A STUDY OF ROLLER COMPACTED CONCRETE
AS A PAVING MATERIAL

By

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Dedicated

to

Norma, my wife and friend

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Roller Compacted Concrete

The development of roller compacted concrete (RCC) has evolved from the early use of cement stabilized bases for pavements and soil cement to the current zero to very low slump concrete that has been successfully used in the construction of mass concrete dams. This application of a cost effective construction material has recently proved to be useful as a replacement for conventionally placed concrete slabs. The constituents of RCC are much the same as for cement stabilized bases and soil cement, in that an aggregate, portland cement, and water are used. The differences in general are the types of aggregate used, the cement content by percentage of weight of mix, and the amount of water used, also expressed as a percentage by weight of mix.

Differences also exist between RCC when used for mass concrete dam construction and for paving purposes. As a general rule, for mass concrete in a dam, the aggregate will have a much larger maximum size and may consist of natural materials or deposits which may contain in excess of 10 percent fines passing the No. 200 sieve. The strength considerations for the two applications are also different. In dam construction the compressive strength and bonding strength between horizontal lifts has priority, while in pavement construction flexural strength and bonding between adjacent paving lanes is critical. Other considerations involved in pavement construction using RCC that are deemed critical are curing and the prevention of segregation of the aggregate during hauling and placement operations. Furthermore, proper curing techniques must be followed and segregation of the aggregate is important in placement of mass concrete. However, more than one successive lift is placed in dam construction while single lifts are usually placed in pavement construction, and any surface imperfections are readily seen. Thus, surface smoothness and texture are products of a proper curing operation, lack of segregation of the aggregates in the mix, and other characteristics such as proper rolling techniques. The advantage of using RCC for either dam or pavement construction is primarily based on economics. The savings are associated with placement operations, utilizing construction equipment for either conventional earth dam or asphalt paving operations, and removing the intense labor requirements from conventional placement of concrete. Savings can also be attributed to construction time saved, as placement operations are very rapid when forming, finishing, and form stripping are not required.

Previous studies on the use of RCC as a paving medium were concerned with placement procedures, compactive efforts, mix designs, and strength tests. Test sections were constructed utilizing a variety of types of construction equipment, lift thicknesses, various mix designs, and methods of predicting field strengths based on laboratory results. The conclusions reached by previous research indicated that it was feasible to utilize RCC for paving, but no large-scale application which would justify the expense of erecting a plant on-site was on the horizon.

Statement of Problem

This report is concerned with the construction of the first RCC pavement section in the United States, using conventional asphalt placement equipment, a central mix plant, and single lift construction. Unknown to the author, similar construction was performed in Canada at an earlier date and results of that construction will be analyzed and discussed in this report. The principal problem in this type of construction is what quantity of material is required to reach a break even point, where an on-site plant can be erected to mix the materials for placement rather than place conventional ready-mix plant concrete. The methods used to predict field strengths are relatively unreliable but are usually on the conservative side of the spectrum.

Scope of Research

The purpose of this research was to investigate the construction of RCC pavements and provide lessons learned for future applications. It is also intended to develop a method of estimating the quantity of RCC paving required, to justify using this construction technique for future projects, on a cost effective basis.

CHAPTER II

LITERATURE SURVEY

Introduction

A survey of current literature pertaining to RCC resulted in the conclusion that the field is so new that little information has been published. Most of the early work done in the United States was by the Tennessee Valley Authority, U.S. Army Corps of Engineers, and Bureau of Reclamation. The literature reviewed can be categorized into two distinct areas: research and construction for both dams and pavements.

Early studies reported by Cannon (1) in 1972 used a 15-ton vibratory roller to achieve consolidation of the cement mass. The studies were sponsored by the Tennessee Valley Authority to verify the feasibility of using conventional earth placement equipment. The Corps of Engineers also was conducting studies on placement operations at the Waterways Experiment Station, as reported by Tynes (2) in 1973. This study was concerned with multiple lift construction and results indicated that the bond between lifts was unsatisfactory and highly permeable in most instances.

As a continuation of studies at the Waterways Experiment Station (WES), research was reported at the Lost Creek Dam in the Portland District, U.S. Army Corps of Engineers, by Hall and Houghton (3) in 1974. This study was significant in that a large-scale test section was constructed using several different mix designs and types of placement equipment. The results indicated that it was feasible to utilize this "new" construction material in mass concrete dam construction. A more detailed review of this work and other significant literature are contained in the next section of this report.

Some of the first work considering RCC as a paving material, also conducted at WES, was reported by Burns and Saucier (4) in 1978. The primary concern of this research was the effectiveness of conventional vibratory and nonvibratory rollers in compacting the zero slump concrete mix. The general conclusions were that vibratory rollers could achieve greater strength properties, both compressive and flexural, in the compacted mix than could be obtained from conventionally placed concrete with the same cement content and with a slump in excess of one inch. Also significant was the fact that an asphalt laydown machine was used to place the uncompacted material in lanes, in a single lift.

The first uses of RCC in large quantities were at the Tarbela Dam in Pakistan between 1975 and 1978, and later at the Guri Dam in Venezuela between 1980 and 1981, as reported by Mass (5) in 1983. Both projects were under the advisement of Harza Engineering Company of the United States. At Tarbela, RCC was used to repair a failed tunnel in the form of a tower consisting of a series of baffles that were similar to a rock ladder. About 457,800 cubic yards were placed in 42 working days using conventional earth placing equipment. Later, an additional nearly 3 million cubic yards were placed for stabilization of the service and auxiliary spillway plunge pools, in the form of slabs. A cofferdam of about 20,365 cubic yards of RCC was constructed at Guri. Although it was a relatively small embankment, approximately 23 feet high and 1,476 feet long, this was a milestone of sorts with respect to cofferdam construction.

The world's first concrete dam constructed using earthmoving equipment and compaction methods was in Japan, in 1981, at the Shimajigawa Dam (6). Subsequent projects have been either designed or in the process of construction in Japan, but the Japanese have been unable to take complete advantage of the economy possible with this type of construction. They tend to take extreme care in treating the vertical lift joints between succeeding layers, which consumes time and money, and apparently the mix designs that were utilized approached conventional concrete in paste content.

The construction of a spillway on the North Fork of the Toutle River in the state of Washington in 1981, and the construction of the first all RCC dam in the United States in 1982, at Willow Creek in Oregon, led to the acceptance of this type of construction in the United States. About 18,000 and 400,000 cubic yards of material were placed on these two projects at Toutle River and Willow Creek, respectively. The prominent factor is that all of the material was placed at Willow Creek in a five-month period during one construction season. According to Schrader (7), the ability to complete a structure in one season has great implications with regard to cost savings in overhead, inflation, and unknown long-term labor agreement costs.

During the period of 1975 to 1981, Saucier (8) conducted further research at WES to study the problems associated with the use of RCC in mass concrete construction. The significance of this work, as applied to pavements, was: (1) Saucier concluded that the moisture content which is best for rolling is about 1 percent less than optimum as determined by soil compaction methods; and (2) that the resistance to freeze-thaw action was poor.

Pertinent Literature

Hall and Houghton (3)

During the period of 14 May to 18 May 1973, several test panels were constructed at the Lost Creek Dam location to establish the bond and permeability qualities of RCC. The nominal lift thickness was 8 inches after compaction and succeeding lifts were placed both after the preceding lift had hardened and prior to hardening of the preceding lift. A total of 11 mix designs were investigated; however, only 8 were used.

The mixes contained from 99 to 275 pounds of cementitious materials per cubic yard, with a portion of the cement replaced with either fly ash or a locally available calcined shale. A 3-inch maximum size aggregate was used and actually four aggregates were combined to provide a gradation between the No. 4 and 3-inch sieve size. Water-cementitious material ratios varied from 0.51 to 0.82.

The materials were mixed in 8 cubic yard batches and hauled a short distance to the test area in end dump trucks. A total of about 32 cubic yards was placed in each section and then spread with a dozer to a nominal loose thickness of 9 inches on a prepared foundation. Compaction was obtained by utilizing two different vibratory rollers: a self-propelled single drum (nondrive) roller and a self-propelled tandem drum (drive) roller. A third vibratory roller--a towed single drum--was used briefly, but was abandoned when it tended to tear up the surface on the backward pass. Four complete passes of the rollers, two in each direction, were used to achieve a field density averaging 154.7 lbs/cf, with a minimum and maximum of 152.5 and 156.3 lbs/cf, respectively.

A Vebe apparatus vibrating table was used to mold laboratory specimens in the form of concrete cylinders with a volume of 0.5 cubic foot in an 11-inch diameter container. An additional surcharge weight of 20 pounds was added for a total of 27.5 pounds, to produce reliable results. No beams were molded for flexural strength testing.

Ten-inch diameter cores were drilled horizontally and vertically through the lift joints for later trimming and testing. It was reported that 90-day age specimens were planned, but later changed to 120-day due to high core loss. Seven different tests were performed to obtain the properties of the hardened mix, with particular emphasis on the bonding of the lift joints.

It was concluded by the authors that it was practical to produce and place RCC by standard soil compaction methods, using a vibratory roller; the permeability and bond at the lift joints compare favorably with that of conventionally placed lean mass concrete; and a modified Vebe apparatus can be used to mold laboratory cylinders for control testing.

Burns and Saucier (4)

This study was conducted to determine the strength properties of RCC associated with pavements and investigated a secondary area--surface smoothness and texture. The first known placement of RCC using an asphalt laydown machine was included as a replacement for costly conventional labor intensive placement procedures. As at Lost Creek, a test section was constructed using two different vibratory compactors with the addition of a 25-ton pneumatic-tired roller at WES.

The test section measured 105 feet long by 12 feet wide, was divided into four test areas using various compactors and two different compacted lift thicknesses--5 and 9 inches. The procedure was much the same as at Lost Creek, except one lift construction was used, spreading the 1½-inch maximum size aggregate mix with a Barber-Green asphalt lay-down machine. No fly ash or other pozzolan was added to the 0.33 water/cement ratio mix.

The test results of cylinders and beams sawed from the test section after 28 days indicated that required strengths for pavements could be met using RCC methods. Compressive and flexural strengths for the vibratory rollers averaged 4910 and 750 psi, respectively, with an average unit weight of 153.3 lbs/cf. The pneumatic roller was not effective in compacting the mixture, resulting in a compressive strength of 2700 psi and a flexural strength of 620 psi, with a unit weight of 148.3 lbs/cf.

The conclusion of the research was that the RCC method would be successful in the construction of pavements for secondary roads and streets, haul roads, service entrances, tank trails, and as a base for any type of pavement system. A savings can be realized in construction costs by a reduction of cement quantity and in placement costs. No visible cracks developed in the 105-foot long slab, which had no expansion, contraction, or construction joints. This appeared to be a significant achievement and was attributed to the low water-cement ratio mix. The surface texture appeared to be sufficient for secondary roads and lesser pavements.

Canadian Portland Cement Association (9)

Pavement construction using RCC has been used since 1976 in British Columbia, primarily for log sorting yards and access roads to the yards. Very heavy concentrated loadings exceeding 120 tons per axle have been applied to the pavements, which for the most part are two-lift construction.

The pavements reportedly functioned very well over the years with little or no maintenance or repairs. In two-lift construction, the first lift is constructed with cement contents between 6 to 9 percent and the top lift with cement contents in the range of 10 to 12 percent to aid in preventing freeze/thaw deterioration. Total thicknesses of the pavements range from 7 to 14 inches.

Much the same construction procedures that were earlier discussed were used, except a pneumatic roller was used for final rolling to seal the surface. Surface tolerances of 3/8 inch in 10 feet were reportedly met and no joints were sawed. Curing for the most part was accomplished by irrigating the surface for seven days and in some instances by spraying with an asphalt emulsion at the end of the day, following continuous spraying with a water truck during the day. Strict avoidance of vertical cold joints in two-lift construction is recommended. The treatment of vertical cold joints consisted of machine cutting the face of the joint vertically and application of cement slurry to the face when construction resumed. Most of the pavements constructed in Canada have performed successfully to date and further uses have been proposed.

Summary

Review of the literature concerning RCC construction of mass concrete dams and pavements, and the associated research work, has resulted in several observations pertinent to the current state of the art. Comments will address the paving aspects of RCC.

It is agreed that RCC as a paving medium has a use in secondary roads, storage and loading areas, and as a base for other pavements. The shortcomings involve obtaining a smooth wearing surface to give satisfactory ridability so that it can be used on primary roads, possible deterioration of the surface due to freeze/thaw cycles, and ability to achieve compaction throughout the lift without segregation. It should be noted that most people involved in RCC construction believe it is a method that has specific applications and is not a "cure all" for all types of mass concrete or paving applications. The economy of placement and speed of construction far outweigh the negative aspects of RCC construction. Water-cement ratios were variable from application to application throughout the literature review. This variance was attributed to the characteristics of the aggregate used in the mix. Processed crushed limestone aggregate mixes had lower water-cement ratios than natural or pit-run aggregates. Apparently the higher content of material finer than the No. 200 sieve contributed to a demand for more water in the pit-run aggregates.

