Rosebraugh

ARIZONA DEPARTMENT OF TRANSPORTATION

REPORT NUMBER: FHWA-AZ88-832

ROLLER COMPACTED CONCRETE PAVEMENT

State of the Art

Final Report

Prepared by:
P.E. Mueller, P.E.
Center for Advanced Research in Transportation
College of Engineering & Applied Sciences
Arizona State University
Tempe, Arizona 85287-6306

May 1990

Prepared for:
Arizona Department of Transportation
206 South 17th Avenue
Phoenix, Arizona 85007
in cooperation with
U.S. Department of Transportation
Federal Highway Administration

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Arizona Department of Transportation or the Federal Highways Administration. This report does not constitute a standard, specification, or regulation. Trade or manufacturer's names which may appear herein are cited only because they are considered essential to the objectives of the report. The U.S. Government and the State of Arizona do not endorse products or manufacturers.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-AZ88-832		

4. Title and Subtitle	5. Report Date
ROLLER COMPACTED CONCRETE PAVEMENT	May, 1990
	6. Performing Organization Code
7. Author (s)	8. Performing Organization Report No.
Paul E. Mueller, P.E.	
9. Performing Organization Name and Address	10. Work Unit No.
Center for Advanced Research in Transportation Arizona State University Tempe, Arizona 85287-6306	11. Contract or Grant No. HPR-PL-1(35)Item 832
12. Sponsoring Agency Name and Address	13. Type of Report & Period Covered
ARIZONA DEPARTMENT OF TRANSPORTATION 206 SOUTH 17TH AVENUE PHOENIX, ARIZONA 85007	Final Report
	14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration

16. Abstract (21 lines including this one - delete this comment)

For the past two decades engineers in the United States, and in many parts of the world, have been experimenting and using a new construction material called roller compacted concrete. This material is broadly defined as a lean concrete which is mixed and placed at a no-slump consistency, and then compacted with vibratory rollers.

The earliest trials in the United States were made by the U.S. Corps of Engineers in the period 1972-1973. This early work demonstrated the potential for the new material, and within a decade major dams and other water resource projects were being designed and constructed.

The use of this material has grown significantly through the 1980's, but the overwhelming volume of construction has been in dams. Pavement applications, particularly in the United States, have been relatively few in number.

Based on the use of roller compacted concrete to date, this engineering material has been shown to have several distinct advantages in terms of cost, ease of construction and inherent structural strength. This report considers the results of experimentation using roller compacted concrete as a road building material, and develops an economic and engineering rationale for using this new construction material for pavements in Arizona. It also recommends experimental roadway construction within Arizona's street and highway system.

17. Key Words	18. Distribution Statement	23. Registrant's Seal
Roller Compacted Concrete, Roller Compacted Concrete Pavement, RCC, RCCP	Document is available to the U.S. Public through the National Technical Information Service, Springfield, Virginia, 22161	

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	34	

TABLE OF CONTENTS

CHAPTER		PAGE
I	Introduction	1
II	Objective and Scope	3
III	An Overview of Roller Compacted Concrete as a Material	4
IV	Construction Methodology	6
V	Materials, Mix Designs and Properties of Roller Compacted Concrete	10
VI	Thickness Design Considerations	16
VII	A Review of Recent State-of-the-Art Studies and Related Documents	18
VIII	RCC Projects and Condition Survey	20
IX	Analyzing Cost Benefits	24
X	Conclusions and Recommendations	26
XI	References	30
XII	Bibliography	32

Technical Report Documentation Page

1. Report No. FHWA-AZ88-832	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle ROLLER COMPACTED CONCRETE PAVEMENT		5. Report Date May, 1990 6. Performing Organization Code
7. Author (s) Paul E. Mueller, P.E.		8. Performing Organization Report No.
9. Performing Organization Name and Address Center for Advanced Research in Transportation Arizona State University Tempe, Arizona 85287-6306		10. Work Unit No. 11. Contract or Grant No. HPR-PL-1(35)Item 832
12. Sponsoring Agency Name and Address ARIZONA DEPARTMENT OF TRANSPORTATION 206 SOUTH 17TH AVENUE PHOENIX, ARIZONA 85007		13. Type of Report & Period Covered Final Report 14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration

16. Abstract (21 lines including this one - delete this comment)

For the past two decades engineers in the United States, and in many parts of the world, have been experimenting and using a new construction material called roller compacted concrete. This material is broadly defined as a lean concrete which is mixed and placed at a no-slump consistency, and then compacted with vibratory rollers.

