Lay-Down Density

Source	DF[1]	SS	MS	F
Paver speed	5	116.21	23.24	5.06
Error	48	220.63	4.60	
Total	52	336.83		

[1] DF = degree of freedom; SS = sum of squares; MS = mean squared; F = F-value.

both error and paver speed. The degrees of freedom (DF) are calculated by taking the total number of a particular source and subtracting 1 from that number. As an example, there are six different paver speeds; therefore, the DF is 5. The sum of squares (SS) for a particular source is the sum of all of the squared differences between the mean and each individual reading. The mean square (MS) is the SS divided by the DF. This gives a measure of the mean-squared difference between the mean and each individual reading. Lastly, the F-value is a measure of the statistical significance of a given source. The F-value is calculated, in this case, by dividing the MS for paver speed by the MS for the error. If the F-value is larger than the specified number determined by the two DF's, then there is a statistical significance to varying the paver speed, but if the F-value is lower, then there is no statistical significance to varying the paver speed. The F-value of 5.06 is greater than the corresponding 95-percent confidence F-value of 2.50, which means that varying the paver speed has a statistical significance on the lay-down density.

Figure 5 shows a graphical representation of Table 7. From this figure, the data seem to follow two trends. The first trend is that lay-down density decreases with increasing paver speed. The second and more overall trend is one in which the lay-down density increases with increasing paver speeds of 0 to 12 - 14 fpm. No conclusions can be drawn above this speed as only one data point was obtained at higher speeds.

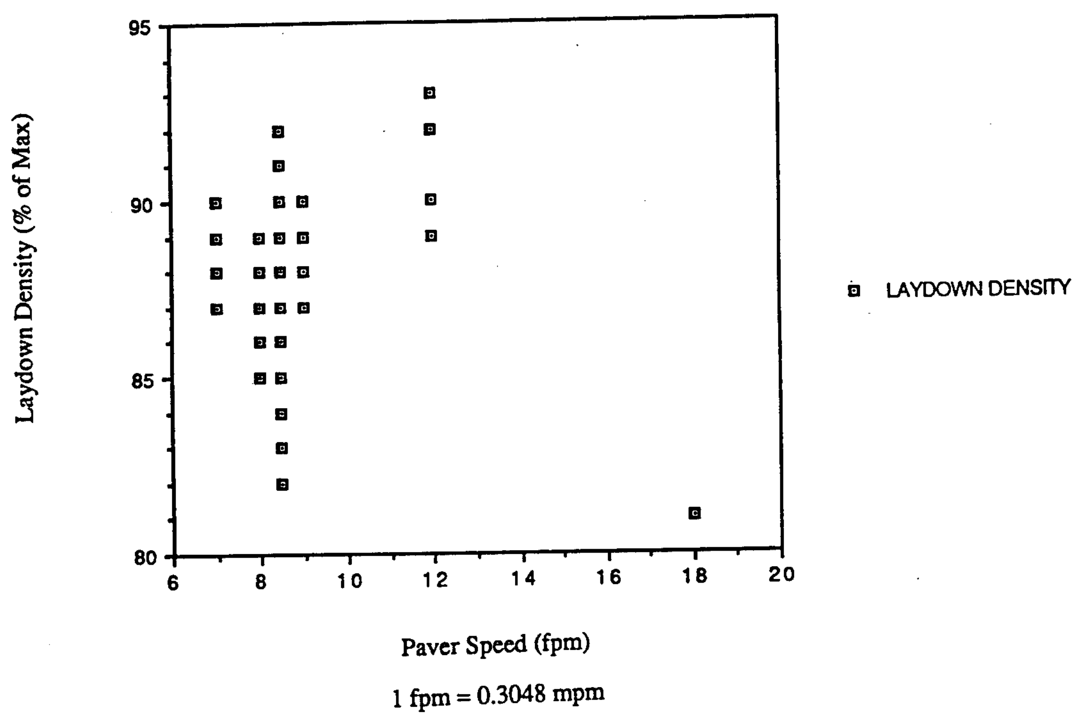

Figure 5. Paver speed versus lay-down density

Of the two aforementioned variables, speed of the paver and amount of rolling, only the paver speed can affect the lay-down densities. On the other hand, both of these variables can affect the final construction densities, which are the densities measured directly after the last pass of the roller. Table 10 lists both the paver speed and the amount of rolling versus the final densities. Table 11 shows the combined effects of paver speed and rolling passes.

Once again, the standard deviations and coefficients of variation are within or slightly above the range expected for conventional PCC. The standard deviations range from 0.0 to 3.3, and COV's range from 0.0 to 3.3 percent. The overall standard deviation is 2.2 POM, and the coefficient of variation is 2.3 percent. This coefficient of variation for final density when the paver speeds and amounts of rolling are varied shows no clear trends.

An analysis of variance cannot be conducted on all of these data because not all of the possible combinations of paver speed and roller passes were used as shown in Table 12. However, if all of the paver speeds in the range of 8 to 10 fpm (2.4 to 3.0 mpm) are held to be equal, an analysis of variance can be performed on that data to determine if the amount of rolling has an

Table 10
Paver Speed and Amount of Rolling Versus Final Density

Lane[1]	Station	Paver Speed fpm (mpm)	Amount of Rolling, passes[2]	Density POM
I	0+25	7 (2.1)	2 s	97
	0+50	7 (2.1)	2 s	98
	1+00	7 (2.1)	2 s	98
	1+50	7 (2.1)	2 s	96
	2+00	7 (2.1)	2 s	96
	2+50	7 (2.1)	2 s	96
	3+00	7 (2.1)	2 s	100
	3+50	7 (2.1)	2 s	96
	4+00	7 (2.1)	2 s	96
	4+50	8-10 (2.4-3.0)	2 s	95
	5+00	8-10 (2.4-3.0)	2 s	97
	5+50	8-10 (2.4-3.0)	2 s	97
	6+00	8-10 (2.4-3.0)	2 s	96
	6+50	8-10 (2.4-3.0)	2 s	90
	7+00	8-10 (2.4-3.0)	2 s	91
	7+50	8-10 (2.4-3.0)	2 s	90
	8+00	8-10 (2.4-3.0)	2 s	90
	8+50	12 (3.7)	2 s	97
	9+00	12 (3.7)	2 s	97
	9+50	12 (3.7)	2 s	98
	10+00	12 (3.7)	2 s	96
	10+50	12 (3.7)	2 s	95
	11+00	8 (2.4)	2 s	97
	11+50	8 (2.4)	2 s	98
	12+00	8 (2.4)	3 s	97
	12+50	8 (2.4)	3 s	96
	13+00	8 (2.4)	3 s	96

(Continued)

[1] All RCC was placed 7 in. (17.8 cm) thick, except from 11+50 to 15+00 the top lift thickness was 4 in. (10 cm).
[2] s = static; v = vibratory.

Table 10 (Concluded)				
Lane	Station	Paver Speed fpm (mpm)	Amount of Rolling, passes[2]	Density POM
I	13+50	8 (2.4)	3 s	97
	14+00	8 (2.4)	3 s	96
	14+50	8 (2.4)	3 s	95
	15+00	8 (2.4)	3 s	96
II	1+00	8-9 (2.4-2.7)	4 s, 2 v	96
	1+50	8-9 (2.4-2.7)	4 s, 2 v	95
	2+00	8-9 (2.4-2.7)	4 s, 2 v	95
	3+50	8-9 (2.4-2.7)	4 s, 2 v	96
	4+50	8-9 (2.4-2.7)	4 s	95
	6+00	8-9 (2.4-2.7)	4 s	95

Table 11 Effects of Paver Speed and Rolling Passes						
Lane	Paver Speed fpm (mpm)	Rolling passes	Density POM	Average Density POM	Standard Dev. POM	COV %
I	7 (2.1)	2 static	97, 98, 98, 96, 96, 96, 100, 96, 96	97.0	1.4	1.4
	8-10 (2.4-3.0)	2 static	95, 97, 97, 96, 90, 91, 90, 90	93.2	3.3	3.5
	12 (3.7)	2 static	97, 97, 98, 96, 95	96.6	1.1	1.1
	8 (2.4)	2 static	97, 98	97.5	0.71	0.73
	8 (2.4)	3 static	97, 96, 96, 97, 96, 95, 96	96.1	0.69	0.72
II	8-9 (2.4-2.7)	4 static 2 vibratory	96, 95, 95, 96	95.5	0.58	0.60
	8-9 (2.4-2.7)	4 static	95, 95	95.0	0.0	0.0
All				95.7	2.2	2.3

Table 12 Combinations of Paver Speeds and Amount of Rolling				
Paver Speeds fpm (mpm)	Rolling, passes			
	2 static	3 static	4 static	4 static 2 vibratory
7 (2.1)	X[1] 9	--	--	--
8 (2.4)	X 2	X 7	--	--
8-9 (2.4-2.7)	--	--	X 2	X 4
9 (2.7)	X 8	--	--	--
12 (3.7)	X 5	--	--	--
18 (5.4)	--	--	X 0	--

[1] X = combination; number = final densities taken at combination.

effect on final density in the range of 8 to 10 fpm (2.4 to 3.0 mpm). This analysis of variance is listed in Table 13.

Table 13 Analysis of Variance for Rolling Amount with Constant Paver Speed				
Source	DF[1]	SS	MS	F
Rolling	3	20.50	6.83	1.21
Error	19	107.33	5.65	
Total	22	127.83		

[1] DF = degree of freedom; SS = sum of squares; MS = mean squared; F = F-value.

The F-value of 1.21 is less than the 95-percent confidence interval value of 3.13; therefore, the rolling has no statistical effect on the final density in the paver speed range of 8 to 10 ft/min (2.3 to 3.0 mpm). There was some statistical significance to the lay-down density by varying the paver speed, but the exact relationship could not be determined. It should be kept in mind that these results are based on limited data. Table 12 shows that only 8 of the 24 possible combinations were obtained on this project. More combinations would have been required to determine the best combination of paver speeds and amount of rolling to produce a dense RCC pavement. Also, the number of density readings taken for each combination was not equal or even close to equal, ranging from 0 to 9 tests. If all of the possible combinations had been used, then an analysis of variance could have been conducted to determine which of paver speeds and amount of rolling has the most influence on final density, and the best combination of paver speed and rolling amount to produce a dense RCC pavement could have been determined.

All of the paver speed and amount of rolling combinations but one produced final densities of 95 percent or more. The one exception is the combination of 8 to 10 ft/min (2.4 to 3.1 mpm) paver speed and two static roller passes. This combination produced four densities greater than 95 percent and four values of approximately 90 percent. No reason could be found for these low density values as they were all in areas of 7-in.- (2.1-m-) thick RCC and there were no discernable differences from the areas with the higher density values. Therefore, 33 of 37 readings taken were greater than or equal to 95 percent. It would seem from this that any combination of paver speeds in the range of 7 to 12 fpm (2.1 to 3.7 mpm) and roller passes ranging from two static up to four static/two vibratory will produce a density greater than or equal to 95 percent.

Moisture Content

It was important during construction to know the moisture content of the RCC pavement to help determine its workability/constructability. The moisture content tests were also performed by BSK and Associates. It was decided by the contractor during construction that a moisture content of 7 to 9 percent provided the most workable concrete. The mix designs shown in Appendix C show moisture percents of about 4 percent. The difference between the design moisture contents and the actual moisture contents can be attributed to the need for contractor control of workability for the day of construction. The moisture contents had to be (in the contractor's opinion) 7 to 9 percent for the RCC to be constructed.

The moisture content of the RCC mixture was obtained by knowing the amount of moisture in the aggregates and the additional water added to the RCC mixture. The moisture content of the aggregates was obtained by periodically testing the aggregates throughout the production of the RCC mixture.

Strength

Photos dealing with the making of RCC specimens for strength testing are provided in Appendix E. Photos E3 through E9 deal with the making of the specimens, including removing concrete from the dump truck, making cylinders, and making beams.

Specimens for compressive, splitting tensile, and flexural strengths were cast on the site by BSK. The cylinders for both compression and tension were 6×12 in. (15.2×30.5 cm) while the beams for flexural strength were $6 \times 6 \times 30$ in. ($15.2 \times 15.2 \times 76.2$). The cylinders for compression and tension were made in three lifts. The RCC mixture for each lift was compacted by mechanically applying a surcharge to the cylinder until a slurry film appeared around the edge of the surcharge. After the final application of the surcharge on the top lift, each cylinder was vibrated. The beams for flexural testing were done in much the same way; the only exception was that the beams were normally loaded at three positions across the length of the beam on all three lifts. The specimens were both formed and tested by BSK.

Table 14 lists the compressive strengths of the specimens. Table 15 lists the splitting tensile strengths of the specimens, and Table 16 lists the flexural strengths of the specimens.

Concrete pavements are designed on the basis of tensile/flexural properties. Beams for flexural strength determination are more difficult and time consuming to fabricate than cylinders. Therefore, compressive and splitting tensile strength tests were widely used on this project.

The RCC mixture used on this project was required by design to have a flexural strength of 700 psi (4.8 MPa).

The design also required each mix to develop a 28-day compressive strength of at least 4,000 psi (27.6 MPa). Every specimen tested under compression had a compressive strength at 28 days of at least 4,830 psi (33.3 MPa). There were only two specimens tested for flexural strength, and they had a 28-day compressive strength of 825 psi (5.7 MPa), which is greater than the design requirement of 700 psi (4.8 MPa). No definite conclusion can be drawn about the flexural strengths since only the two specimens were tested. No cores were taken for in situ strength.

Profilograph

On 3 December 1992, a California profilographer measured the roughness of the RCC roadway. The profilographer was run according to ASTM E 1274-88, Standard Test Method for Measuring Pavement Roughness Using a Profilograph. The test was performed by the California Transportation Department (CALTRANS). The California profilographer is 32.5 ft (9.9 m) long with six wheels at each end and a recording wheel at the center. A tracing pen is connected to the recording wheel. As the recording wheel moves up and down over the texture of the pavement, the pen leaves a tracing of the road surface roughness. Photos E10 through E12 in Appendix E show the California profilographer in use.

The intended path for the profilograph was cleared of all foreign objects. The path was considered to be the area both the left and right wheels traveled on each roadway portion tested. The profilograph was then moved forward at a speed no faster than 3 miles/hr (4.8 km/hr) along the road surface to measure the roughness.

The output was on a scroll that graphically gave a representation of the roadway roughness. The output was then broken down by using a blanking band template, a clear plastic strip 2 in. (5.0 cm) wide and at least 4 in.

Table 14
Compressive Strengths of Specimens

Date Cast	Mix	Relative Compaction %	Age (days) 1	2	4	5	6	7	28
			Strength, psi (MPa)[1]						
4-15/16-92	A	97	--	--	--	3540 (24.4)	--	3710 (25.6)	5550 (38.3)
	B	97	--	2300 (15.9)	--	2900 (20.0)	--	3240 (22.3)	4890* (33.7)
		96	--	--	--	3080 (21.2)	--	3450 (23.8)	4830 (33.3)
	B-1	97	2000 (13.8)	--	3500 (24.1)	--	--	4170 (28.8)	5370* (37.0)
	B-2	96	--	--	2830 (19.5)	--	3590 (24.8)	3610 (24.9)	5340 (36.8)
4-24-92	A-2	97	--	--	--	--	--	4600 (31.7)	6045* (41.7)
		97	--	--	--	--	--	4840 (33.4)	5970 (41.2)

[1] All values are for one specimen unless an asterisk (*) appears, in which case the value is an average of two values.

Table 15
Splitting Tensile Strengths of Specimens

Date Cast	Mix	Relative Compaction %	Age (days) 7	28
			Strength, psi (MPa)[1]	
4-15/16-92	A	97	465 (3.2)	520* (3.6)
	B	97	395 (2.7)	550 (3.8)
	B	96	400 (2.8)	540* (3.7)
	B-1	97	380 (2.6)	560* (3.9)
	B-2	96	390 (2.7)	580 (4.0)
4-24-92	A-2	97	430 (3.0)	605* (4.2)
	A-2	98	440 (3.0)	615* (4.2)
	B-2	96	390 (2.7)	580 (4.0)

[1] All values are for one specimen unless an asterisk (*) appears, in which case the value is an average of two values.

Table 16
Flexural Strengths of Specimens

Date Cast	Mix	Relative Compaction %	Age (days) 7	28
			Strength, psi (MPa)[1]	
4-15/16-92	B-2	97	550 (3.8)	825* (5.7)

[1] All values are for one specimen unless an asterisk (*) appears, in which case the value is an average of two values.

(10.1 cm) long. The center of the template was marked with an opaque strip 0.1 in. (2.54 mm) wide. Parallel lines were placed at 0.1-in. (2.5-mm) intervals from the opaque strip. The template was placed over the graphical output in such a manner that the opaque strip blocked out as much of the output as possible. Readings were taken by measuring the heights of the peaks above or below the opaque strip (blanking band) truncating to the nearest 0.1 in. (2.5 mm). This yielded the number of tenths of an inch of profilograph roughness in the test section. This value was then converted to inches per mile, which was the final profilograph of road roughness, also known as the profile index (PI).

The data for the curved portion (sta 9+40 to 15+25) of both lanes were analyzed along with the data for the straight portion (sta 0+00 to 9+40) for information only. Due to the inaccuracy of the California profilographer in curves of short radius, the numbers are not quantitatively valid. The data for the curved portion are questionable because the profilographer is long and rigid; therefore the end supports (six wheels) and the recording wheel may not be in the same plane in a superelevated portion of a roadway. The results will also be impacted in curves with a radius less than 2,000 ft (610 m). The curve tested had a radius of less than 500 ft (152 m). Because of this, the data collected from the recording wheel will be skewed in the curved portion of this project. Since the width of each lane is 14 ft (4.3 m) and the average truck is 8 ft (2.4 m) center to center of wheels, the profilographer path was 3 ft (0.9 m) from each longitudinal edge of each lane. These paths yielded a right wheel value and a left wheel value for each lane. The actual average profilograph values or PI for each of the two lanes are given in Table 17. Current CALTRANS specifications require a PI of 7 in./mile (11.1 cm/km) or less for new PCC pavement (CALTRANS Specifications, 1992).

Several of the construction parameters in this project could have had an effect on the profilograph readings. Those parameters include paver speed, amount of rolling, and joint spacing.

The effect of the paver speed on the profilograph is listed in Table 18. The profilograph values are broken down, first by lane, then by straight versus curved, and then by paver speed.

Table 17
Overall Profilograph Values

Lane	Geometry	Wheel	Value in./mile (cm/km)
I[1]	Straight	Left Right Average	46.0 (73.0) 46.6 (74.0) 46.3 (73.5)
	Curved	Left Right Average	101.1 (160.5) 65.9 (104.6) 83.5 (132.6)
II[2]	Straight	Left Right Average	38.2 (60.6) 33.2 (52.7) 35.7 (56.7)
	Curved	Left Right Average	91.2 (144.8) 107.4 (170.5) 99.3 (157.6)

[1] Cut with a wet-cut saw.
[2] Cut with a dry-cut saw.

Table 18
Paver Speed Effect on Profilograph

Lane	Geometry	Paver Speed fpm (mpm)	Profilograph Value in./mile (cm/km)
I[1]	Straight	7 (2.1) 8-10 (2.4-3.0) 12 (3.7)	64.2 (101.9) 38.7 (61.4) 8.8 (14.0)
	Curve	8 (2.4) 18 (3.7)	89.0 (141.3) 67.6 (107.3)
II[2]	Straight	8-9 (2.4-2.7) 18 (5.5)	35.7 (56.7) 35.2 (55.9)
	Curve	8-9 (2.4-2.7) 18 (5.5)	93.3 (148.1) 78.2 (124.1)

[1] Cut with a wet-cut saw.
[2] Cut with a dry-cut saw.

The effect of the amount of rolling on the profilograph is listed in Table 19. These profilograph values are also broken down by lane, then by straight versus curved, and then by the amount of rolling.

The effect of joint spacing on the profilograph is listed in Table 20. Once again the values are broken down first by lane, then by straight versus curved,

Table 19
Amount of Rolling Effect on the Profilograph

Lane	Portion	Amount of Rolling, passes	Profilograph Value in./mile (cm/km)
I[1]	Straight	2 static	46.3 (73.5)
	Curve	2 static	56.7 (90.0)
		2 static bottom, 3 static top	98.5 (156.4)
II[2]	Straight	4 static, 2 vibratory	50.2 (79.7)
	Curve	4 static	30.0 (47.6)
		4 static	99.3 (157.6)

[1] Cut with a wet-cut saw.
[2] Cut with a dry-cut saw.

Table 20
Joint Spacing Effect on the Profilograph

Lane	Portion	Joint Spacing ft (m)	Profilograph Value in./mile (cm/km)
I[1]	Straight	20 (6.1)	79.2 (125.7)
		40 (12.2)	71.5 (113.5)
		60 (18.3)	45.5 (72.2)
		100 (30.5)	23.8 (37.8)
	Curve	20 (6.1)	92.4 (146.7)
		60 (18.3)	52.8 (83.8)
		100 (30.5)	63.4 (100.6)
		uncut	83.6 (132.7)
II[2]	Straight	7.5 (2.3)	70.4 (111.8)
		20 (6.1)	110.0 (174.6)
		40 (12.2)	38.5 (61.1)
		60 (18.3)	25.7 (40.8)
		80 (24.4)	23.1 (36.7)
		92.5 (28.2)	31.4 (49.8)
		100 (30.5)	31.7 (50.3)
	Curve	20 (6.1)	118.8 (188.6)
		50 (15.2)	73.9 (117.3)
		60 (18.3)	118.8 (188.6)
		80 (24.4)	79.2 (125.7)
		100 (30.5)	73.9 (117.3)
		uncut	99.5 (158.0)

[1] Cut with a wet-cut saw.
[2] Cut with a dry-cut saw.

and then finally by joint spacing. Each of these tables is subdivided into each respective lane because each lane's joints were cut using a different type of saw. To reiterate, Lane I was cut with a wet-cut saw, and Lane II was cut with a dry-cut saw.

The combined effects of paver speed, rolling, and joint spacing are listed in Table 21.

In 1988, a report was published concerning a correlation between the Present Serviceability Index (PSI) and the 0.1-in. blanking band for the California profilograph (Walker and Lin 1988). As stated earlier, the 0.1-in. blanking California profilograph was used in an attempt to determine the roadway roughness and rideability for this project. PSI is the most widely used rideability condition survey in the United States. The PSI is based on the concept of correlating user opinions with measurements of road roughness, cracking, patching, and rutting (Yoder and Witczak 1975). PSI values range from 0 to 5. A value of 5 is excellent, while a value of 0 is very poor. In most states, a PSI value of 2.5 or less means that the pavement needs to be replaced or overlaid. From Walker and Lin's report, the correlation between the 0.1-in. blanking California profilograph and PSI can be expressed as follows:

$$\text{PSI Value} = 4.61 - 0.039\ (\text{Profilograph Value}) \tag{1}$$

Equation 1 is for use with rigid pavements. Since RCC is similar to PCC, Equation 1 was used to determine PSI values for this project. The calculated PSI values for this project are listed in Tables 22 through 26. Table 22 lists the overall PSI values for this project. Table 23 lists the paver speeds versus PSI. Table 24 lists the effects of rolling PSI, and Table 25 lists the effect of joint spacing on PSI. Finally, Table 26 lists the effects of various combinations of paver speed, roller amount, and joint spacing on PSI. Since PSI values less than 2.5 generally mean pavement replacement, any PSI value that is less than 2.5 is listed as <2.5 in the tables.

Since there is a relationship between the profilograph and PSI, this discussion will deal with the profilograph. In looking at the overall profilograph values for each lane, the only data considered will be the data for the straight portion. The profilograph values for Lane I are, on average, 30 percent greater than Lane II. Generally, there is a learning curve with RCC pavement construction, and at least a portion of the improvement could be contributed to this. Another contributing factor could have been that the joints in Lane I were cut using a wet-cut saw while the joints in Lane II were cut using a dry-cut saw. The joints in Lane II appeared to be cleaner and smoother than the joints in Lane I. A smoother/cleaner joint should reduce the profilograph value and therefore increase the PSI. At least for this RCC pavement, the dry-cut saw improved the PSI and should be investigated on other RCC pavement construction.

Table 21
Combined Effects of Paver Speed, Rolling, and Joint Spacing of Profilograph

Lane	Paver Speed fpm (mpm)	Rolling passes[1]	Joint Spacing ft (m)	Profilograph in./mile (cm/km)	Length ft (m)
I[2] straight	7 (2.1)	2 s	20 (6.1) 40 (12.2) 60 (18.3)	79.2 (125.7) 71.5 (113.5) 44.0 (69.9)	40 (12.2) 240 (73.2) 120 (36.6)
	8-10 (2.4-3.0)	2 s	60 (18.3) 100 (30.5)	46.2 (73.3) 31.4 (49.8)	240 (73.2) 210 (64.0)
	12 (3.7)	2 s	100 (30.5)	5.9 (9.4)	90 (27.4)
I[2] curve	12 (3.7)	2 s	20 (6.1) 60 (18.3) 100 (30.5)	118.8 (188.6) 0.0 63.4 (100.6)	20 (6.1) 5 (1.5) 100 (30.5)
	8 (2.4)	2 s	60 (18.3) uncut	57.6 (91.4) 96.8 (153.7)	55 (16.8) 30 (9.1)
		3 s	uncut	93.6 (148.6)	375 (114.3)
II[2] straight	8-9 (2.4-2.7)	4 s 2 v	20 (6.1) 40 (12.2) 60 (18.3)	151.8 (241.0) 38.5 (61.1) 35.2 (55.9)	40 (12.2) 240 (73.2) 120 (36.6)
		4 s	20 (6.1) 60 (18.3) 80 (24.4) 92.5 (28.2) 100 (30.5)	26.4 (41.9) 20.9 (33.2) 23.1 (36.7) 31.2 (49.5) 31.7 (50.3)	20 (6.1) 360 (109.7) 80 (24.4) 10 (3.0) 100 (30.5)
	18 (5.5)	4 s	92.5 (28.2) 7.5 (2.3)	25.6 (40.6) 70.4 (111.8)	82.5 (25.1) 7.5 (2.3)
II[3] curve	18 (5.5)	4 s	20 (6.1) 60 (18.3) 100 (30.5)	118.8 (188.6) 52.8 (83.8) 63.4 (100.6)	20 (6.1) 15 (18.3) 100 (30.5)
	8-9 (2.4-2.7)	4 s	50 (15.2) 60 (18.3) 80 (24.4) uncut	73.9 (117.3) 135.8 (215.6) 79.2 (125.7) 99.5 (158.0)	50 (15.2) 105 (32.0) 80 (24.4) 215 (65.5)

1 s = static; v = vibratory.
2 Cut with a wet-cut saw.
3 Cut with a dry-cut saw.

Table 22
Overall PSI Values

Lane	Portion	Wheel	Profilograph in./mile (cm/km)	PSI (KPa)
I[1]	Straight	Left	46.0 (73.0)	2.82 (19.4)
		Right	46.6 (74.0)	2.79 (19.2)
		Average	46.3 (73.5)	2.80 (19.3)
	Curved	Left	101.1 (160.5)	<2.50 (<17.2)
		Right	65.9 (104.6)	<2.50 (<17.2)
		Average	83.5 (132.6)	<2.50 (<17.2)
II[2]	Straight	Left	38.2 (60.6)	3.12 (21.5)
		Right	33.2 (52.7)	3.32 (22.9)
		Average	35.7 (56.7)	3.22 (22.2)
	Curved	Left	91.2 (144.8)	<2.50 (<17.2)
		Right	107.4 (170.5)	<2.50 (<17.2)
		Average	99.3 (157.6)	<2.50 (<17.2)

[1] Cut with a wet-cut saw.
[2] Cut with a dry-cut saw.

Table 23
Paver Speed Effect on the Profilograph and PSI

Lane	Portion	Paver Speed fpm (mpm)	Profilograph in./mile (cm/km)	PSI (KPa)
I[1]	Straight	7 (2.1)	64.2 (101.9)	<2.50 (<17.2)
		8-10 (2.4-3.0)	38.7 (61.4)	3.10 (21.4)
		12 (3.7)	8.8 (14.0)	4.27 (29.4)
	Curve	12 (3.7)	67.6 (107.3)	<2.50 (<17.2)
		8 (2.4)	89.0 (141.3)	<2.50 (<17.2)
II[2]	Straight	8-9 (2.4-2.7)	35.7 (56.7)	3.22 (22.2)
		18 (5.5)	35.2 (55.9)	3.24 (22.3)
	Curve	18 (5.5)	78.2 (124.1)	<2.50 (<17.2)
		8-9 (2.4-2.7)	93.3 (148.1)	<2.50 (<17.2)

[1] Cut with a wet-cut saw.
[2] Cut with a dry-cut saw.

Table 24
Amount of Rolling Effect on the Profilograph and PSI

Lane	Portion	Amount of Rolling passes	Profilograph in./mile (cm/km)	PSI (KPa)
I[1]	Straight	2 static	46.3 (73.5)	2.80 (19.3)
	Curve	2 static	56.7 (90.0)	<2.50 (<17.2)
		2 static bottom 3 static top	98.5 (156.4)	<2.50 (<17.2)
II[2]	Straight	4 static 2 vibratory	50.2 (79.7)	2.65 (18.3)
		4 static	30.0 (47.6)	3.44 (23.7)
	Curve	4 static	99.3 (157.6)	<2.50 (47.2)

[1] Cut with a wet-cut saw.
[2] Cut with a dry-cut saw.

Table 25
Joint Spacing Effect on the Profilograph and PSI

Lane	Portion	Joint Spacing ft (m)	Profilograph Value in./mile (cm/km)	PSI (KPa)
I[1]	Straight	20 (6.1)	79.2 (125.7)	<2.50 (<17.2)
		40 (12.2)	71.5 (113.5)	<2.50 (<17.2)
		60 (18.3)	45.5 (72.2)	2.84 (19.6)
		100 (30.5)	23.8 (37.8)	3.68 (25.4)
	Curve	20 (6.1)	92.4 (146.7)	<2.50 (<17.2)
		60 (18.3)	52.8 (83.8)	2.55 (17.6)
		100 (30.5)	63.4 (100.6)	<2.50 (<17.2)
		uncut	83.6 (132.7)	<2.50 (<17.2)
II[2]	Straight	7.5 (2.3)	70.4 (111.8)	<2.50 (<17.2)
		20 (6.1)	110.0 (174.6)	<2.50 (<17.2)
		40 (12.2)	38.5 (61.1)	3.11 (21.4)
		60 (18.3)	25.7 (40.8)	3.61 (24.9)
		80 (24.4)	23.1 (36.7)	3.71 (25.6)
		92.5 (28.2)	31.4 (49.8)	3.39 (23.4)
		100 (30.5)	31.7 (50.3)	3.37 (23.2)
	Curve	20 (6.1)	118.8 (188.6)	<2.50 (<17.2)
		50 (15.2)	73.9 (117.3)	<2.50 (<17.2)
		60 (18.3)	118.8 (188.6)	<2.50 (<17.2)
		80 (24.4)	79.2 (125.7)	<2.50 (<17.2)
		100 (30.5)	73.9 (117.3)	<2.50 (<17.2)
		uncut	99.5 (158.0)	<2.50 (<17.2)

[1] Cut with a wet-cut saw.
[2] Cut with a dry-cut saw.

Table 26
Combined Effects of Paver Speed, Rolling Amount, and Joint Spacing on PSI

Lane	Paver Speed fpm (mpm)	Rolling passes[1]	Joint Spacing ft (m)	Profilograph in./mile (cm/km)	PSI (KPa)
I[2] straight	7 (2.1)	2 s	20 (6.1) 40 (12.2) 60 (18.3)	79.2 (125.7) 71.5 (113.5) 44.0 (69.9)	<2.50 (<17.2) <2.5 (<17.2) 2.89 (19.9)
	8-10 (2.4-3.0)	2 s	60 (24.4) 100 (30.5)	46.2 (73.3) 31.4 (49.8)	2.81 (19.4) 3.39 (23.4)
	12 (3.7)	2 s	100 (30.5)	5.9 (9.4)	4.38 (30.2)
I[3] curve	12 (3.7)	2 s	20 (6.1) 60 (18.3) 100 (30.5)	118.8 (188.6) 0.0 63.4 (100.6)	<2.50 (<17.2) 4.61 (31.8) <2.50 (<17.2)
	8 (2.4)	2 s	60 (18.3) uncut	57.6 (91.4) 96.8 (153.7)	<2.50 (<17.2) <2.50 (<17.2)
		3 s	uncut	93.6 (148.6)	<2.50 (<17.2)
II[3] straight	8-9 (2.4-2.7)	4 s 2 v	20 (6.1) 40 (12.2) 60 (18.3)	151.8 (241.0) 38.5 (61.1) 35.2 (55.9)	<2.50 (<17.2) 3.11 (21.4) 3.24 (22.3)
		4 s	20 (6.1) 60 (18.3) 80 (24.4) 92.5 (28.2) 100 (30.5)	26.4 (41.9) 20.9 (33.2) 23.1 (36.7) 31.2 (49.5) 31.7 (50.3)	3.58 (24.7) 3.79 (26.1) 3.71 (25.6) 3.39 (23.4) 3.37 (23.2)
	18 (5.5)	4 s	7.5 (2.3) 92.5 (28.2)	70.4 (111.8) 25.6 (40.6)	<2.50 (<17.2) 3.61 (24.9)
II[3] curve	18 (5.5)	4 s	20 (6.1) 60 (18.3) 100 (30.5)	118.8 (188.6) 52.8 (83.8) 63.4 (100.6)	2.50 (<17.2) <2.55 (17.6) <2.50 (<17.2)
	8-9 (2.4-2.7)	4 s	50 (15.2) 60 (18.3) 80 (24.4) uncut	73.9 (117.3) 135.8 (215.6) 79.2 (125.7) 99.5 (158.0)	<2.50 (<17.2) <2.50 (<17.2) <2.50 (<17.2) <2.50 (<17.2)

[1] s = static; v = vibratory.
[2] Cut with a wet-cut saw.
[3] Cut with a dry-cut saw.

For this project, it is not apparent what, if any, effect the speed of the paver had on the roughness of the pavement. In Lane I, as the paver speed was increased, the pavement roughness decreased, but in Lane II, as the paver speed was increased, the pavement roughness remained essentially the same. With limited data, it is difficult to know to what extent the amount of rolling and paver speed were interacting, making it difficult to determine the effect of each. No conclusions can be drawn about the paver speed.

It is also not apparent from the work done on this project that the amount of rolling had any impact on the profilograph value obtained because the project was not large enough to allow for much variation in the area of compaction by rolling. As stated earlier, the only rolling on Lane I was two static passes. While in Lane II, two types of rolling were used, four static passes and four static combined with two vibratory passes. These three variations were not enough to be able to make any conclusions. Also, rubber-tire rollers were not used on this project; therefore, it is difficult to say which is the best rolling pattern. No conclusions can be drawn about the effects of the amount of rolling on the profilograph value.

The joint spacings used in this project had a definite effect on the profilograph value. Overall, the profilograph value decreased as the joint spacings increased. In Lane I, the value decreased from 79.2 in./mile (125.7 cm/km) at a joint spacing of 20 ft (6.1 m) to 23.8 in./mile (37.8 cm/km) at a joint spacing of 100 ft (30.5 m). Likewise, in Lane II the value decreased from 110.0 in./mile (174.6 cm/km) at 20 ft (6.1 m) to 31.7 in./mile (50.3 cm/km) at 100 ft (30.5 m). From these data, it can be said that to decrease the initial roughness, RCC pavements should be constructed with large joint spacings. However, large spacing between joints, either sawn joints or cracks, are associated with large movements of these joints. Experience has shown that large movements at long joint spacings make proper sealing more difficult than with shorter spacings. This suggests that large joint spacings may cause increased long-term maintenance requirements and eventual increases in pavement roughness.

The length of the roadway test section placed limited the number of the construction parameters that could be evaluated for their effect on roughness. The possible construction parameters consist of paver speed, amount of rolling, joint spacing, and lift thickness. For illustration purposes, Table 27 shows all of the possible construction parameter combinations except for lift thickness. By placing an X in those combinations on the straight section and an O on those combinations that were used on the curved section, it shows which ones were utilized.