CHAPTER III

DESIGN AND CONSTRUCTION PROCEDURES

Introduction

During the period of July 9-24, 1983, approximately 20,000 square yards of RCC were placed at Fort Hood, Texas, which is located about halfway between Dallas and San Antonio, just west of Temple. The project was a parking area for a tactical equipment maintenance facility measuring 550 feet by 328 feet. As a part of the contract, the contractor was required to construct a test section to demonstrate the capability of achieving the desired results. The test section was also utilized to verify the laboratory mix design and design strength parameters which would be used to control actual field placement.

Construction of the test section was on June 4, 8, and 11, 1983. The test section, as required by the contract, was two lanes 50 feet in length by 12 feet wide, abutted against one another. Actually, three test sections were constructed and this will be discussed later. A 30-day waiting period was specified prior to beginning the hardstand (parking area) construction to evaluate the 28-day strengths of the concrete and make final adjustments, if needed, to the mix design and placing procedures.

A chronological approach was taken to present the methods used in selecting design parameters, mix design, and construction techniques.

Mix Design

Preliminary mix design studies were conducted at the Waterways Experiment Station (WES) using stock aggregates and cementitious materials. Three trial batches were made to determine the two-component coarse aggregate proportioning. The first trial consisted of 40 percent No. 4 to 3/4-inch sieve (finer) and 60 percent 3/4-inch to 1½-inch sieve (coarser) aggregates. Segregation of the two-part coarse aggregate occurred in the resulting mixture. A 50/50 ratio of the finer to coarser aggregate was used for the second trial with the same result. The third trial of 60 percent finer and 40 percent coarser aggregate contained minimal segregation and was selected for further water-cement ratio studies. The fine aggregate was a sand.

At the U.S. Army Southwestern Division Laboratory (SWDL) in Dallas, Texas, 20 mixtures were made: 16 used aggregates, cement, and fly ash from the project; and 4 used base course materials. The contractor had made a value engineering proposal to use base course material in lieu of limestone aggregate as a cost saving measure. A summary of the mix proportioning is contained in Table I (all tables are presented in Appendix B). A mix design with a water-cementitious materials ratio of 0.35 and a theoretical density of 158 lbs/cf was selected. Approximately 33 percent of the Type I cement was replaced with a Class C fly ash. Table II contains the details of this mix and the field adjustments made during construction. The selection of the mix design was based on the flexural strength and apparent workability of the mix. The base course material mixtures were rejected because of low strengths.

Materials

The cement for the RCC was portland Type I furnished by the Capitol Cement Company of San Antonio, Texas. The cement had a Wagner fineness of 1900; 3- and 7-day compressive strengths of 3615 and 4945 psi, respectively; and a bulk specific gravity of 3.15. As previously mentioned, the fly ash was Type C with a bulk specific gravity of 2.49, and the source was the Alcoa Aluminum Plant, located at Rockdale, Texas.

The two-component coarse aggregate was a high quality crushed limestone used for conventional ready mix. The bulk specific gravity of the finer portion was 2.78 and the coarser portion was 2.77. The fine aggregate was a natural sand with a bulk specific gravity of 2.62. The gradations of the aggregates are contained in Tables III through V.

Laboratory Strength Testing

Test specimens consisting of nine cylinders and six beams were prepared from each of the mixtures to verify strengths. Standard size cylinder and beam molds were used in making the specimens using external vibration according to the method contained in ASTM C 192-81 (10). It was attempted to proportion each mixture so as to require a vibration duration between 15 and 30 seconds. Compressive and flexural strength testing was conducted on the specimens from the mixtures with and without fly ash after aging 7 and 28 days. Results of the strength tests are contained in Table VI. The selected mixture had an average compressive and flexural strength of 6605 and 914 psi, respectively, after 28 days.

Pavement Design

The original pavement design for the hardstand was based on concrete with a flexural strength of 650 psi and a modulus of subgrade reaction of 150 pounds per cubic inch (pci). The design loading was for 60 Kip tracked vehicles, primarily tanks, and two to five axle trucks. Using Corps of Engineers design procedures, a design index of 6 was obtained, resulting in a 9-inch thickness of RCC on 6 inches of lime treated subgrade.

Prior to initiation of construction of the test section, but after award of the contract, the using agency increased the loading requirements of the pavement to include 120 Kip loadings as normal traffic. This requirement was based on the decision that the facility may be used for the larger M-1 tank. The pavement was redesigned with the new criteria and the design index was 9, resulting in a pavement thickness of 11 inches, on a 6-inch lime stabilized subgrade.

After construction of the test section, the strengths or cores and beams taken from the section far exceeded the laboratory design strengths of the vibrated specimens (see Table VI). A decision was made to reduce the pavement thickness accordingly, by backing into the design curves with the actual strengths obtained in the field. With the new required loadings and all other parameters constant, the resulting thickness was 10 inches of RCC on the 6-inch lime stabilized subgrade, with a flexural strength of 800 psi.

Plant Operation

The plant the contractor used to mix the RCC was a continuous feed pug mill with a maximum production rate of 650 tons per hour. The plant was calibrated for a 250 tons per hour production rate. A conveyor belt starting with the fine aggregate bin, followed by two coarse aggregate bins, then a 70 ton capacity fly ash silo, and the 90 ton capacity cement silo, fed the 8 foot long mixing chamber of the pug mill. The water was added to the mix at the pug mill. The mixture was then discharged on a second conveyor which lifted the mixture and discharged it into 12 cubic yard end-dump trucks.

The plant was completely self-contained and portable. Erection and calibration was performed from May 11 to June 1, 1984; power was supplied by a portable diesel generator. Figure 1 contains photographs of the three aggregate bins, two silos, and the pug mill (all figures are presented in Appendix A).

Construction of Test Section

The first test section, consisting of two 70-foot adjacent lanes, was constructed on June 4, 1984. A foundation was prepared similar to what would be used on the actual hardstand. The plant mix was trucked the short distance to the foundation and dumped into the laydown machine hopper (see Figure 2). An attempt to place a single 13- to 14-inch loose lift of RCC with a Blaw-Knox model PF 220 asphalt laydown machine met with little success. The lift thickness was too great for the machine to place without tearing the surface of the mix, as is shown in Figure 3. The surface defects were hand-filled with a shovel prior to the rolling operation. The contractor elected to construct the second lane in two lifts (also shown in Figure 3), first by dumping the mix directly on the foundation, then by spreading with a motor patrol to about 8 to 10 inches in thickness. This lift was compacted by initial rolling only, then the laydown machine was used to bring the mix to grade, followed by initial and final rolling of the combined lifts.

Compaction was accomplished by rolling with a self-propelled tandem 10 ton, Tampo, smooth steel wheel vibratory roller (see Figure 4). An attempt to seal the surface with a 10 ton static pneumatic tired roller resulted in rutting of the surface. The steel wheeled roller was able to remove most of the ruts but not satisfactorily. During placement of the second lane, a thunderstorm with intense rainfall and lightning stopped all operations. No density-moisture measurements were taken as a result of the storm.

On June 8, 1984, the contractor began construction of a second test section, a single lane 12 feet wide and 100 feet long. During the interim between test sections, the contractor modified the augers on the laydown machine on the assumption the augers would distribute the RCC better and prevent the tearing that occurred the first time. Placement of the second test section consisted of a single loose lift between 11 and 12 inches thick with the laydown machine and compaction with the vibratory roller. Half of the section, longitudinally, was moist cured and the remaining half was cured with curing compound applied directly to the surface. Rolling patterns were experimented with and moisture-density measurements were made with a Troxler Road Reader nuclear gage, Model No. 3411-B, with a 12-inch probe.

A third short test section was placed abutting the second section to evaluate bonding of longitudinal cold joints on June 11, 1984. Three different joints were evaluated: a vertical face, a 45-degree angle face, and the natural face as left by the laydown machine.

Record specimen cylinders and beams, made from the mix taken from each test section, were compacted on a small portable vibrating table in the field. In situ beams were sawed, and 4- and 6-inch diameter cores were cut from the cured test section for strength testing. Molding of a beam and a view of a core hole can be seen in Figure 5 and the layout of the test section is shown in Figure 6.

Construction of Hardstand

Construction of the hardstand began on July 9, 1984; 12-, 14-, and 16-foot wide lanes were paved during the succeeding days of the operation. A layout of the paving sequence is shown in Figure 7. The lime-stabilized subgrade was prewetted and placement began. The foundation before placement operations and the mating of the laydown machine against the conventionally placed concrete section is shown in Figure 8. The laydown machine traveled only a short distance before problems developed with the augers. After a considerable delay to repair the augers, paving was resumed. Three complete lanes measuring 405 feet by 42 feet, 12 inches loose lift thickness compacted to 10 inches, were placed the first day. Initial placement and compaction of the first lane is shown in Figure 9. Some problems arose with compaction along the unconfined outer edge of the first lane, where the surface tended to undulate or wave. Other problems occurred with breakdowns of the plant, conveyor belt breakage and slippage, and breakdown of the laydown machine. The entire area was completed in 12 working days, including breakdowns and about a half day for a planned recalibration of the plant at the halfway point of the placement. Photographs of taking moisture-density measurements and verifying thickness are shown in Figure 10. Compaction was achieved by two to three complete passes of the roller in the vibratory mode. Rolling was done until the density was verified with the nuclear gage. Hand compaction was required adjacent to the conventional concrete in the area of the protection bullards, which are protective barriers in the area of the maintenance platform supports. The 10-ton roller was not able to maneuver in this area. This is shown in Figure 11. A mix using the finer of the coarse aggregates as a maximum size was tried in an attempt to obtain a smoother surface. The mix proportions of the materials for this work is shown in Table VII and the areas of placement are presented in Figure 7. Curing was specified to be a 24-hour moist cure with mats, followed by an application of curing compound. About the first ten lanes were cured in this manner before it was decided to apply the curing compound directly to the finished surface without moist curing. Figures 11 and 12 show the placement and moist curing operation as originally specified. The bottom photograph of Figure 12 shows the sawing of a joint; the material behind the saw was wasted and lanes were paved in the other direction at this juncture. Initially, transverse and longitudinal joints were to be sawed on 50-foot intervals; however, saw cutting tended to ravel the concrete surface and natural transverse cracks developed on about 70-foot intervals within 48 hours of placement.

CHAPTER IV

BREAK EVEN ANALYSIS

Introduction

The primary basis for using RCC as a paving material is economics. In comparison with conventional concrete, sacrifices have to be made with respect to surface smoothness and horizontal tolerances. When economics may dictate a project's justification on a benefit-to-cost basis, RCC should be considered. The savings may possibly justify the total project if the previously mentioned detriments are not objectional. In other cases, savings in paving costs could be spent on other project features or accrued to the owner. To assist in making a decision to use RCC for paving purposes, a break even analysis was performed to determine the quantity of RCC required for an application to be under consideration economically.

Method Used

The present hardstand project at Fort Hood consisted of not only RCC pavement but a considerable quantity of conventional PCC paving with the same design parameters, loading, and obvious use. Rather than use a hypothetical situation for a break even analysis, it was decided to use this actual situation where quantities, estimated costs, actual bid prices, and modifications to the contract affecting paving costs were known. To further verify the results, a check was made using the Means Building Construction Cost Data book, with some assumptions since RCC paving is not included.

Analysis

The total area of the RCC paving was about 20,044 square yards (sy), or expressed as volume, approximately 5,568 cubic yards (cy), excluding test sections. The volume of conventional PCC paving, excluding structural concrete, was 2200 cy. Customary Corps of Engineers bidding procedures contain a separate bid item for cement, per hundred weight (cwt), which was the case for this project. The bid price for cement was $3.00/cwt. As mentioned previously, modifications to the contract were considered. In the case of the fly ash, which normally is less expensive than portland cement, the negotiated price by modification was $2.90/cwt. The bid price of the RCC was a lump sum item, bid at $175,000 or when converted to a cubic yard price was $31.42/cy. The bid price of the conventional PCC paving was also a lump sum, bid at $120,000 which converts to $54.54/cy. Using the above quantities and associated cement factors, the cost of cement for PCC and cost of cement and fly ash for RCC would be $16.92 and $13.35, per cy respectively, with a total cost of $71.46 for the PCC and $44.77 for the RCC, per cy.

The total costs associated with mobilization, setup and breakdown, leasing, and operating and maintaining the RCC plant are unknown. On this particular project, a conventional ready-mix plant owned by the contractor was on site and in operation for another construction contract.

Equating the cost of the PCC/cy for "X" cy to the cost of the RCC/cy for "C" cy, plus the cost associated with mobilization and demobilization of the plant ($25,000), the break even point on using RCC can be determined. The operating costs associated with the plant can also be disregarded, since these costs are included in the production costs of the RCC/cy.

The computations indicate that 937 cubic yards of RCC would be required to justify using this method of construction. As a rule of thumb on large volume projects, one could assume a savings between the range of 30 to 40 percent over PCC, based on unit prices from this project. By selecting a percentage within this range, subtnacting from 100, multiplying times the ready-mix costs, and adding the estimated plant costs, one would be able to estimate the cost of the RCC. A selection within the range would depend on the degree of risk in estimating that one was willing to take.

CHAPTER V

RESULTS AND DISCUSSION

Results

This chapter presents the results of the work involved in this project. Each applicable area of the research is presented with accompanying tables of collected data which summarize the results of the testing performed. A discussion follows the same pattern of the results.

Laboratory Data and Test Section

The results of the compression and flexural testing of all the molded specimens for the selected laboratory mixtures and molded specimens from the test section are contained in Table VII. All results from the test sections, with the exception of the beam specimens from the June 4, la location, are lower in value than the laboratory specimens.