The earliest trials in the United States were made by the U.S. Corps of Engineers in the period 1972-1973. This early work demonstrated the potential for the new material, and within a decade major dams and other water resource projects were being designed and constructed.

The use of this material has grown significantly through the 1980's, but the overwhelming volume of construction has been in dams. Pavement applications, particularly in the United States, have been relatively few in number.

Based on the use of roller compacted concrete to date, this engineering material has been shown to have several distinct advantages in terms of cost, ease of construction and inherent structural strength. This report considers the results of experimentation using roller compacted concrete as a road building material, and develops an economic and engineering rationale for using this new construction material for pavements in Arizona. It also recommends experimental roadway construction within Arizona's street and highway system.

17. Key Words Roller Compacted Concrete, Roller Compacted Concrete Pavement, RCC, RCCP		18. Distribution Statement Document is available to the U.S. Public through the National Technical Information Service, Springfield, Virginia, 22161	23. Registrant's Seal
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages 34	22. Price

ATRC - MAN FACULTY AGREEMENT 88-1

HPR-PL-1(35) ITEM 832

ROLLER COMPACTED CONCRETE

PREFACE

This report was sponsored by the Arizona Transportation Research Center through the man-year faculty agreement with Arizona State University and its Center for Advanced Research in Transportation. The objective of the study is to review the ongoing state-of the-art studies on roller compacted concrete currently being conducted by various agencies and technical groups. Further, it is the aim of the report to determine the performance of various types of pavements made with this material and determine if a basis exists to build roller compacted concrete pavements in Arizona, on an experimental basis, for both repair/replacement applications and/or for new road and street construction.

TABLE OF CONTENTS

CHAPTER		PAGE
I	Introduction	1
II	Objective and Scope	3
III	An Overview of Roller Compacted Concrete as a Material	4
IV	Construction Methodology	6
V	Materials, Mix Designs and Properties of Roller Compacted Concrete	10
VI	Thickness Design Considerations	16
VII	A Review of Recent State-of-the-Art Studies and Related Documents	18
VIII	RCC Projects and Condition Survey	20
IX	Analyzing Cost Benefits	24
X	Conclusions and Recommendations	26
XI	References	30
XII	Bibliography	32

I

INTRODUCTION

In the early 1970's the attention of many engineers and contractors was drawn to a new construction material called roller compacted concrete (RCC). It is a material which developed from standard portland cement concrete technology, coupled with experience gained by using compacted mixtures of soil and gravel materials combined with portland cement. These later materials, usually called soil-cement or cement treated base, have been used extensively as base course materials for asphalt pavements in many countries of the world, throughout the United States, and in Arizona.

By way of definition, roller compacted concrete can be broadly described as a lean concrete which is mixed and placed at no-slump consistency, then compacted with vibratory rollers. It differs from conventional concrete in several regards. Principally, however, it requires a "0" slump consistency at point of placement. This allows the concrete material to be dry and stable enough to immediately support the weight of heavy, vibratory steel-wheeled rollers. Yet, this material contains enough water to permit adequate distribution of cement paste binder throughout its mass during both the mixing and compaction process. This allows the normal cement hydration process to develop. Also, unlike conventional concrete, RCC does not usually require forming or special surface finishing.

First experiments with RCC in the United States were conducted by the U.S. Army, Corps of Engineers at Jackson, Mississippi in 1972, and at Lost Creek Dam in Oregon in 1973. At about that time, Canadian engineers were mixing portland cement with crushed limestone aggregate in Vancouver to produce heavy duty concrete pavements using this early "rollcrete" theory. These early trials demonstrated the potential for the new material. Within a decade, major dams and other water resource projects were being designed and constructed of roller compacted concrete, both here in the United States and in numerous other countries.

The use of this material has grown significantly through the 1980's. However, that increase in use has been concentrated in dam construction. Pavement applications in the United States have been relatively few in number, with somewhat greater use evident in Canada, Australia, and Europe.