Of the 168 possible combinations, only 20 were used. Because of this, there is not a large enough statistical base to work with to determine statistically which of the three parameters is the most critical to producing a good profilograph value. Additional projects should be done either diminishing the number of combinations so that all of the combinations can be

Table 27
All Possible Combinations of Paver Speed, Rolling Amount, and Joint Spacings

Paver Speeds fpm (mpm)	Joint Spacings ft (m)	Roller Amounts, passes			
		2 static	3 static	4 static	4 static 2 vibratory
7 (2.1)	20 (6.1)	X	--	--	--
	40 (12.2)	X	--	--	--
	50 (15.2)	--	--	--	--
	60 (18.3)	X	--	--	--
	80 (24.4)	--	--	--	--
	100 (30.5)	--	--	--	--
	uncut	--	--	--	--
8 (2.4)	20 (6.1)	--	--	--	--
	40 (12.2)	--	--	--	--
	50 (15.2)	--	--	--	--
	60 (18.3)	O	--	--	--
	80 (24.4)	--	--	--	--
	100 (30.5)	--	--	--	--
	uncut	O	O	--	--
8-9 (2.4-2.7)	20 (6.1)	--	--	X	X
	40 (12.2)	--	--	--	X
	50 (15.2)	--	--	O	--
	60 (18.3)	--	--	X,O	X
	80 (24.4)	--	--	O	--
	100 (30.5)	--	--	X	--
	uncut	--	--	O	--
8-10 (2.4-3.0)	20 (6.1)	--	--	--	--
	40 (12.2)	--	--	--	--
	50 (15.2)	--	--	--	--
	60 (18.3)	X	--	--	--
	80 (24.4)	--	--	--	--
	100 (30.5)	X	--	--	--
	uncut	--	--	--	--
12 (3.7)	20 (6.1)	O	--	--	--
	40 (12.2)	--	--	--	--
	50 (15.2)	--	--	--	--
	60 (18.3)	O	--	--	--
	80 (24.4)	--	--	--	--
	100 (30.5)	X,O	--	--	--
	uncut	--	--	--	--
18 (5.5)	20 (6.1)	--	--	O	--
	40 (12.2)	--	--	--	--
	50 (15.2)	--	--	--	--
	60 (18.3)	--	--	O	--
	80 (24.4)	--	--	--	--
	100 (30.5)	--	--	O	--
	uncut	--	--	--	--

accomplished, or a large project should be undertaken to handle all of the combinations that are listed in Table 27.

To summarize, the only construction parameters that can be judged to have an effect on the pavement roughness are the joint cutting method and the joint spacing. Both a dry-cut saw and large joint spacings led to lower profilograph values, at least initially. The speed of the paver and the amount of rolling cannot be determined from this project to have an effect on the profilograph value for a RCC pavement.

Skid Resistance

Skid resistance tests were conducted on Lanes I and II in an attempt to help determine the suitability of RCC for high-speed traffic. These tests were performed 2 December 1992 by CALTRANS. The ability of a pavement to resist skidding is very important in high-speed applications because if a pavement does not have sufficient skid resistance, then an increased number of accidents due to skidding, hydroplaning, etc., will be expected. Low skid resistance is unacceptable for high-speed traffic.

The test method used for this project was ASTM E 274-90 -- Standard Test Method for Skid Resistance of Paved Surfaces Using a Full Scale Tire. ASTM E 274-90 uses a full-scale automotive tire on a test wheel to determine the skid resistance. Photos of the skid resistance tester appear in Appendix E (Photos E13 through E16). The quantity being measured is the steady-state friction force on a locked wheel, as the wheel is dragged over a wetted pavement while under a constant load and at a constant speed. A truck towed the trailer that was equipped with the test wheel and other test equipment including transducers, instrumentation, a water supply, and brake controls. The truck and trailer were brought to the desired speed, and water was sprayed on the pavement immediately in front of the test wheel. The skid number was determined by measuring the horizontal force on the wheel, dividing that by the effective load on the wheel, and then multiplying by 100. Skid numbers were calculated for both lanes. The skid numbers for this project are given in Table 28. Values in the mid 50's would be considered very good for new PCC pavement construction. Values of 30 or below are normally considered an indication that improvements to the skid resistance of the pavement surface are required.

Similar to the profilograph, the skid numbers are compared to paver speed and amount of rolling. This is done to determine the effects, if any, these parameters have on the skid resistance. The combined effects of the paver speed and rolling amount are listed in Table 29.

Similar to the final density, an analysis of variance cannot be performed on the skid resistance numbers because not enough of the possible combinations were used. The possible combinations are listed in Table 30.

Table 28
Skid Numbers

Lane	Station	Skid Numbers	Average Skid Number
I	0+53	42,43	42.5
	1+06	48	48
	2+11	54	54
	3+70	60,64	62
	6+34	51	61
	8+45	55,57	56
	9+50	59	59
	11+62	52	52
	12+14	53	53
	13+73	47	47
II	0+53	64	64
	1+06	62	62
	2+11	63	63
	2+64	58	58
	4+75	57	57
	6+34	58	58
	7+92	47,52	49.5
	8+45	51	51
	11+09	48	48
	11+62	51	51
	12+67	52	52
	13+20	50	50

Table 29
Combined Effects of Paver Speed and Rolling Amount on Skid Resistance

Paver Speed fpm (mpm)	Rolling Amount passes	Skid Numbers
7 (2.1)	2 static	42,60,54,48,43,64
8 (2.4)	3 static	58,53,47
8-10 (2.4-3.0)	2 static	61,55,57
12 (3.7)	2 static	57
8-9 (2.4-2.7)	4 static	58,48,47,50,57,51,51,52,52
8-9 (2.4-2.7)	4 static, 2 vibratory	64,63,62,58

Table 30 Possible Combinations and Test Locations				
Paver Speeds fpm (mpm)	Rolling, passes			
	2 static	3 static	4 static	4 static, 2 vibratory
7 (2.1)	X[1] 6	--	--	--
8 (2.4)	X 0	X 3	--	--
8-9 (2.4-2.7)	--	--	X 9	X 4
8-10 (2.4-3.0)	X 3	--	--	--
12 (3.7)	X 1	--	--	--
18 (5.5)	--	--	X 0	--

[1] X = combination used; number = skid numbers taken.

As stated before, there were not enough possible combinations used to determine which of paver speed and rolling combinations has the most critical impact on the skid resistance. But, also similar to final density, the effect of rolling amount on skid resistance can be examined if all of the paver speed values in the range of 8 to 10 fpm (2.4 to 3.0 mph) are held to be the same. The analysis of variance under this scenario is listed in Table 31.

Table 31 Analysis of Variance for Rolling Amount Versus Skid Number with Paver Speed Held Constant				
Source	DF	SS	MS	F
Rolling	3	313.3	104.4	7.54
Error	15	207.6	13.8	
Total	18	520.9		

The F-value of 7.54 is greater than the 95-percent confidence interval F-value of 3.24; therefore, the amount of rolling has a statistical significance on the skid resistance.

The values in Table 29 are plotted in Figure 6. The one problem with this figure is that a rolling amount of four static and two vibratory passes is plotted as six (static) passes. This is probably an incorrect assumption, but

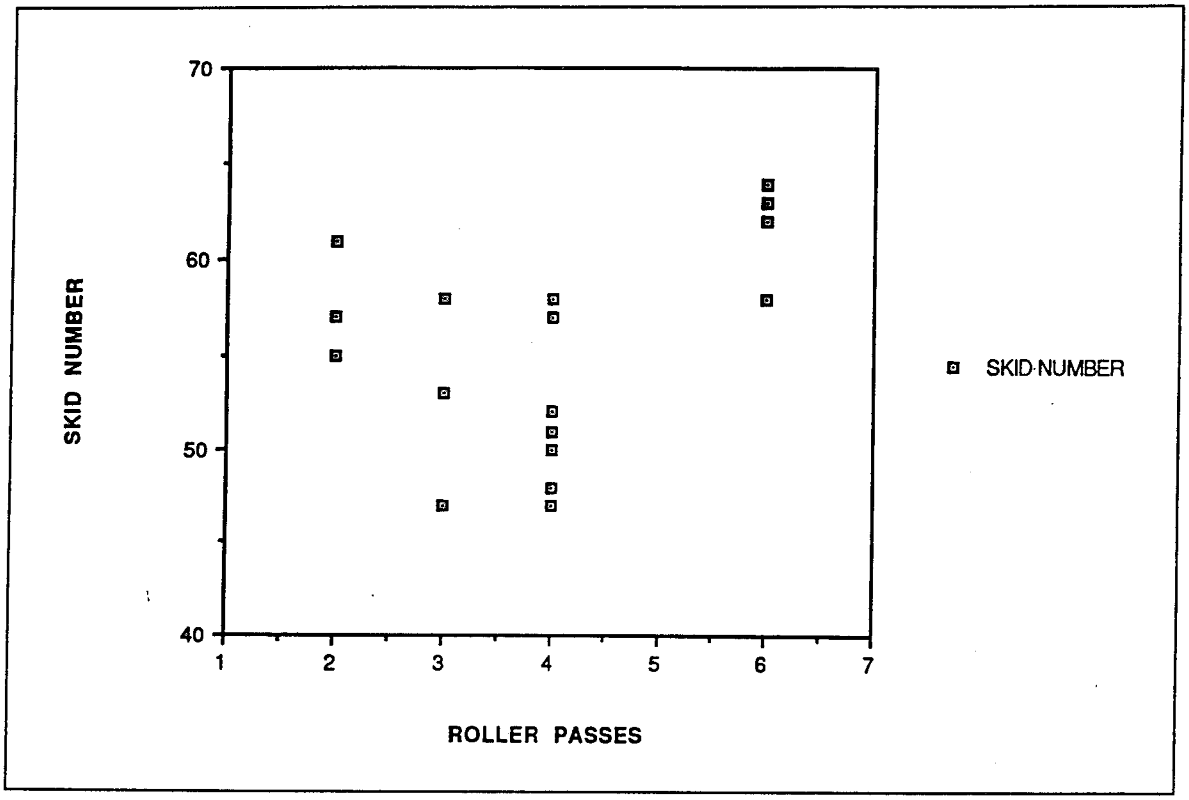

Figure 6. Rolling amount versus skid number

with the limited data for this project, that assumption was made. This figure shows the wide range of skid numbers obtained. From the limited data available, the addition of vibratory passes increased the skid number; however, the addition of static passes decreased the skid number.

Under similar test conditions to that used for this project, previous PCC pavements have produced average skid numbers in the upper 40's (Tomita 1964). Skid numbers in the mid 50's would be considered very good for new PCC pavement (Shoenberger et al. 1994). Since these test skid numbers for RCC ranged from 42 to 64, the RCC placed for this project has the same or slightly greater skid number range as PCC. There are several factors such as shape and type of aggregates used for this project which may have had a greater effect on skid resistance than type or number of roller passes.

Crack Mapping

Photos of the cracking appear in Appendix F. Photos F1 through F8 show both transverse and longitudinal cracks in both Lane I and Lane II. A graphical representation of the cracking for Lanes I and II is in Appendix G.

On 3 December 1992, a cracking survey was conducted on the two 1,525 ft (464.82-m) by 14-ft (4.26-m) RCC lanes. This survey was conducted approximately 7-1/2 months after placement of the RCC pavement. The survey was conducted by walking along the roadway and locating the cracks by pacing. Each crack was checked visually for width and spalling. There were 36 transverse cracks and 2 longitudinal cracks in Lane I. Lane II had 52 transverse and 5 longitudinal cracks. There were also a few minor cracks in the corners of a handful of slabs, throughout both lanes. All of the cracks in the test section were ranked to determine whether they were of low, medium, or high severity. Low severity means the crack width was less than 1/8 in. (3.1 mm) with minor spalling or any sealed crack. Medium is a width of 1/8-in. up to 1 in. (3.1 to 25.4 mm) with moderate spalling. A severe crack is one with a width greater than 1-in. (25.4 mm) and heavy spalling (Headquarters, Department of the Army 1989). A large majority of the cracks were low severity with only five being classified as high severity. A large number of the cracks were classified as low severity because many of those cracks had been sealed by granite rock. All five high-severity cracks appeared in the curved portions of Lanes I and II.

All of the transverse cracks ran for a total width of one lane, which was 14 ft (4.26 m). On 10 different occasions, cracks on both lanes matched to make up one crack which runs the full width of 28 ft (8.534 m) across both lanes.

The longitudinal cracks varied in length, but all of them began or ended at either a transverse joint, a transverse crack, or the longitudinal construction joint between lanes. In Lane I, the two longitudinal cracks were 42 and 203 ft (12.8 and 61.9 m) long, and in Lane II the lengths were 8, 28, 33, 34, and 35 ft (2.44, 8.53, 10.1, 10.4, and 10.7 m). Several longitudinal cracks occurred in the midpoint of the paving lane and would appear to be associated with the distributing auguring system of the paver. The majority of these cracks appeared in the curved section of the roadway. These cracks are similar to those noted on previous roadway paving in Australia (Jameson et al. 1989).

The average length of the uncracked sections throughout both lanes and all slab lengths was 22.8 ft (6.95 m). An uncracked section length is defined as the distance between two transverse joints, a transverse joint and a transverse crack, or two transverse cracks. Observation of the sawed longitudinal construction joint prior to placement of the second paving lane showed that the sawed contraction joints in Lane I (inbound) had cracked full depth. The average length of the uncracked sections for the various slab lengths are listed in Table 32.

Since the joints in Lane I were cut using a wet-cut saw and the joints in Lane II were cut using a dry-cut saw, the cracking data are further broken down into the lanes. The average uncracked section lengths for the slabs in Lane I are listed in Table 33, while the average uncracked section lengths for the slabs in Lane II are listed in Table 34.

Table 32
Slab Length Versus Average Uncracked Section Length -- Overall

Slab Length ft (m)	Number of Slabs	Average Uncracked Section Length	
		ft	m
7.5 (2.3)	1	7.5	2.29
20 (6.1)	7	17.5	3.81
40 (12.2)	15	20.9	6.37
50 (15.2)	1	16.7	5.09
60 (18.3)	15	22.0	6.71
80 (24.4)	2	20.0	6.10
92.5 (28.2)	1	18.5	5.64
100 (30.5)	6	24.0	7.32
uncut	2	31.0	9.45

Table 33
Slab Length Versus Average Uncracked Section Length -- Lane I

Slab Length ft (m)	Number of Slabs	Number of Non-Cracked Slabs	Average Uncracked Section Length	
			ft	m
20 (6.1)	3	3	20	6.10
40 (12.2)	6	2	24	7.32
60 (18.3)	7	0	26.2	8.00
100 (30.5)	4	0	28.6	8.71
uncut	1	--	28.9	8.81

Table 34
Slab Length Versus Average Uncracked Section Length -- Lane II

Slab Length ft (m)	Number of Slabs	Number of Non-Cracked Slabs	Average Uncracked Section Length	
			ft	m
7.5 (2.3)	1	1	7.5	2.29
20 (6.1)	4	3	16	4.88
40 (12.2)	6	1	20	6.10
50 (15.2)	1	0	16.7	5.09
60 (18.3)	8	0	17.8	5.42
80 (24.4)	2	0	20	6.10
92.5 (28.2)	1	0	18.5	5.64
100 (30.5)	2	0	18.2	5.54
uncut	1	--	35.8	10.9

The longest uncracked section length was 96 ft (29.3 m), which appeared in the uncut slab area of Lane II, while the shortest length was 2 ft (0.61 m), which appeared in the uncut slab area of Lane I. It is not known when or in what order these cracks occurred. One of them matched a saw-cut joint in Lane II. It is possible that the RCC cracked in one location and then later cracked 2 ft away to match the sawed joint.

Overall, the average uncracked section length increased as the joint spacings increased. The overall average uncracked section length for a 20-ft (6.1 m) joint spacing was 17.5 ft (5.3 m), and this generally increased to 31.0 ft (9.4 m) where the lanes were uncut. The same trend also occurred in each individual lane. In Lanes I and II, for the 20-ft (6.1-m) sawed slab length, none of the three slabs cracked in Lane I, while one of four did in Lane II. There was a noticeable difference in the uncut areas of each lane; the average uncracked section lengths were 28.9 ft (8.8 m) and 35.8 ft (10.9 m) for Lanes I and II, respectively. From these data, it can be seen that leaving the RCC uncut leads to a larger average uncracked section length. It can also be seen that slabs that are cut to be 20 ft (6.1 m) in length do not tend to crack as much, as there was only one cracked slab in the seven 20-ft (6.1-m) slabs.

Falling Weight Deflectometer

Falling weight deflectometer (FWD) was used to determine the joint efficiency across joints and cracks. Photos of the FWD apparatus are in Appendix E (Photos E19 and E20). The tests were conducted in accordance with ASTM D 4694 (ASTM 1993). A summary of the test is as follows.

The test is a plate-bearing type test. A force pulse is generated by dropping a weight on a spring system, and the load is transmitted through a plate to the pavement. The testing apparatus is mounted on a trailer towed behind a vehicle. The load plate is positioned over the desired test location. The plate and deflection sensors are lowered to the pavement. The weight is raised to a position where it will impart the desired force to the plate and pavement when dropped. Multiple tests are generally performed. For this project, there were two repetitions of three separate weights (drop heights) for a total of six tests at each location. The sensors were located at the following distances from the load center -- 0, -12, 24, 36, 48, 60, and 72 in. (0, -30.5, 61.0, 91.4, 121.9, 152.4, 182.9 cm). With the 12-in.- (30.3-cm-) diameter plate located next to a joint or crack, the -12-in.- (-30.5-cm-) sensor was actually 6 in. (15.2 cm) on the other side of the joint or crack from the plate. The peak deflections at each sensor were measured, and the peak load was also measured. The tests were performed on the first 520 ft (158 m) of each lane at every joint and crack in this length. The entire length of each lane could not be tested due to time constraints. All joint tests were conducted away from the corners; only the midslab portion of each slab was tested. In addition, deflection basins were taken at the center of each slab to compare the defections relative to the joint and crack deflections.

An aggregate interlock calculation was not performed because there was no sensor placed at positive 12 in. (30.5 cm) from the load center. To determine if the data were from the same population and could be used to joint efficiency calculations, several graphs were constructed. The first sets of these graphs appear in Figures 7 through 10. These figures are deflection curves for the midslabs. Since there is no crack or joint, the -12-in.- (-30.5-cm-) deflection is assumed to be the same as what the 12 in. (30.5 cm) would be. These were plotted to compare to the plots at the cracks and joints. Figure 7 shows the deflection of slabs 1 through 6 of Lane I under a low load, approximately 6,000 lb (26.7 kN). A letter designation means that the slab was cracked. As an example, 3A means that slab 3 was cracked, and A means that this is the first smaller slab in slab 3. Figure 8 shows the deflection of slabs 23 through 28 of Lane II. This is also under a low load. Figure 9 shows the deflection of slabs 1 through 4 of Lane I under high loads (approximately 12,000 lb (53.4 kN)). Figure 10 shows the deflection of slabs 23 through 25 in Lane II under high loads also. For all four figures, the curves were smooth, which indicates that the data can be considered to be from the same population.

Figures 11 through 14 show the deflection curves for selected joints in the RCC roadway. Here, the -12-in. (-30.5-cm) deflection is also plotted as though it were the 12-in. (30.5-cm) deflection, but in this case, since these reading were taken at joints, there should not be a smooth curve -- the -12-in. (-30.5-cm) deflection should be less than or equal to the expected 12-in. (30.5-cm) deflection. The expected deflection is determined by comparing the joint curves to the midslab curves.