Testing of the in situ 4- and 6-inch diameter cores and sawcut beams compared more favorably to the laboratory results, as shown in Table IX. A misunderstanding occurred when the cores and beams were taken by a separate contractor, resulting in some 7- and 11-day specimens. Only the 28-day results were considered for this analysis. Locations where the specimens were taken on the test section are shown in Figure 13.

Testing was performed using the Troxler Road Reader to determine the density and moisture characteristics of the compacted mix, for control during construction of the RCC hardstand. The results of this endeavor are presented in Table X. A standard was established from the laboratory mix of 96 percent of the maximum theoretical density of 158.4 pounds per cubic foot (lbs/cf), assuming no air, or about 152.0 lbs/cf. Three complete passes on high vibration were necessary to achieve the required density with a corresponding moisture content of about 3.7 percent. The results of the rolling pattern determination are presented in Table XI. No attempt was made to change either the amplitude or frequency of the vibratory compactor after one trial in the low vibrate mode.

Hardstand

A minimum of one density-moisture reading was taken on each lane of the hardstand during construction. The first lane placed received a considerable amount of attention. Here, four sets of data, including retesting of deficient areas, were conducted to verify the control parameters established from the results of the test section construction. The results of the testing varied from a low moisture content of 2.9 percent and corresponding wet density of 153.1 lbs/cf to a high moisture content of 5.2 percent, with two corresponding wet densities of 144.1 and 152.5 lbs/cf. The original thought was that three complete passes of the roller were required to achieve the target density, at 3.7 percent moisture content. The maximum wet density was 158.9 lbs/cf with a corresponding moisture content of 3.5 percent and the minimum wet density, excluding those prior to rechecks or rerolling, was 144.0 lbs/cf with a corresponding moisture content of 3.8 percent. A complete listing of test results is contained in Table XII.

Application of the curing compound directly to the compacted surface versus moist cure with blankets appeared to be satisfactory in some areas and not in others. Moist curing with blankets did not particularly prove to be satisfactory either.

Joint treatment was a problem. The bonding of the joints at the end of a day's construction, both transverse and longitudinal joints between lanes, did prove to be sufficient. No apparent problems existed in these areas. However, maintaining tolerances between lanes was in some cases very poor. A ridge developed along some joints which tended to spall with time and in some locations the spalling developed without the ridge. Junctures with the previously placed PCC were in all cases satisfactory. A felt bond breaker was used at all of these junctures to separate the two concretes. Even the areas on which the hand compactor had to be used because of lack of work space for the larger vibratory roller appeared good. Figure 14 shows a spalled area at a longitudinal joint and a juncture of the PCC and RCC in the area of a drive entrance.

Break Even Analysis

The break even analysis calculations indicated that a relatively small quantity of RCC can be economically placed on a construction project. According to the analysis, as little as 936 cy of RCC would justify setting up a plant to produce the mixture.

Discussion

Laboratory Data and Test Section

In molding specimens for strength testing in the field, a small portable vibrating table was used on the ground surface. Consequently, the majority of the vibrations generated by the table were absorbed into the ground rather than the specimen. A smaller surcharge weight was used in the field than in the laboratory. These factors primarily account for the strength reduction in the field specimens with respect to the laboratory molded specimens. In the laboratory, much more stringent control can be exerted in proper proportioning of the various materials in the mix than at a plant mixing large volumes.

This theory was apparent with the cored and sawed specimens, since both compressive and flexural strength test results approached laboratory values. Visual inspection of cores and beams before trimming for testing indicated that compaction was achieved throughout the mix. It was apparent that the top or bottom was indistinguishable in the cores, with the exception of the finish where the curing compound had been applied. This was a concern expressed by Burns and Saucier (4) in their work.

Hardstand

The theory that three complete passes of the roller would be required to achieve the target density, at 3.7 percent moisture content, proved to be in error. It became apparent during construction of the hardstand that variations in the moisture content, caused by plant operations, delays in placement of loaded trucks, and ambient temperature, were also a factor. In most instances, only two complete passes of the roller in the high vibration mode, were sufficient to make the required density. Additional passes were required in some areas. Records were not specifically maintained of the ambient temperature, but temperatures during placement operations exceeded 100 degrees Fahrenheit nearly every day. Moisture contents in the range of 3.7 to 4.1 percent appeared to yield good densities during the cooler portions of the day. That range increased to about 3.8 to 4.4 percent during the heat of the afternoon.

Naturally, some moisture-density relationships were affected by the length of time between placement and initial rolling. The roller operator was reluctant to begin the rolling of the mix for fear the roller would "wave" the surface or even worse would sink somewhat. As the placement operation progressed, this initial concern on the operator's part slightly dissipated. As with any new type of operation, most phases of the work improved with time.

The areas where the 3/4-inch maximum aggregate size was used appeared to have a better surface. The surface had a tighter, smoother texture and a general overall better look. It should be noted that the curing compound was applied directly to the surface in this area. It is apparent that the less porous the surface is, the better it accepts the curing compound, which in turn aids in providing a better finish. Figure 15 contains photographs of the completed hardstand. Photograph (a) is a view to the south from the entrance drive that is PCC and shows the east-west constructed lanes in the middle of the photograph and the north-south constructed lanes at the top. Photograph (b) is an example of the 3/4-inch maximum size mix on the right and the 1½-inch maximum size mix on the left.

Attempts to saw joints failed; the surface of the RCC pavement raveled and tore, leaving the joint with a ragged appearance. Several factors contributed to the problem. Saw cutting was started before the proper time, the large aggregate size was partially to blame, and the method of curing was a factor. It is the author's opinion that if any one factor was prominent, it was the timing of the sawing. Hall and Houghton (3) had reported high core loss when taking in situ specimens on the Lost Creek test section. It is apparent that the low cement content of RCC mixes, 10.5 percent by weight in this project, require some additional set time before sawing-coring operations can begin with respect to conventional concrete. If this assumption is true, then the maximum aggregate size is also a contributing factor. Curing is discarded as being a factor in the sawing of joints, as no evidence tends to support the theory. Joints were successfully sawed in the test sections, but at a much later date. By the time the RCC has reached a set to support sawing, natural cracking will have already occurred. Figure 16 indicates a sawed and sealed joint and a natural transverse crack that has been highlighted with a felt tip marker for clarity.

Break Even Analysis

The break even analysis is considered valid for the following reasons. The bid prices were reasonable, i.e., below the government estimate, which indicates prices were not unbalanced and within an acceptable range of most of the other ten project bidders. Cement and aggregate materials were from the same source for both mixtures.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Mix Designs

The procedures for determining proportioning of materials for RCC mix designs are relatively easily performed and are contained in ACI 207.5R-80 (11). The reliability of the consistency type determinations are good but individually interpretative. Not every laboratory has experienced personnel who are skilled in these procedures, as is the case at WES. However, with some training the necessary skills can be obtained.

Pavement Design

Greater implications for changes are in the area of pavement design. The consideration of achieving high flexural strengths in RCC rigid pavements leads to a reduced design thickness of the pavement section. Another consideration of importance is the possibility of using base course aggregates or standard state highway gradations for base materials as an aggregate for RCC. It may be cost effective to increase the thickness of the pavement section and reduce the flexural strength requirements for this type of aggregate rather than use more costly processed materials. Being a first time project, good selective crushed limestone concrete aggregate was used for the RCC construction at Fort Hood. An analysis of existing Corps of Engineers design curves for rigid pavement needs to be considered. The much higher flexural strengths are at the limit of the curves if higher strengths are to be specified.

Plant Operation

The plant was able to produce a relatively consistent mix over the placement duration. Minor adjustments in the amount of moisture were constantly made along with the calibration check at the midpoint of placement. With the exception of minor breakdowns, which can and do occur on any type of machinery, the plant operation was good. The only addition to the plant that was recommended but not adopted was a discharge hopper at the end of the conveyor to prevent segregation of the mix when dropped to dump trucks.

Placement

The placement operation had much room for improvement. The Blaw-Knox laydown machine was leased equipment and not in the best condition. The contractor had newer equipment in inventory but was hesitant to utilize good equipment for fear the concrete would be detrimental to the equipment that is normally used to place asphalt. The RCC proved to be much less of a detriment than asphalt when cleaned after use with a medium pressure water hose. The plant production rate was much higher than the laydown machine placement rate. This resulted in numerous shutdowns for short periods of time. The contractor expressed the opinion that more than one laydown machine could have been used on a project of this volume. The use of multiple laydown machines would also have eliminated some of the cold joints.

The roller evaluation on the test section was as comprehensive as possible at the time. More experimentation with changes in amplitude and frequency of the vibrations may have been prudent. Also, sealing of the surface with the pneumatic roller was not examined to the fullest. Time was a factor as well as the terms of the contract to do the work, which prevented a pure research effort. Another limitation was the physical size of the test section. The machinery was limited to a very short operation which did not benefit the government or contractor. The additional test sections were built at the contractor's expense. A test section no less than 100 feet in length and consisting of three lanes should be considered in future designs. No RCC paving placement should be specified without a test section.

The field control established by a test section is a valid method to construct RCC. The problems associated with molding field specimens can be overcome by utilizing the same type and model of equipment, etc. used in the laboratory. This is especially true in the case of the vibrating table to achieve similar results in the field that were obtained in the laboratory. Use of the nuclear device to determine moisture-density relationships works well. Some error is introduced when using an instrument that is designed for earthfill in fresh concrete. The benefits far outweigh the disadvantages with the speed measurements can be made in a rapid placement operation.

Surface texture can be improved by using a smaller maximum size aggregate. The addition of more fines to the mix, as opposed to the gradation of the 1½-inch maximum size aggregate, apparently contributes to this characteristic that was exhibited in lanes constructed with the finer mix.

Joints

Extreme care must be taken not to spill uncompacted material on previously compacted material at cold or live joints to prevent later spalling at the joint. Joint construction is an area that was not completely resolved, both from the viewpoint of meeting tolerances between lanes and prevention of spalling. Bonding and the structural integrity of the joints appeared to be satisfactory.

Saw cutting of joints appears to be out of the question. The natural joints, although somewhat irregular, have no apparent effect on the structure and have functioned with no signs of distress. The cracks do extend through the complete thickness of the section, vertically, on 65- to 70-foot centers.

Curing

The effectiveness of the moist curing was not satisfactorily determined. Most contractors dislike blanket curing and this was not an exception on this project. After placing the blankets, a laborer was tasked to keep the blankets wet using a garden hose connected to about a 500-gallon water truck. With the temperature in the 100 degree range and usually a breeze, the blankets would be virtually dry about 20 feet either side of the watering operation. In some locations the blankets did appear to disturb the surface. This could be attributed to the roller traveling on the blankets when rolling an adjacent lane.

As previously mentioned, direct application of the curing compound appeared to provide a good cure in the areas with the smaller maximum size aggregate. In areas where the surface was more porous, the direct application was not satisfactory. Some slight spalling or powdering occurred in these locations after a period of weeks. Some of the deficiencies in the curing could be attributed to spotty application of the curing compound also.

Recommendations

This research has produced three categories of items for further consideration in the construction of RCC pavements. The categories are in the area of equipment, materials, and practices.

Equipment

1. The use of a heavy duty laydown machine with a tamping screed to achieve initial compaction and enable a thicker lift to be placed needs to be evaluated.

2. Research in the area of varying amplitude and frequency of vibrating rollers is needed. This item is limited due to individual characteristics of an RCC mix.

3. Standards need to be established to calibrate nuclear moisture-density gages for applications in fresh concrete.

Materials

1. Research is needed in the area of pit run or standard state specification base materials for aggregates in RCC mix designs.

2. Curing procedures need to be analyzed and a further study of the fog cure and bituminous membrane curing done by the Canadians needs consideration.

3. Maximum size aggregate determinations for desired surface characteristics need additional research. Again, this will be related to specific mix designs but should be valuable information to assist future designs.

Practices

1. Unconfined edges should be avoided. It is recommended that a strip of conventional concrete, concrete curb flush with the RCC surface, asphalt, or bridge timbers be placed either permanently or temporarily around the area where the RCC is to be placed.

2. Always require a test section to be constructed, using the same equipment, labor, materials, and procedures that are to be used on the actual paving section. Make the size of the test section large enough for the contractor to adequately demonstrate the necessary skills required to accomplish the construction.

3. A determination needs to be made if sawed joints are really need in RCC paving construction. If so, studies need to be implemented to determine when sawing should commence to prevent natural cracking.

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(3) Hall, Donald J., and Donald L. Houghton. Roller Compacted Concrete Studies at Lost Creek Dam. Portland, OR, June, 1974.

(4) Burns, Cecil D., and Kenneth L. Saucier. "Vibratory Compaction Study of Zero-Slump Concrete." American Concrete Institute Journal, Title No. 75-12 (March, 1978), pp. 86-90.