II

Objective and Scope

Roller compacted concrete is a comparatively new engineering construction material which has potential cost/benefit advantages not identifiable with conventionally placed portland cement concrete. It is the intent of this study to review ongoing state-of-the-art studies on roller compacted concrete currently being conducted by various agencies and technical groups. Further, it is the aim of the report to determine the performance of various types of pavements made with this material. This will help establish if a basis exists to build roller compacted concrete pavements in Arizona, on an experimental basis, for both repair/replacement applications and/or for new road and street construction.

III

AN OVERVIEW OF ROLLER COMPACTED CONCRETE AS A MATERIAL

Roller compacted concrete (RCC) differs from conventional concrete principally in its requirement for a zero-slump consistency at the time of mixing and placement. This allows the material to be placed in successive layers using earthmoving construction methods. When vibratory compaction is added to these individual layers, the resulting material exhibits comparatively high compressive strengths relative to the quantities of portland cement used in the mixtures. In addition, RCC mixtures are often able to utilize marginal aggregates which could not be tolerated in conventional concrete mix designs. (Ref. 1) This obviously adds to its potential uses.

These factors alone were enough to attract, in the early 1970's, the interest of engineers designing two types of projects; dams and heavy-duty industrial pavements. Of the two, dam construction utilizes, by far, the largest volume of RCC.

Historically, Shihman dam in Taiwan claims first use of this no-slump material by earthfill construction methodology. In this 1960 project, fill concrete for the foundation of the powerhouse was batch mixed and then transported to the site in small dump trucks. It was then spread with a bulldozer, with compaction accomplished in one section using small immersion vibrators. In another section the compaction was tried with rollers. The term "rollcrete" was applied to the resulting material, and this evolved into todays more acceptable term - roller compacted concrete, or RCC. (Ref. 2, 3)

Dam projects continue to be the predominant use for this new engineering material. Tarbela Dam in Pakistan (1974), Shimajigawa Dam in Japan, (1982) and Willow Creek Dam in Oregon (1982), were the beginning of RCC dam construction on a world-wide basis. In the United States alone, over a dozen dams have since been constructed. These range in size from a small gravity dam in Austin, TX using 13,000 cy., to Upper Stillwater Dam in Utah which required over 1.3

million cubic yards of RCC. In addition, over 25 new dam structures are now being evaluated as potential RCC projects in the United States alone. (Ref. 4, 3)

In Arizona, there are two major RCC dam projects of note. The first was a relatively small (18,000 cy) dam built by the Phelps Dodge Corp. at their Morenci mine, on Lower Chase Creek. The second is still in design and is planned to be built for the Apache Indian Tribe at Miner Flat. This dam is presently undergoing design refinements. It will probably use 120,000 cy of RCC and may start construction in 1990. RCC has also been proposed for a flood control and recreation dam project in Navajo County. (Ref. 5,6)

The concern of this report, of course, is in the use of RCC as a paving material. In this particular regard the use of the material has not grown very rapidly. From early use by the Canadians as an all-weather platform for log-sort operations in British Columbia in the early 1970's, (Ref. 7) and its initial trials by the US Army at Ft. Gordon, GA in 1983, (Ref. 8) almost every project has been a heavy duty pavement built to take advantage of the structural strength and toughness of the material. The problems of a smooth riding surface, shrinkage crack control, and surface durability during the pavements early life, have all apparently caused designers to delay adopting or even experimentally using RCC for any significant road or street applications. A better understanding of the assumed difficulties in developing RCC as an unsurfaced, rigid paving material is best approached by studying a history of early usage as well as the construction and mix design requirements for RCC pavements.

IV

CONSTRUCTION METHODOLOGY

From its inception, roller compacted concrete was meant to be mixed in a central plant facility and hauled to the site with dump trucks or scrappers. After spreading and leveling, the no-slump material is compacted with vibratory steel- wheeled rollers. In RCC dam construction, successive layers are built, with little attention given to many physical properties usually required of conventional concrete. Watertightness and layer bonding are the most critical concerns in RCC dam construction.

When roller compacted concrete is used as a pavement, however, other matters must be considered and analyzed:

a. Flexural strength and durability requirements of the resulting pavement.

b. Thickness requirement for given traffic loadings.

c. Methods of efficiently and cost effectively placing a layer of RCC on the subgrade. ready for compaction.

d. The method of compacting this layer to required density, including the critical edge areas.

e. Curing processes.

f. Shrinkage crack control.

g. Surface smoothness for various traffic modes.

h. Surface durability relative to early opening of the pavement to traffic.