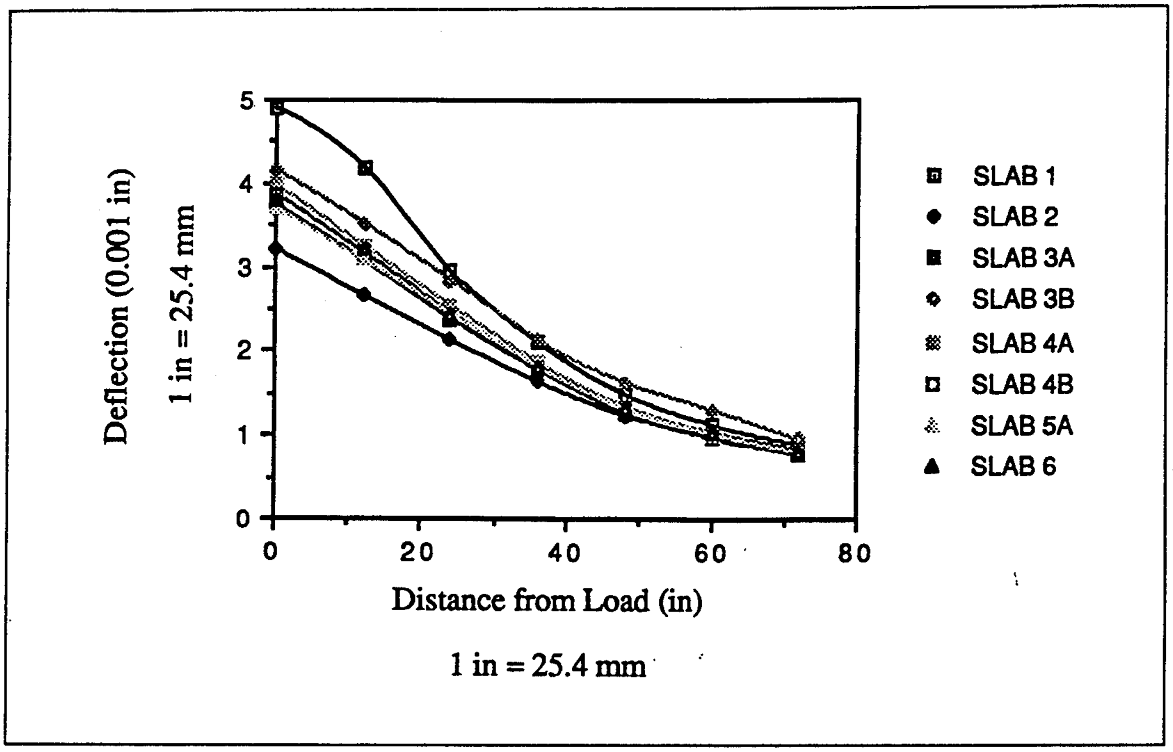

Figure 7. Deflection curves--low weight, midslab, Lane I

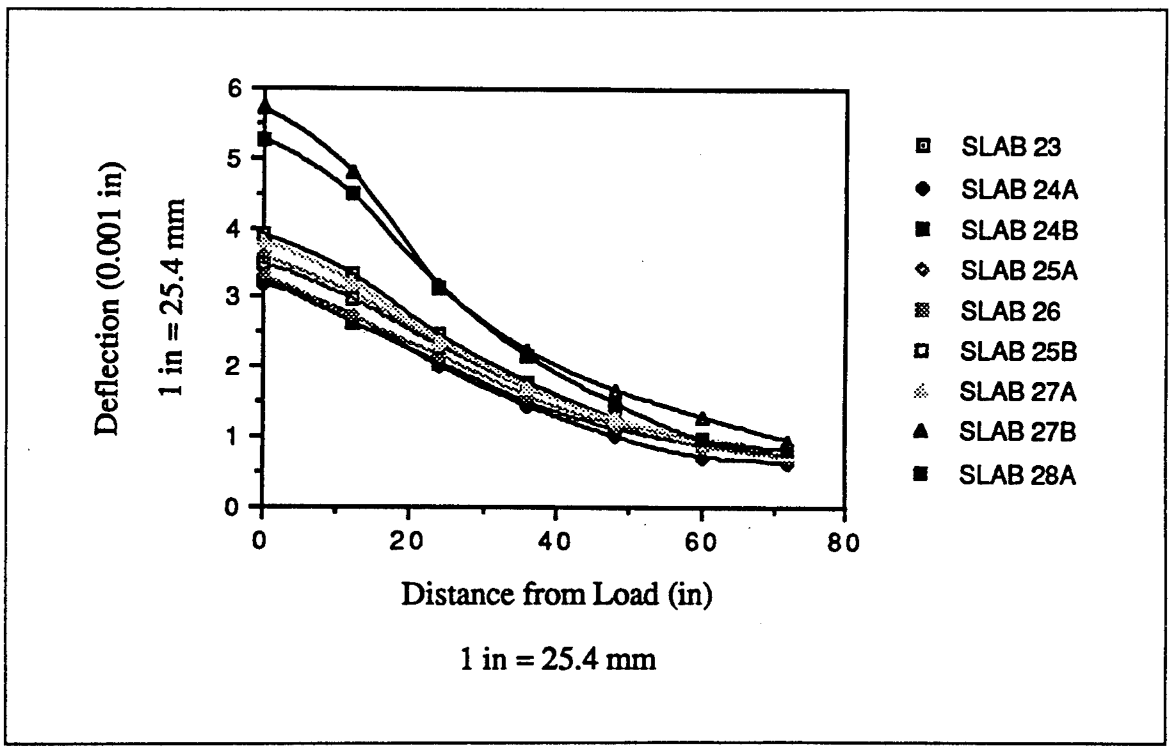

Figure 8. Deflection curves--low weight, midslab, Lane II

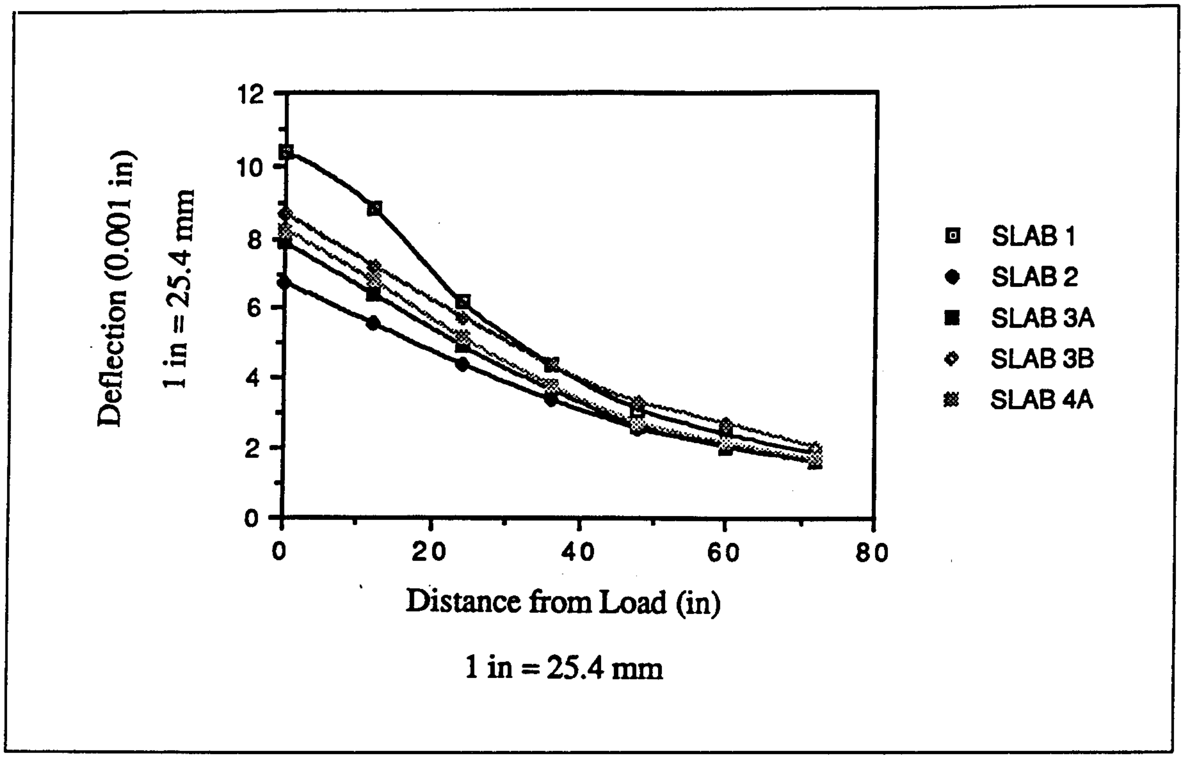

Figure 9. Deflection curves--high weight, midslab, Lane I

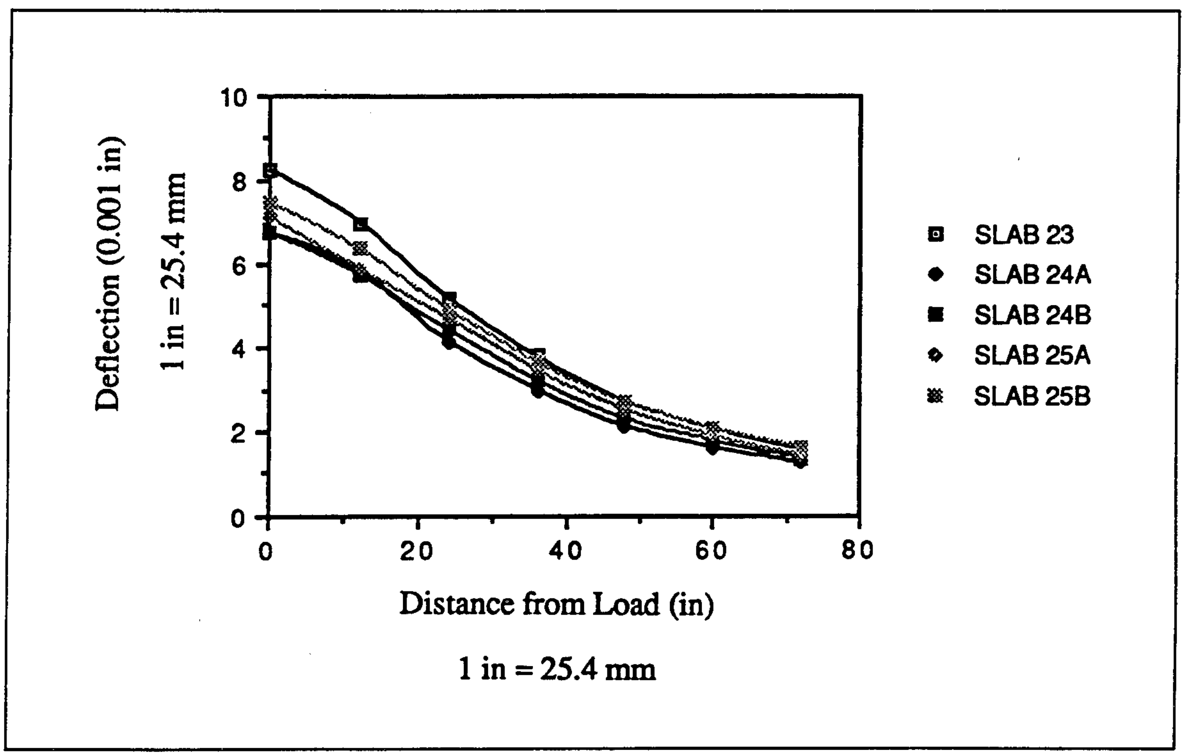

Figure 10. Deflection curves--high weight, midslab, Lane II

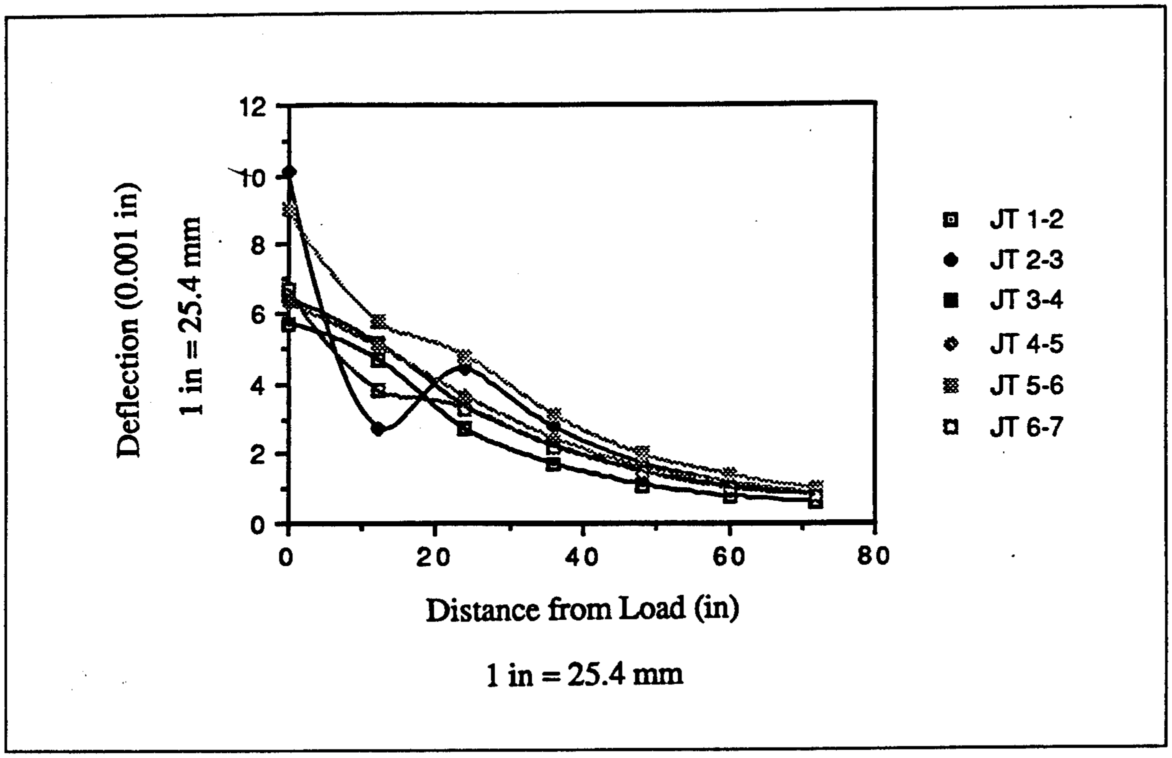

Figure 11. Deflection curves--low weight, joints, Lane I

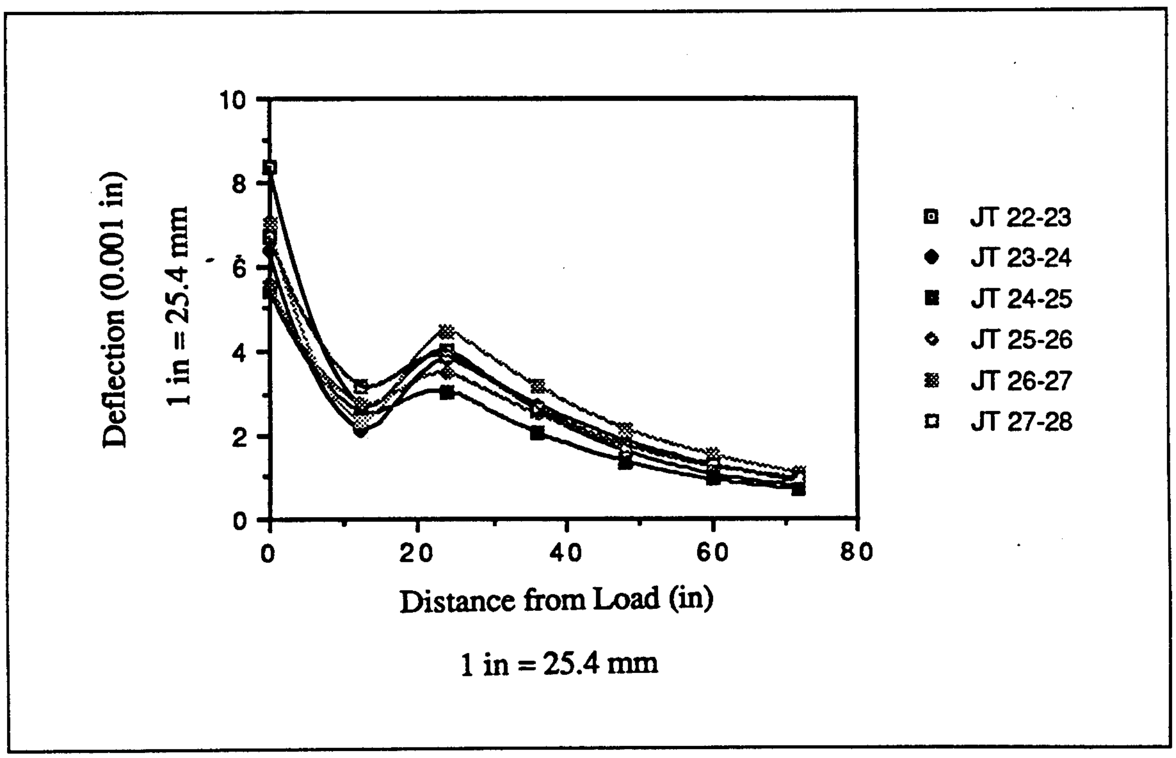

Figure 12. Deflection curves--low weight, joints, Lane II

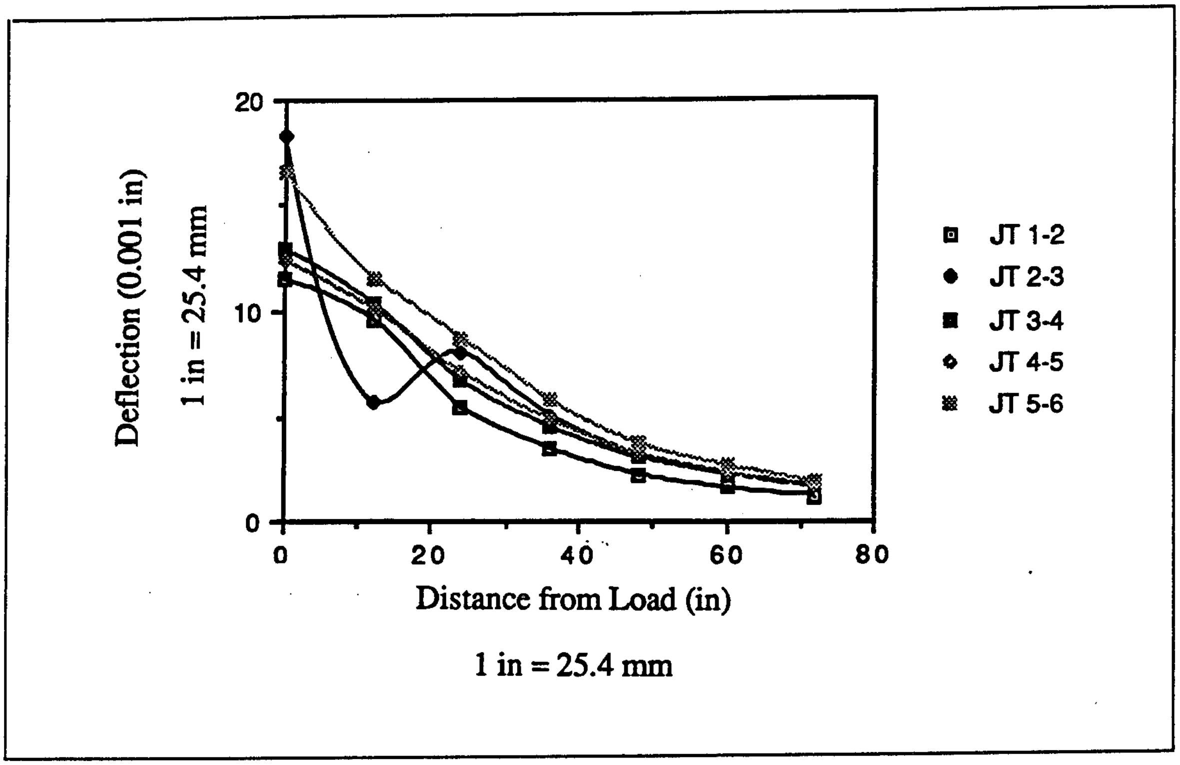

Figure 13. Deflection curves--high weight, joints, Lane I

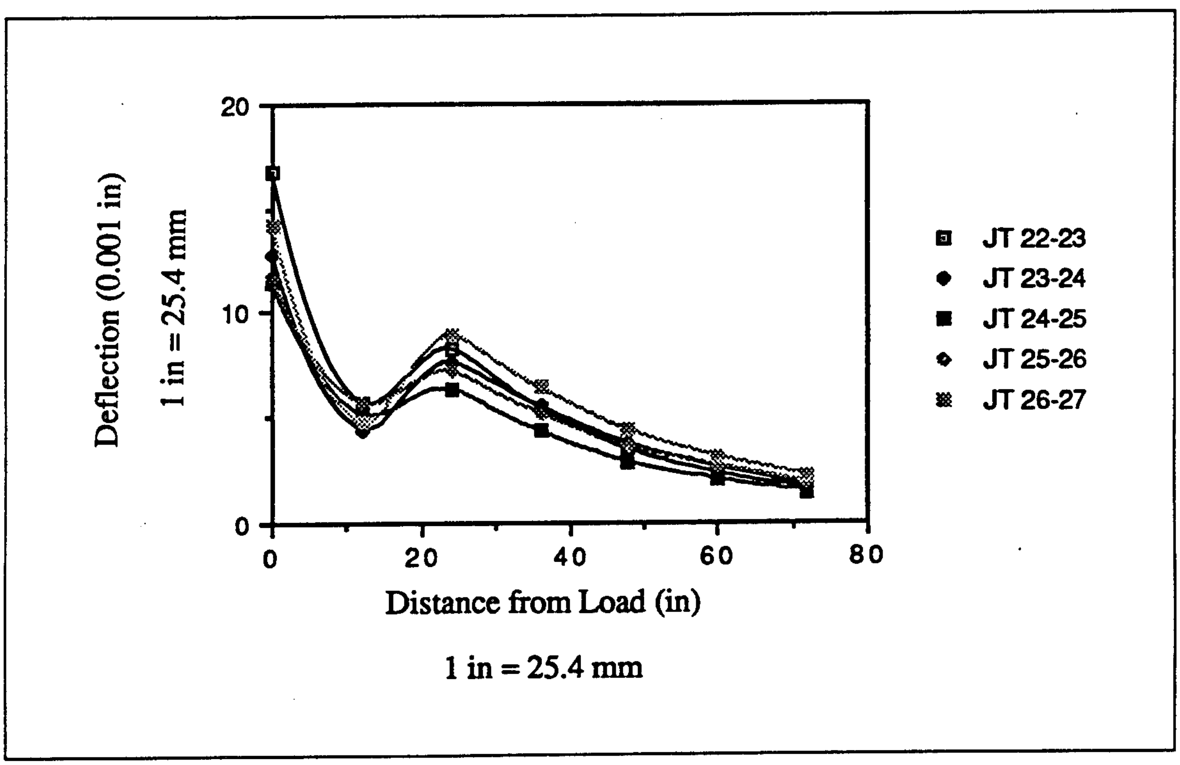

Figure 14. Deflection curves--high weight, joints, Lane II

Figure 11 shows joint 1-2 through joint 6-7 for Lane I under low load. Joints 2-3, 5-6, and 6-7 show the expected results with the curve dipping at the 12-in. (30.5-cm) reading. On the other hand, joints 1-2, 3-4, and 4-5 actually show a deflection reading which is higher than expected. This could be contributed to possible failure to properly seat the plate or sensors used in the FWD equipment or some other testing abnormality. As replicate tests were not performed, the reason for these results is unknown.

Figure 12 shows joint 22-23 through joint 27-28 of Lane II under low load. In these cases, all of the joints show the expected results of the -12-in. (30.5-cm) deflection dipping from the smooth curve. Figure 13 shows the deflection curves for joints 1-2 through 5-6 of Lane I under high load. Once again, joints 2-3 and 5-6 show the expected results while joints 1-2, 3-4, and 4-5 show the curve actually rising at the -12-in. (30.5-cm) sensor. This is consistent with Figure 11. Figure 14 shows the deflection curves for joints 22-23 through 26-27 of Lane II under high load. Once again, all of the curves show the expected result with the -12-in. (-30.5 cm) deflection dipping away from the curve. All of the curves that dip away from or do not have a smooth curve lead to the assumption that there is some loss of efficiency in those joints.

Figures 15 through 18 show the deflection curves for selected cracks in the RCC roadway. Similar to the joint curves, the -12-in. (-30.5-cm) deflection is plotted as though it were the 12-in. (30.5-cm) deflection. Once again, these curves are expected to have dips at the 12-in. (30.5-cm) deflection sensor. The cracks are designated as follows: crack 3 means that this is the only crack in slab 3, while crack 29A means that this is the first of multiple cracks in slab 29. Figure 15 shows cracks 3 through 9 of Lane I under low weight. None of the curves show much of a dip at the -12-in. (-30.5-cm) sensor, but none of the curves show an increased value at that sensor either. Since there is no dip, the assumption would be that there is not much of a loss of efficiency at these cracks. The term "efficiency" at cracks is the same as joint efficiency, except it is for cracks. Figure 16 shows cracks 24 through 29A of Lane II under low load. All of these curves show at least a minor dip at the -12-in. (-30.5-cm) sensor, which is expected. Therefore, these cracks show some loss of efficiency. Figure 17 shows cracks 3 through 9 of Lane I under high load. Once again, none of the curves show any dip at the -12-in. (-30.5-cm) sensor. Therefore, the assumption would be that there is little to no loss of efficiency at these cracks. Figure 18 shows cracks 24 through 29A of Lane II under high load. Similar to Figure 16, all of these curves show at least a minor dip at the -12-in. (-30.5-cm) sensor, which leads to the assumption that there is some loss of efficiency.

From these 12 figures, it can be seen that most if not all of the FWD data were consistent, because in most cases the -12-in. (-30.5-cm) deflection for the jointed/cracked conditions is less than the -12-in. (-30.5-cm) deflection in the uncracked conditions. The best way to calculate the joint or crack efficiency percentage would be to divide the deflection at -12 in. (-30.5 cm) (D_{-12}) by the deflection at 12 in. (30.5 cm) (D_{12}), but there was no sensor

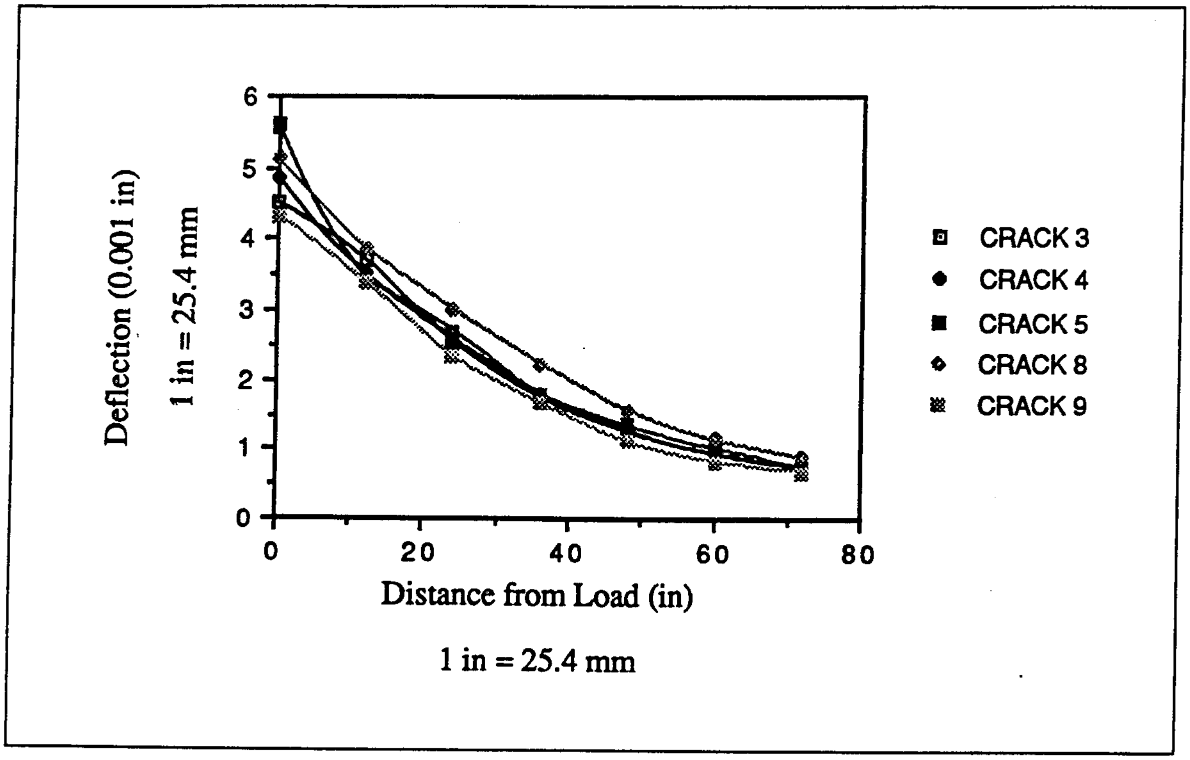

Figure 15. Deflection curves--low weight, cracks, Lane I

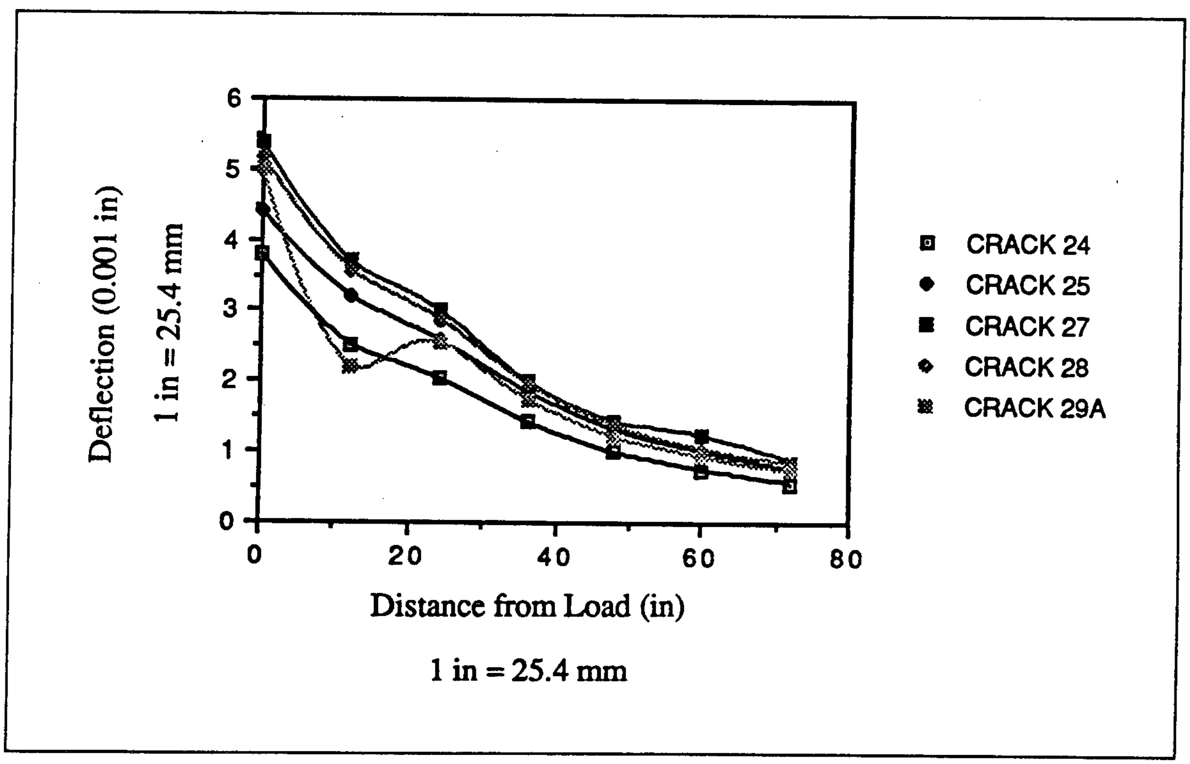

Figure 16. Deflection curves--low weight, cracks, Lane II

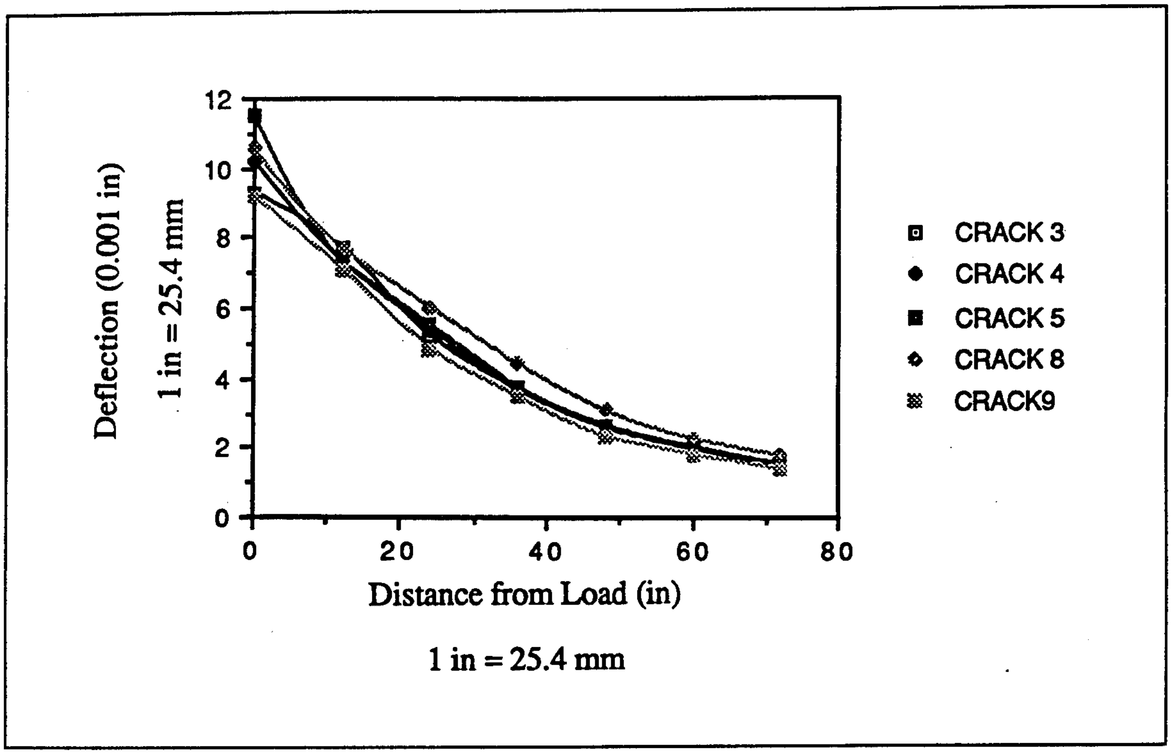

Figure 17. Deflection curves--high weight, cracks, Lane I

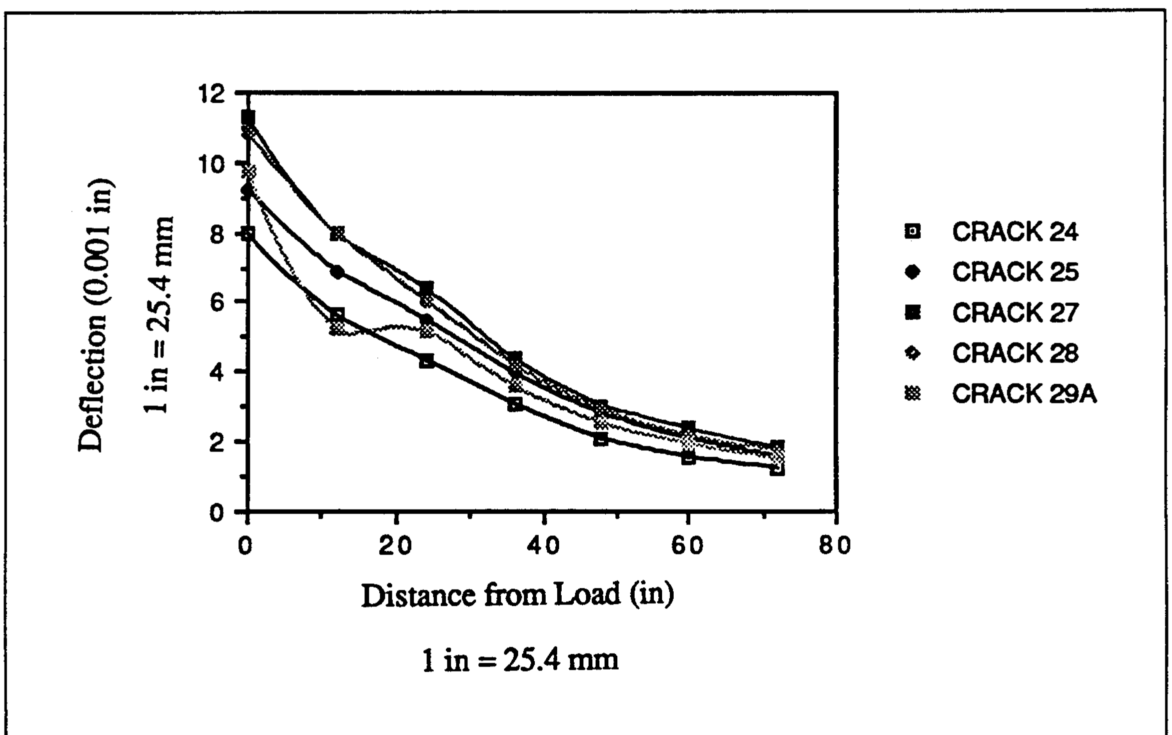

Figure 18. Deflection curves--high weight, cracks, Lane II

placed at 12 in. (30.5 cm). Therefore, to calculate the joint efficiency, an assumption was made. It was assumed that at midslab conditions, the deflection at 0 in (0 cm) (D_0) is the same as D_{-12}. This is a conservative assumption because it was shown in Figures 7 through 10 that the D_{-12} is always less than D_0. The joint or crack efficiency (JE) percentage was then calculated by using the following equation.

$$JE = \frac{D_{-12}}{D_o} \times 100 \qquad (2)$$

The joint efficiency calculations can be seen in Appendix H.

Figures 19 and 20 show graphical representations of the joint efficiency calculations. All of the figures show the joint efficiency percentages versus the applied loads. They also show a best fit linear regression connecting the points for the same joint or crack. The results indicate that the joint efficiency tends to increase with increasing load, especially for low levels of joint efficiency. This is illustrated in Figures 19 and 20.

These figures show that there was a significant amount of joint efficiency retained in the joints and cracks of the RCC pavement.

Joint efficiency results for the other test locations (Lane I cracks, Lane II joints, etc.) appear in Appendix I.

To determine whether the slab length before and after a crack occurs has an impact on the joint efficiency, Table 35 was developed. The hypothesis is that a larger slab length will correspond to a wider crack width and therefore a lower joint efficiency. Due to the varying depth of saw cuts between Lanes 1 and 2, only cracks were used for this analysis. Ideally, only cracks with equal distances on each side to the next crack or joint would be used; however, limited available data required the use of unequal lengths. Test results where the slab on one side of the crack was more than twice as large as the other were not used for this analysis. Table 35 lists the joint efficiency for the medium FWD weight and considering the direction of the nuclear-density test (NDT) device, the uncracked length before the crack (Before), the uncracked length after the crack (After), and the average of the before and after lengths (Average).

Figure 21 shows average plotted versus joint efficiency. The data plotted in Figure 21 may indicate a trend that as the average slab length increases so does the joint efficiency; however, these are very limited data and are also contrary to the assumption that as slab length increases, joint efficiency decreases. If this trend is correct, a possible explanation for this phenomenon is that in the areas where there are larger uncracked slab lengths, the RCC strength is greater, indicating a better quality concrete that is less prone to losing aggregate interlock with each application of load.

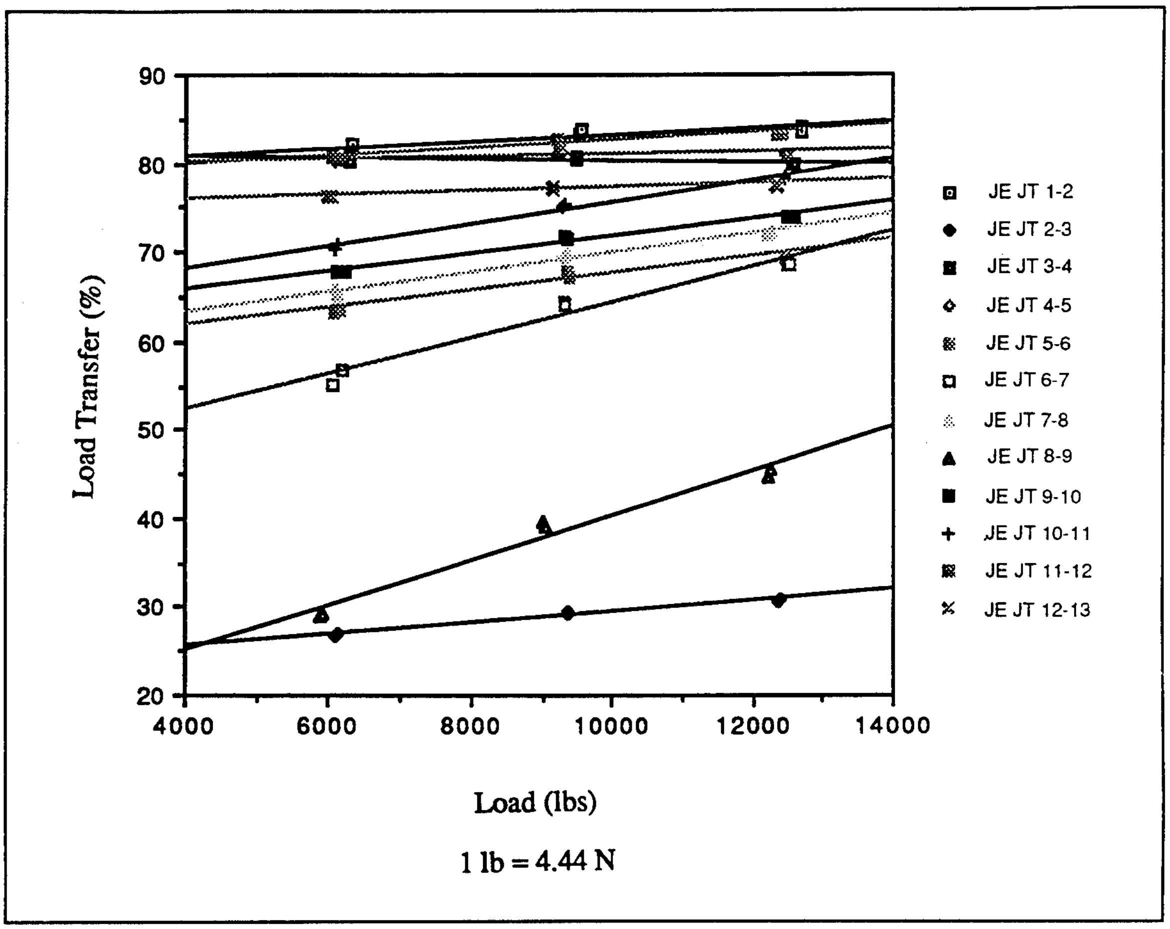

Figure 19. Joint efficiency--joints, Lane I

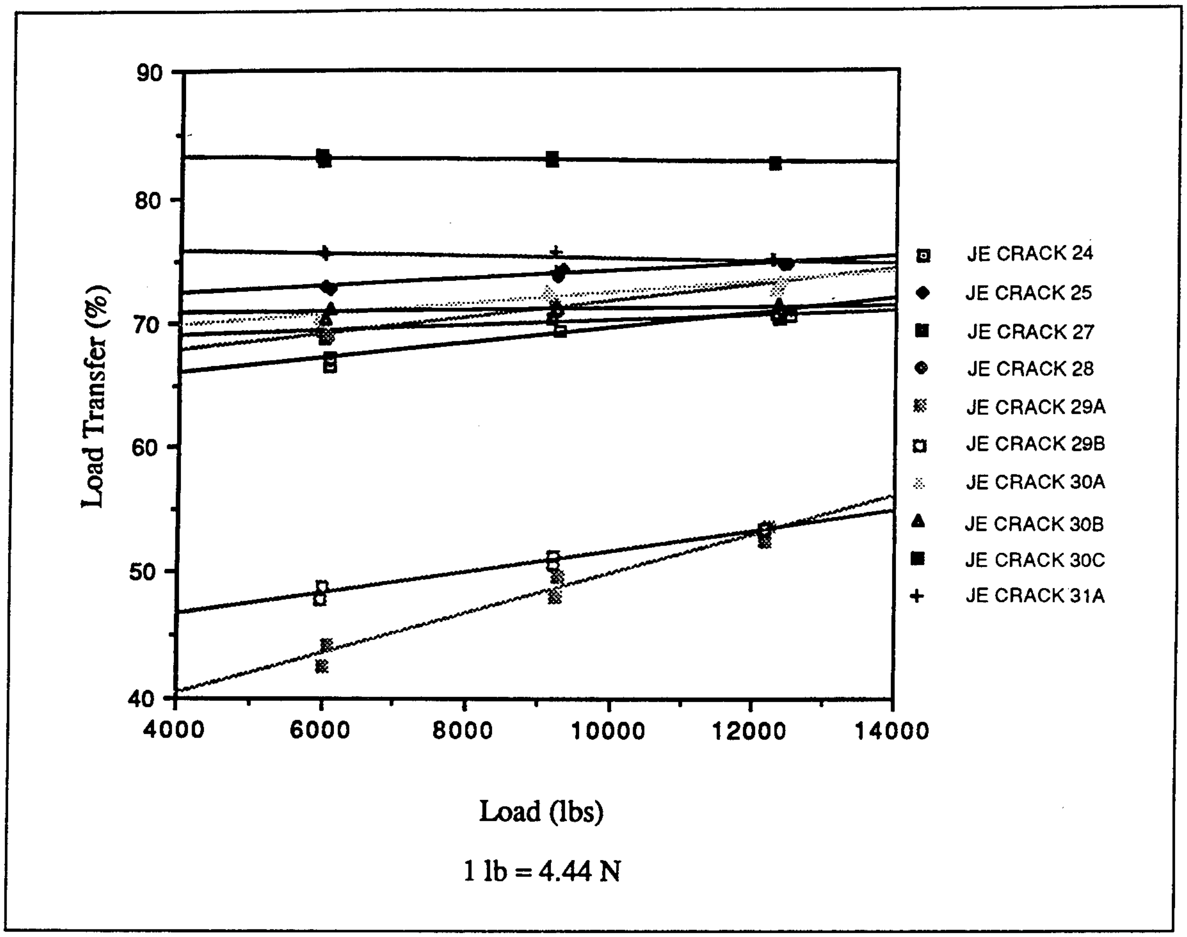

Figure 20. Joint efficiency--cracks, Lane II

Table 35 -
Joint Efficiency Versus Slab Length

Joint Efficiency %	Before ft (m)	After ft (m)	Average ft (m)
83.38	25 (7.6)	15 (4.6)	20 (6.1)
72.53	20 (6.1)	20 (6.1)	20 (6.1)
62.59	23 (7.0	17 (5.2)	20 (6.1)
73.49	31 (9.4)	29 (8.8)	30 (9.1)
77.73	15 (4.6)	10 (3.0)	12.5 (3.8)
76.75	24 (7.3)	36 (11.0)	30 (9.1)
69.39	20 (6.1)	20 (6.1)	20 (6.1
74.62	20 (6.1)	20 (6.1)	20 (6.1)
70.31	24 (7.3)	16 (4.9)	20 (6.1)
71.38	15 (4.6)	25 (7.6)	20 (6.1)
48.93	12 (3.7)	15 (4.6)	13.5 (4.1)
50.94	15 (4.6)	18 (5.5)	16.5 (5.0)
72.40	20 (6.1)	15 (4.6)	17.5 (5.3)
71.08	15 (4.6)	25 (7.6)	20 (6.1)
83.05	9 (2.7)	16 (4.9)	12.5 (3.8)
74.85	16 (4.9)	8 (2.4)	12 (3.7)

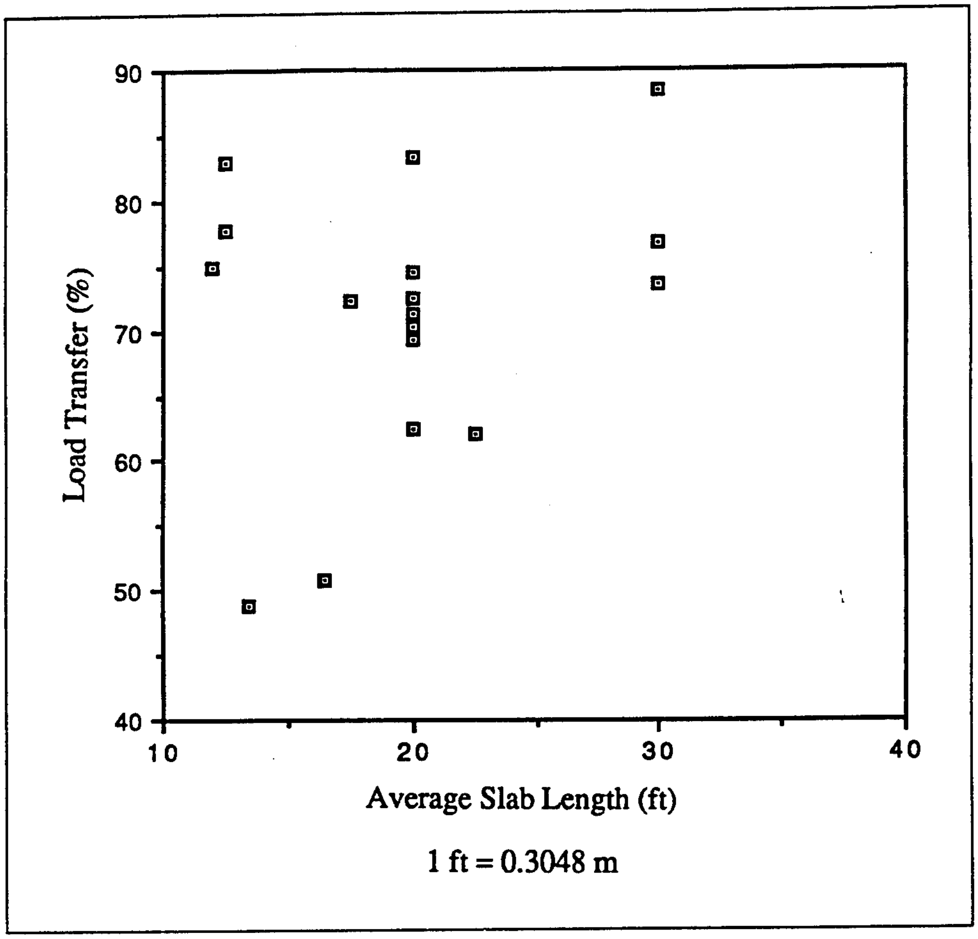

Figure 21. Joint efficiency versus average slab length

Density Profiles

On 3 December 1992, 14 cores were taken from the RCC parking lot. These cores were used to determine the uniformity of the density throughout the thickness of the RCC pavement sections. A uniform density throughout the full depth of an RCC pavement is desirable to ensure that adequate strength is obtained, especially at the bottom where the maximum tensile stresses occur. An adequate and uniform density will also help ensure that a frost-resistant and rideable pavement has been produced.

The cores were 4 in. (10 cm) in diameter and ranged from 4 to 7 in. (10 to 18 cm) in height. To determine the profiles, each core was sliced parallel to the diameter at thicknesses of 1-1/2 in. (3.8 cm). Depending on the height of the core, this slicing pattern lead to two to four slices per core. The cores were designated A through N. A map of the core locations is in Appendix B (Figure B2). Cores A, C, E, and K were taken from a section that was placed at a paver speed of 8 fpm (2.4 mpm) and no additional compaction. B, D, F, G, I, J, M, and N were taken from a section that was constructed using a paver speed of 12 fpm (3.7 mpm) and compaction consisting of four static passes. H and L were taken from a section constructed with a paver speed of 4 fpm (1.2 mpm) and a compaction of four static passes and two vibratory passes.

Each slice was labeled by its letter and its depth. The depth was denoted by number: 1 for the top 1.5 in. (3.8 cm), 2 for the second 1.5 in. (3.8 cm), 3 for the third 1.5 in. (3.8 cm), and 4 for the fourth 1.5 in. (3.8 cm). As an example, a designation of Q3 would be a slice from core Q at a depth of 3 to 4.5 in. (7.6 to 11.4 cm).

First, each slice was allowed to air dry after slicing to determine the air dry weight. This process was done over a period of 14 days, during which four representative slices were weighed every 2 to 3 days. The weight loss due to water evaporation then stabilized to a point where there was little to no weight loss between weighings. After the weights of the four independent slices had stabilized, all of the slices were weighed and the values were recorded.

Next, each core slice was submerged in water in order to be able to determine the soaked weight of each slice and the volume of each slice. After each slice had been submerged for 14 days and the weights of the four representative slices had stabilized, all of the slices were weighed. Then, to determine the volume, a jar was constructed that could be repeatedly filled to the same water level. The jar was filled with water only and weighed. Next, a slice was placed into the jar, and water was placed into the jar to fill it the rest of the way. Then, the soaked slice and water were weighed. By knowing the weight of the jar filled with only water and the weight of the soaked slice and water in the jar, the volume could be determined. This was done by subtracting the weight of the soaked slice and water from the weight of the water. This yielded the weight of the water that was displaced by the slice, and since water has a unit weight of 1 g/cc, it then becomes the volume of water that would be occupied by the soaked slice, and therefore the volume of the soaked slice.