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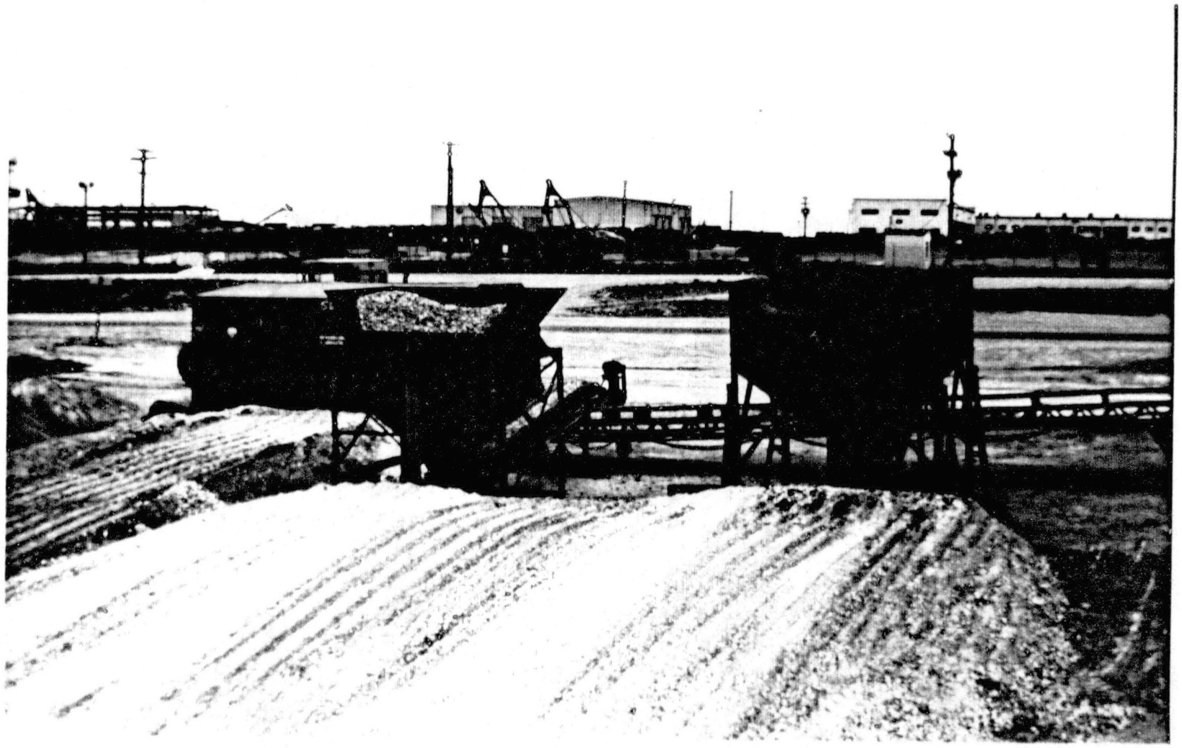
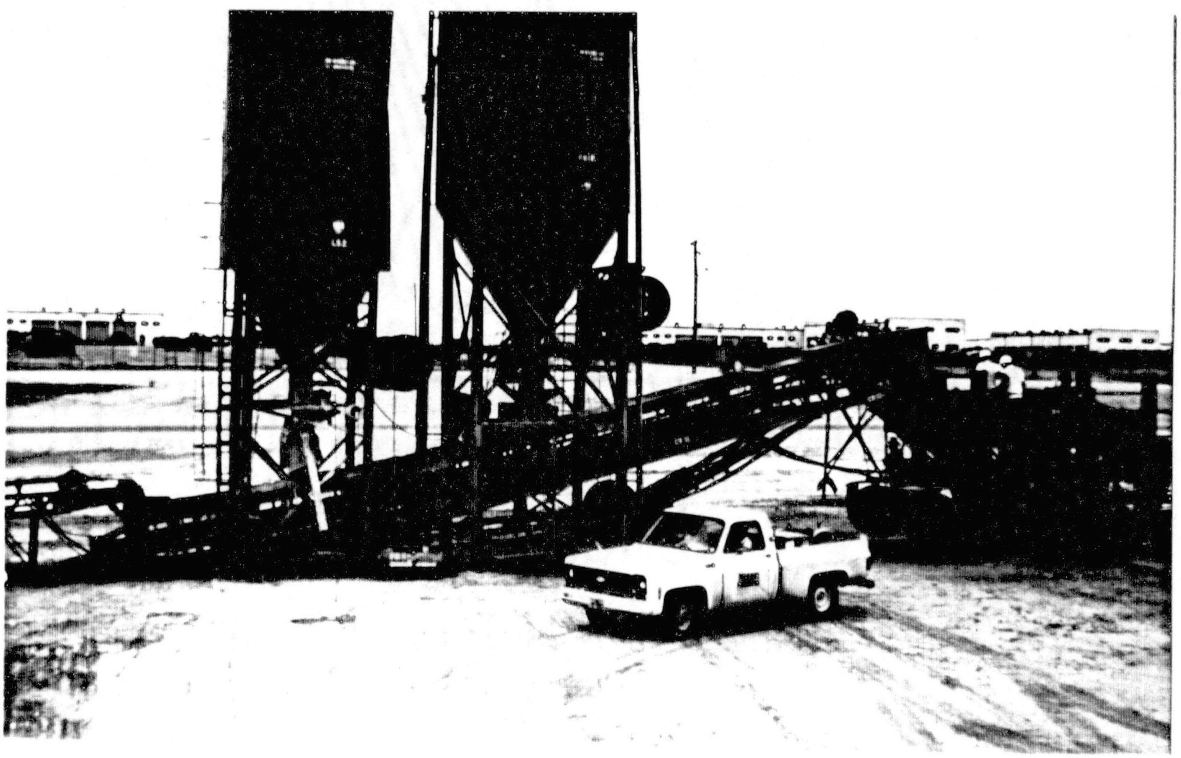
(11) Roller Compacted Concrete. Committee Report No. 207.5R-80. Detroit: American Concrete Institute, 1980.