Successful solutions to a majority of these items centers on the construction process. The evolution presently underway in RCC pavements is moving forward, to a great degree, through the efforts and experiences of two entities;

- Contractors and engineers who are specializing in this unique material.
- A small group of construction equipment manufacturers who have apparently recognized the future of this new paving material.

To see where we are presently in this regard we can again view the developments historically. The best starting place for this is the Canadian experience and their early use (1972) of RCC for heavy duty pavements. (Ref. 9, 10)

Canadian engineers had a long and successful relationship with cement-treated base and soil cement in pavement construction. Those materials have many physical properties similar to RCC. The experience made it relatively easy to make a transition to pavements constructed with "0" slump concrete compacted on a subgrade using vibratory rollers. In the process they recognized two important differences between the traditional cement-treated materials and RCC:

1. The portland cement content of the new RCC material is higher than that usually used in soil-cement. This results in significantly higher compressive and flexural strengths of the hardened material.

2. Cement-treated bases and soil-cement are always covered with a protective wearing surface of asphalt. RCC pavements would have their greatest potential *if* they could be placed in service without a bituminous wearing surface.

The first Canadian trials took place in 1972 when portland cement was mixed with crushed limestone material to build a heavy duty pavement for lumber and cargo storage. The construction method was typical of a cement- treated base project except the contractor chose to place the treated material through an asphalt lay-down machine rather than through a traditional spreader box.

This small innovation led to another change in a cement- treated base project on Vancouver Island in 1976. Here a 14-inch CTB layer was required to be placed in two layers and then surfaced with plant-mix asphalt. Again a modified asphalt paver was used in the lay-down process. With the nearest asphalt plant 20 miles away, the contractor suggested the top 7-inches of CTB be built with more cement (i.e. RCC) and left unsurfaced. This suggestion was accepted using 13% cement, which resulted in compressive strengths close to conventional 4000 psi concrete. The cost of the extra cement was paid for through the elimination of the asphalt mat. This old RCC pavement still serves to this day and claims only nominal maintenance costs, mainly in raveled construction joints and some surface delamination.

In the United States the potential value of RCC as a paving material was recognized by the US Corps of Engineers during their successful design and construction of Willow Creek Dam in Oregon. The Corps was particularly interested in three factors. First, RCC could possibly be constructed during times of war, rapidly, using simple and minimal equipment. Secondly, the material could provide a strong, durable and economical pavement for military installations where surface smoothness and texture are of little concern. Lastly, the material could, in all probability, be produced and constructed at costs appreciably less than conventional concrete pavements. (Ref. 11)

This led to a small test section built at Ft. Gordon, GA in 1983. It was constructed in two thicknesses (10 and 13 inches) and subjected to tank loads and maneuvering. It was deemed successful enough to warrant additional test sections in 1984. These involved:

- 10" thick tank hard stand at Ft. Hood, TX
- 8 1/2" test road at Ft. Lewis, WA
- 8" freeze/thaw test slab at the Cold Regions Laboratory in New Hampshire.

Close observation and analysis of these test projects have led the Corps to select RCC for the single largest paving project to date. Located at Fort Drum, New York, the expansion of this military base requires the construction of over 420,000 square yards of roller compacted concrete pavement. The 10 inches thick, unsurfaced RCC is being placed in hard stand areas and heavy vehicle access ways. Paving operations began in the summer of 1988 and will be concluded during the 1989 construction season. No standard street or road pavement sections will be built of RCC at this project, however. This fact follows what seems to be a major difference in philosophy regarding the use of RCC for pavements in the United States compared to Europe. Our applications have been mostly in heavy-duty pavement designs with very little use in roads and streets. Europe, on the other hand, rarely uses RCC in heavy-duty pavements while making extensive use of the material in street and roadways. (Ref. 12, 13, 14)

The aversion of engineers and public agencies in the United States towards the use of RCC as an exposed street or road is, in many cases, related to the difficulty in obtaining a smooth,

durable surface. Texture and appearance are improved with the use of rubber-tired and steel-wheeled rollers in the static mode following vibratory rolling. The results are still unsatisfactory, however, and our tendency in the U.S. has been to limit RCC exposed pavements to traffic speeds of 35 m.p.h. or less. Higher speed roadways, when built, are designed with a plant-mix asphalt wearing surface to provide smoothness. An example of this is the planned 12 mile section of U.S. 191 in Montana scheduled for construction in 1990. The M.D.O.T. has designed this as a 10 1/2" RCC pavement, placed in one layer, with a 2 1/2" plant mix A/C surface.