The following formula was used to determine the volume.

$$\text{Volume} = \text{Water} - (\text{SLWA} - \text{Soak})$$

where

Volume	=	volume of soaked slice
Water	=	weight of water
SLWA	=	weight of water and soaked slice
Soak	=	weight soaked slice

After solving for the volume, the air dry and soaked densities were then calculated.

Next, the slices were placed into an oven set at 230° F (110° C) for 7 days. After the 7 days, the slices were weighed, and dry densities were calculated. Since the soaked and dry weights were now known, void percentages could also be calculated. This was done by the following formula:

$$\text{Void \%} = (\text{Soak} - \text{Dry})/\text{Volume}$$

where

Void	=	volume of permeable void space
Soak	=	weight of soaked slice
Dry	=	weight of dry slice
Volume	=	volume of soaked slice

The air dry densities, soaked densities, dry densities, and void percentages are listed in Table 36.

To determine the effects of paver speed and rolling amounts, the dry densities were the only values that were analyzed. All three values -- air dry, dry, and soaked -- did not need to be analyzed because parallels can be drawn between them. Analyses of variance tests were conducted on the data to determine which of the following two variables, paver speed or the amount of rolling, would play the most significant role in producing a uniform density profile.

Table 37 shows a statistical analysis of the dry density combining all of the specimens with the same amount of rolling and the same paver speed. Listed are the means, standard deviations, and coefficients of variations (COV's). These same quantities are also listed for all of the specimens considered together.

Some of the data in Table 37, especially at the lower paving speeds, are based on a very limited number of density readings. Density was determined by weight and volume measurements of core slices. This results in some questionable data, with COV's ranging from 0.9 to 20.7 percent. None of the combinations of paver speed and amount of rolling produce a uniform density. The combination that comes the closest is the combination of a paver speed of 8 fpm (2.4 mpm) and no rolling (compacted only by paver). But even in this case, the density has peaks and valleys.

Performing an analysis of variance on the density profile data in regards to paver speed and rolling amount is shown in Tables 38 and 39, respectively.

The F-value for each level is less than the corresponding 95-percent confidence F-value for that level. That means that varying the paver speed has no statistical influence on the density at each level; therefore, varying the paver speed has no statistical influence on the density profile.

Table 36
Density Profile -- Air Dry Density, Soaked Density, Dry Density, and Void Percentage

Specimen	Air Dry Density pcf (g/cc)	Soaked Density pcf (g/cc)	Dry Density pcf (g/cc)	Voids %
A1	149.42 2.3904	155.01 2.4797	145.90 2.3340	14.57
A2	148.48 2.3753	153.81 2.4606	144.50 2.3116	14.89
A3	148.92 2.3823	155.53 2.4882	145.19 2.3227	16.54
B1	157.83 2.5249	162.78 2.6041	154.63 2.4737	13.04
B2	134.00 2.1437	137.85 2.2052	130.48 2.0874	11.78
B3	141.19 2.2587	146.21 2.3391	137.39 2.1979	14.12
C1	158.91 2.5422	163.44 2.6146	155.12 2.4816	13.30
C2	158.88 2.5417	163.21 2.6109	154.40 2.4717	13.92
C3	151.50 2.4237	156.11 2.4973	147.33 2.3570	14.03
C4	145.05 2.3205	151.07 2.4167	140.99 2.2555	16.12
D1	134.48 2.1514	138.22 2.2111	131.39 2.1019	10.92
D2	149.69 2.3947	153.91 2.4621	145.84 2.3330	12.91
D3	157.23 2.5153	162.17 2.5944	153.38 2.4536	14.07
E1	135.52 2.1681	140.28 2.2441	132.05 2.1125	13.16
E2	147.04 2.3523	151.66 2.4262	142.89 2.2860	14.02
E3	146.22 2.3392	152.51 2.4398	142.46 2.2790	16.08
F1	136.81 2.1886	140.78 2.2521	133.54 2.1363	11.58
F2	155.07 2.4807	159.58 2.5524	150.86 2.4134	13.91

(Sheet 1 of 3)

Table 36 (Continued)				
Specimen	Air Dry Density pcf (g/cc)	Soaked Density pcf (g/cc)	Dry Density pcf (g/cc)	Voids %
F3	136.36 2.1814	140.93 2.2545	132.77 2.1241	13.05
G1	139.39 2.2299	143.59 2.2971	136.21 2.1791	11.80
G2	158.16 2.5301	162.42 2.5983	153.76 2.4598	13.85
G3	155.69 2.4907	160.34 2.5650	151.47 2.4252	14.19
H1	156.07 2.4968	160.80 2.5725	152.20 2.4359	13.65
H2	155.46 2.4871	159.73 2.5553	151.00 2.4159	13.94
H3	152.64 2.4419	157.26 2.5158	148.53 2.3761	13.96
I1	142.41 2.2782	146.64 2.3459	138.92 2.2224	12.35
I2	154.12 2.4655	158.76 2.5402	150.05 2.4005	13.98
J1	146.46 2.3430	151.81 2.4287	143.10 2.2894	13.93
J2	133.10 2.1293	137.15 2.1941	129.58 2.0729	12.12
K1	155.88 2.4937	161.12 2.5775	152.70 2.4428	13.47
K2	132.94 2.1267	136.99 2.1915	129.48 2.0713	12.01
K3	159.97 2.5591	166.01 2.6557	155.41 2.4862	16.95
K4	148.12 2.3696	154.42 2.4703	143.86 2.3014	16.90
L1	131.32 2.1007	135.73 2.1714	128.05 2.0485	12.29
L2	153.41 2.4542	158.36 2.5333	149.04 2.3842	14.91
L3	148.62 2.3775	154.14 2.4659	144.24 2.3074	15.84
L4	146.43 2.3426	152.94 2.4466	142.80 2.2840	16.22
				(Sheet 2 of 3)

Table 36 (Concluded)

Specimen	Air Dry Density pcf (g/cc)	Soaked Density pcf (g/cc)	Dry Density pcf (g/cc)	Voids %
M1	141.93 2.2706	146.46 2.3430	138.86 2.2215	12.16
M2	132.11 2.1134	135.78 2.1722	128.51 2.0559	11.63
M3	149.46 2.3909	154.38 2.4697	145.37 2.3256	14.40
M4	147.05 2.3524	153.48 2.4553	143.47 2.2951	16.02
N1	131.78 2.1082	137.12 2.1935	128.60 2.0586	13.50
N2	132.15 2.1141	136.47 2.1833	128.50 2.0562	12.70
N3	150.91 2.4142	156.03 2.4962	146.57 2.3448	15.13
N4	124.48 1.9913	129.33 2.0690	121.04 1.9363	13.27

(Sheet 3 of 3)

Table 37
Density Profile Statistics

Speed fpm (m)	Rolling passes	Level	Number of Readings	Mean Dry Density pcf (MPa)	Standard Dev pcf (KPa)	COV %
4 (1.2)	4s,2v[1]	1 2 3 4	2 2 2 1	140.16 (2.25) 150.03 (2.40) 146.39 (2.34) 142.80 (2.29)	17.13 (274.4) 1.40 (22.4) 3.03 (48.5) --	12.2 0.9 20.7 --
8 (2.4)	0	1 2 3 4	4 4 4 2	146.44 (2.35) 142.84 (2.29) 147.60 (2.36) 142.43 (2.28)	10.36 (166.0) 10.28 (164.7) 5.58 (89.4) 2.03 (32.5)	7.1 7.2 3.8 1.4
12 (3.7)	4s	1 2 3 4	8 8 6 2	138.17 (2.21) 139.70 (2.24) 144.49 (2.31) 132.26 (2.12)	8.09 (129.6) 11.37 (182.1) 8.01 (128.3) 15.86 (254.1)	5.9 8.1 5.5 12.0
All	All	1 2 3 4	14 14 12 5	140.82 (2.26) 142.07 (2.28) 145.84 (2.34) 138.43 (2.22)	9.83 (157.5) 10.37 (166.1) 6.37 (102.0) 9.78 (156.7)	7.0 7.3 4.4 7.1

[1] s = static; v = vibratory.

Table 38
Analysis of Variance for Paver Speed Versus Density Profile

Level	Source	DF	SS	MS	F	F--95%
1	Speed Error Total	2 11 13	183.7 1072.9 1256.5	91.8 97.5	0.94	3.98
2	Speed Error Total	2 11 13	174 1224 1398	87 111	0.78	3.98
3	Speed Error Total	2 9 11	23.9 423.1 447.0	11.9 47.0	0.25	4.26
4	Speed Error Total	2 4 6	127 256 383	64 128	0.5	6.94

Table 39
Analysis of Variance for Rolling Amount Versus Density Profile

Level	Source	DF	SS	MS	F	F--95%
1	Rolling Error Total	2 11 13	183.6 1072.9 1256.5	91.8 97.5	0.94	3.98
2	Rolling Error Total	2 11 13	174 1224 1398	87 111	0.78	3.98
3	Rolling Error Total	2 11 13	23.9 423.1 447.0	11.9 47.0	0.25	4.26
4	Rolling Error Total	2 11 13	127 256 383	64 128	0.5	6.94

Once again, the F-values for the amount of rolling versus the density profiles are less than the 95-percent confidence F-value, which means that varying the amount of rolling has no statistical effect on the density profiles.

It cannot be determined which combination of paver speed and rolling amount will produce the best density profile because not all of the possible combinations have been used. Only three of the possible nine combinations were used. This means that there was no overlap and each variable must be looked at independently. In order to determine what the best combination is, all combinations should be used on another project.

To get a feeling for the general trends within the cores that were placed at the same paver speed and compacted with the same rolling amount, Figures 22 through 24 were plotted. Figure 22 shows the density versus depth for cores A, E, I, and Q which were constructed at a paver speed of 8 fpm (2.4 mpm) and no rolling. Figure 23 shows the density versus depthrelationship for cores B, F, J, K, N, O, V, and W which were constructed at a paver speed of 12 fpm (3.7 mpm) and four static roller passes. The density versus depth relationship for cores L and T is shown in Figure 24. L and T were constructed with a paver speed 4 fpm (1.2 mpm) and four static roller passes combined with two vibratory roller passes. From looking at these three figures, no definite conclusions can be drawn because there are various density/depth relationships within each figure. As an example, there are four distinctly different curves in Figure 22. There is one (E) in which the density decreases with increasing depth. There is also one (I) in which the density increases with increasing depth. There is one (A) which appears to take the shape of an inverted parabola with the minimum being at depth 2. Lastly, there is one (Q) which starts high at depth 1, drops drastically to depth 2, then rises quickly to depth 3, and finally drops off at depth 4. There is not one standard shape to any of the curves; therefore, no conclusions can be drawn about the general trends within each construction type.

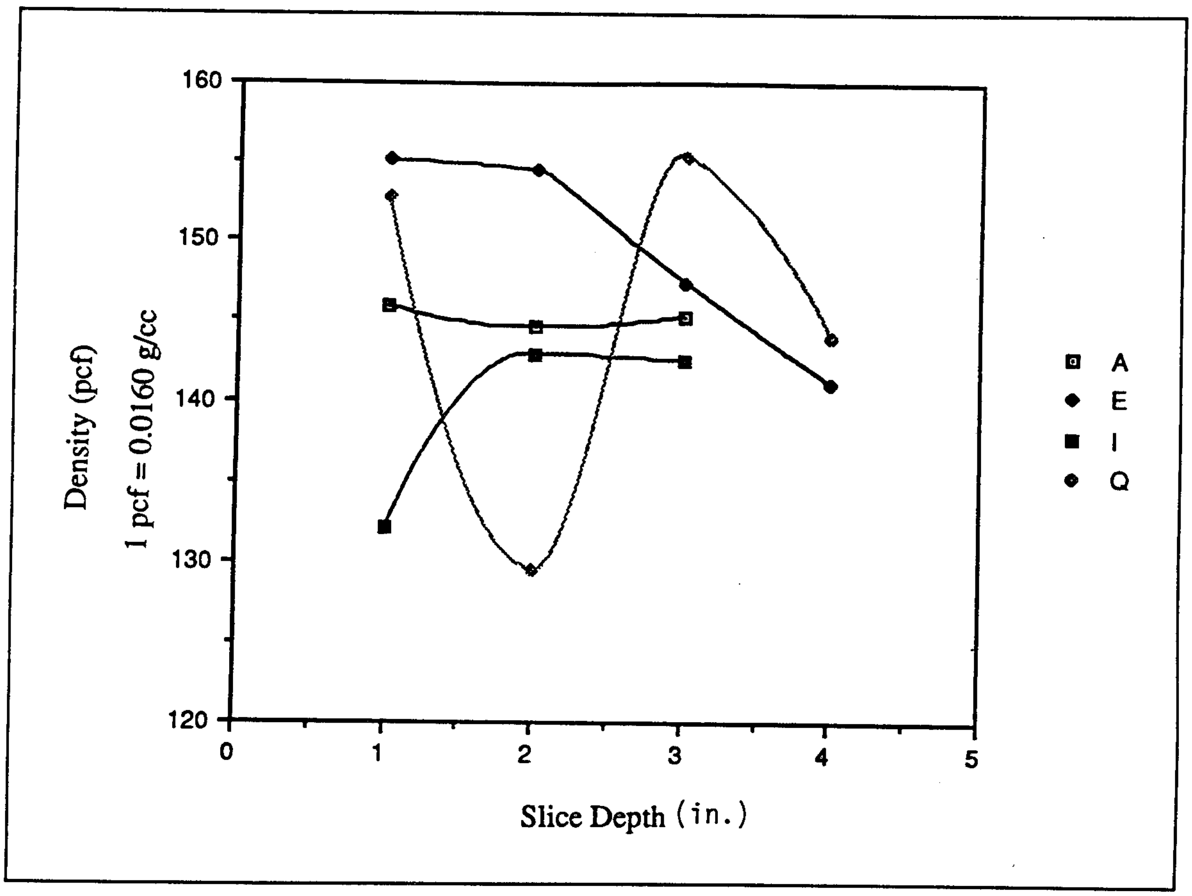

Figure 22. Density versus depth curves--A, E, I, and Q

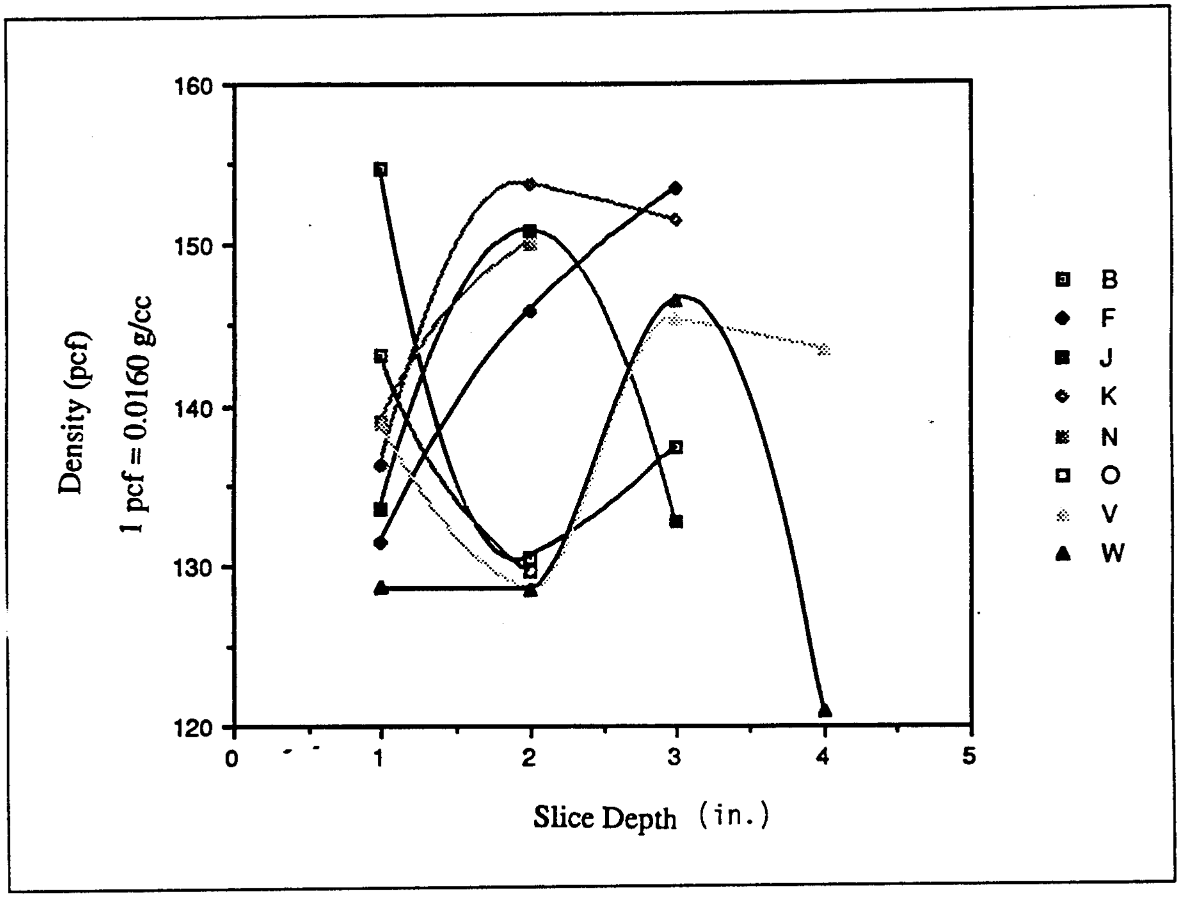

Figure 23. Density versus depth curves--B, F, J, K, N, O, V, and W

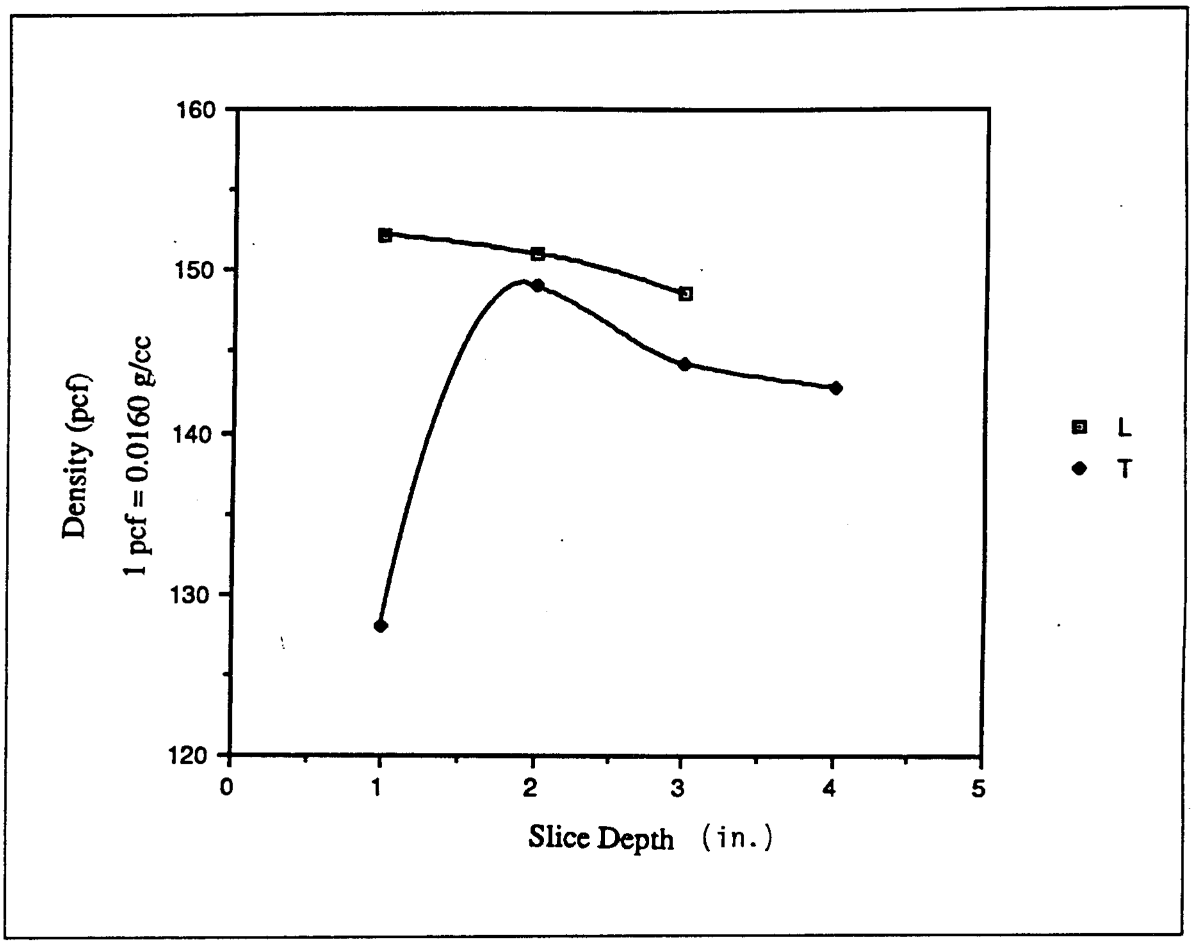

Figure 24. Density versus depth curves--L and T

6 Conclusions

The objective of this project was only partially achieved. To restate, the objective was to determine if RCC was suitable for high-speed traffic use (acceptable rideability and skid resistance). The difficulty in meeting this objective can be attributed to the size of the project combined with the number of parameters that were varied. Basically, the project was too small for the number of parameters varied.

From this project, smoothness or rideability of RCC pavement could not be increased to allow for high-speed applications with the following:

a. Use of high-quality paver with tamping bars and vibratory screed.

b. Adjustments (increase or decrease) in paver speed.

c. Adjustments (increase or decrease) in amount or types of rolling.

d. Multiple lift construction.

e. Various jointing patterns.

f. Various saw-cutting techniques for jointing.

Most of these parameters could not be thoroughly examined due to limitations allowed by the test program.

This project showed that adequate skid resistance could be obtained for high-speed applications. The skid resistance obtained was greater than previously obtained in other test sections and projects. This project did not use a rubber-tire roller, which may have resulted in an increased macrotexture of the pavement surface and increased skid resistance.

The RCC placed for this project was able to meet desired designed strengths for the physical properties of compression, tension, and flexure. As with previous experiences with RCC, there was a general trend of decreasing density with depth. Nearly any combination of paver speed and rolling amount produced a 95-percent or greater density.

The use of dry sawing within hours of placement achieved results equal or superior to wet sawing the day following placement.

From this project, no adjustments in paver speed, rolling (types or patterns), or joint spacing will significantly enhance RCC pavement properties so that it may be used for high-speed applications.

Achieving satisfactory surface-smoothness or rideability is the main stumbling block preventing RCC from performing well in high-speed pavement applications. This project used what is widely considered one of the best pavers available. It had the temping bar and vibratory screed combination along with automatic grade controls. Satisfactory surface-smoothness or rideability was not achieved; however, from this project it is unclear whether this is due to limitations of the machine or other construction procedures or if other limiting factors for this project such as the size or layout prevented achieving the project goals.

7 Recommendations

From the data gained from this project, it would seem that RCC should not be used for high-speed pavement applications, but the authors feel that it would be unwise to dismiss RCC just on the basis of this project. This reservation is due to the fact that there were several problems with the construction of this project, not the least of which was the lack of a statistical base from which definite conclusions can be drawn. It is the opinion of the authors from visiting the site and observing construction that the rideability could be improved so that RCC could be used in high-speed traffic applications. More research needs to be performed to prove or disprove this belief, and a better experiment needs to be designed. The needed experiment must have enough combinations of the varied parameters to produce a large enough statistical base from which some definite conclusions can be drawn.

Obtaining surface-smoothness or rideability must be the main goal of any additional research with RCC pavement. If surface-smoothness or rideability cannot be obtained while retaining satisfactory skid resistance, then RCC will not be suitable for high-speed pavement applications.

To obtain the required information in regards to paver type, paving speed, joint spacing, and amount and type of rolling, the amount and distance of RCC paving must be sufficient to develop a large enough statistical base from which to draw definite conclusions. These factors and various combinations can then be evaluated for their effect on surface-smoothness or rideability and skid resistance.

The effects of rubber-tire rollers skid resistance need to be evaluated due to the high skid resistance obtained in this project without this type of roller. Also, the density obtained with and without rubber-tire and other types of rollers should be investigated.

In addition to the variables previously mentioned, durability and frost resistance of the RCC could be investigated.

References

American Concrete Institute Committee 325. (1991). "State-of-the-art report on roller compacted concrete pavements," Draft Report.

American Society for Testing and Materials. (1985). "Standard test methods for density unhardened and hardened concrete in place by nuclear methods," Designation: C 1040, Philadelphia, PA.

__________. (1987). "Standard test method for deflections with a falling-weight impulse load device," Designation: D 4694, Philadelphia, PA.

__________. (1988). "Standard test method for measuring pavement roughness using a profilograph," Designation: E 1274, Philadelphia, PA.

__________. (1990a). "Standard specification for concrete aggregates," Designation: C 33, Philadelphia, PA.

__________. (1990b). "Standard test method for skid resistance of paved surfaces using a full-scale tire," Designation: E 274, Philadelphia, PA.

__________. (1993). "Deflections with a falling-weight-type impulse load device," Designation: D 4694, Philadelphia, PA.

Borges, S. K. (1987). "Roller compacted concrete pavement: U.S. Air Force decision model," *Journal of Construction Engineering and Management* 113(3), 480-487.

Burns, C. D. (1976). "Compaction study of zero-slump concrete," Miscellaneous Paper S-76-16, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

California Department of Transportation (CALTRANS). (1992). "Standard Specifications," Publication Distribution Unit, Sacramento, CA.

Concrete Construction. (1992). "RCC meets owner's needs for strength, durability under heavy wheel loads," 6(87), 481-482.

Grau, R. W. (1979). "Utilization of marginal construction materials for LOC," Technical Report GL-79-21, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hague, M. N. (1981). "No-slump concrete with fine sand and clay." *Cement and Concrete Research* II(4), Pergamon Press, Ltd.

Headquarters, Department of the Army. (1989). Technical Manual, TM 5-626-6/AFR 93-5, "Procedures for U.S. Army and U.S. Air Force Airfield Pavement Condition Surveys," Washington, DC.

Helmuth, R. (1987). *Fly ash in cement and concrete.* Portland Cement Association, Skokie, IL.

Highway and Heavy Construction. (1986). "RCC slab carries heavy loads at railroad hub facility," 129, 50-51.

Hutchinson, R. L., Ragan, S. A., and Pittman, D. W. (1987). "Heavy-duty pavement," American Concrete Institute, Compilation No. 8, 43-49, reprinted from *Concrete international: design and construction* 9(2).

Jameson, G. W., Sharp, K. G., Bailey, D. P., and Warwick, R. A. (1989). "An investigation of the suitability of roller compacted concrete for high-speed traffic pavements," Document No. 1690, Australian Road Research Board, Victoria, Australia.

Jofre, C., Fernandez, R., Josa, A., and Molina, F. (1988). "Spanish experience with RCC pavements." *Roller compacted concrete II*, American Society of Civil Engineers, New York, 467-483.

Keifer, O., Jr. (1987). "Paving with roller compacted concrete," *Civil Engineering*, 65-68.

Kosmatka, S. H., and Panarese, W. C. (1988). *Design and control of concrete mixtures.* 13th ed., Portland Cement Association, Skokie, IL, 3.

Lawrence, D. (1988). "Rolling in a new technology," *ASTM Standard News* 16, 26-28.

Munn, W. D. (1989). "Thick RCC pavements placed in one pass," *Highway and Heavy Construction* 132, 63-65.

__________. (1989). "Roller concrete wins airbase test," *Highway and Heavy Construction* 132, 58-60.

__________. (1989). "Roller compacted concrete paves factory roads," *Highway and Heavy Construction* 132, 36-38.

Murphy, H. W. (1987). "Highway construction in queensland," American Concrete Institute, Compilation No. 8, 30-36, reprinted from *Concrete international: design and construction* 9(2).

Philleo, R. E. (1986). "Freezing and thawing resistance of high-strength concrete," NCHRP Synthesis of Highway Practice, No. 129, Transportation Research Board, National Research Council, Washington, DC.

Piggott, R. W. (1986). "Roller compacted concrete for heavy duty pavements: past performance, recent projects, and recommended construction methods," *Roller Compacted Concrete Pavements and Concrete Construction, Transportation Research Record 1062,* Transportation Research Board, Washington, DC.

Pittman, D. W. (1986). "Construction of roller compacted concrete pavements," *Roller Compacted Concrete Pavements and Concrete Construction, Transportation Research Record 1062,* Transportation Research Board, Washington, DC.

__________. (1989). "The effects of the construction process on selected fresh and hardened properties of roller-compacted concrete (RCC) pavements," Miscellaneous Paper GL-89-22, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Popovics, S. (1979). *Concrete making materials.* Hemisphere Publishing Corporation, Washington, DC.

Ragan, S. A. (1988). "Proportioning of RCC pavement mixtures." *Roller compacted concrete II.* American Society of Civil Engineers, New York, 380-393.

Shoenberger, J. E., Pittman, D. W., Rollings, R. S., Ragan, S. A., Hammons, M. I., and Smith, D. M. (1994). "Roller compacted concrete pavement for general aviation," Federal Aviation Administration, DOT/FAA/RD-93/12, Washington, DC.

Tomita, M. (1964). "Friction coefficients between tires and pavement surfaces," Technical Report R303, United States Naval Civil Engineering Laboratory, Port Hueneme, CA.

Walker, R. S., and Lin, H. T. (1988). "Profilograph correlation study with present serviceability index (PSI), Demonstration Project No. 72, automated pavement data collection equipment," FHWA-DP-88-072-002, U.S. Department of Transportation, Federal Highway Administration, Washington, DC.

White, T. D. (1986). "Mix design, thickness design, and construction of roller compacted concrete pavements," *Roller Compacted Concrete Pavements and Concrete Construction*, Transportation Research Record 1062, Transportation Research Board, Washington, DC.

Yoder, E. J., and Witczak, M. W. (1975). "Principles of pavement design," New York.

Appendix A
General Site Photos

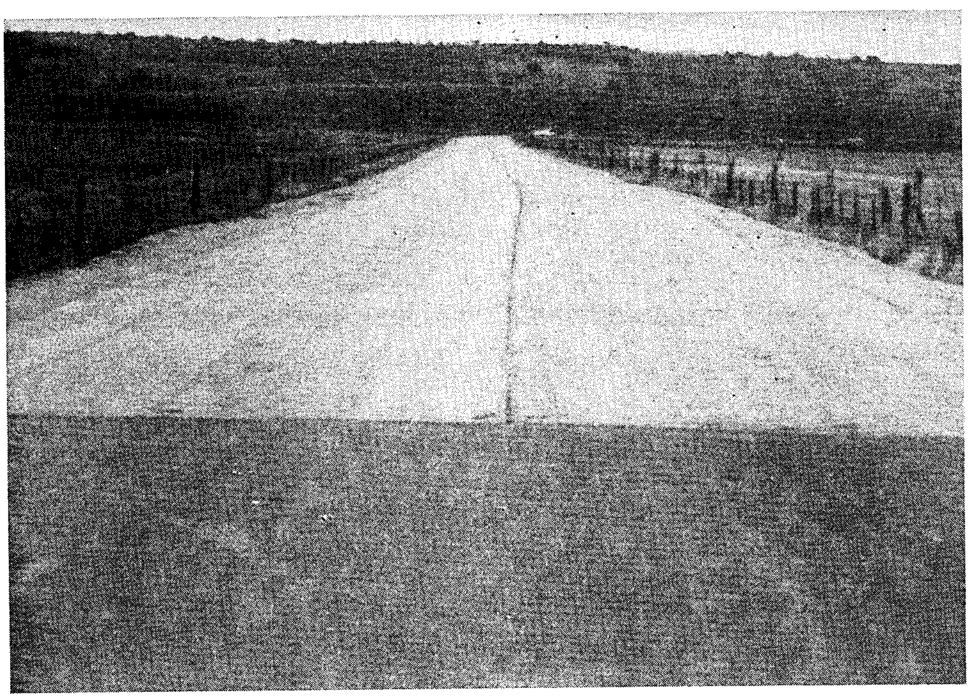

Photo A1. Beginning of the roller-compacted concrete (RCC) roadway looking from sta 0+00 left-Lane II, right-Lane I