APPENDIX A

FIGURES CONTAINING PHOTOGRAPHS AND DRAWINGS OF ACTIVITIES



(a) Aggregate Bins



(b) Silos and Pugmill

Figure 1. Photographs of Aggregate Bins, Silos, and Pugmill

(a) Prepared Foundation for Test Section

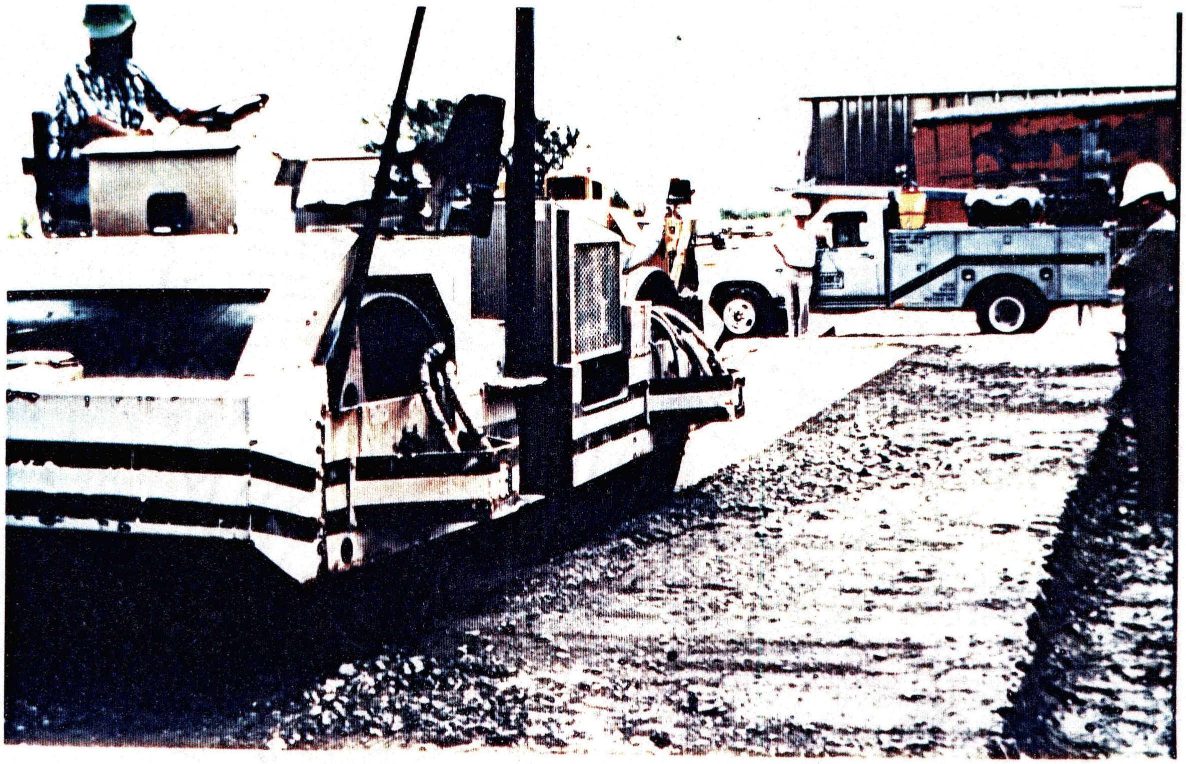
(b) Dumping of First Load of RCC

Figure 2. Photographs of Foundation and First Load of RCC

(a) Surface Tears Caused by Augers

(b) Second Lane, Two-Lift Construction

Figure 3. Tears in Surface and Two-Lift Construction

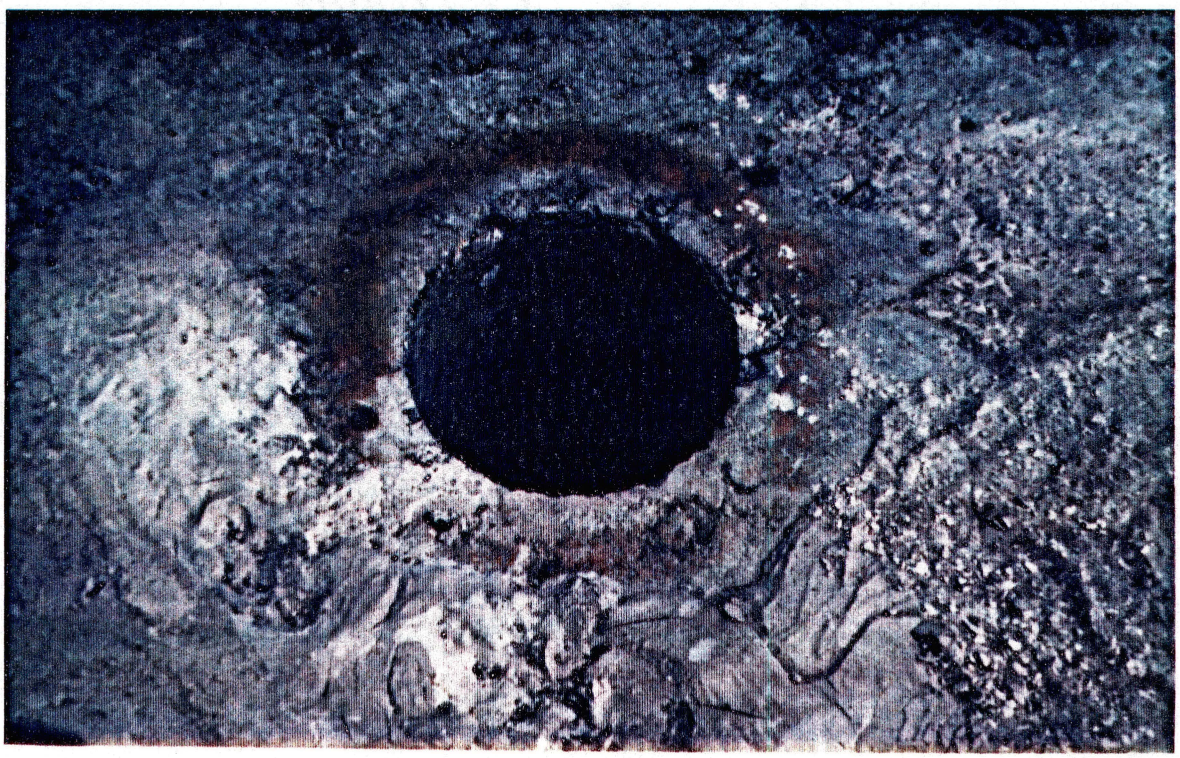


(a) Initial Rolling of First Lane of Test Section

(b) Results of First Pass of Roller

Figure 4. Initial Rolling of Test Section

(a) Field Molding of Beam on Portable Vibrating Table



(b) Surface Where 6-Inch Core Was Extracted

Figure 5. Beam Molding and 6-Inch Core Hole

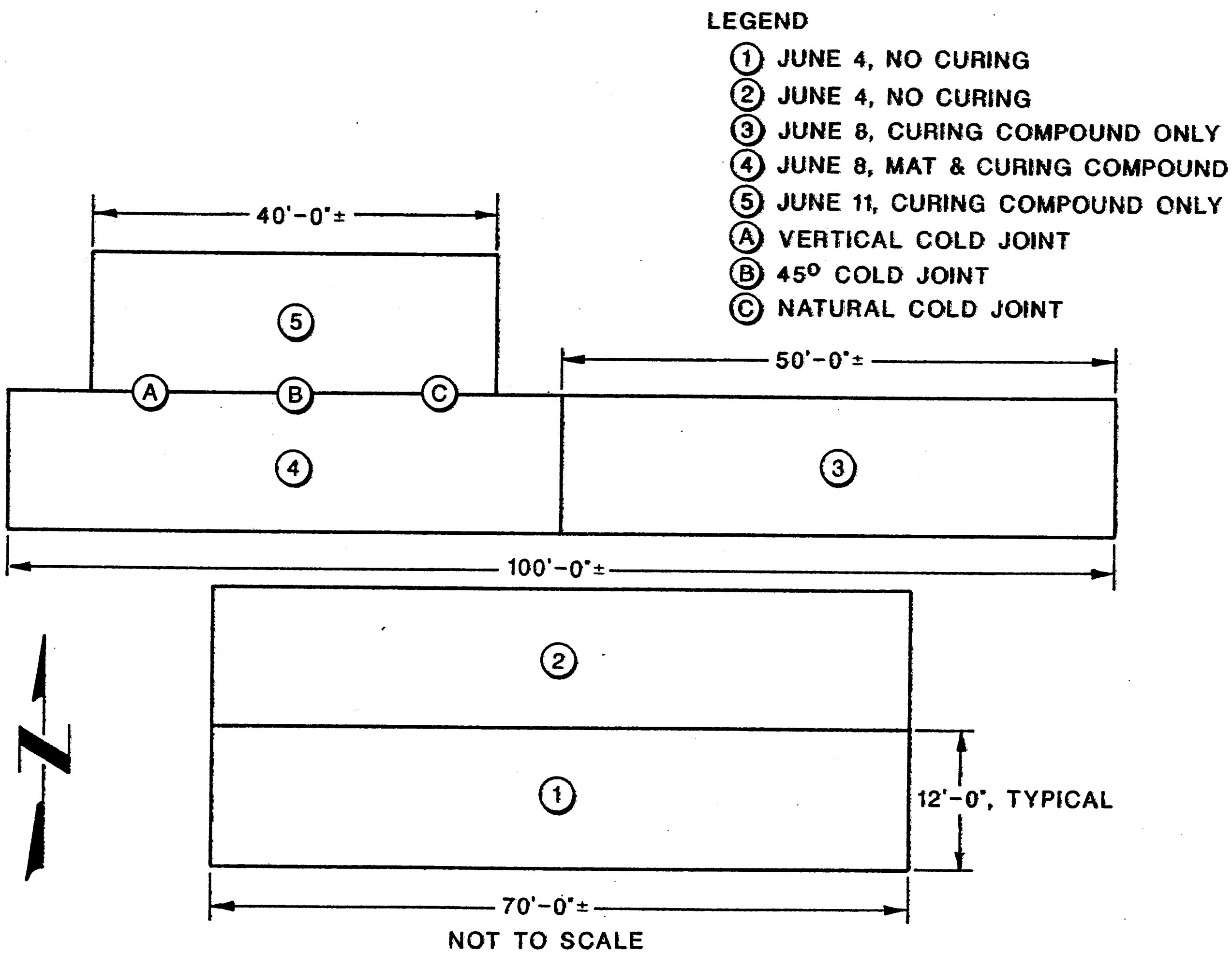


Figure 6. Layout of Test Section

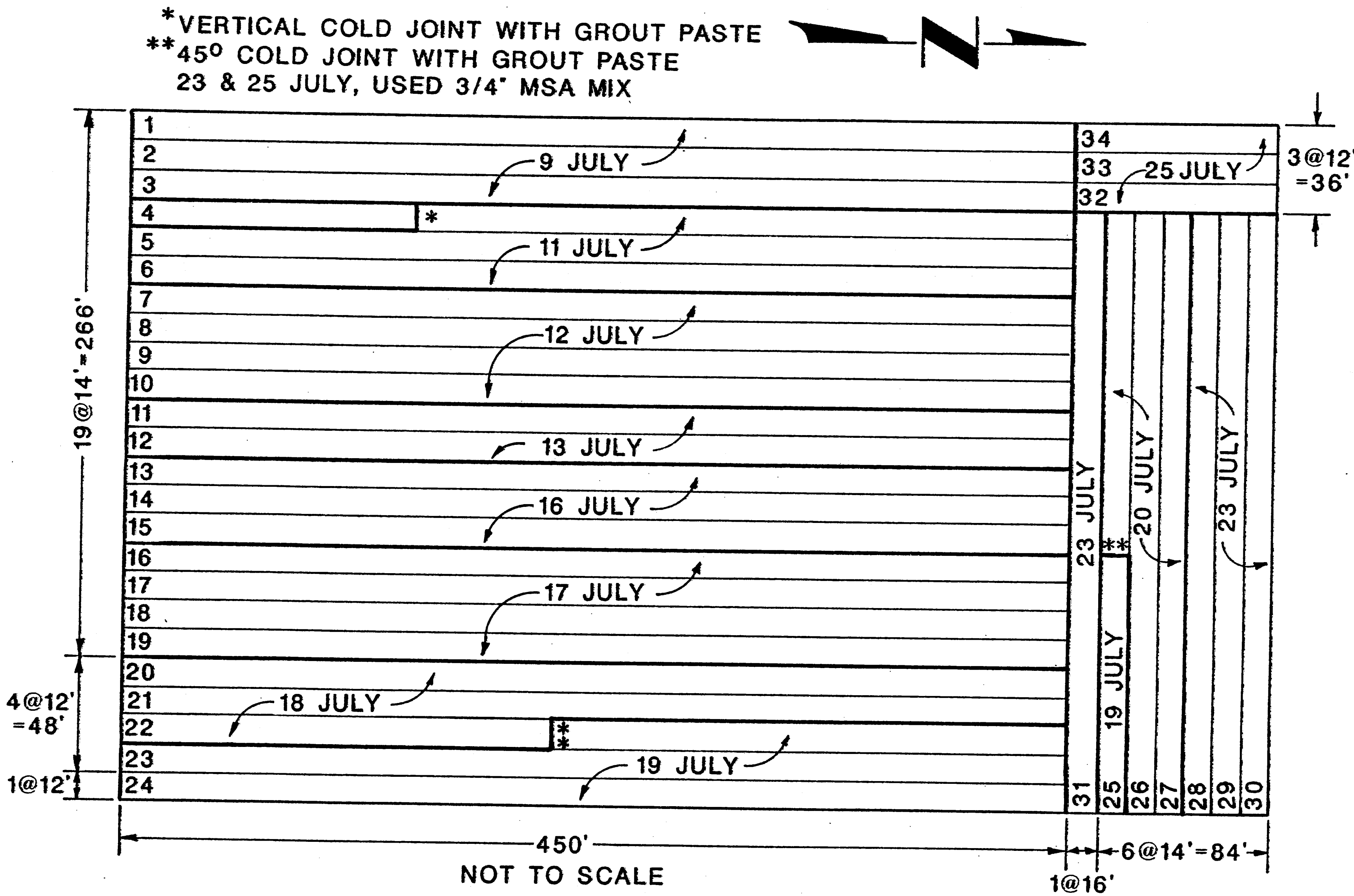
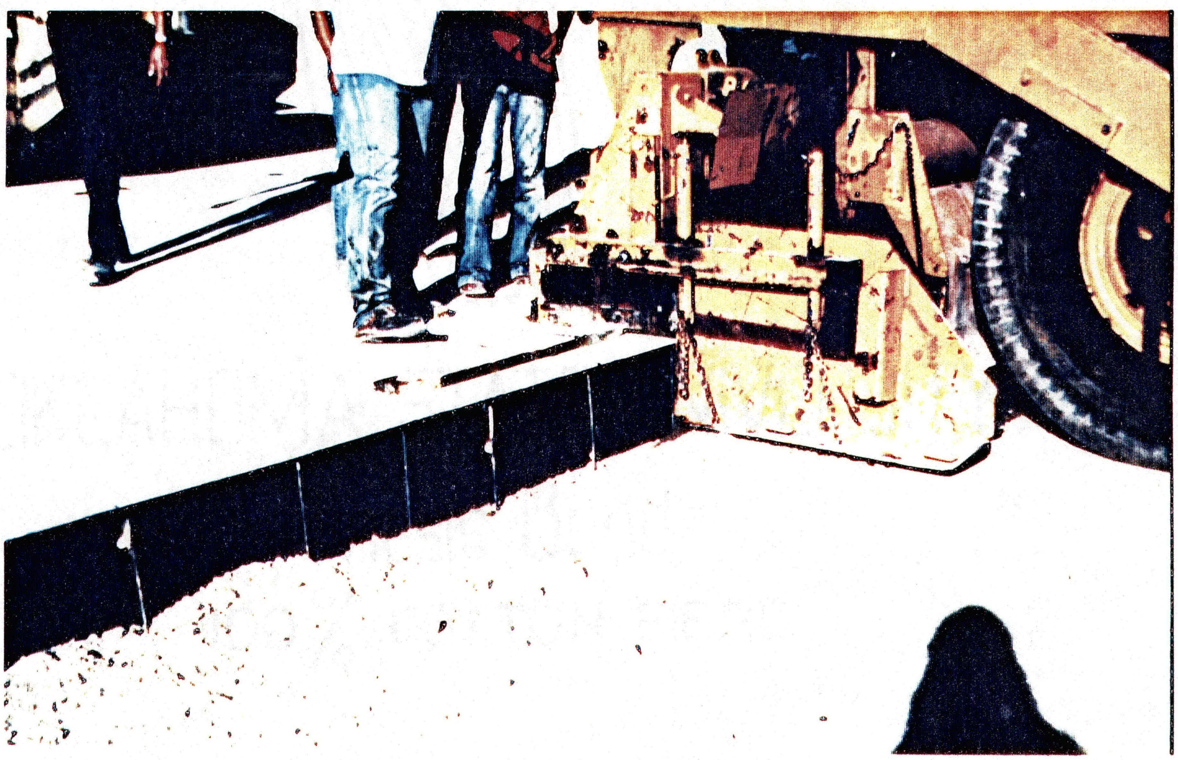