Another concern related to the exposed surface of an RCC pavement is the curing requirement. The dry consistency and open graded texture of the compacted RCC made the curing process extremely important and more sensitive to the methods used to accomplish that. Seven days of water curing are thought to be almost necessary to assure strength and durability at that part of the pavement layer. This does not lend itself to the efficient construction process needed to obtain an economical pavement, however. A double layer of liquid curing compound is a possible answer, yet some engineers feel the water curing also replaces water used by the dry RCC during hydration, and the curing compounds are not able to do that. (Ref. 15)

The difficulties related to surface smoothness, durability, and curing requirements for RCC pavements, will only be overcome thru experimentation. This means more agencies must try constructing RCC pavements using innovative methods of overcoming these apparent difficulties. This can only happen if those agencies are themselves convinced to RCC to provide them with both economical and related advantages over alternative and more traditional pavement design & materials.

V

MATERIALS, MIX DESIGNS AND PROPERTIES OF ROLLER COMPACTED CONCRETE

In choosing and proportioning materials for roller compacted concrete pavements, the resulting mixtures must be designed to meet most of the requirements of conventional portland cement concrete pavements. This includes, but is not limited to, concerns regarding flexural strength and durability against environmental forces. Compressive strengths of 6000 psi are common, as are flexural strengths of 700 psi in 28 days.(Ref. 16) In addition, however, the design of mixtures for RCC pavements must include consideration of several other factors. These include:

1- The potential of the mixture to segregate during placement.

2- The finishability of the material during laydown and compaction.

3- Enhancing the workability of the no-slump material in terms of the lay-down equipment and vibratory compaction.

4- The durability of the finished surface if exposed to traffic in the first few days after construction.

Aggregates comprise a major proportion of the materials in roller compacted concrete, as is the case in conventional concrete. Their selection is of major importance. They must be hard, clean, durable, and non-reactive sand, gravel and stone materials. These are requirements similar to those in conventional portland cement concrete mix designs. There is a departure from the standard procedures, however, when we chose the maximum size of coarse aggregate and the gradations of both fine and coarse aggregates.

Experience to date indicates that compactability is relatively easier with 3/4 inch maximum size coarse aggregate (MSCA) than with sizes 1-1/2 inch and greater. (Ref. 17)

The need to follow the uniform gradation requirements of ASTM C-33 is not critical . It is necessary, however, for the aggregate materials to lend themselves to changes in consolidation, and to the finishing process. (Ref. 18) This is essentially predicated by the use of steel-wheeled vibratory compaction equipment and the substitution of an asphalt laydown machine in place of the

traditional slip-form paver. The gradation of aggregates are therefore selected in terms of the RCC product's compactability throughout the full thickness of any layer, and its surface finishability.

Aggregate selection will also affect both the water requirements and the amount of portland cement and (usually) pozzolonic material needed to achieve strength and durability. It is necessary to coat all aggregate particles with cementitious paste. This is similar to conventional concrete, but differs from soil-cement and/or cement-treated base mixes where such is not the case. Ideal gradations for minimizing paste requirements would still be that which produces the maximum dry rodded density with the least amount of aggregate surface area. All voids are essentially, but not necessarily completely, filled with paste. (Ref. 19)

Conventional concrete production facilities necessarily have separate stockpiles for fine and coarse aggregates. This is not required with roller compacted concrete. If a suitable and consistent source of mixed aggregates is located and is found to have economical benefits, it can be used. All mix designs are run with this combined, natural, in-place material. It is important, however, that the aggregate durability requirements of ASTM C-33 still be met. This would include determining soundness of the aggregate material and the amount of deleterious substances in the material.