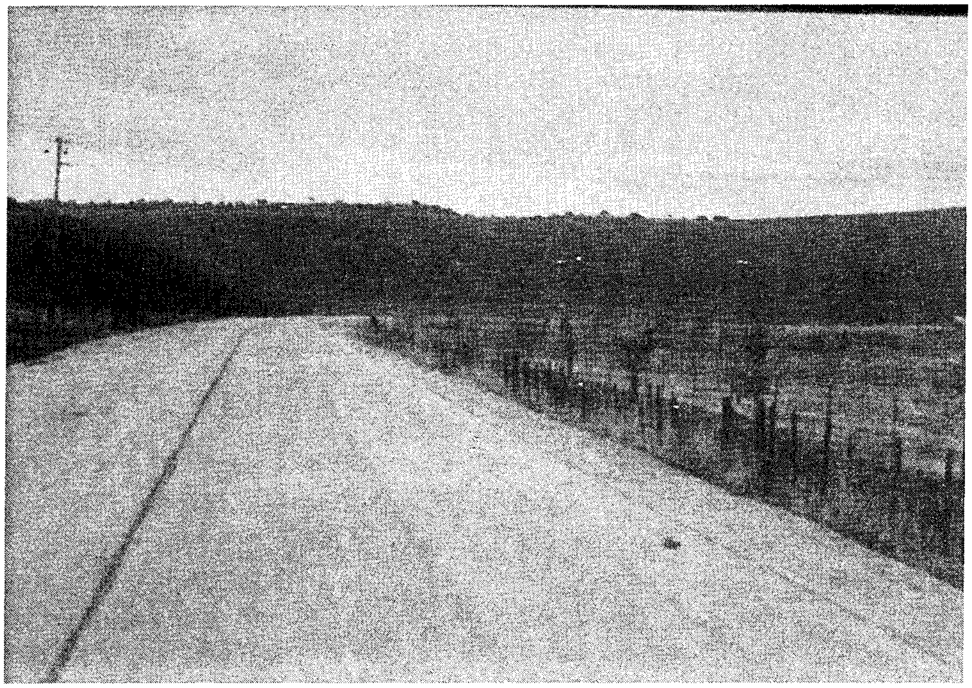

Photo A2. Middle of the RCC roadway, curve in the background

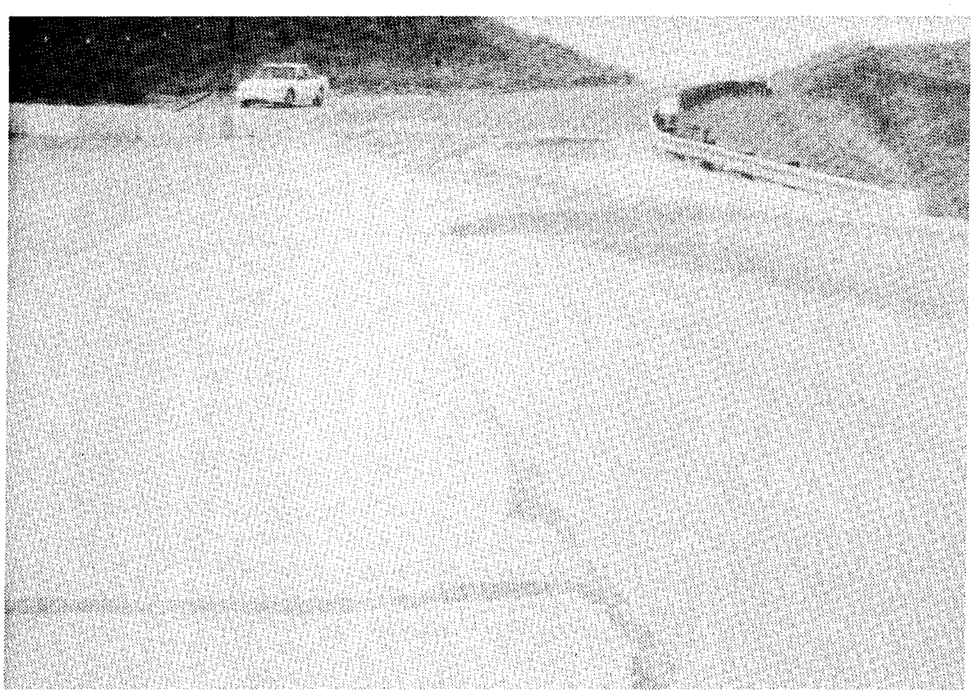

Photo A3. End of RCC roadway

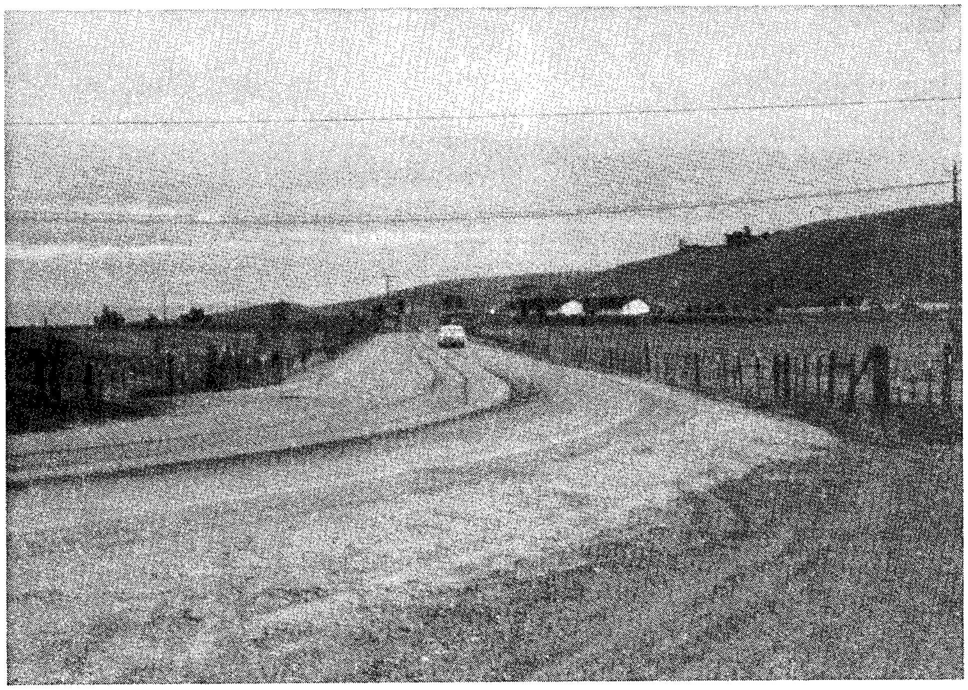

Photo A4. View of RCC roadway from curve looking toward sta 0 + 00

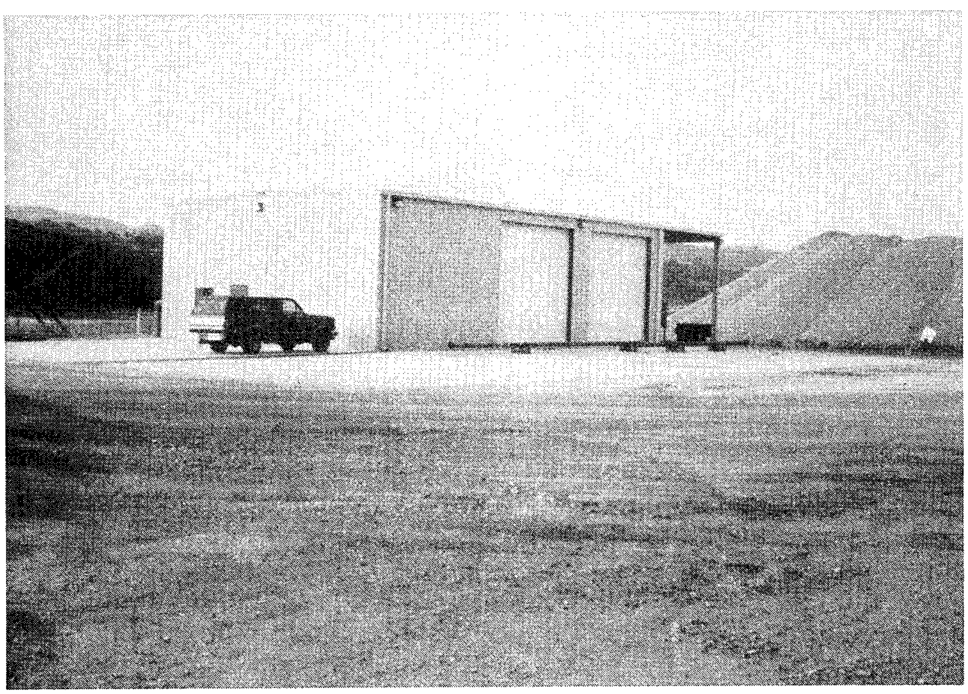

Photo A5. RCC parking lot, in front of large doors and to the right of the vehicle

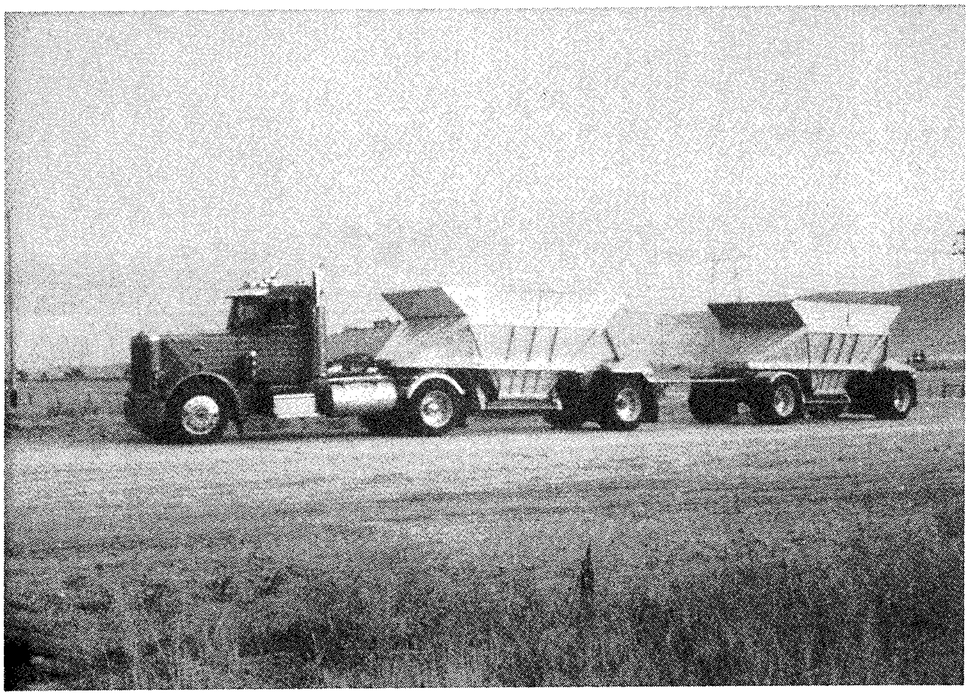

Photo A6. Typical dump truck traffic

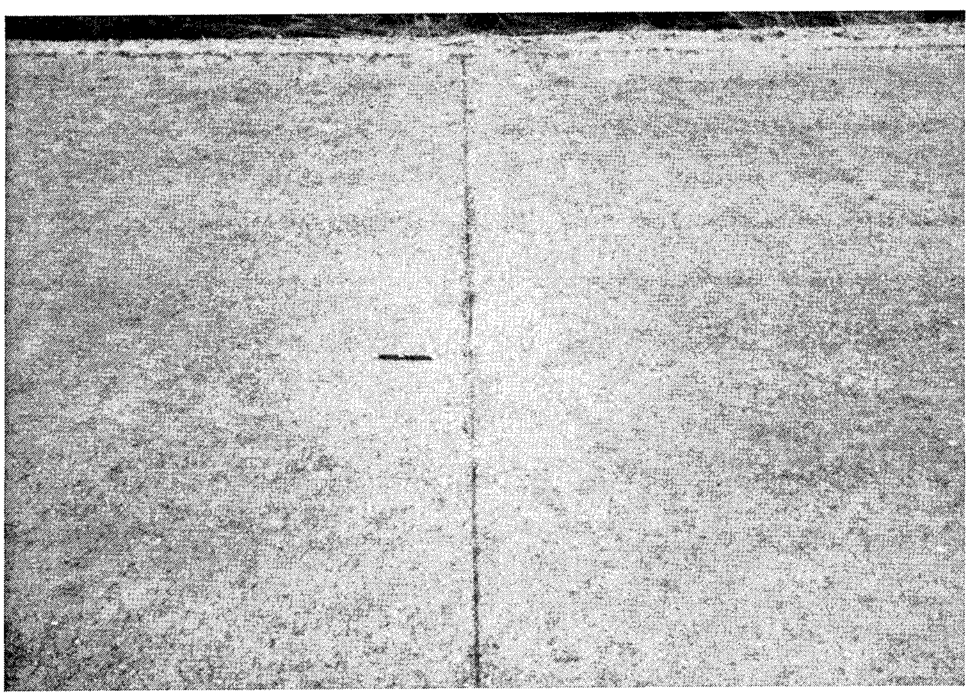

Photo A7. Transverse joint, sawcut, shown with a pencil to demonstrate scale

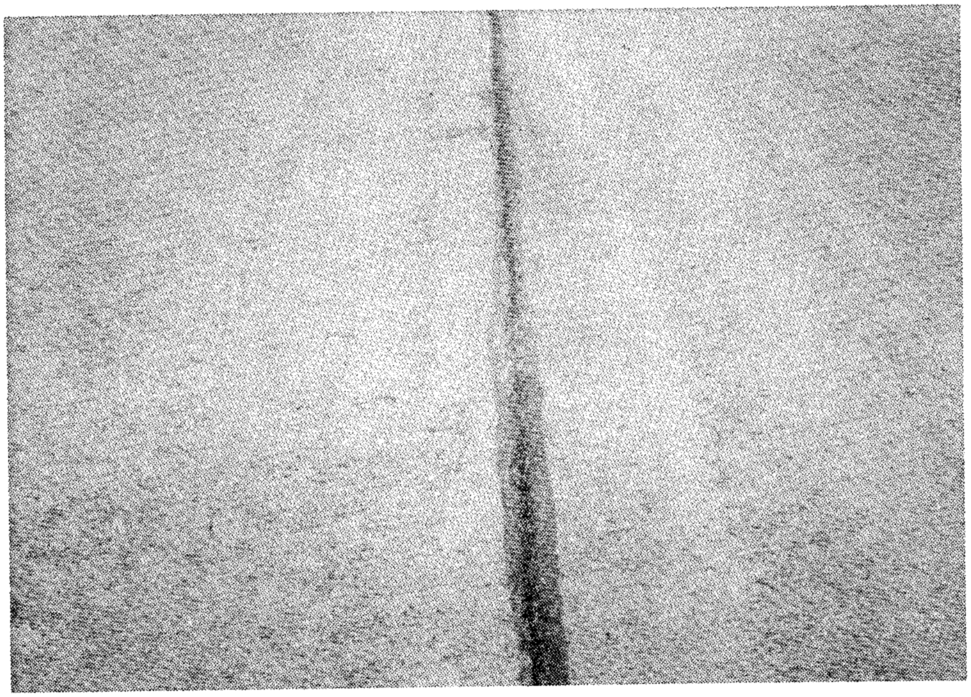

Photo A8. Longitudinal joint sealed with emulsion

Photo A9. Transverse joint crossing both lanes, Lane I in foreground

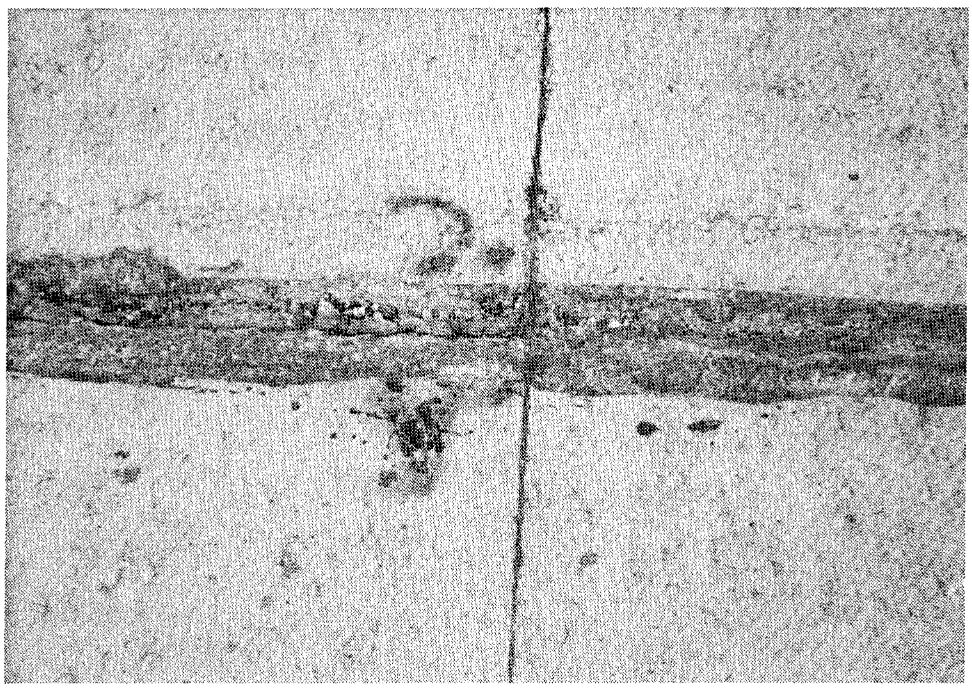

Photo A10. Close up of jointing, Lane II/dry-cut/background,Lane I/wet-cut/foreground

Appendix B
Parameter Layout for Test Section

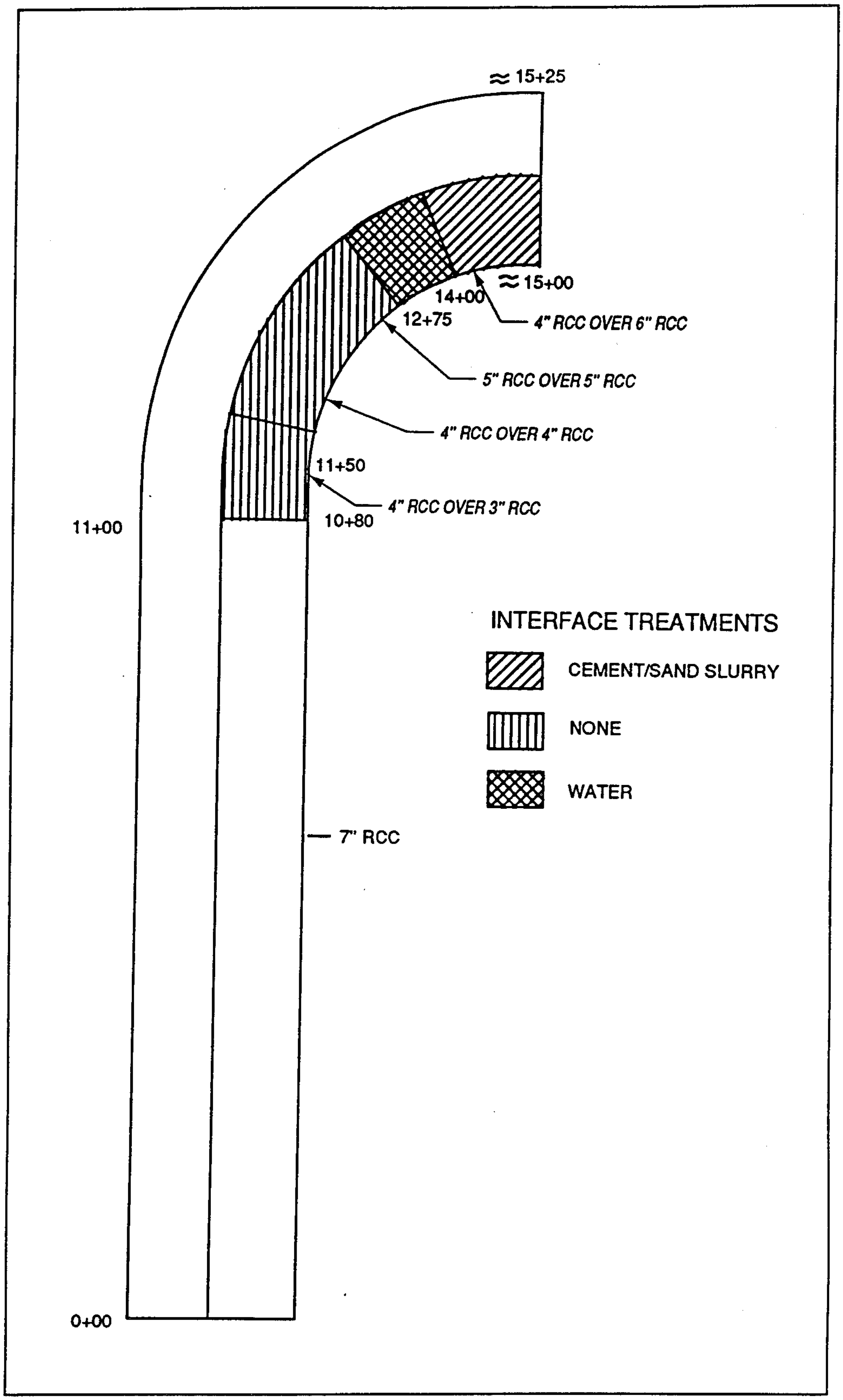

Figure B1. Layout of test section

Table B1
Parameter Layout for Lane I (Inbound)

Section	Begin	End	Mix	Total Thick in. (cm)	Paver Speed fpm (mpm)	Rolling	Joint Spacing ft (m)	Cutting Method	Vibrating Screed	Interface Treatment
1	0+00	0+40	b-2	7 (17.8)	7 (2.1)	2 static passes	2 @ 20 (6.1)	wet	on	--
2	0+40	2+80	b-2	7 (17.8)	7 (2.1)	2	6 @ 40 (12.2)	wet	on	--
3	2+80	4+00	b-2	7 (17.8)	7 (2.1)	2	6 @ 60 (18.3)	wet	on	--
4	4+00	6+40	b-2	7 (17.8)	8-10 (2.4-3.0)	2	6 @ 60 (18.3)	wet	on	--
5	6+40	6+50	b-2	7 (17.8)	8-10 (2.4-3.0)	2	4 @ 100 (30.5)	wet	on	--
6	6+50	8+00	b-1	7 (17.8)	8-10 (2.4-3.0)	2	4 @ 100 (30.5)	wet	off	--
7	8+00	8+50	b-1	7 (17.8)	8-10 (2.4-3.0)	2	4 @ 100 (30.5)	wet	on	--
8	8+50	10+40	b-1	7 (17.8)	12 (3.7)	2	4 @ 100 (30.5)	wet	on	--
9	10+40	10+60	b-1	7 (17.8)	12 (3.7)	2	1 @ 20 (6.1)	wet	on	--
10	10+60	10+65	b-1	7 (17.8)	12 (3.7)	2	1 @ 60 (18.3)	wet	on	--
11	10+65	10+80	b-1	7 (17.8)	8 (2.4)	2	1 @ 60 (18.3)	wet	on	--
12	10+80	11+20	b-1	4 (10.2)	8 (2.4)	2	1 @ 60 (18.3)	wet	on	--
13	11+20	11+50	b-1	4 (10.2)	8 (2.4)	2	uncut	--	on	--
14	11+50	12+75	b-1	8 (20.3) 4 top (10.2) 4 bottom (10.2)	8 (2.4)	2 bottom 3 top	uncut	--	on	water
15	12+75	14+00	b-1	9 (22.9) 4 top (10.2) 4 bottom (12.7)	8 (2.4)	2 bottom 3 top	uncut	--	on	none
16	14+00	15+25	b-1	10 (25.4)	8 (2.4)	2 bottom 3 top	uncut	--	on	slurry

Note: Lane I was cured by means of a white pigmented curing compound.

Table B2
Parameter Layout for Lane II (Outbound)[1]

Section	Begin	End	Thickness in. (cm)	Paver Speed fpm (mpm)	Rolling	Joints ft (m)
1	0+00	0+40	--	8-9 (2.4-2.7)	4 s[2] 2 v	2 @ 20 (6.1)
2	0+40	2+80	7 (17.8)	8-9 (2.4-2.7)	4s, 2v	6 @ 40 (12.2)
3	2+80	4+00	7 (17.8)	8-9 (2.4-2.7)	4s, 2 v	6 @ 60 (18.3)
4	4+00	6+40	7 (17.8)	8-9 (2.4-2.7)	4s	6 @ 60 (18.3)
5	6+40	7+20	7 (17.8)	8-9 (2.4-2.7)	4s	1 @ 80 (24.4)
6	7+20	7+40	7 (17.8)	8-9 (2.4-2.7)	4s	1 @ 20 (6.1)
7	7+40	8+40	7 (17.8)	8-9 (2.4-2.7)	4s	1 @ 100 (30.5)
8	8+40	8+50	7 (17.8)	8-9 (2.4-2.7)	4s	1 @ 92.5 (28.2)
9	8+50	9+32.5	7 (17.8)	18 (5.5)	4s	1 @ 92.5 (28.2)
10	9+32.5	9+40	7 (17.8)	18 (5.5)	4s	1 @ 7.5 (2.3)
11	9+40	10+40	7 (17.8)	18 (5.5)	4s	1 @ 100 (30.5)
12	10+40	10+60	7 (17.8)	18 (5.5)	4s	1 @ 20 (6.1)
13	10+60	10+75	7 (17.8)	18 (5.5)	4s	2 @ 60 (18.3)
14	10+75	10+80	7 (17.8)	8-9 (2.4-2.7)	4s	2 @ 60 (18.3)
15	10+80	11+50	4 (10.2)	8-9 (2.4-2.7)	4s	2 @ 60 (18.3)
16	11+50	11+80	7 (17.8)	8-9 (2.4-2.7)	4s	2 @ 60 (18.3)
17	11+80	12+30	7 (17.8)	8-9 (2.4-2.7)	4s	1 @ 50 (15.2)
18	12+30	13+10	7 (17.8)	8-9 (2.4-2.7)	4s	1 @ 80 (24.4)
19	13+10	15+25	7 (17.8)	8-9 (2.4-2.7)	4s	uncut

[1] The mixture used was mix A-2. The cutting method for the joints was a dry-cut saw. The vibrating screed was on for the entire length of Lane II. Lane II was cured by means of a white cure.
[2] s = static; v = vibratory.

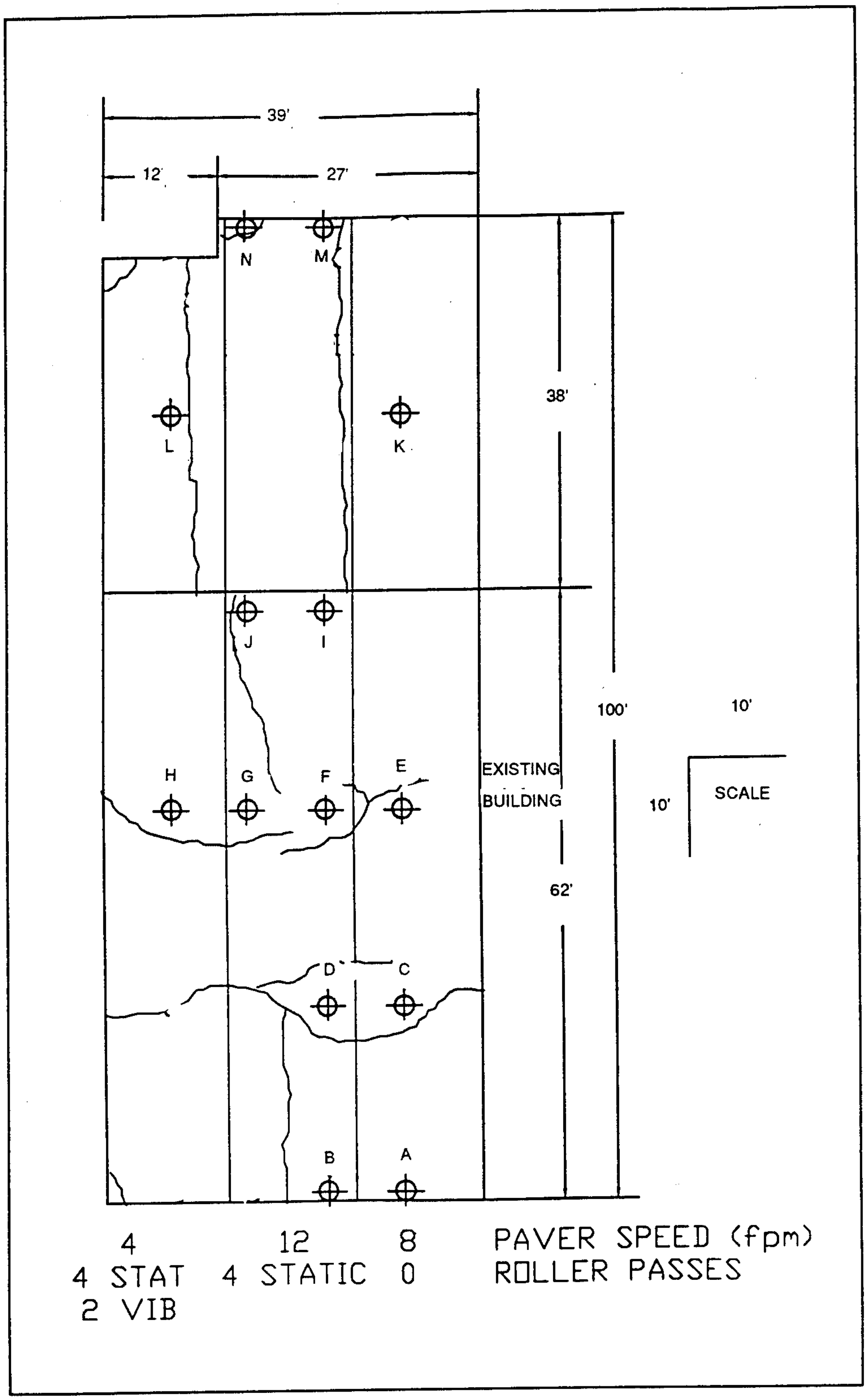

Figure B2. Layout of parking lot

Appendix C
Mixes

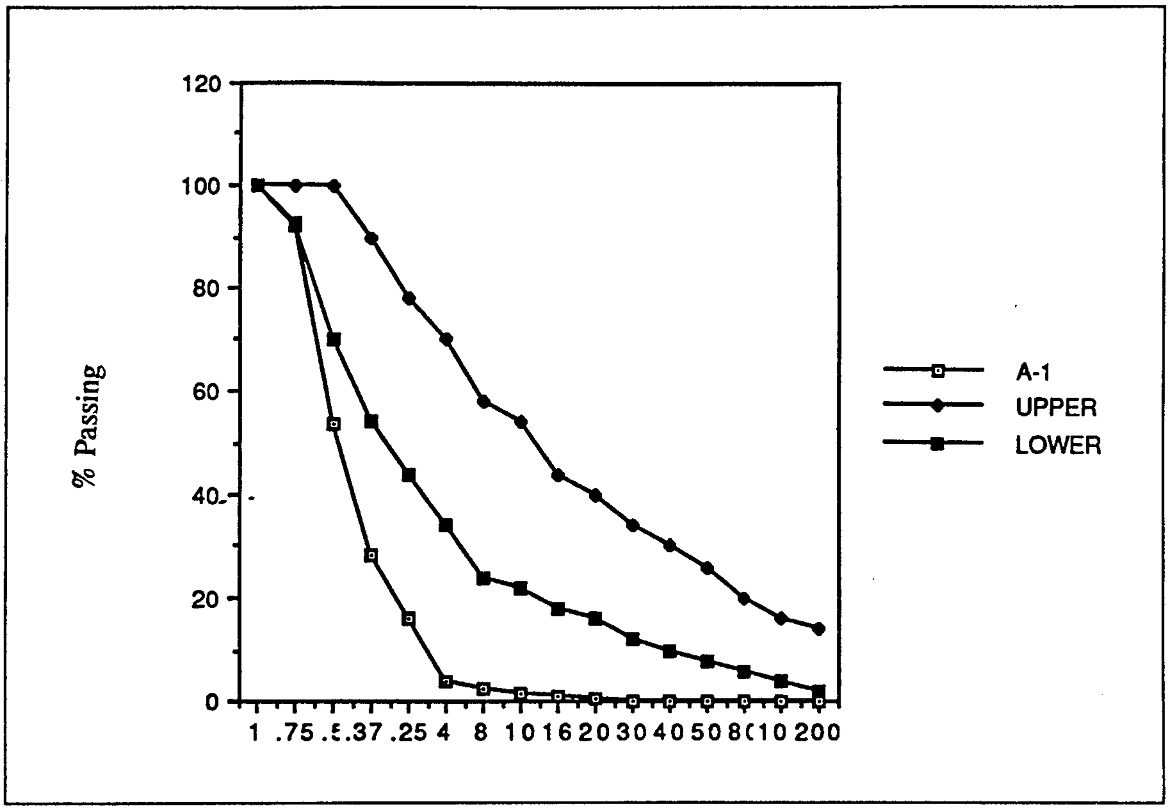

Figure C1. Mix A-1, coarse aggregate gradation curve

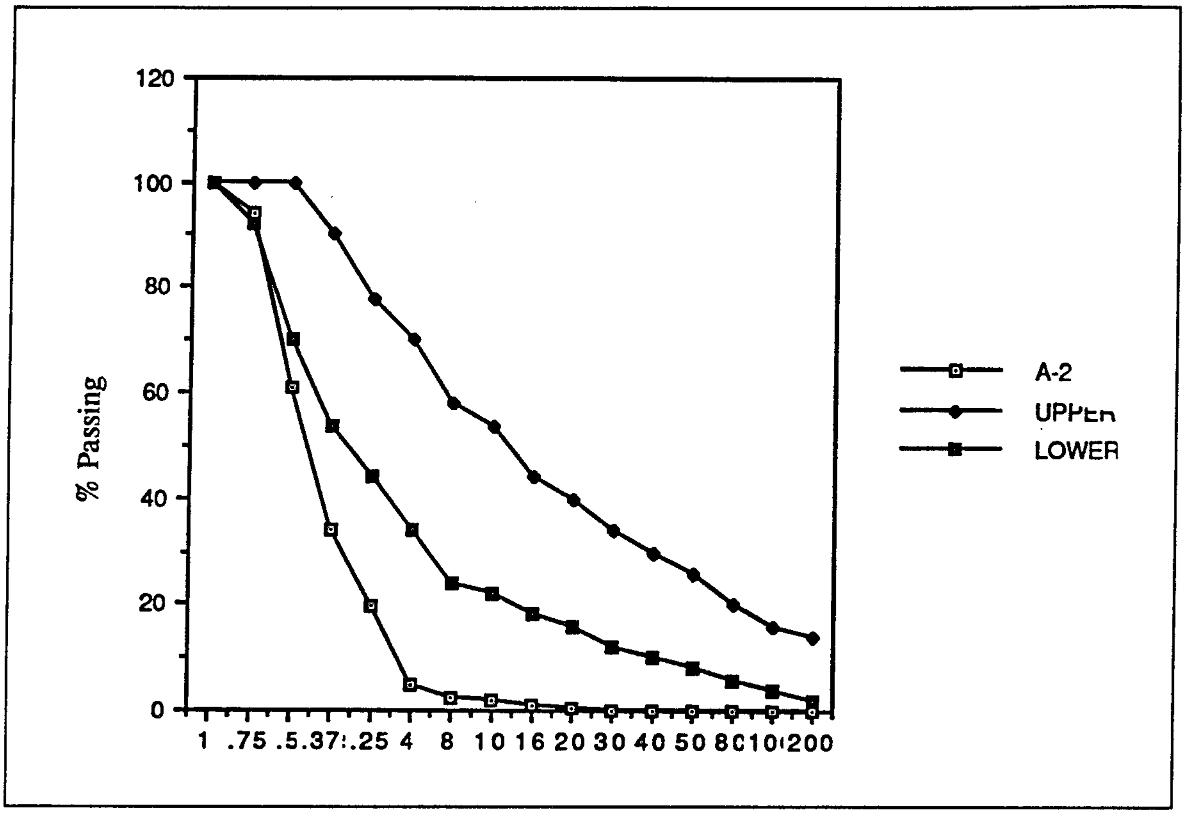

Figure C2. Mix A-2, coarse aggregate gradation curve

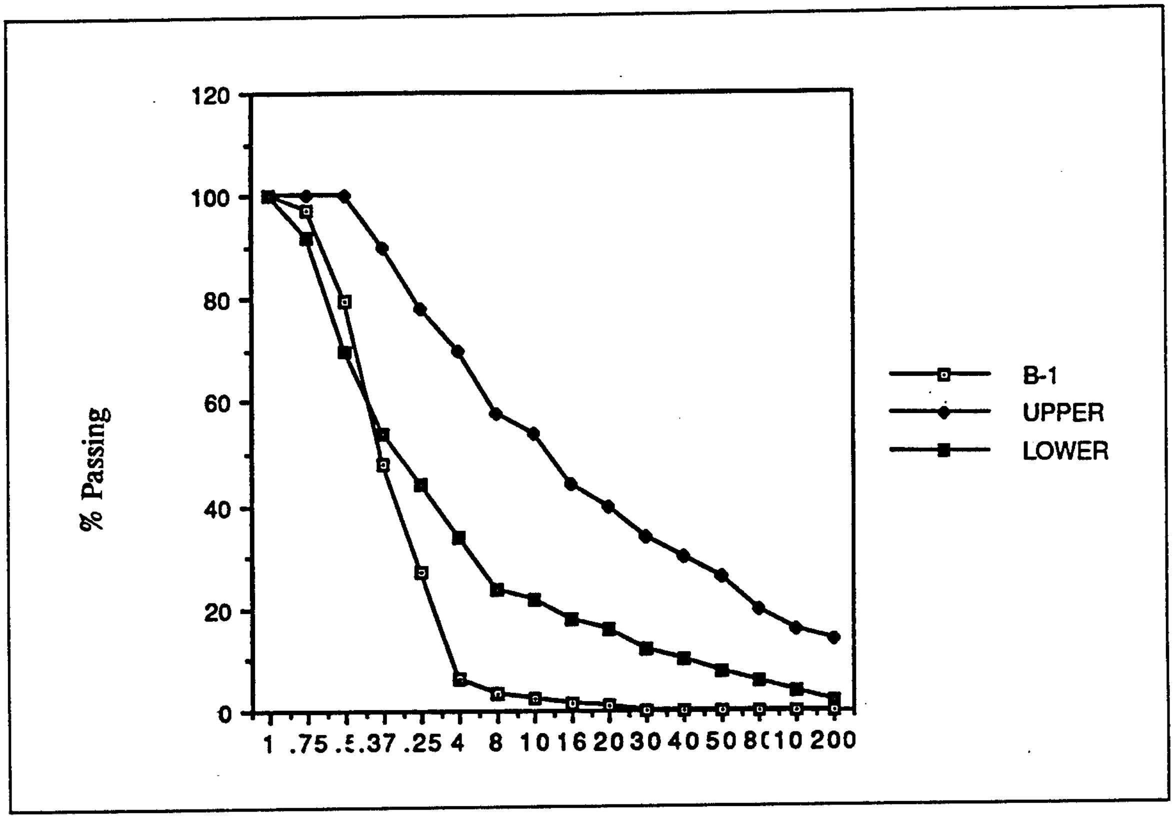

Figure C3. Mix B-1, coarse aggregate gradation curve

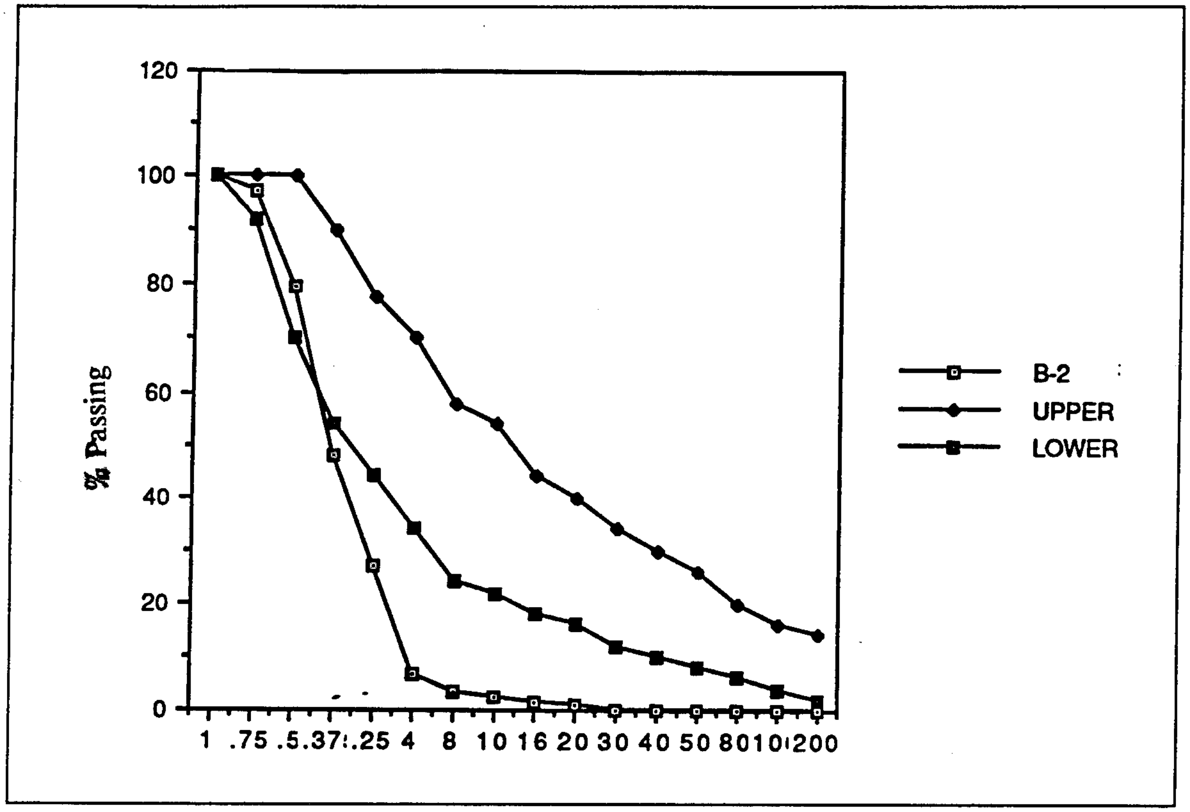

Figure C4. Mix B-2, coarse aggregate gradation curve

Table C1
Mix Compositions

Mix	Portland Type IP Cement lb/yd^3	Water	Coarse Aggregate	Fine Aggregate lb/yd^3	Daracem 55 oz/cwt
A-1	500	167	2016	1687	6
A-2	500	167	2000	1734	6
B-1	500	167	1860	1838	6
B-2	500	167	1960	1787	6
I lb/yd^3 = 0.59 kg/m^3					