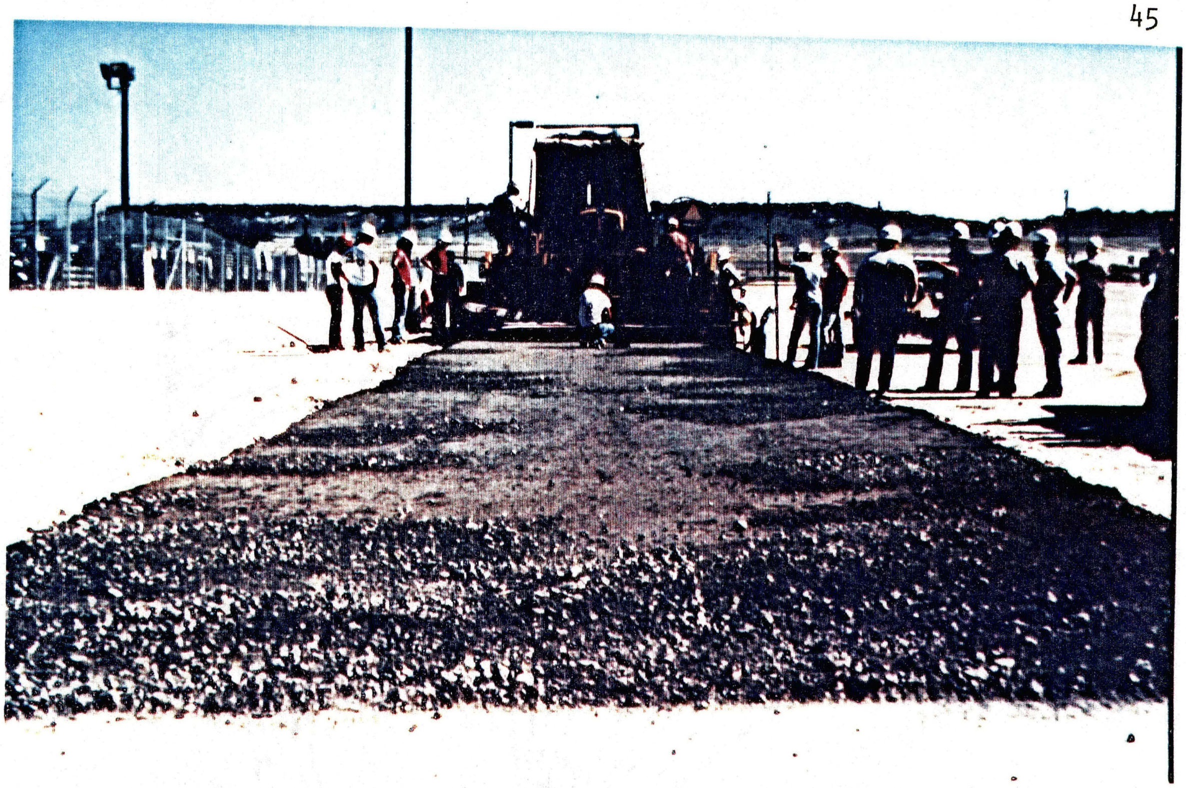
Figure 7. Layout of Paving Operation

(a) Prepared Foundation Before Placement Began

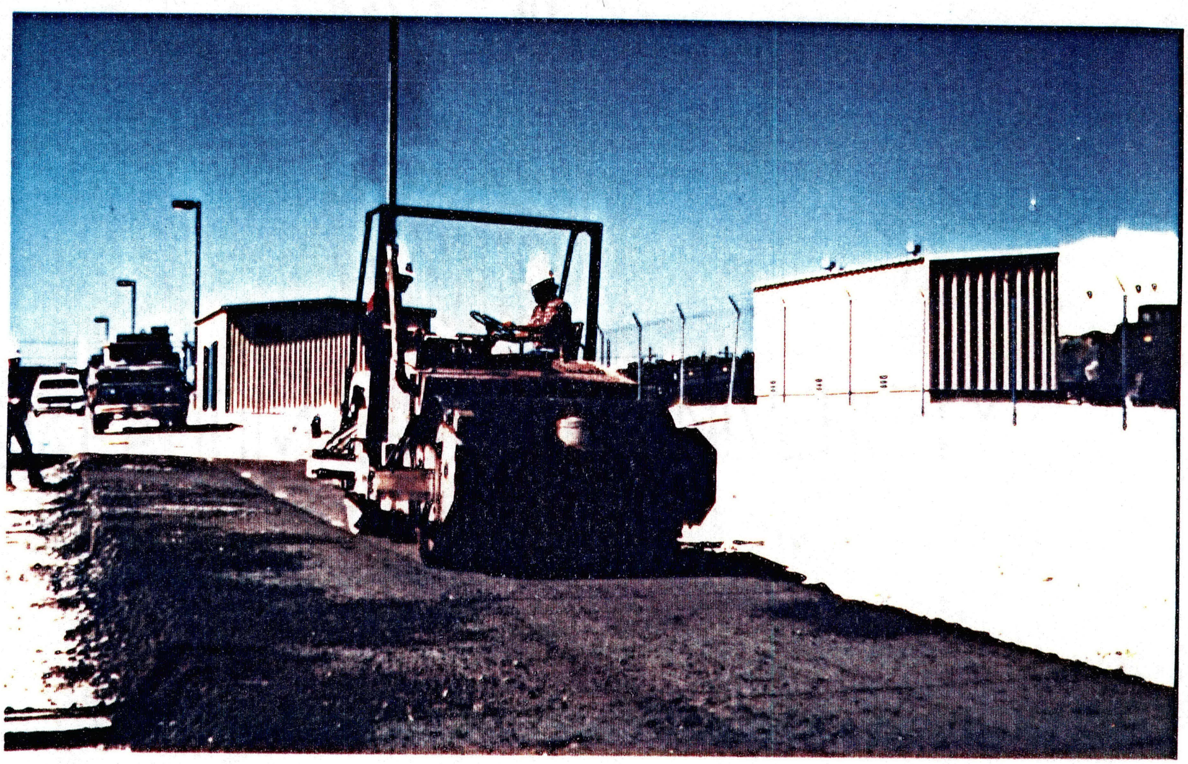


(b) Adjusting of Height for Uncompacted Mix

Figure 8. Prepared Foundation and Initial Setting of Laydown Machine



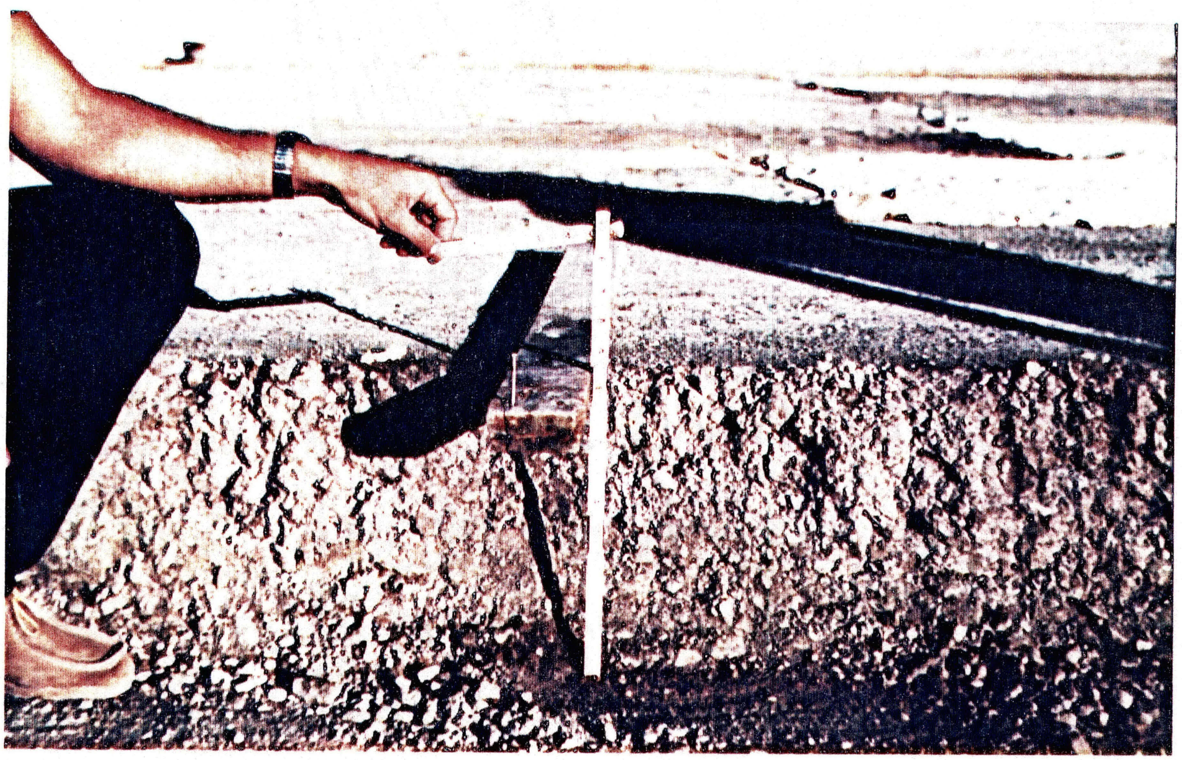
(a) Placement of First Lane of Hardstand



(b) Compaction of First Lane of Hardstand

Figure 9. Initial Placement and Compaction of Hardstand

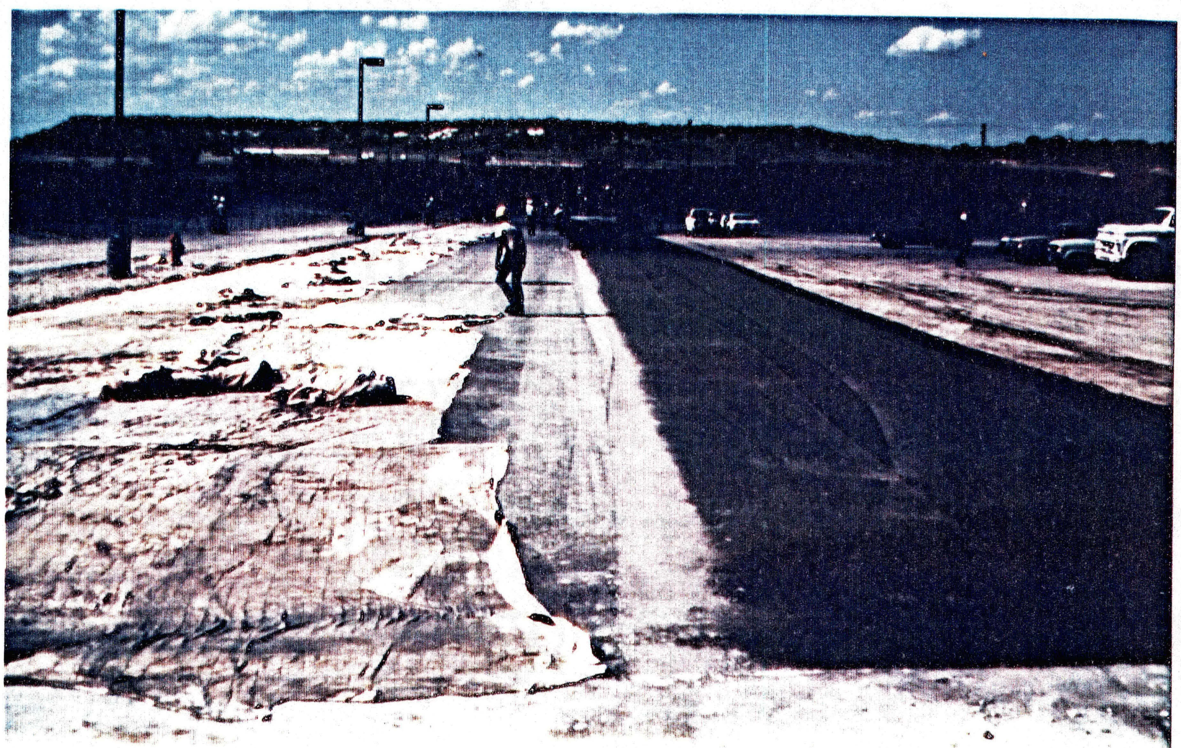
(a) Using Troxler Road Reader



(b) Verifying Specified Thickness of RCC Lift

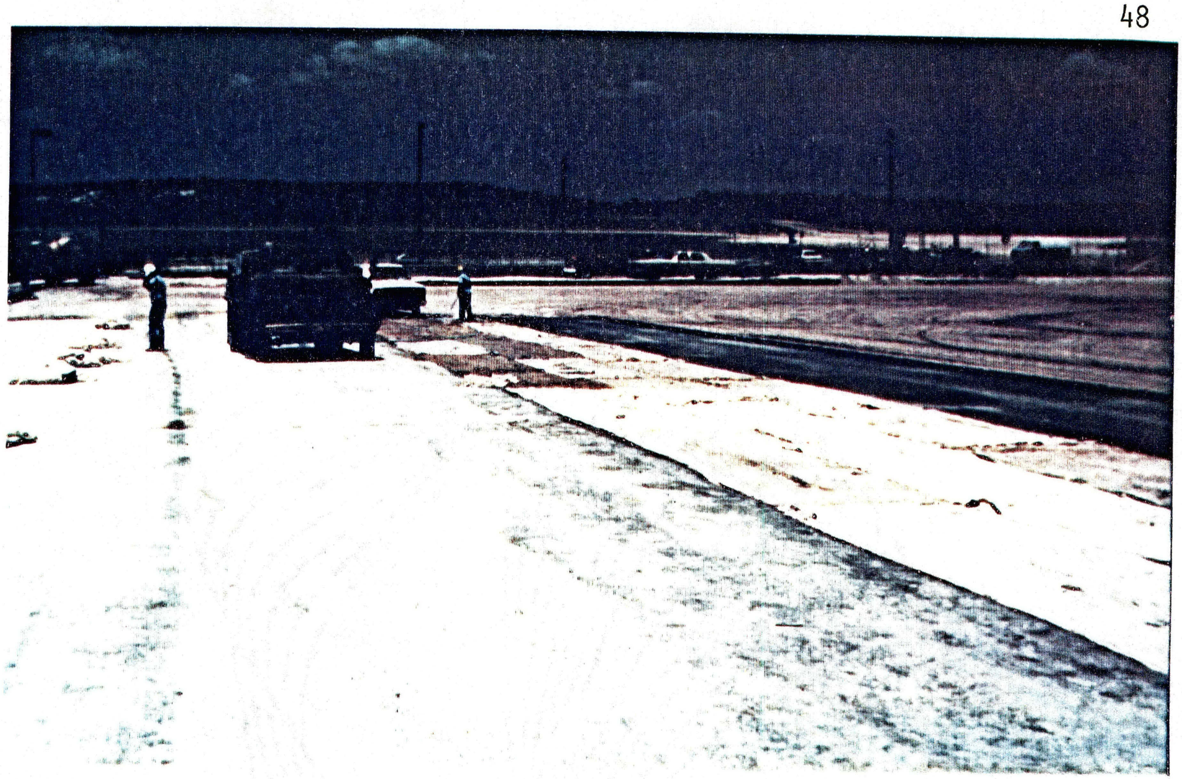
Figure 10. Measuring Moisture-Density and Lift Thickness