The ratio of crushed to rounded particles has a direct influence on roller compacted concrete's mix water requirements , its compactability, and its tendency to segregate. Rounded particles tend to be more easily compacted, but are more liable to segregate. Crushed aggregates, conversely, require more compactive effort, but have the advantage of being much less likely to segregate. Crushed particles also achieve somewhat higher flexural strengths. Which has a distinct advantage in RCCP thickness designs calculations.

At this point in time there seems to be agreement that when RCC is used for dam construction, the maximum size coarse aggregate should be two (2) or three (3) inches. In RCC pavements, however, this is reduced to maximum sizes of 5/8 to 3/4 inch. This is predicated essentially on the needed requirements of the final surface. Larger size aggregates will cause surface tearing and probably decrease smoothness and rideability of the pavement. (Ref. 20)

With the recent evolution to the use of asphalt paving equipment to place RCC, it is also becoming increasingly common to use aggregate gradations approximating those found in various state Department of Transportation's specifications for hot-mix bituminous materials. This generally results in the use of a well-graded aggregate with 5% to 10% material passing the No. 200 sieve. The finer material, if non- plastic, can be a beneficial mineral filler and may result in reducing cementitious material contents. Silts and clays must be avoided, however, as they will probably increase shrinkage and reduce strength. It is also felt that maximizing the plasticity index of the minus No. 40 material to four (4) would be beneficial.

Portland cement is, of course, a most important ingredient in RCC. As in conventional concrete, the combination of portland cement with fly ash is common. To date, all dams and many pavements constructed of RCC have used this combination of cementitious material. The use of pozzolanic material in RCC is effective in increasing paste volume at reasonable costs, and in adding fines to facilitate compaction. Cement to fly ash ratios generally range from 80/20 to 60/40. Some recent projects have been proposed and built with mix designs using 50/50 ratios. Heavy-duty pavements built in the U.S. have typically used cement contents of 450 to 600 pounds of cementitious material. Fly ash usually replaces 15-30% of the portland cement. (Ref. 3)

Both Class F and Class C ashes have been utilized, although the Class F ash seems to be predominant. Higher ash contents have also been tried in an effort to modify poor aggregate gradations.

Selection of particular portland cement types seems to have followed normal practice in the design of conventional concrete mixes. Applicable limits on chemical composition of portland cement remains important in roller compacted concrete. Exposure conditions and potential aggregate reactivity must be considered. In Arizona this means the use of ASTM C-150 Type II with a maximum allowable total alkali content of 0.6% must be adhered to. The local Type IP (MS), Portland pozzolan cement, as produced by the Phoenix Cement Company at their Clarkdale plant, can be utilized. Special care must be exercised if additional fly ash is needed with the Type IP cement for purposes of compaction or gradation improvement of a selected aggregate.

Admixtures other than pozzolans have been used sparingly during the brief history of roller compacted concrete. There seems to be a building interest on the part of European engineers in this regard. In the United States particular attention has been directed at freeze-thaw durability and the use of air-entraining admixtures (AEA) in exposed RCC. The Corps of Engineers experimental work at their Waterways Experiment Station has had limited success in developing an air-void system using presently available AEA's. They are continuing their work in this regard, however, and have included air-entrained test sections in the RCC pavements at the on-going Ft. Drum, New York project. Other agencies have had similar experiences. There seems to be agreement that if properly sized air bubbles can be entrained in RCC mixtures, the resistance to freeze-thaw damage would be improved.

Considering the present technological shortcomings in attempts to properly entrain air in the paste portion of RCC mixtures, alternatives are still being sought. The most widely accepted method of reducing freeze-thaw damage centers on designing the RCC using very low water/cement or water/cement+fly-ash mixes. This essentially results in an impermeable paste. When this is combined with compaction efforts that will minimize entrapped air content, the resulting high-strength, low permeability concrete material will have improved freeze-thaw performance, possibly equal to that of a conventional air-entrained portland cement concrete mixture. (Ref. 17)

Water reducing agents and retarders are admixtures widely used in conventional concrete throughout the United States, and also in Arizona. Their use in RCC has been limited and experimental. There seems to be doubt, based on limited laboratory testing, that the addition of water- reducers to a properly designed RCC mixture will effectively reduce water contents or improve its workability.