Table C2
Coarse Aggregate Ratios

Mix	3/4 to 1/2 %	1/2 by No. 4 %
A-1	60	40
A-2	50	50
B-1	25	75
B-2	25	75

Appendix D
Construction Photos

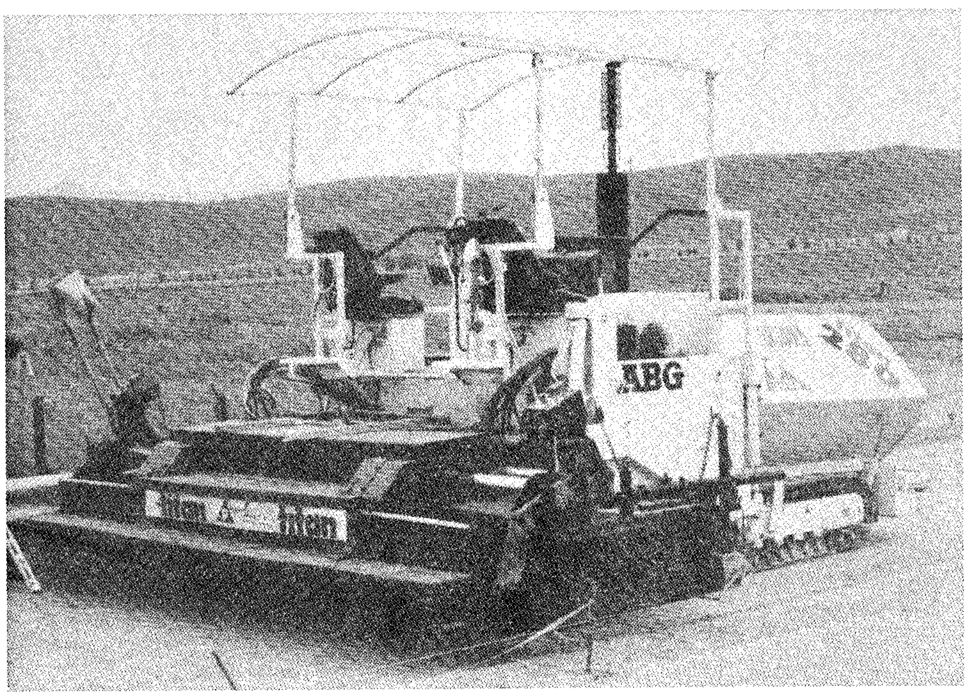

Photo D1. Paver used for this project

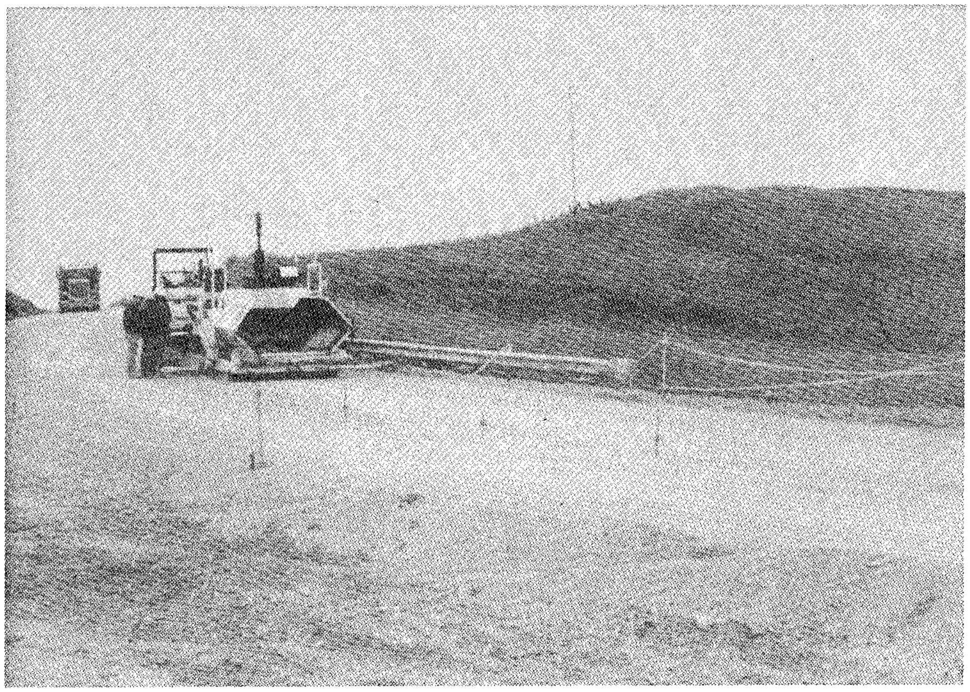

Photo D2. String line for automatic grade control (foreground)

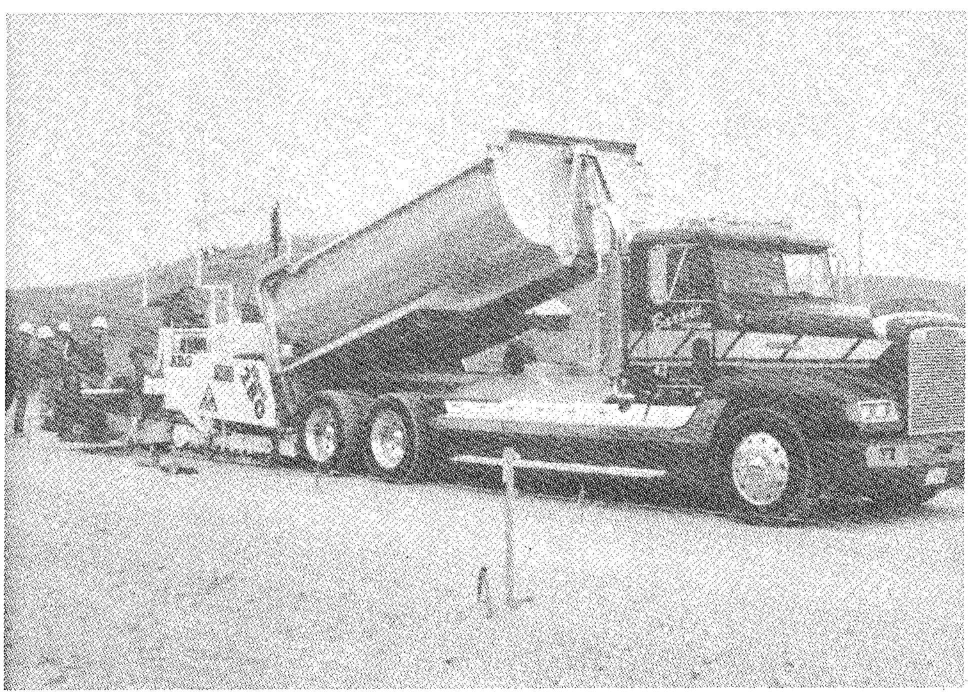

Photo D3. Dump truck filling the paver hopper

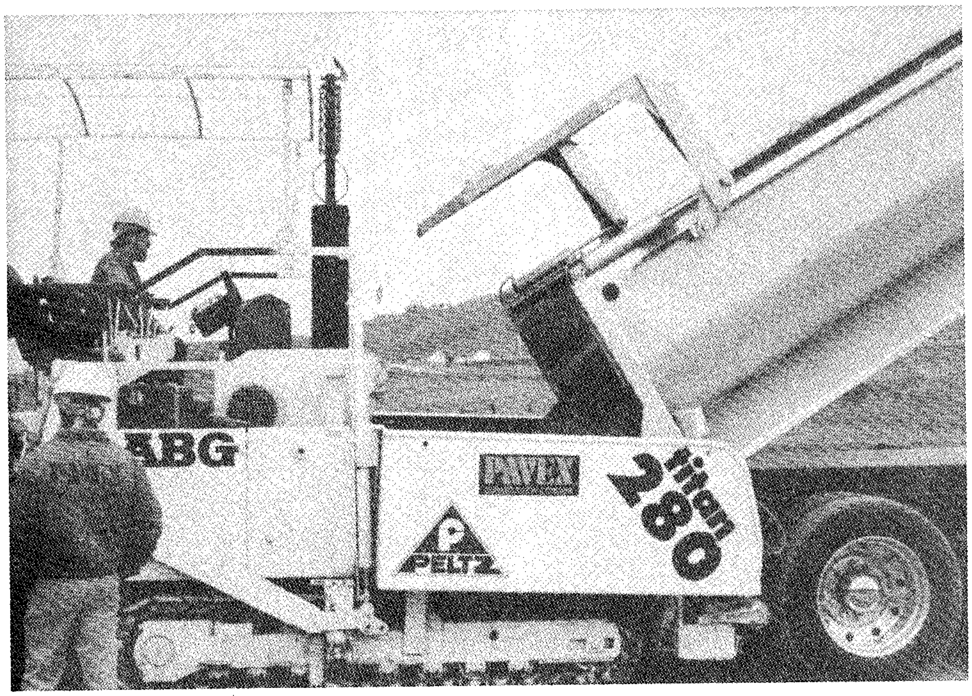

Photo D4. The paver hopper being loaded with RCC

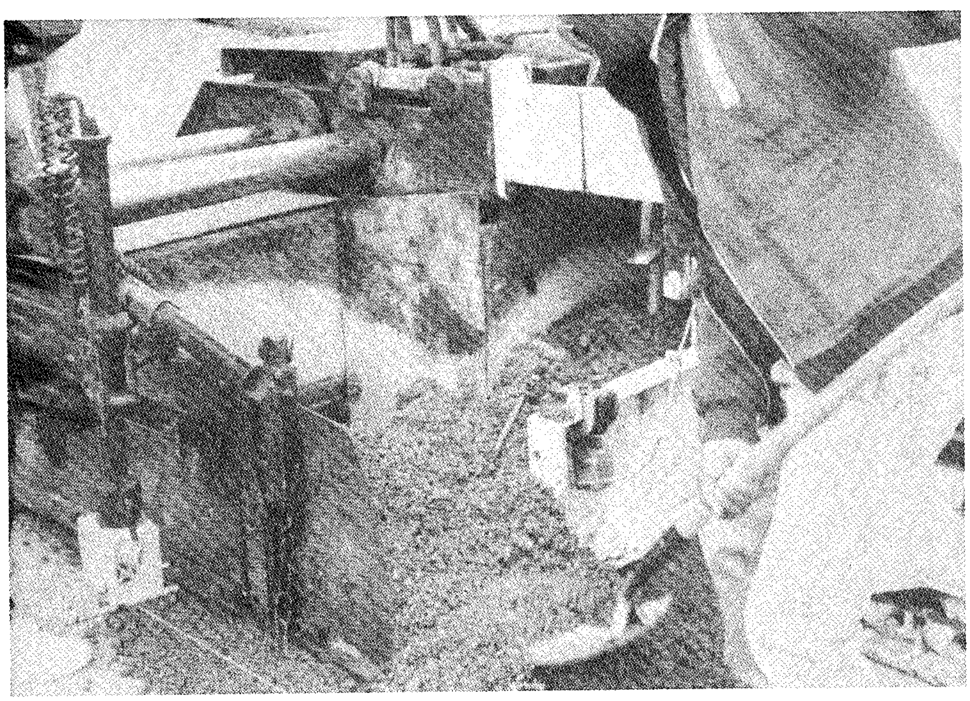

Photo D5. End of screed and auger--grade control sensor on stringline

Photo D6. Freshly placed RCC with the stringline for automatic grade control (right)