(a) Using Hand Compactor in Tight Areas



(b) Placement and Curing Operations, Second Day

Figure 11. Hand Compaction and Second Day Operations



(a) Blankets Removed and Curing Compound Applied on Left

(b) Concrete Saw Used for Joints and Waste Removal

Figure 12. Curing and Sawing Operations

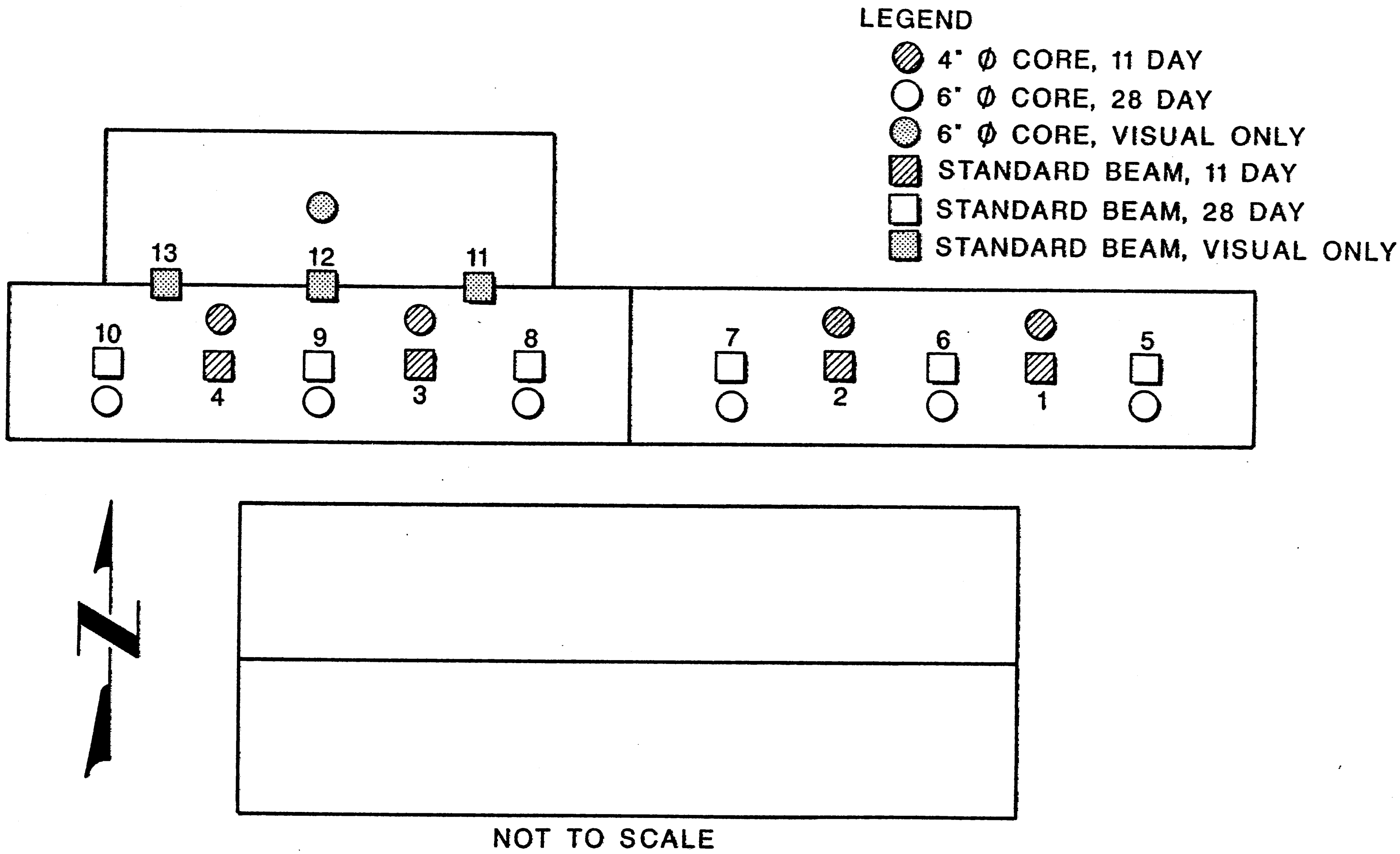
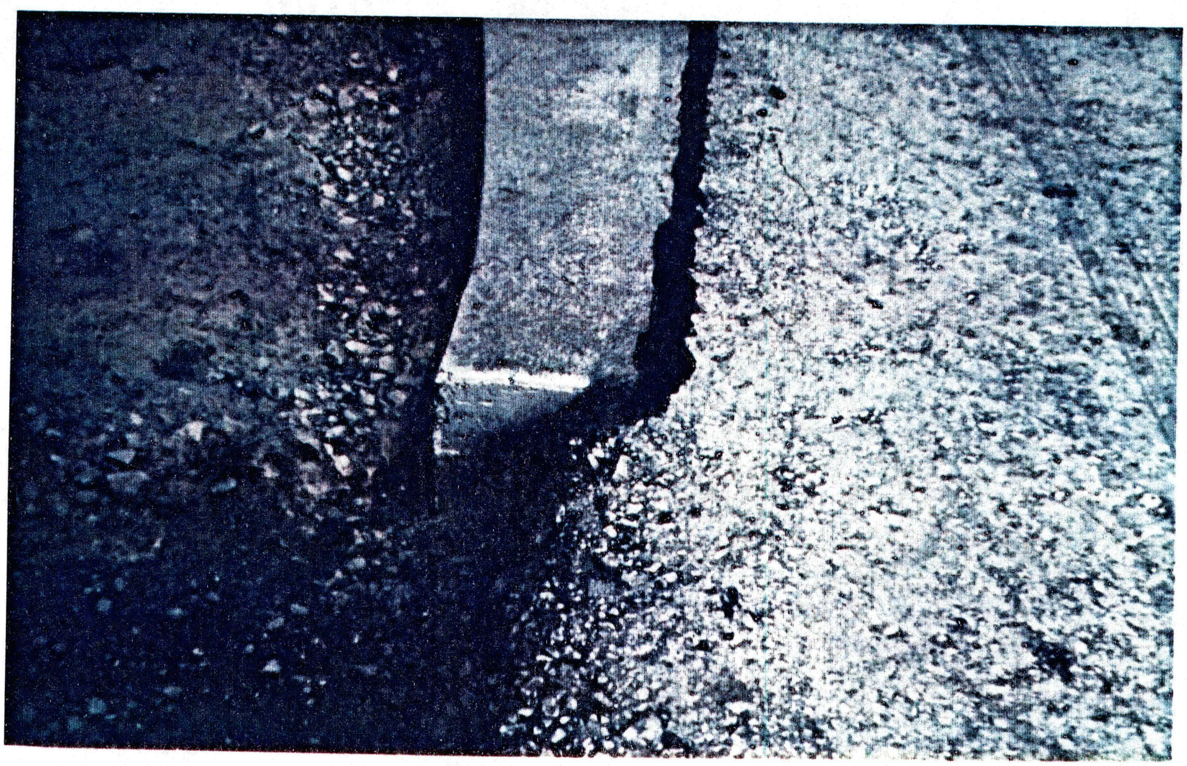


Figure 13. Location of In Situ Cores and Beams

(a) Close-Up of Spalled Surface at a Cold Joint



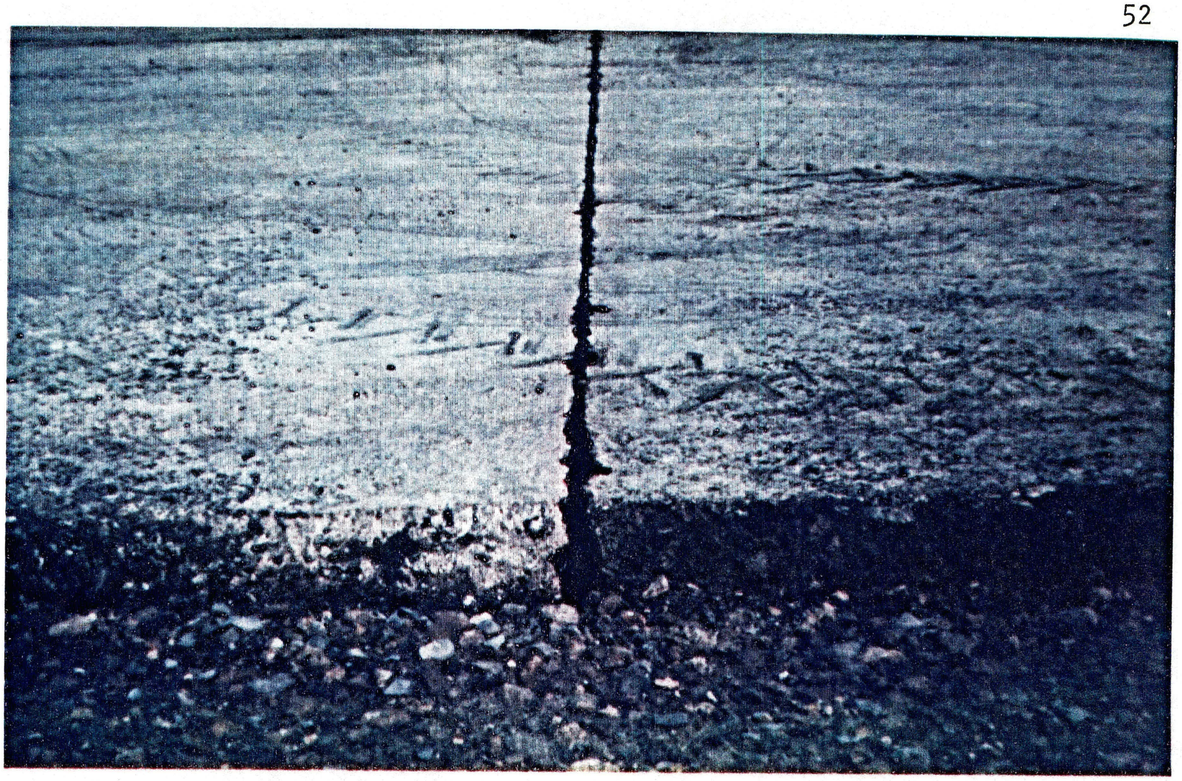
(b) Joint Treatment of Existing PCC With New RCC

Figure 14. Spalled Surface Area and RCC-PCC Juncture

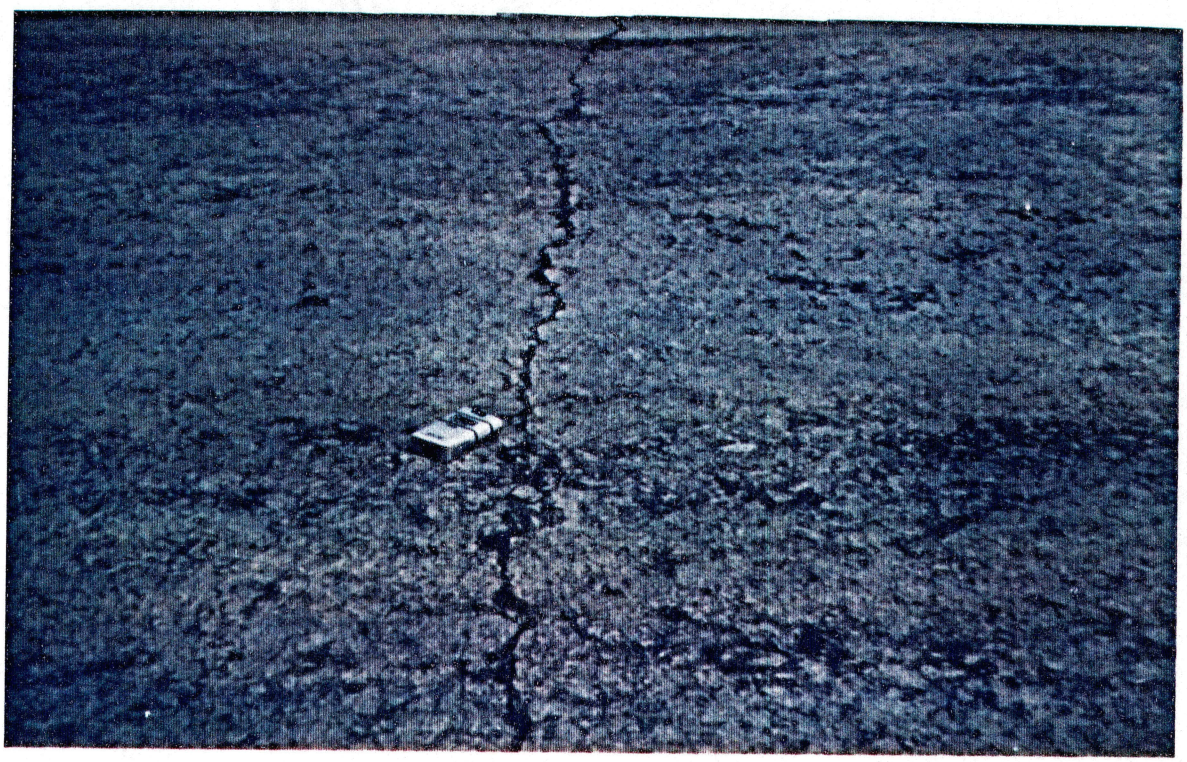
(a) Immediate Foreground, PCC; Remainder Completed RCC

(b) 1½ Mix on Left and 3/4 Mix on Right

Figure 15. Photographs of Completed RCC Paving



(a) Sawed and Filled Expansion-Contraction Joint



(b) Natural Transverse Crack Highlighted With Marking Pen

Figure 16. Sawed Joint and Natural Transverse Crack

APPENDIX B

TABLES OF PERTINENT DATA

TABLE I

MIX PROPORTIONING

Mix No.	Actual Density	Theoret-ical Density	Vibration Time	Cement/ Fly Ash	W/C Ratio	S/A Ratio	3-Day Breaks Cylinder	3-Day Breaks Beams	7-Day Breaks Cylinder	7-Day Breaks Beams	28-Day Breaks Cylinder	28-Day Breaks Beams
1	154.6	159.5	15 sec	572.0 0.0	0.35	39.4	6128					
2	152.9	157.8	3½ sec	572.0 0.0	0.40	38.0	5159					
3			4 sec	537.5 0.0	0.40	37.0						
4	153.4	159.3	7 sec	505.0 0.0	0.40	36.0						
5	155.2	160.4	16 sec	450.0 0.0	0.40	37.0	4754	630				
6	154.6	160.3	29.5 sec	528.0 0.0	0.35	39.4						
7	154.1	159.8	10 sec	449.3 87.6	0.35	38.4	4877					
8	154.4	160.6	41 sec	412.8 80.5	0.35	38.4						
9	152.7	160.1	14 sec	542.9 0.0	0.35	38.0	6780	773	6713	1019	8128	1025
10	155.2	160.2	14 sec	400.0 149.7	0.30				7050			
11	156.8	160.3	29 sec	450.0 0.0	0.40	38.0	5181	706	6572	784	7631	915
12	154.2	159.6	8.5 sec	350.0 168.6	0.33	37.2			5676			
13	153.8	160.2	11 sec	400.0 149.7	0.30	37.1			6183	856	8213	992
14		160.2	11 sec	350.0 170.4	0.31				6548	783	8139	961
15*	136.7	143.5	90 sec	419.9 0.0	0.67						3626	496
16*	136.4	141.4	10 sec	419.9 94.3	0.49				3085	498	3790	516
17*	138.2	143.2	21 sec	500.0 103.6	0.48				4086	550	4326	582
18*	135.3	142.1	13 sec	350.0 170.4	0.54				3106	454	4264	552
19		160.0	11 sec	300.0 150.0	0.35	38.0			5478	791		930
20		160.3	---	266.7 135.3	0.38	36.0			4591	683		803

*Base course aggregate mix.