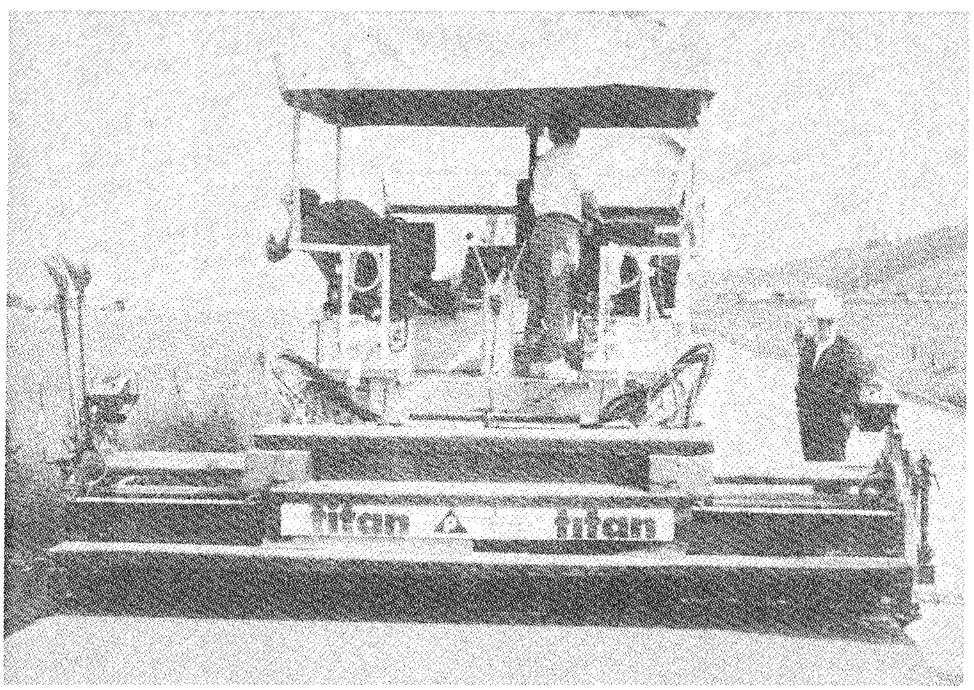

Photo D7. Paver with freshly placed RCC

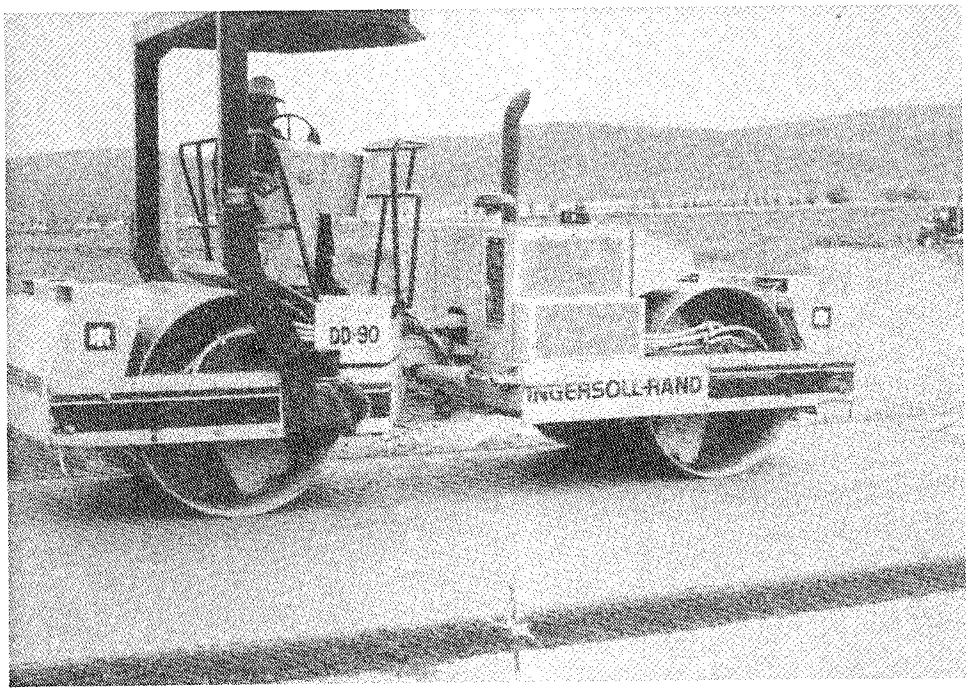

Photo D8. Ten-ton vibratory steel-drum roller

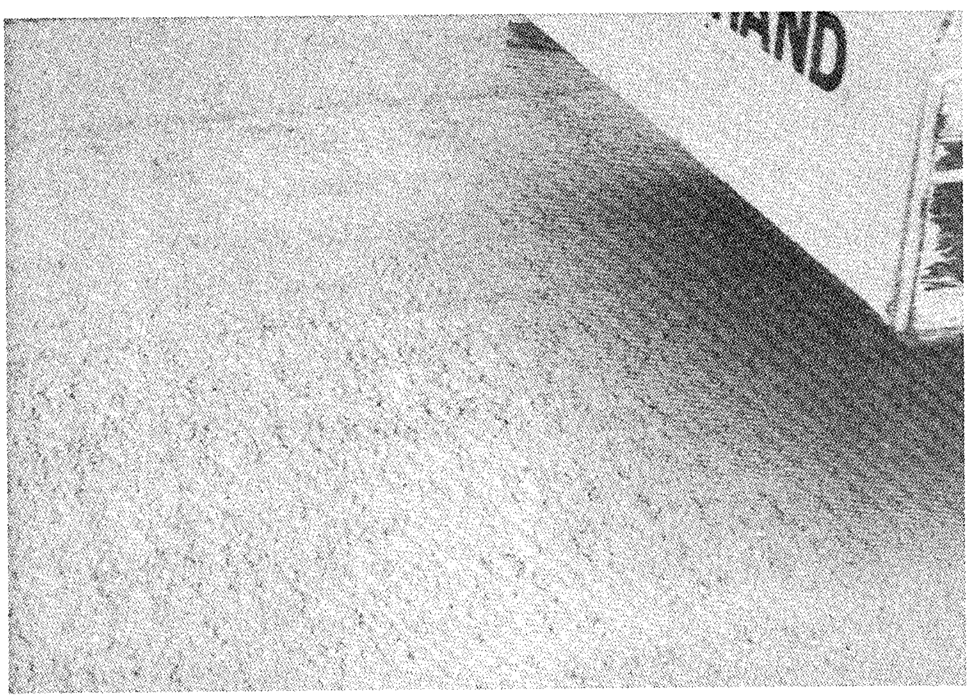

Photo D9. Freshly compacted RCC behind roller

Appendix E
Testing Photos

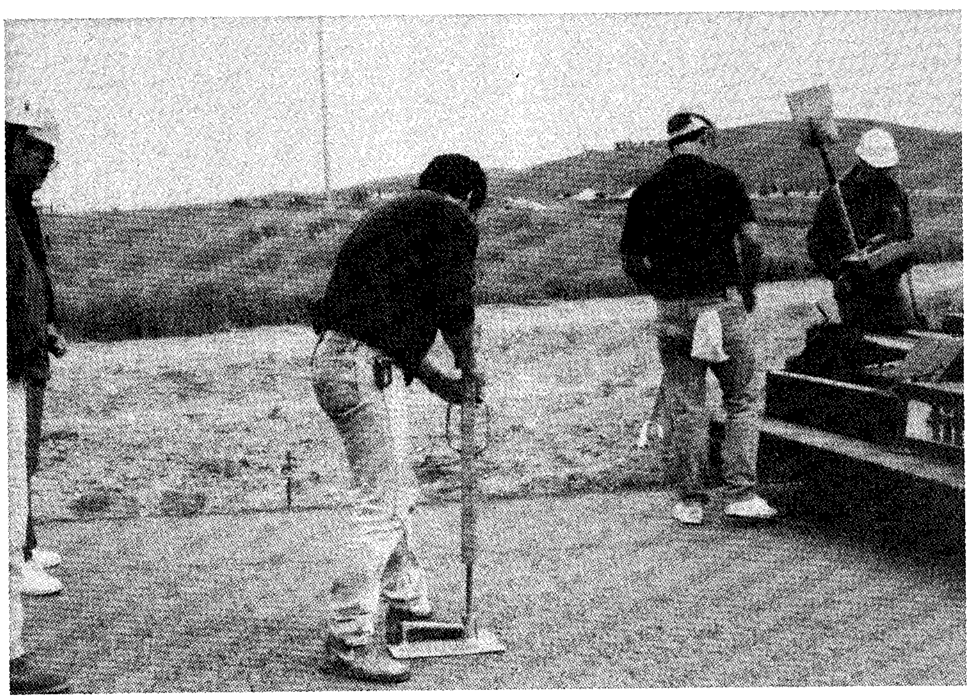

Photo E1. Nuclear density test just after RCC placement

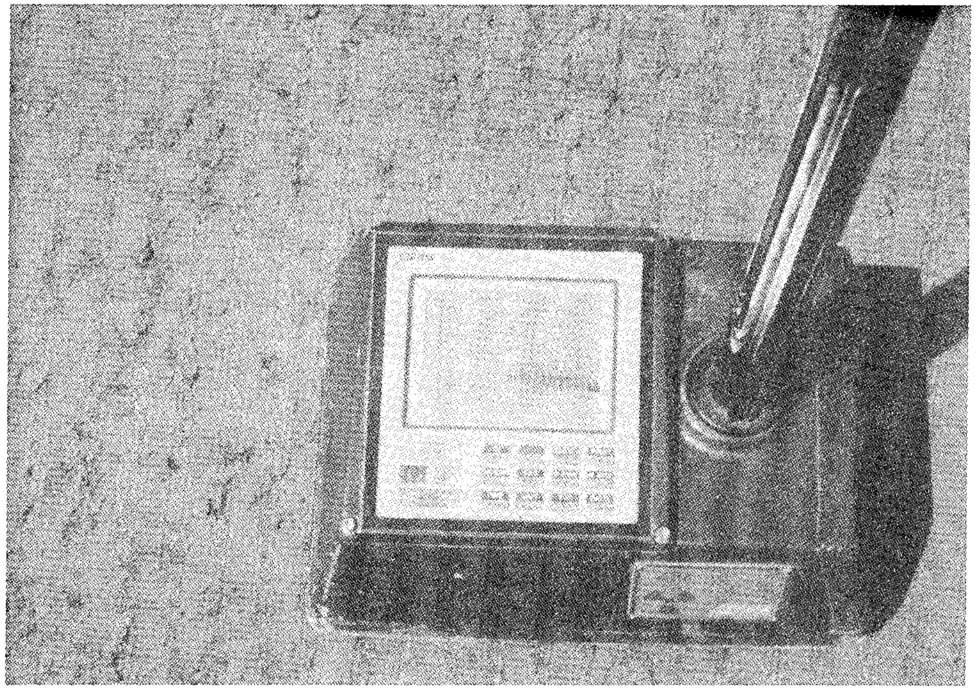

Photo E2. Nuclear density readout

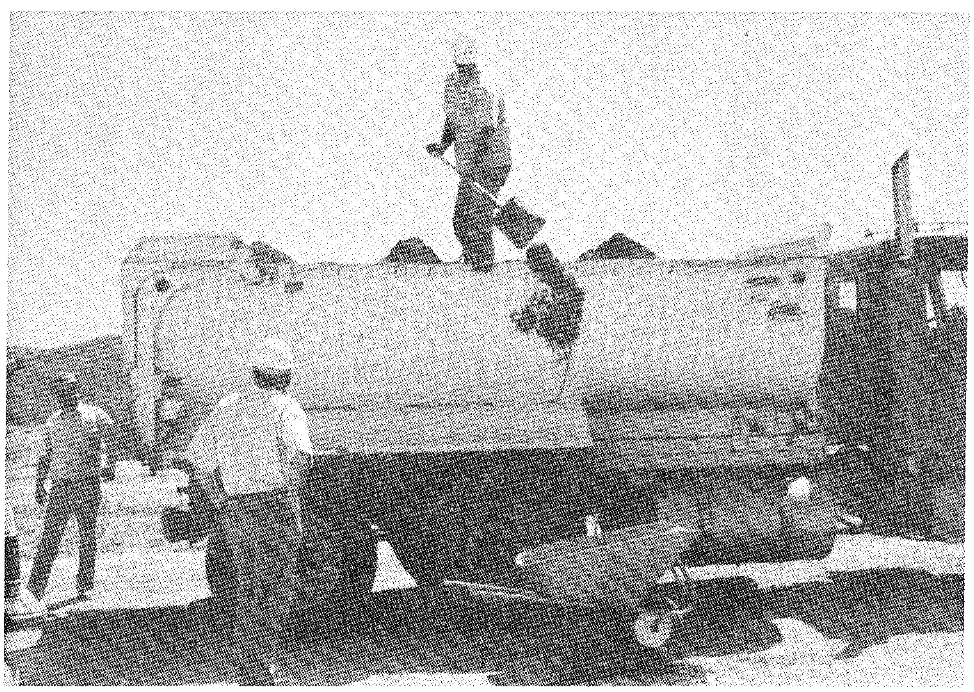

Photo E3. Concrete being removed from the dump truck for specimen making

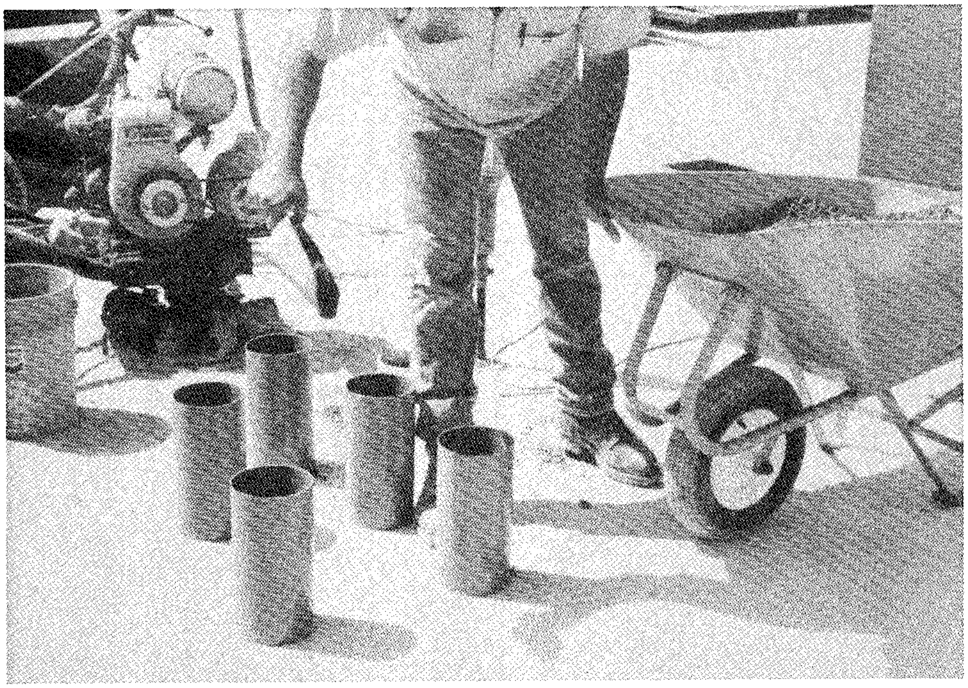

Photo E4. Filling cylinders for compressive/tensile strength testing

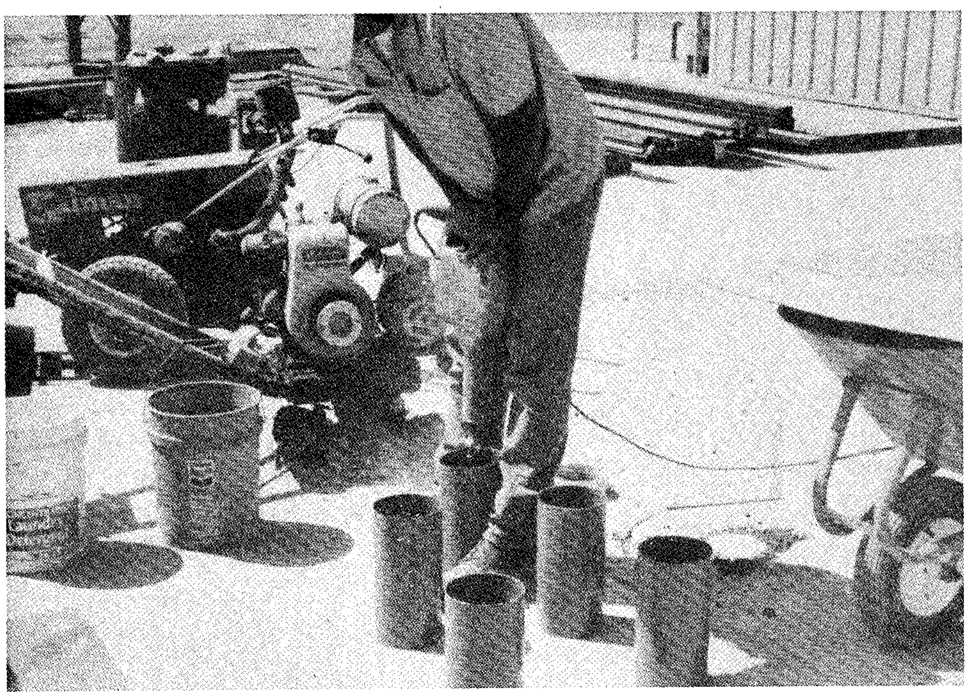

Photo E5. Compaction of cylinders

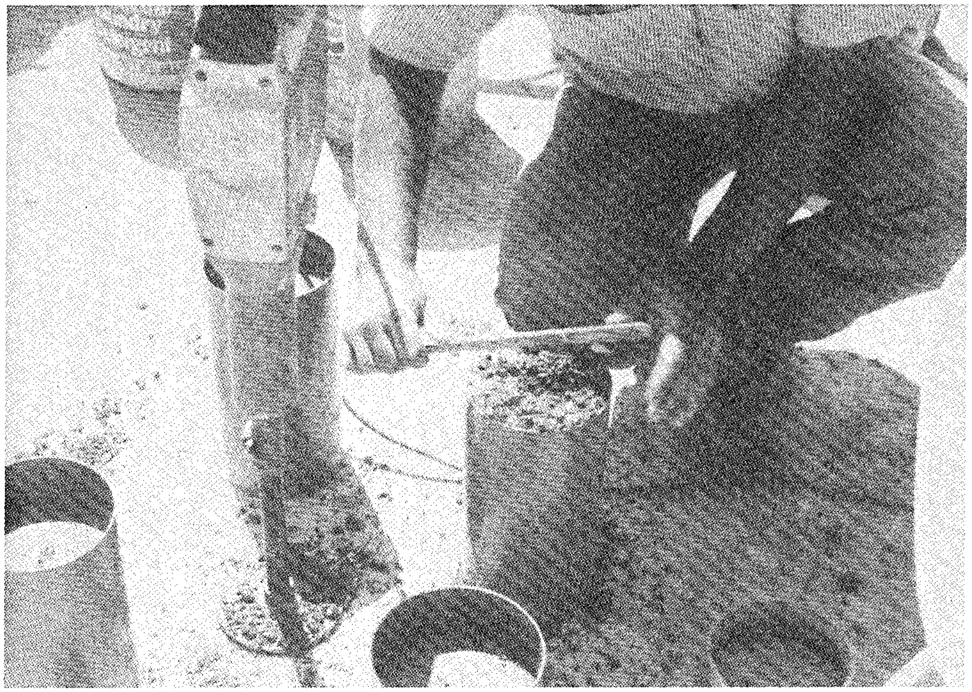

Photo E6. Striking off of cylinders

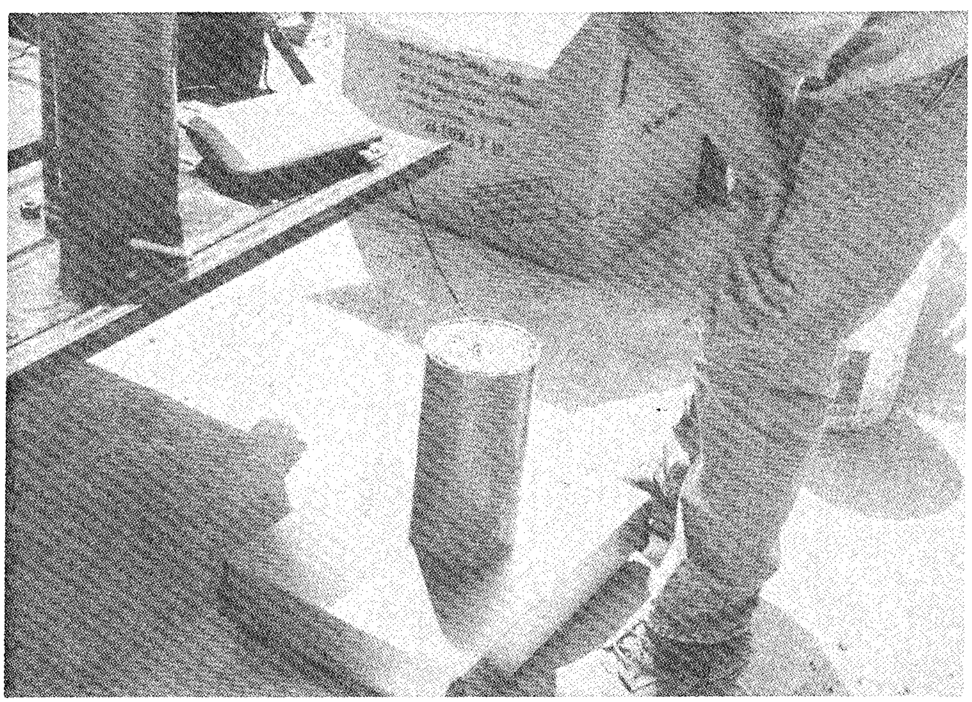

Photo E7. Vibration of cylinders

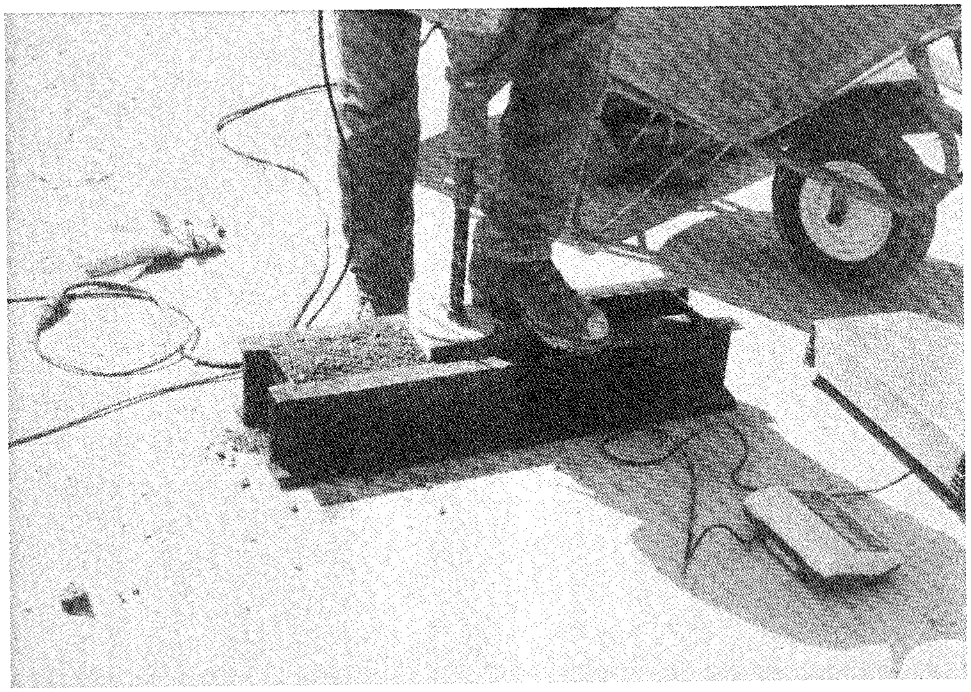

Photo E8. Compaction of beams for flexural testing

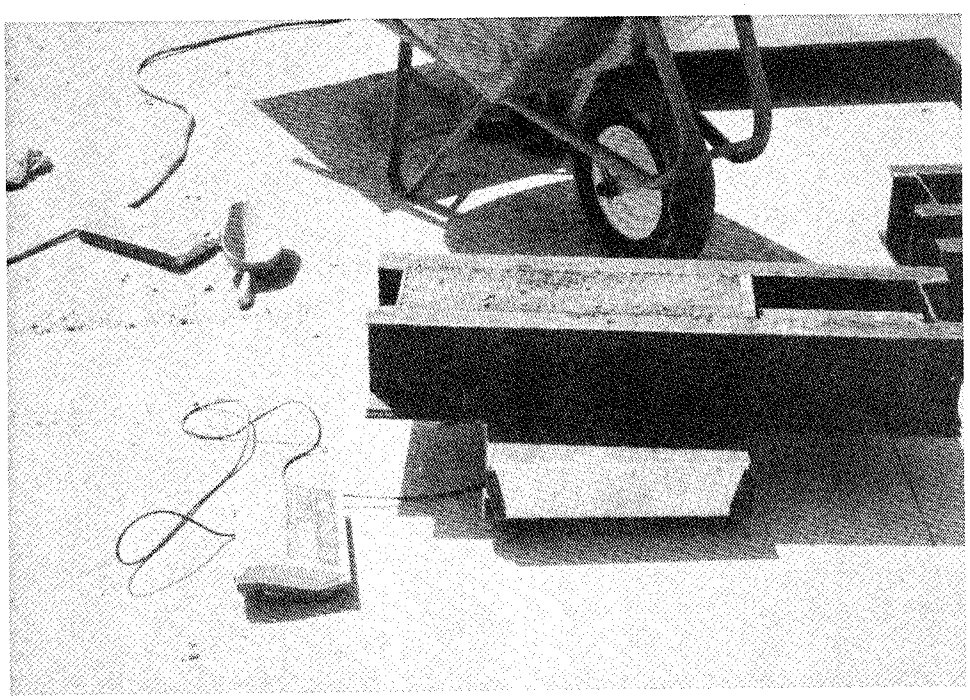

Photo E9. Vibration of beams

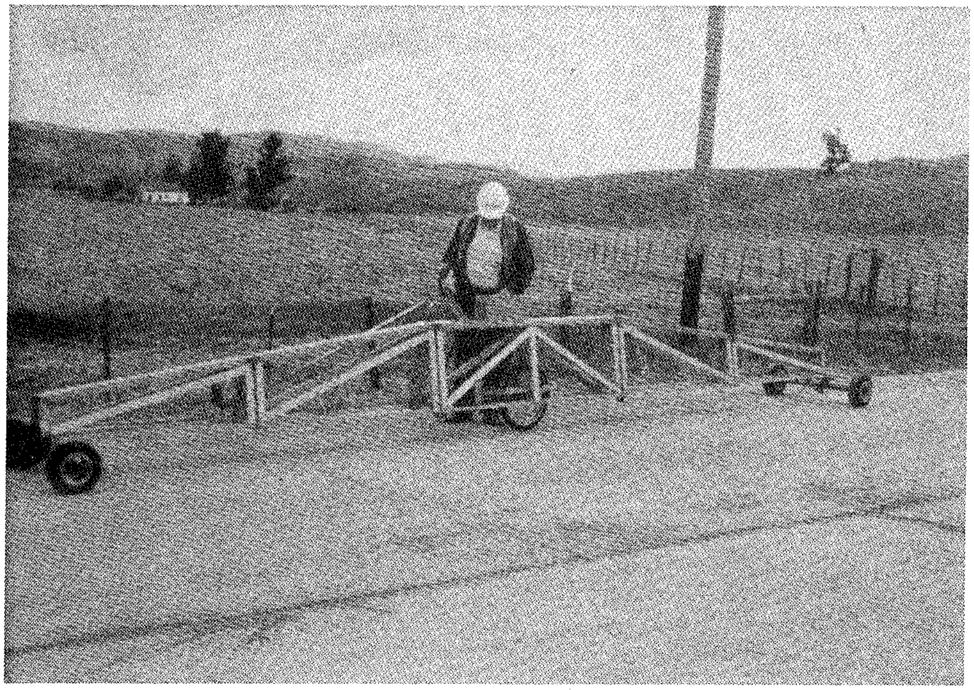

Photo E10. California profilograph

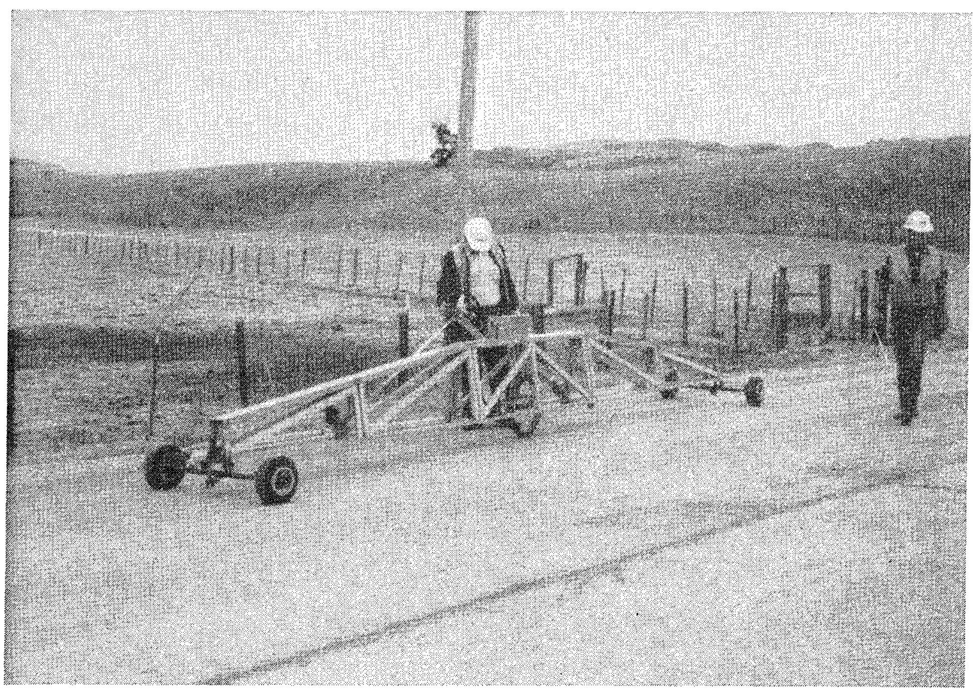

Photo E11. Profilograph traveling on Lane II

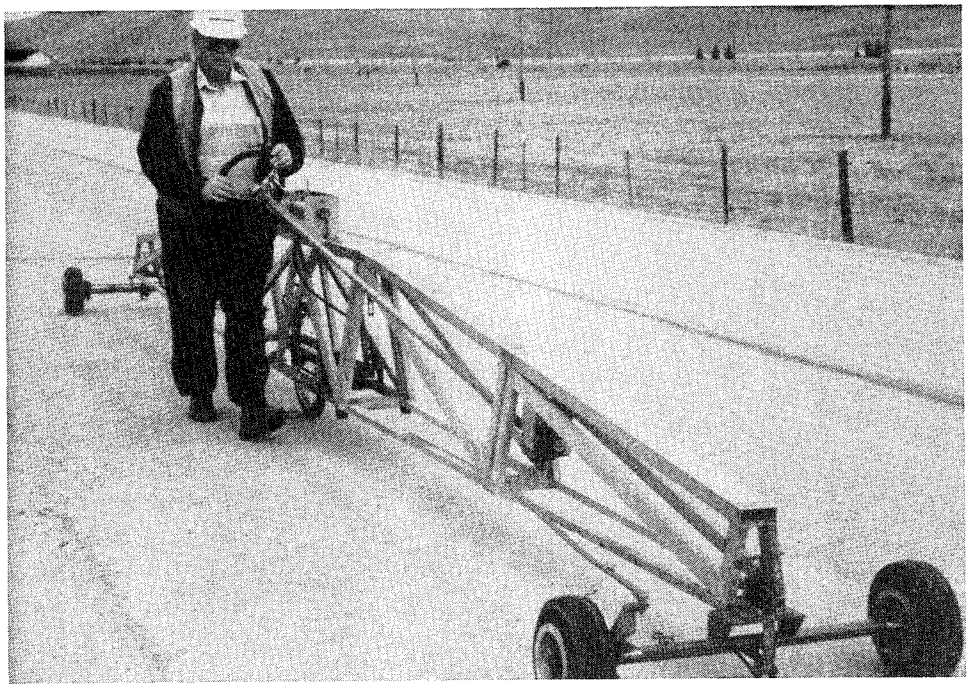

Photo E12. Close-up of operator with scroll to right of steering wheel in photo

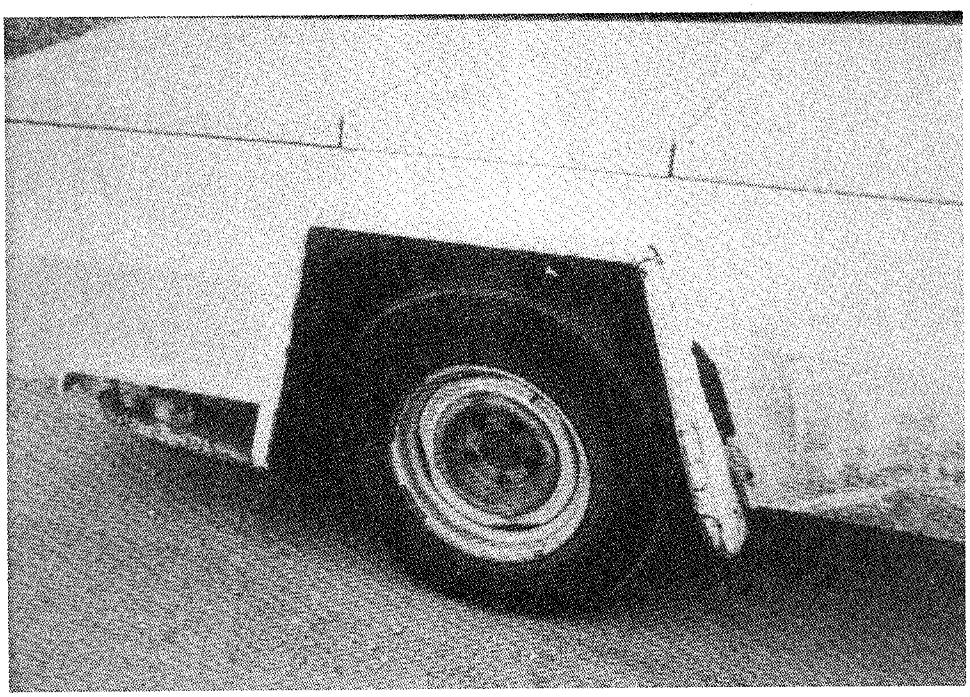

Photo E13. Close-up of skid resistance tester trailer

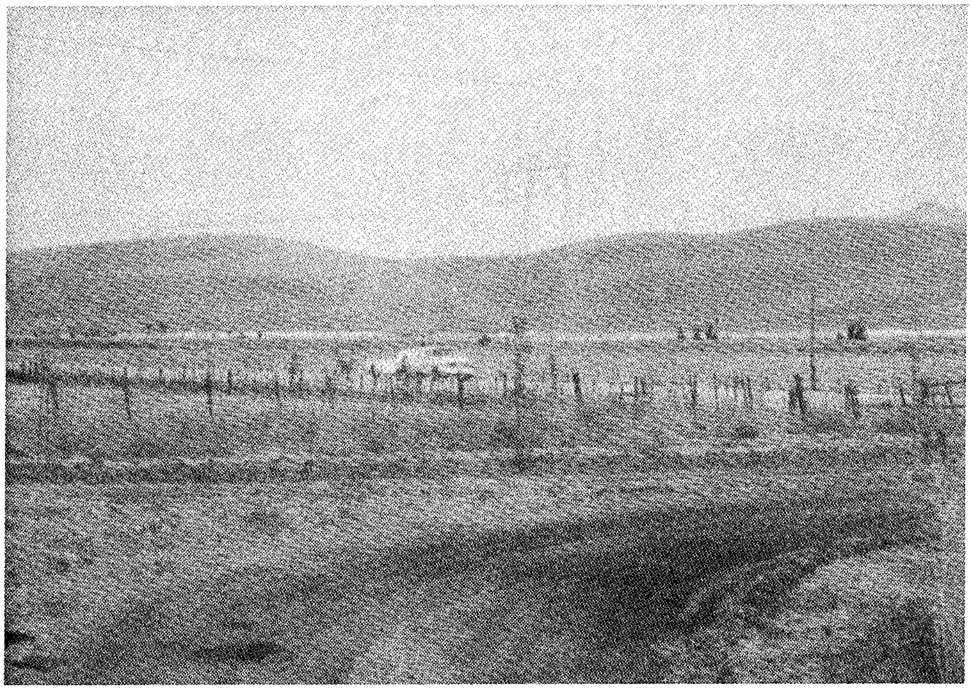

Photo E14. Skid resistance tester on Lane I

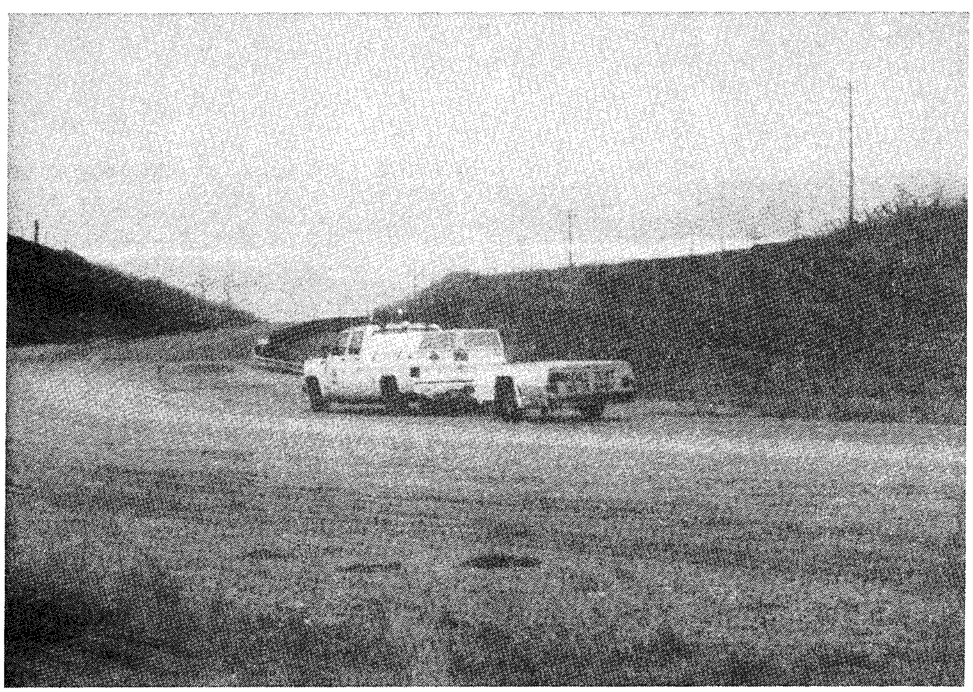

Photo E15. Skid resistance tester in curve of Lane I

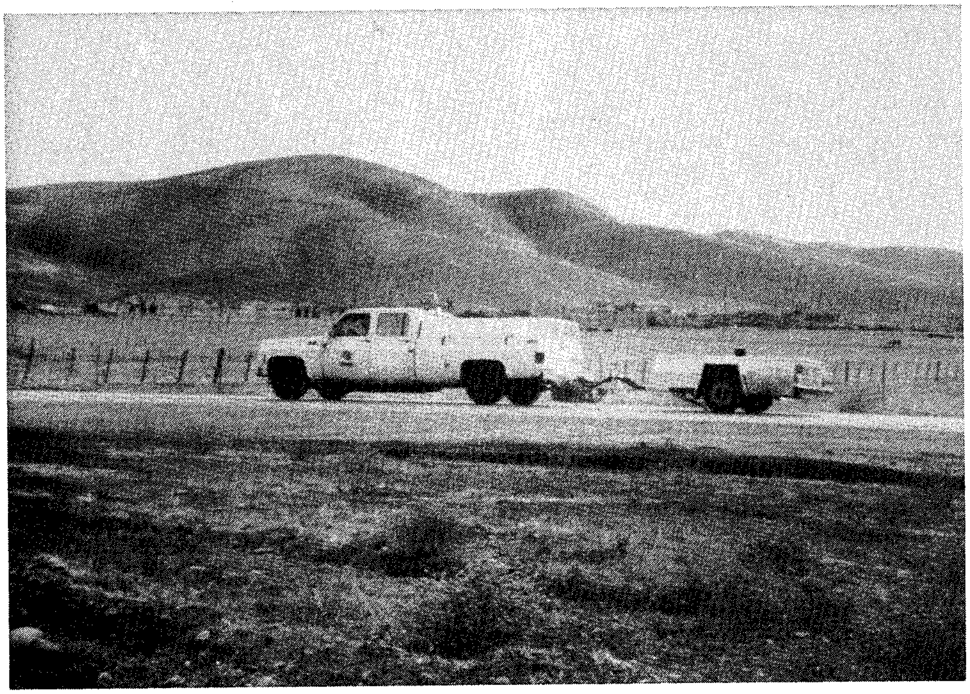

Photo E16. Skid resistance tester in curve of Lane II

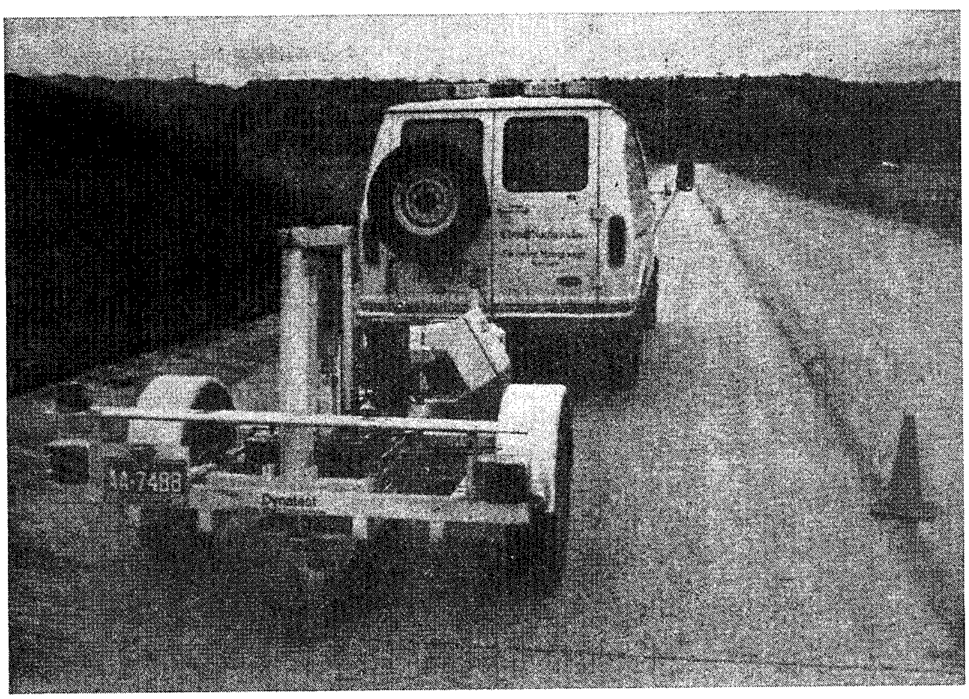

Photo E17. Falling weight deflectometer testing on Lane II at a joint

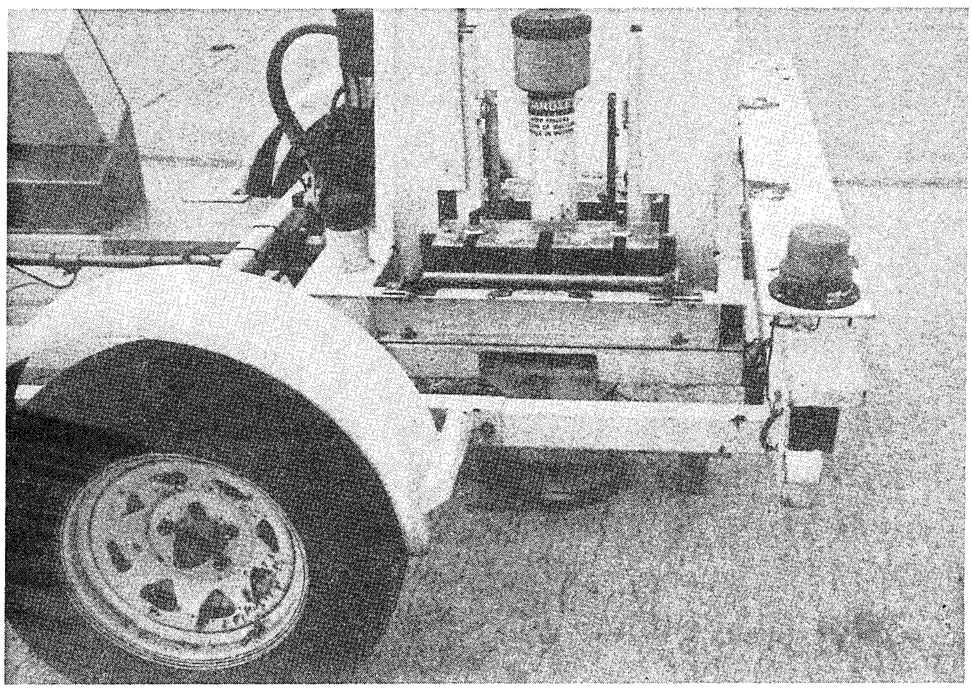

Photo E18. Weight dropping mechanism

Appendix F
Photos of Cracks and Joints

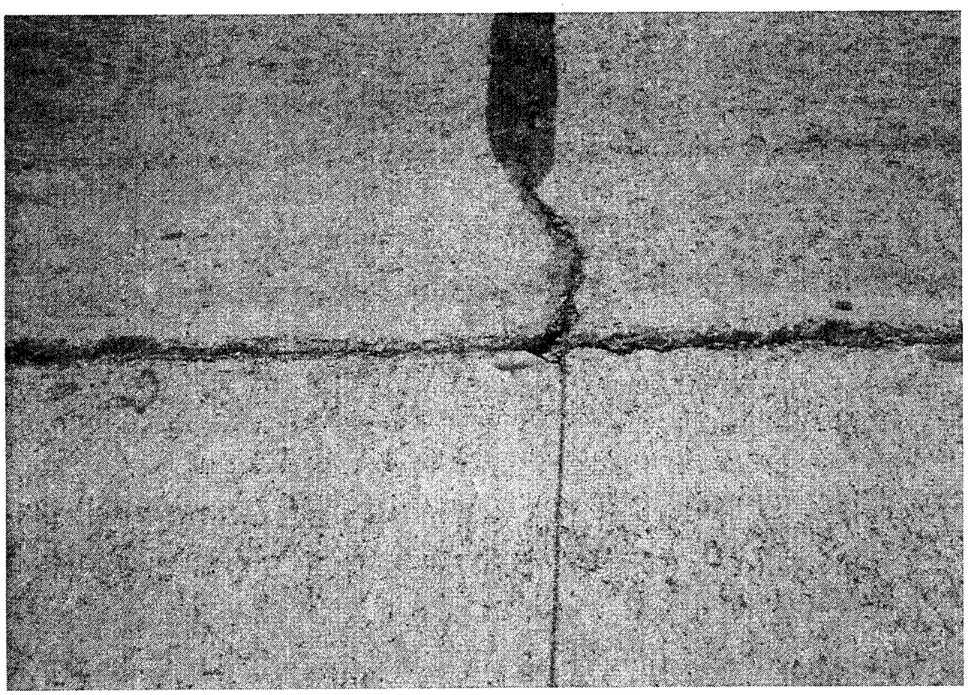

Photo F1. Sealed crack (Lane I) opposite a transverse joint (Lane II)

Photo F2. Asphalt patched crack (Lane II)

Photo F3. Longitudinal crack in Lane II 1-1/2 ft offset from longitudinal construction joint in the curve

Photo F4. Sealed transverse crack with longitudinal crack centerline crack (Lane I)

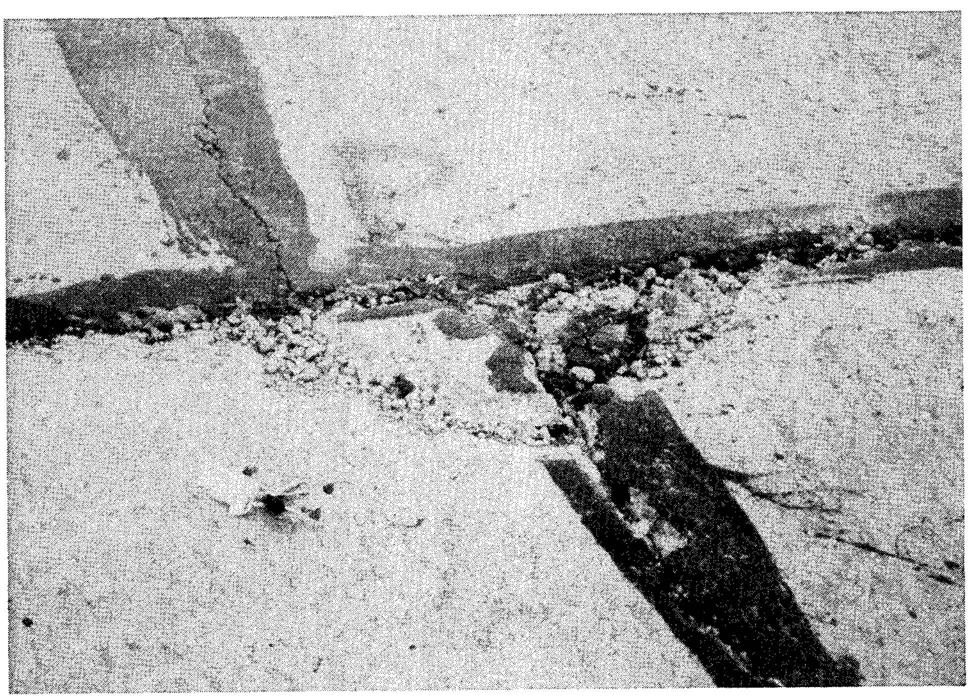

Photo F5. Spalling (Lane I) at intersection of transverse crack and longitudinal construction joint

Photo F6. Typical transverse crack

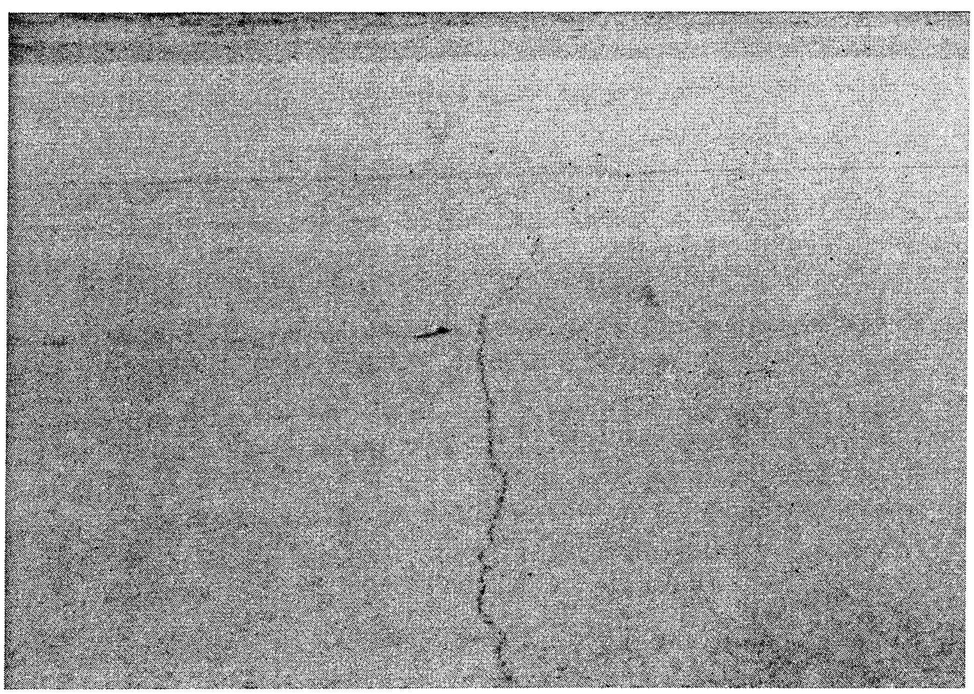

Photo F7. Transverse crack running through both lanes

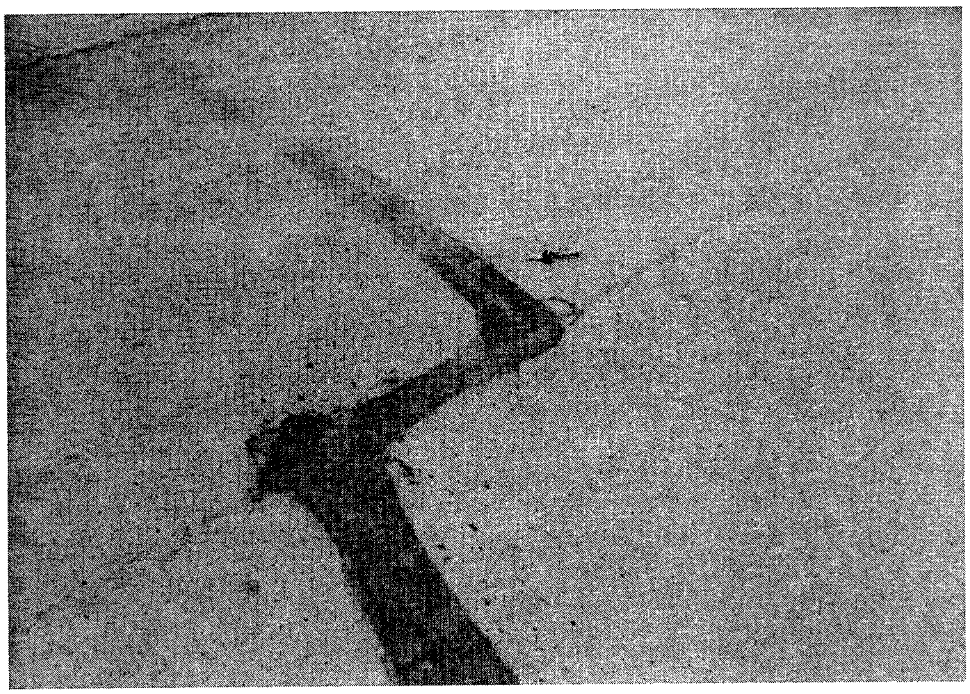

Photo F8. Sealed cracks (Lane I)

Appendix G
Crack Mapping

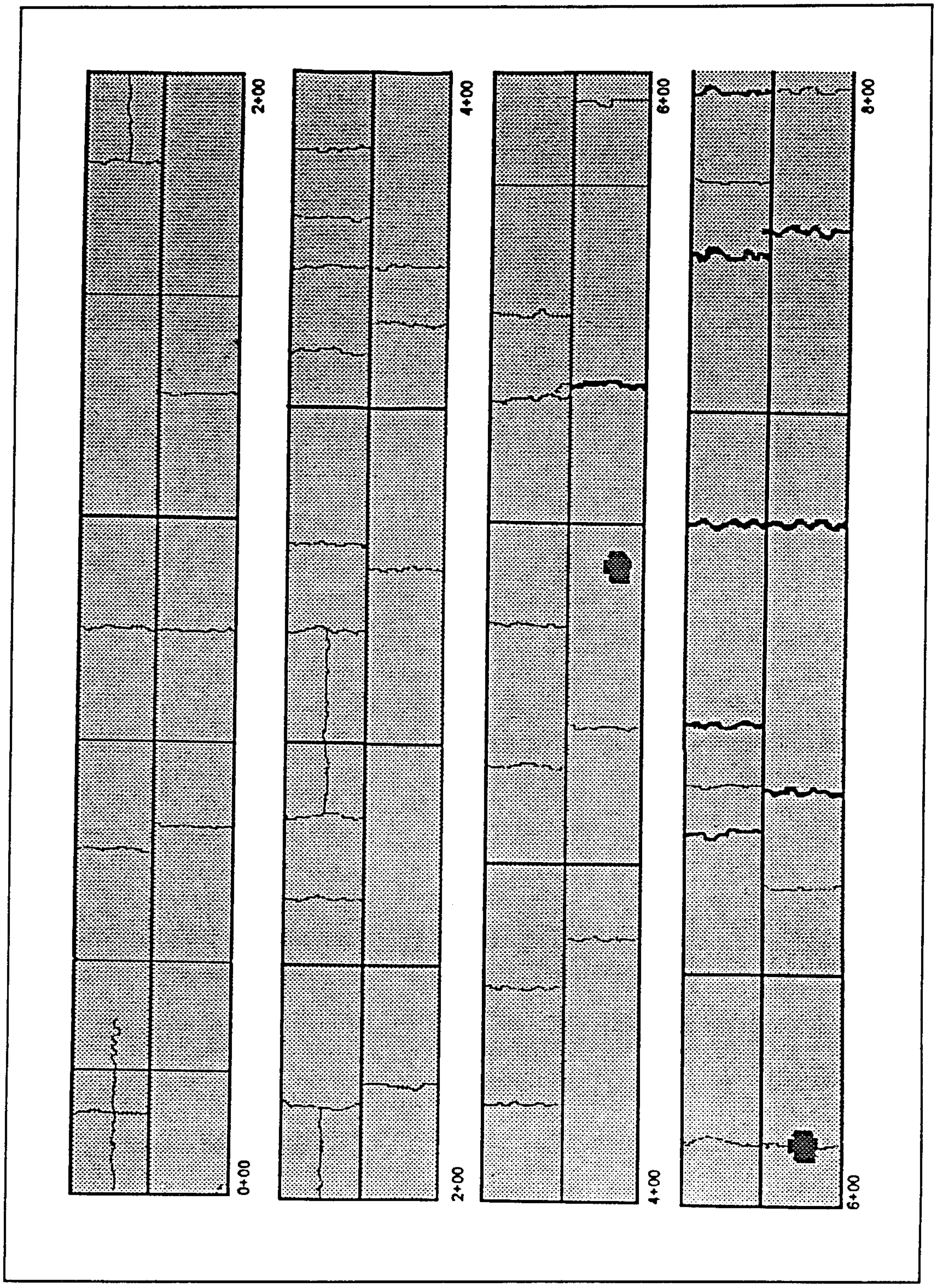

Figure G1. Layout of sawed joints and cracks 7 months after placement. (Note: the two areas shown at about 5+10 and 6+10 are areas of surface raveling.) (Continued)

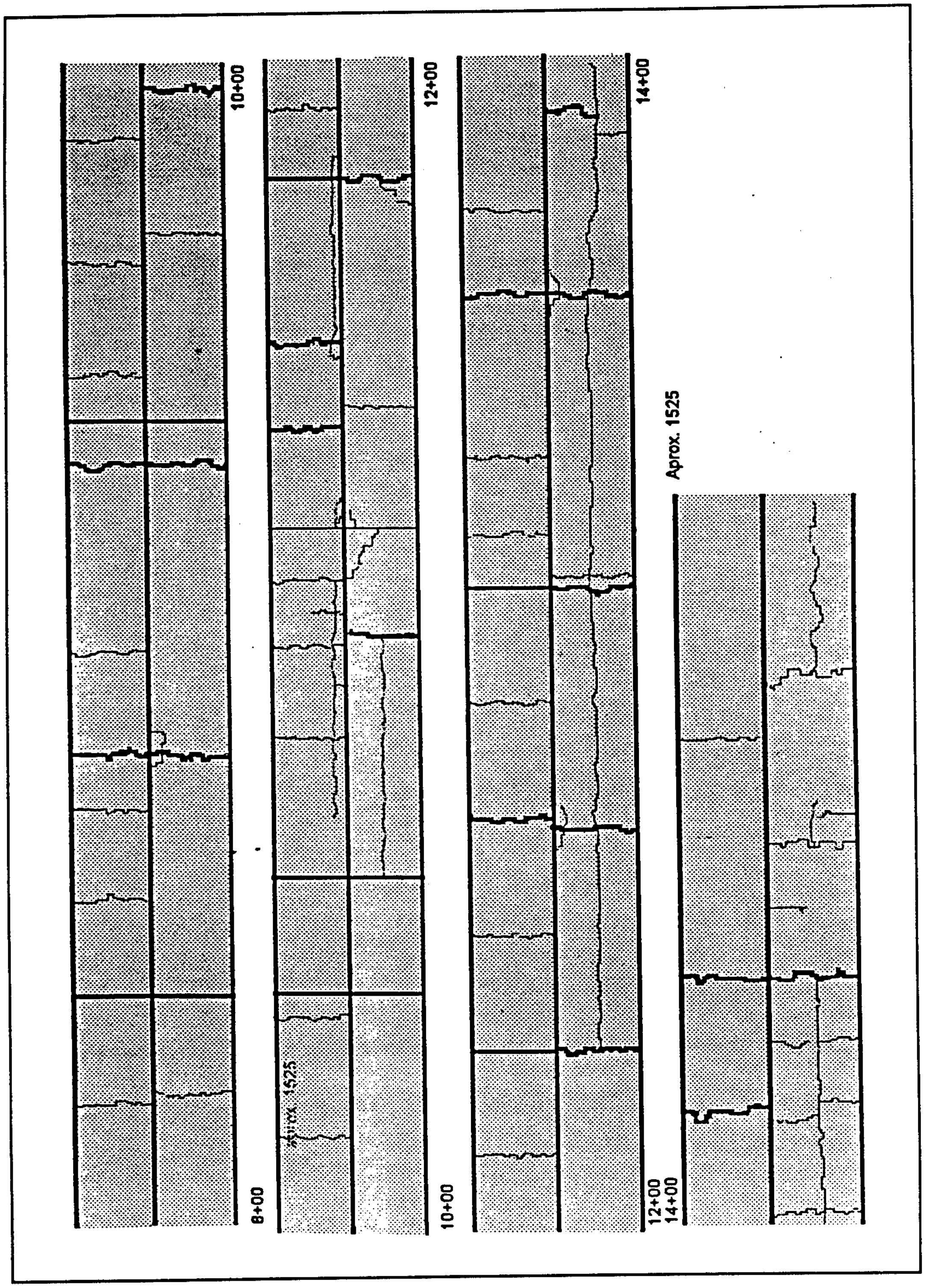

Figure G2. (Concluded)

Appendix H
Joint Efficiency Calculations

LANE I LT AM JT

SLAB	LOAD	0 DEFLECTION	12 dEFIECTION	L T	
1 to 2	6340	5.72	4.69	81.99	81.39
	6316	5.62	4.54	80.78	
	9550	8.60	7.17	83.37	83.59
	9590	8.58	7.19	83.80	
	12724	11.54	9.63	83.45	83.80
	12704	11.54	9.71	84.14	
2 to 3	6122	10.14	2.74	27.02	26.90
	6074	10.08	2.70	26.79	
	9355	14.32	4.24	29.61	29.41
	9355	14.48	4.23	29.21	
	12394	18.36	5.71	31.10	30.91
	12359	18.52	5.69	30.72	
3 to 4	6289	6.43	5.15	80.09	80.34
	6165	6.23	5.02	80.58	
	9522	9.69	7.81	80.60	80.59
	9518	9.68	7.80	80.58	
	12597	12.98	10.38	79.97	79.92
	12581	12.97	10.36	79.88	
4 to 5	6161	6.28	5.05	80.41	80.29
	6074	6.15	4.93	80.16	
	9312	9.36	7.61	81.30	81.15
	9224	9.37	7.59	81.00	
	12490	12.46	10.11	81.14	81.08
	12474	12.44	10.08	81.03	
5 to 6	6177	9.03	5.75	63.68	63.45
	6078	8.89	5.62	63.22	
	9379	12.97	8.81	67.93	67.53
	9395	13.02	8.74	67.13	
	12462	16.68	11.60	69.54	69.43
	12454	16.69	11.57	69.32	
6 to 7	6185	6.71	3.81	56.78	55.99
	6070	6.63	3.66	55.20	
	9335	9.83	6.32	64.29	64.18
	9339	9.85	6.31	64.06	
	12541	12.87	8.84	68.69	68.66
	12517	12.85	8.82	68.64	
7 to 8	6102	8.48	5.58	65.80	65.51
	6130	8.48	5.53	65.21	
	9351	12.27	8.57	69.85	69.65
	9343	12.28	8.53	69.46	
	12251	15.70	11.36	72.36	72.23
	12212	15.74	11.35	72.11	

LANE I LT AM JT

SLAB	LOAD	0 DEFLECTION	12 dEFIECTION	L T	
8 to 9	5899	14.70	4.31	29.32	29.19
	5887	14.80	4.30	29.05	
	9034	18.94	7.49	39.55	39.37
	9041	18.98	7.44	39.20	
	12271	22.71	10.33	45.49	45.18
	12212	23.00	10.32	44.87	
9 to 10	6221	6.07	4.12	67.87	67.78
	6114	5.91	4.00	67.68	
	9367	9.11	6.52	71.57	71.58
	9331	9.08	6.50	71.59	
	12569	12.05	8.91	73.94	73.99
	12486	12.06	8.93	74.05	
10 to 11	6138	6.34	4.49	70.82	70.53
	6094	6.25	4.39	70.24	
	9308	9.41	7.07	75.13	75.25
	9324	9.38	7.07	75.37	
	12470	12.31	9.65	78.39	78.28
	12452	12.32	9.63	78.17	
11 to 12	6062	6.54	5.28	80.73	80.70
	6062	6.57	5.30	80.67	
	9228	9.77	8.07	82.60	82.58
	9268	9.80	8.09	82.55	
	12422	12.83	10.69	83.32	83.35
	12378	12.87	10.73	83.37	
12 to 13	6050	6.30	4.80	76.19	76.16
	6002	6.20	4.72	76.13	
	9153	9.64	7.44	77.18	77.22
	9165	9.59	7.41	77.27	
	12335	12.85	9.98	77.67	77.56
	12351	12.86	9.96	77.45	

LANE II JT LT

SLAB	LOAD	0" DEFLECTION	12" DEFLECTION	L T	AVE LT
22-23	6018	8.41	2.70	32.10	32.34
	5979	8.26	2.69	32.57	
	9184	12.67	4.18	32.99	33.07
	9177	12.67	4.20	33.15	
	12243	16.76	5.62	33.53	33.51
	12212	16.81	5.63	33.49	
23-24	6050	6.37	2.13	33.44	33.81
	6038	6.32	2.16	34.18	
	9236	9.72	3.33	34.26	34.45
	9244	9.70	3.36	34.64	
	12370	12.83	4.39	34.22	34.16
	12398	12.87	4.39	34.11	
24-25	6070	5.42	2.56	47.23	47.35
	5967	5.33	2.53	47.47	
	9188	8.46	3.83	45.27	45.27
	9181	8.46	3.83	45.27	
	12434	11.45	5.09	44.45	44.09
	12374	11.46	5.01	43.72	
25-26	6002	5.60	2.75	49.11	49.46
	5967	5.52	2.75	49.82	
	9188	8.72	4.23	48.51	48.71
	9161	8.71	4.26	48.91	
	12363	11.68	5.64	48.29	48.25
	12343	11.70	5.64	48.21	
26-27	5943	7.01	2.34	33.38	33.55
	5959	6.97	2.35	33.72	
	9093	10.70	3.56	33.27	33.40
	9101	10.71	3.59	33.52	
	12227	14.25	4.72	33.12	33.18
	12299	14.29	4.75	33.24	
27-28	5935	6.74	3.18	47.18	47.25
	5959	6.72	3.18	47.32	
	9089	10.68	4.81	45.04	45.09
	9105	10.70	4.83	45.14	
	12152	14.45	6.37	44.08	44.02
	12172	14.47	6.36	43.95	
28-29	6006	7.65	2.82	36.86	36.76
	5963	7.64	2.80	36.65	
	9109	11.31	4.35	38.46	37.98
	9129	11.36	4.26	37.50	
	12271	14.64	5.77	39.41	39.11
	12164	14.69	5.70	38.80	

LANE II JT LT

	LOAD	0" DEFLECTION	12" DEFLECTION	L T	AVE LT
29-30	5971	7.21	2.86	39.67	39.76
	5979	7.15	2.85	39.86	
	9161	11.37	4.49	39.49	39.58
	9129	11.37	4.51	39.67	
	12084	15.25	6.10	40.00	39.84
	12053	15.27	6.06	39.69	
30-31	5943	7.22	3.36	46.54	46.43
	5903	7.19	3.33	46.31	
	9117	10.85	4.85	44.70	44.55
	9093	10.88	4.83	44.39	
	12239	14.25	6.20	43.51	43.36
	12212	14.28	6.17	43.21	
31-32	5947	5.59	4.52	80.86	83.42
	5879	5.42	4.66	85.98	
	9117	8.63	6.48	75.09	78.29
	9109	8.48	6.91	81.49	
	12311	11.63	8.32	71.54	72.93
	12303	11.53	8.57	74.33	
32-33	5863	7.12	2.92	41.01	40.68
	5832	7.04	2.84	40.34	
	9018	10.99	4.42	40.22	40.02
	8978	10.95	4.36	39.82	
	12212	14.53	5.74	39.50	39.25
	12176	14.59	5.69	39.00	

LANE 1 CRACK LT

SLAB	LOAD	0" DEFLECTION	12" DEFLECTION	L T	AVE LT
CRACK 3	6376	4.51	3.71	82.26	82.17
	6217	4.35	3.57	82.07	
	9610	6.85	5.72	83.50	83.38
	9614	6.81	5.67	83.26	
	12641	9.31	7.74	83.14	83.07
	12625	9.30	7.72	83.01	
CRACK 4	6316	4.86	3.51	72.22	72.52
	6237	4.71	3.43	72.82	
	9474	7.50	5.45	72.67	72.53
	9510	7.46	5.40	72.39	
	12696	10.22	7.37	72.11	71.99
	12700	10.20	7.33	71.86	
CRACK 5	6257	5.61	3.47	61.85	61.38
	6146	5.50	3.35	60.91	
	9534	8.57	5.41	63.13	62.59
	9542	8.59	5.33	62.05	
	12545	11.53	7.33	63.57	63.29
	12533	11.54	7.27	63.00	
CRACK 9	6189	5.14	3.87	75.29	75.17
	6058	4.97	3.73	75.05	
	9335	7.87	5.83	74.08	73.44
	9355	7.87	5.73	72.81	
	12549	10.61	7.68	72.38	71.59
	12510	10.65	7.54	70.80	
CRACK 10A	6193	4.34	3.39	78.11	78.25
	6062	4.21	3.30	78.38	
	9300	6.76	5.25	77.66	77.73
	9300	6.71	5.22	77.79	
	12462	9.17	7.11	77.54	77.66
	12462	9.14	7.11	77.79	
CRACK 10B	5804	4.44	2.74	61.71	61.13
	5740	4.41	2.67	60.54	
	8974	7.02	4.39	62.54	61.99
	8958	7.03	4.32	61.45	
	12164	9.52	6.03	63.34	62.82
	12152	9.60	5.98	62.29	
CRACK 11	6102	5.48	4.85	88.50	88.36
	6078	5.43	4.79	88.21	
	9184	8.24	7.35	89.20	88.83
	9181	8.24	7.29	88.47	
	12366	10.92	9.74	89.19	88.98
	12394	10.94	9.71	88.76	

LANE 1 CRACK LT

SLAB	LOAD	0" DEFLECTION	12" DEFLECTION	L T	AVE LT
CRACK 12	6106	5.51	4.24	76.95	77.22
	5963	5.33	4.13	77.49	
	9169	8.23	6.33	76.91	76.75
	9157	8.20	6.28	76.59	
	12382	10.94	8.35	76.33	76.25
	12315	10.91	8.31	76.17	

LANE II CRACK LT

SLAB	LOAD	0" DEFLECTION	12" DEFLECTION	L T	AVE LT
CRACK 24	6090	3.80	2.53	66.58	66.85
	6098	3.74	2.51	67.11	
	9264	5.88	4.08	69.39	69.39
	9276	5.88	4.08	69.39	
	12521	7.96	5.62	70.60	70.65
	12486	7.95	5.62	70.69	
CRACK 25	6086	4.40	3.20	72.73	72.81
	6030	4.39	3.20	72.89	
	9228	6.87	5.07	73.80	74.02
	9220	6.87	5.10	74.24	
	12458	9.25	6.91	74.70	74.69
	12418	9.24	6.90	74.68	
CRACK 27	6006	5.38	3.70	68.77	69.04
	5983	5.31	3.68	69.30	
	9157	8.33	5.85	70.23	70.31
	9161	8.34	5.87	70.38	
	12366	11.30	7.95	70.35	70.29
	12339	11.32	7.95	70.23	
CRACK 28	6050	5.19	3.57	68.79	68.99
	6042	5.13	3.55	69.20	
	9220	8.06	5.76	71.46	71.38
	9200	8.05	5.74	71.30	
	12327	10.87	7.95	73.14	73.05
	12343	10.84	7.91	72.97	
CRACK 29A	6090	5.01	2.22	44.31	43.44
	6026	4.98	2.12	42.57	
	9268	7.48	3.72	49.73	48.93
	9256	7.48	3.60	48.13	
	12223	9.76	5.23	53.59	52.97
	12176	9.78	5.12	52.35	
CRACK 29B	6006	9.39	4.58	48.78	48.30
	5995	9.43	4.51	47.83	
	9208	13.56	6.96	51.33	50.94
	9192	13.69	6.92	50.55	
	12168	17.13	9.17	53.53	53.36
	12148	17.24	9.17	53.19	
CRACK 30A	5951	5.16	3.63	70.35	70.25
	5983	5.16	3.62	70.16	
	9113	8.02	5.82	72.57	72.40
	9117	8.03	5.80	72.23	
	12355	10.75	7.89	73.40	73.08
	12283	10.76	7.83	72.77	

LANE II CRACK LT

SLAB	LOAD	0" DEFLECTION	12" DEFLECTION	L T	AVE LT
CRACK 30B	6078	5.87	4.17	71.04	70.72
	6002	5.81	4.09	70.40	
	9226	8.98	6.39	71.16	71.08
	9204	9.00	6.39	71.00	
	12347	11.87	8.48	71.44	71.12
	12311	11.92	8.44	70.81	
CRACK 30C	5983	6.50	5.39	82.92	83.10
	5955	6.46	5.38	83.28	
	9133	9.85	8.17	82.94	83.05
	9125	9.85	8.19	83.15	
	12263	12.95	10.72	82.78	82.83
	12267	12.96	10.74	82.87	
CRACK 31A	6018	6.32	4.78	75.63	75.66
	5995	6.21	4.70	75.68	
	9208	9.70	7.34	75.67	74.88
	9204	9.92	7.35	74.09	
	12255	12.92	9.72	75.23	75.15
	12239	12.96	9.73	75.08	

Appendix I
Joint Efficiency Plots

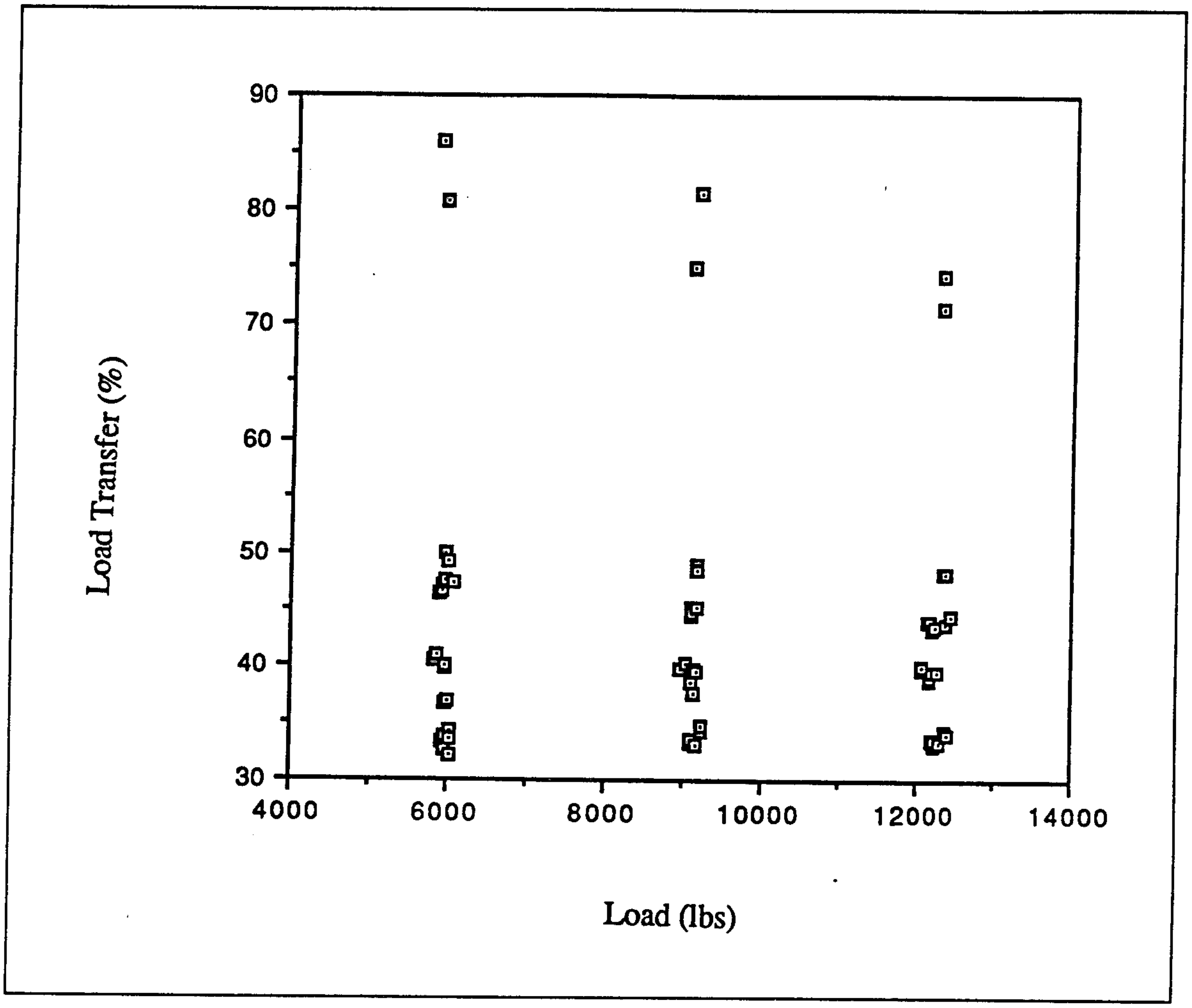

Figure I1. Joint efficiency--joints, Lane II (1 lb = 0.4535924 kg)

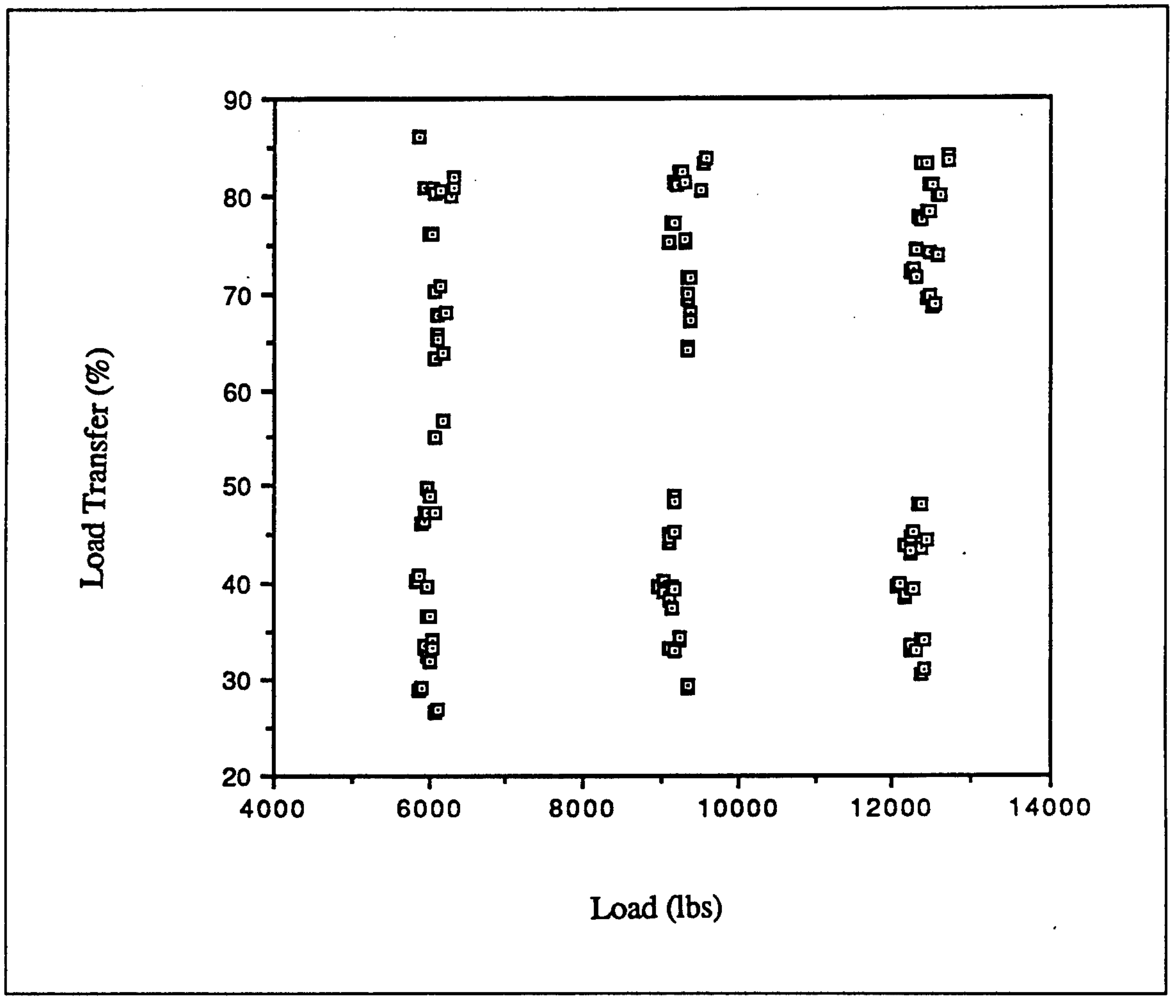

Figure I2. Joint efficiency--joints, all (1 lb = 0.4535924 kg)

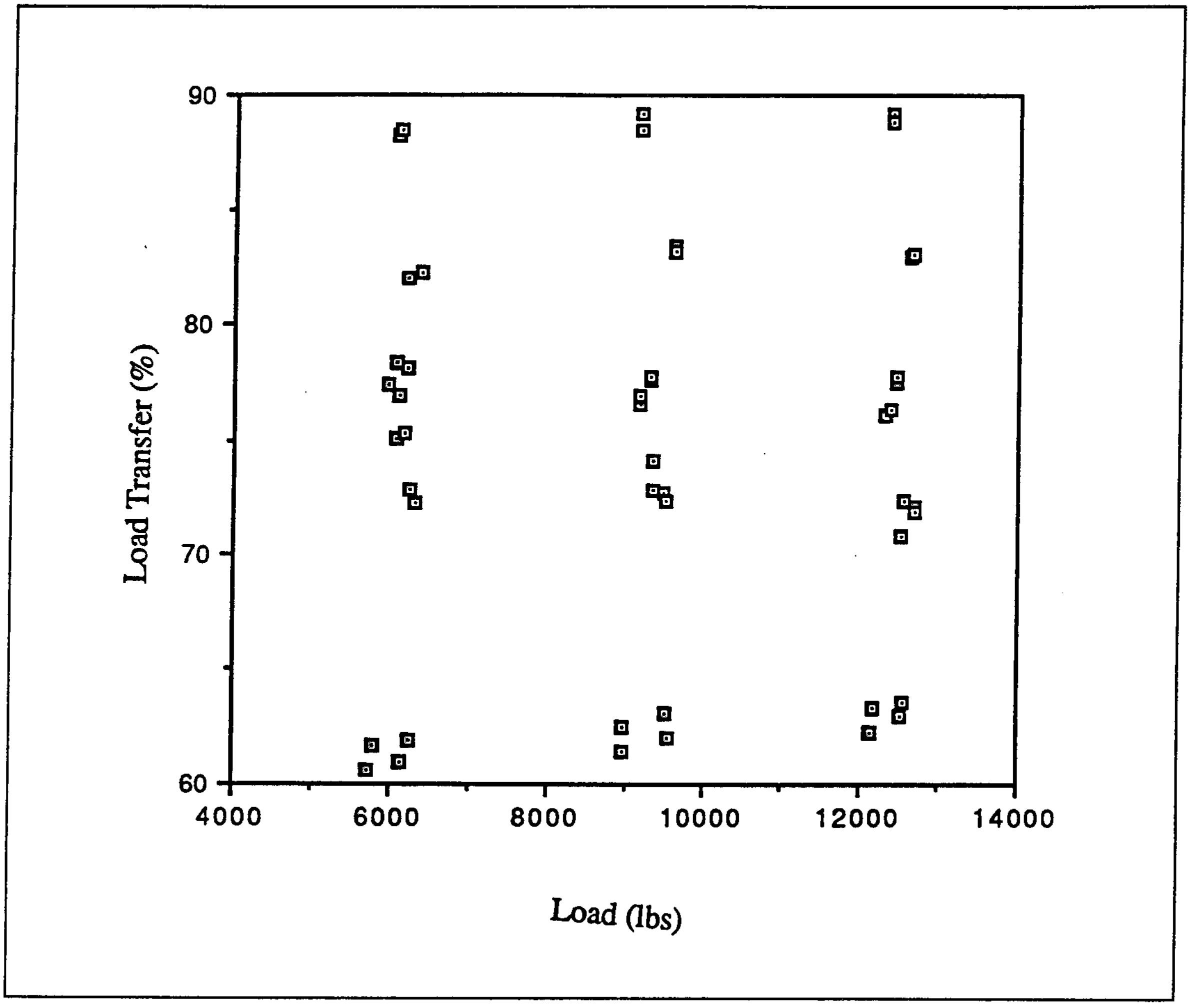

Figure 13. Joint efficiency--cracks, Lane 1 (1 lb = 0.4535924 kg)

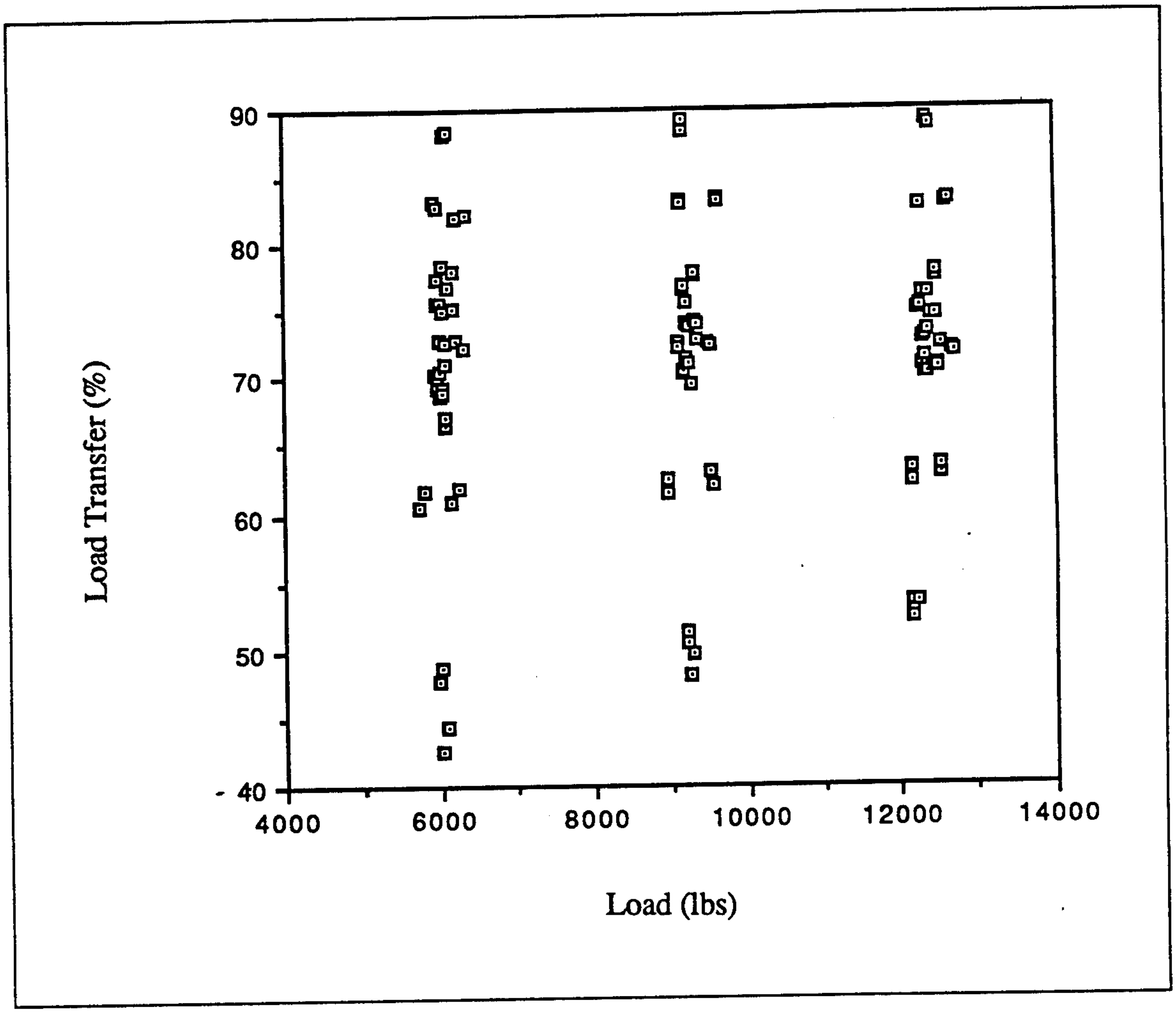

Figure 14. Joint efficiency--cracks, all (1 lb = 0.4535924 kg)

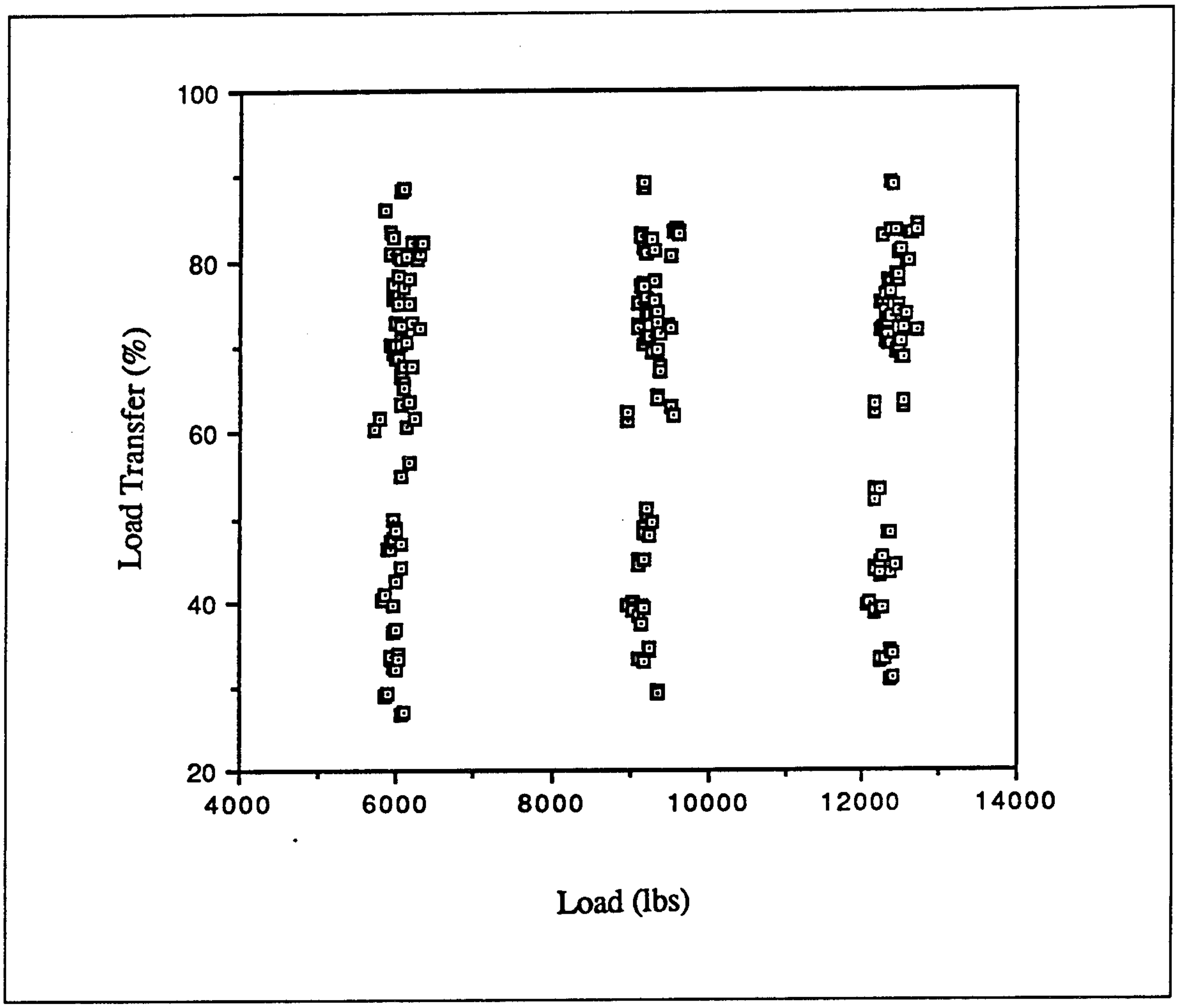

Figure I5. Joint efficiency--all joints and cracks (1 lb = 0.4535924 kg)

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13. ABSTRACT *(Maximum 200 words)*

The purpose of this project was to investigate the performance of a roller-compacted concrete (RCC) pavement for use as a high-speed surface. A test section consisting of a small parking lot and a two-lane roadway was constructed. During construction, three major parameters were varied: paver speed, rolling amount, and joint spacing. The paver speed was varied to determine what effect, if any, this has on average lay-down density, average final density, rideability, skid resistance, load transfer, and density profiles. The average lay-down and final densities of the RCC pavement were determined using a nuclear density device, which determined the density of various depths throughout the pavement. The load transfer was determined at transverse joints and transverse cracks by using falling weight deflectometer data. The rolling amount was varied to determine its effect on all of the same properties as paver speed except lay-down density. The joint spacing was varied to examine an optimum spacing that would not develop intermediate cracking and would provide the desired rideability and load transfer.

From this project, it was determined that no adjustments in paver speed, rolling (types of patterns), or joint spacing will significantly enhance RCC pavement properties so that it may be used for high-speed applications.

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