TABLE II

1½ INCH DESIGN DATA

Materials	SWD Laboratory Lbs/Cu Yd	Field (8 Jun 84) Lbs/Cu Yd	Field (17 Jul 84) Lbs/Cu Yd
Cement Type 1	300.00	306.00	132.00
Fly Ash	150.00	162.00	155.00
Sand (F.A.)	1341.00	1285.00	1372.00
Aggregate 3/4" to 1½"	925.30	901.00	834.00
Aggregate #4 to 3/4"	1393.30	1393.00	1441.00
Water (Total)	157.50	153.30	158.20
Air Admixture	None	None	None
Other Additives	None	None	None
W/C*	0.35	0.33	0.34
Unit Weight	158 lbs/cf	156 lbs/cf	158 lbs/cf

*W/C equals ratio of water to total cementitious materials (cement and fly ash).

TABLE III

FINE AGGREGATE GRADATION

Sieve Size	Specifi-cations % Passing	SWD Laboratory % Passing	Field (8 Jun 84) % Passing	Field (17 Jul 84) % Passing
3/8 inch	100	100.0	100.0	100.0
No. 4	94-100	100.0	100.0	92.2
No. 8	80-90	93.0	90.0	85.5
No. 16	60-80	72.0	69.0	67.9
No. 30	30-60	50.0	45.0	90.2
No. 50	10-30	22.0	17.0	12.8
No. 100	2-10	4.0	4.0	2.0
No. 200	0-7	1.0	1.0	0.0
Specific Gravity	---	2.6	2.6	---

TABLE IV

COARSE AGGREGATE GRADATION
(NO. 4 TO 3/4 INCH)

Sieve Size	Specifications % Passing	SWD Laboratory % Passing	Field (19 Jun 84) % Passing	Field (17 Jul 84) % Passing
1 inch	100	100.00	100.00	100.00
3/4 inch	90-100	95.00	97.00	94.10
1/2 inch	---	66.00	---	---
3/8 inch	20-54	46.00	42.00	31.10
No. 4	0-10	11.00	8.00	4.60
No. 8	0-6	3.00	0.10	1.10
No. 200	0-5	0.60	0.40	0.00
Specific Gravity	---	2.78	2.78	2.78

TABLE V

COARSE AGGREGATE GRADATION
(3/4 INCH TO 1½ INCH)

Sieve Size	Specifications % Passing	SWD Laboratory % Passing	Field (19 Jun 84) % Passing	Field (17 Jul 84) % Passing
2 inch	100	100.00	100.00	100.00
1½ inch	90-100	100.00	98.00	97.50
1 inch	20-54	56.00	30.00	36.20
3/4 inch	0-14	14.00	8.00	5.50
1/2 inch	---	5.00	---	---
3/8 inch	0-6	4.00	0.70	0.90
No. 4	---	2.00	0.00	0.00
No. 200	0-5	0.20	0.00	0.00
Specific Gravity	---	2.77	2.78	2.78

TABLE VI

STRENGTH TESTS

Specimens	7-Day	28-Day
	Strengths--Cast	
Cylinders		
SWD Lab	5478	6605
Test Section	2980	3740
Beams		
SWD Lab	791	914
Test Section	499	824
	Strengths--In-Place	
Drilled Cores	4651	5220
Sawed Beams	637	834

Note: Average values expressed in psi.

TABLE VII

3/4 INCH MIX DESIGN DATA

Materials	WES Design Lbs/Cu Yd	Field Lbs/Cu Yd
Cement Type 1	373	376
Fly Ash	181	186
Sand (F.A.)	1331	1366
Aggregate 3/4" to #4	2154	2165
Water (Total)	180	130
Air Admixture	None	None
Other Additives	None	None
W/C*	0.35	0.23
Unit Weight	156.0 lbs/cf	156.3 lbs/cf

*W/C equals ratio of water to total cementitious materials (cement and fly ash)

TABLE VIII

CAST SPECIMENS--TEST SECTION

Age	SWD Laboratory	Test Strip 4 June 84		Test Strip 8 June 84	
		Cylinders			
7	5211	2725	4455	2265	2650
7	5262	3075	3785	2265	2620
7	5962	---	---	---	---
Avg	5478	2900	4120	2265	2635
28	7105	2725	5375	3025	4385
28	6105	1590	6085	2810	3925
Avg	6605	2158	5730	2917	4155
90		---	---	---	---
90		---	---	---	---
Avg		---	---	---	---
		Beams			
7	808	620	720	425	360
7	774	595	625	325	325
Avg	791	608	673	375	342
28	947	715	1000+	700	730
28	882	875	1000+	910	665
Avg	914	795	1000+	805	697
90		---	---	---	---
90		---	---	---	---
Avg		---	---	---	---

TABLE IX

IN SITU SPECIMENS--TEST SECTION

Age	Test Strip 4 June 84 1	Test Strip 8 June 84 No.	1 & 2 Compound		Test Strip 8 June 84 No.	3 & 4 Wet Matt	
			4 and 6 Inch Cores				
11	---	1	4260		3	5174	
11	---	2	6330		4	4498	
Avg	---			5295			4836
28	---	5	5307		8	2885	
28	---	6	4671		9	5499	
28	---	7	4671		10	5952	
Avg	---			4883			4778
			Saw Cut Beams				
11	---	1	410		3	635	
11	---	2	720		4	880	
Avg	---			565			758
28	---	5	1023		8	729	
28	---	6	686		9	871	
28	---	7	808		10	889	
Avg	---			839			830

Note: Odd numbered beams at lower portion; even numbered beams at top portion.

TABLE X

IN SITU DENSITY TESTS

Instrument: Troxler Road Reader
Model 3411-B with 12-inch probe

Contract Specifications: 96% compaction

Standard Used: 158 lbs/cf (maximum theoretical density)

Field Tests:

% Density	% Moisture
Second Test Strip--8 June 84	
96.5	4.2 @ 6" depth
97.0	3.5 @ 6" depth
97.4	4.4 @ 6" depth
Third Test Strip--11 June 84	
96.3	5.7 @ 6" depth
96.3	5.7 @ 8" depth

TABLE XI

ROLLING PATTERN DETERMINATIONS--TEST SECTION
(4 JUNE 1984)

Lane No. 1	Depth Inches	2 Passes LVR	4 Passes HVR	6 Passes HVR	8 Passes HVR
WD	8	140.5	146.6	148.4	152.2
DD		136.5	141.3	144.4	147.0
WC		2.9%	3.3%	2.4%	3.5%
WD	6	141.0	142.9	146.9	152.6
DD		137.1	138.7	142.5	147.3
WC		2.8%	3.1%	3.1%	3.6%
WD	4	140.8	---	---	---
DD		137.1	---	---	---
WC		2.7%	---	---	---

Lane No. 1A	Depth Inches	2 Passes HVR	4 Passes HVR	6 Passes HVR	10 Passes HVR
WD	8	147.5	149.7	154.2	149.4
DD		142.4	144.4	148.6	144.9
WC		3.2%	3.7%	3.7%	2.7%
WD	6	146.5	151.2	153.2	150.7
DD		142.0	145.6	147.2	145.9
WC		2.9%	3.8%	3.8%	3.3%
WD	4	144.8	---	---	---
DD		139.6	---	---	---
WC		3.7%	---	---	---

Notes:
1. LVR is low vibration rate.
2. HVR is high vibration rate.
3. WD is wet density in lbs/cf.
4. DD is dry density in lbs/cf.
5. WC is water content in percent.
6. Based on 96% maximum theoretical density of 158.4 lbs/cf, or 152 lbs/cf.

TABLE XII

MOISTURE-DENSITY RELATIONSHIP--HARDSTAND

Date	Lane No.	Location	Wet Density Lbs/Cf	Water Content Percent	Compaction Percent
July 9	1	50' from south end	146.9	3.7	92.7
	1	50' from south (retest)	152.8	3.5	96.4
	1	60' from south (rerolled)	147.7	4.3	93.2
	1	110' from south end	156.4	3.3	98.7
	1	250' from south end	155.4	4.0	98.1
	2	40' from south end	151.7	4.2	95.8
	3	35' from south end	155.7	4.5	98.3
July 11	4	130' from south end	147.0	3.4	92.8
	4	150' from south end	148.8	3.8	93.9
	4	150' from south (retest)	152.5	3.5	96.3
	4	230' from south end	152.0	3.2	95.9
	5	350' from south end	149.7	4.0	94.5
	5	350' from south (retest)	153.0	3.7	96.6
	6	30' from south end	152.4	3.0	96.2
	6	320' from south end	155.9	4.1	98.4
July 12	7	50' from south end	152.0	4.0	96.0
	7	275' from south end	152.0	3.9	96.0
	7	295' from south end	152.2	4.0	96.1
	8	325' from south end	152.8	3.8	96.1
	8	105' from south end	138.6	3.9	87.7
	8	105' from south (retest)	144.0	3.8	90.9
	9	100' from south end	152.4	4.1	96.2
	9	325' from south end	154.0	3.9	97.2
	10	20' from south end	153.0	3.9	96.6
	10	100' from south end	152.7	3.8	96.4
July 13	11	30' from south end	152.5	3.7	96.3
	11	170' from south end	148.5	3.6	93.7
	11	170' from south (retest)	147.9	3.0	93.4
	11	270' from south end	153.9	3.7	97.1
	12	75' from south end	150.8	3.3	95.1
	12	75' from south (retest)	152.6	3.2	96.3
	12	200' from south end	152.1	3.3	96.0
July 16	13	75' from south end	151.8	3.6	95.8
	13	125' from south end	152.2	3.5	96.1
	13	300' from south end	154.4	4.0	97.4
	14	50' from south end	146.2	3.7	92.3
	14	50' from south (retest)	151.3	4.1	95.5
	14	300' from south end	153.1	4.8	96.6
	15	60' from south end	151.2	4.4	95.5

TABLE XII (Continued)

Date	Lane No.	Location	Wet Density Lbs/Cf	Water Content Percent	Compaction Percent
July 17	16	60' from south end	156.0	4.5	98.4
	16	300' from south end	151.6	5.2	95.6
	17	80' from south end	149.3	2.8	94.2
	17	80' from south (retest)	153.3	2.4	96.7
	17	220' from south end	152.3	3.8	95.1
	17	300' from south end	152.7	3.3	96.4
	18	100' from south end	152.6	4.0	96.3
	18	225' from south end	149.1	4.4	94.3
	18	225' from south (retest)	154.2	4.1	97.3
	19	125' from south end	152.1	4.2	96.0
	20	220' from south end	151.3	3.5	95.5
July 18	20	120' from south end	156.4	4.6	98.7
	20	200' from south end	151.5	4.1	95.6
	20	200' from south (retest)	153.5	4.0	96.9
	20	205' from south end	144.1	4.8	91.0
	20	250' from south end	144.1	5.2	89.0
	21	170' from south end	153.1	2.9	96.6
	21	300' from south end	148.5	3.5	93.7
	21	300' from south (retest)	153.2	3.4	96.7
	22	50' from south end	156.9	3.0	99.0
July 19	22	175' from south end	153.1	3.9	96.6
	22	300' from south end	155.6	3.6	98.2
	23	100' from south end	158.9	3.5	100.3
	23	275' from south end	156.5	4.3	98.7
	24	75' from south end	155.9	3.2	98.4
	24	340' from south end	155.5	4.3	98.1
	25	70' from east end	156.6	3.2	98.8
July 20	25	260' from east end	155.0	3.8	97.8
	26	65' from east end	156.0	4.0	98.4
	26	220' from east end	155.3	3.7	98.0
	27	30' from east end	153.8	3.8	97.1
	27	220' from east end	154.2	3.8	97.3
July 23	28	60' from east end	154.7	3.5	97.6
	28	225' from east end	152.5	4.3	96.3
	29	60' from east end	152.8	3.3	96.4
	29	225' from east end	154.1	4.0	97.2
	30	40' from east end	155.4	3.7	97.4
	30	240' from east end	153.5	3.2	96.3
	31	100' from east end	149.4	4.2	95.6
	31	100' from east (retest)	151.9	4.3	97.2
	31	250' from east end	151.4	4.5	96.9

TABLE XII (Continued)

Date	Lane No.	Location	Wet Density Lbs/Cf	Water Content Percent	Compaction Percent
July 25	32	330' from south end	152.0	4.5	97.2
	33	350' from south end	152.5	5.2	97.5
	34	340' from south end	144.4	4.6	92.4
	34	340' from south (retest)	143.4	4.3	91.7
	34	340' from south (retest)	152.8	4.0	97.7

VITA 2

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