The use of retarders, which may be beneficial in certain aspects of the construction process of RCC, is beginning to draw more attention. Studies are fragmented, however. In Arizona's environment, such an admixture could help in allowing a slightly longer "working time," particularly in terms of dealing with longitudinal construction joints.

One additional admixture that is receiving very recent attention is the addition of fibers to the RCC mix. In conventional concrete, the use of steel or synthetic fibers is assumed to improve the strength and several other properties. In an RCC mix these assumptions are not necessarily true. Recently concluded research indicates a significant improvement in the fatigue strength of RCC using steel fibers. This could lead to reductions in layer thickness requirements when compared to an RCC mix without such steel fiber additions. Apparently, this does not hold true for synthetic fibers. Such fibers, like the polypropylene materials marketed by FiberMesh and Forte Fibre, have little structural capacity and are used primarily to reduce shrinkage in conventional concrete. RCC, due to its low water content at zero slump, would receive little benefit in this regard. As a result, early research on fibers is showing potential advantages from using steel fibers, but no meaningful advantage to the addition of synthetic, organic fibers.

The ***proportioning of materials*** for roller compacted concrete differs from convention concrete in several regards

1. RCC does not generally contain purposely entrained air.
2. RCC has a much lower water content and lower w/c ratios.
3. RCC has less paste content.
4. RCC uses more aggregate fines as a means of controlling segregation for mixing and placement.

To date, RCC mixtures used for pavement projects have, in most cases, been proportioned by using soil-compaction methods or by evaluating consistency tests. (Ref. 21,22,23)

Mix proportioning by soil-compaction follows closely the widely used methods of establishing cement contents and moisture-density relationships for soil-cement and cement treated base mixtures. ASTM D-1557 serves a the basis for much of the procedures presently being tried. However, the method of compaction (falling hammer or vibration table), size of mold, and compactive effort are often varied. The procedure calls for the cement content to be varied for several aggregate gradations and the minimum cement contents then selected to meet certain design requirements.

The alternative method employing consistency tests utilizes the Vebe apparatus as described in the American Concrete Institute (ACI) Standard 211.3-75, with some modification. (Ref. 21) This procedure basically measures the compactability of an RCC mix. It allows the determination of an optimum workability and the aggregate proportions needed to attain that. It is necessary to fix certain mix parameters, such as water content, cementitious material content, and aggregate content, and then vary one parameter to attain a desired consistency. Compressive strengths of the mixes at the parameter change points are also determined.

Standard test procedures for RCC are only now being developed by a special task force of ASTM under their Committee C-9. It is expected that proposed standards could be published on an interim basis before the end of 1989. Such standards would then be tried and commented on by industry and agencies for a period of two years. Final standardization would then take place.

VI

THICKNESS DESIGN CONSIDERATIONS

It is possible to determine the layer thickness of roller compacted concrete needed to support given weights and configuration of traffic loadings. The Portland Cement Association (PCA) publication "Structural Design of Roller Compacted Concrete Industrial Pavements" is considered a rational method for calculating those dimensions. It is based on flexural fatigue considerations. (Ref. 24)

Although this PCA method is excellent for use in designing heavy duty pavements for aircraft loadings and those wheel loadings associated with storage areas, it is not applicable to road and street pavement design. That matter was dealt with to some extent in the Tayabji/Halpenny paper, "Thickness Design of RCC Pavements" as presented to the Transportation Research Board Meeting in Jan., 1987. In that paper the authors suggested a method of calculating the cumulative fatigue damage due to any assumed traffic mix. What they essentially did was to use the standard PCA method of designing concrete street pavements, as outlined in their publication, "Thickness Design of Concrete Highway and Street Pavements" and make certain changes in fatigue consumption and flexural strength data. (Ref. 25)

There are several problems involved in attempting to use the presently available thickness design methods for conventional concrete pavements and make any simple transition to roller compacted concrete material. One important matter involves the wide variabilities that can be found in the in-place strengths for RCC. Unlike conventional concrete placed with a slip-form paver, where assumptions relating to flexural strengths of 600 or 650 psi in 28 days can easily be assured, RCC does not allow for that level of confidence. Variations in the mix, and in the construction process, will cause standard deviations to be quite high. This could cause flexural strengths to range from 400 psi to 700 psi on the same project. That will require a very high safety factor placed within the design method, or a flexural strength level chosen which will assure that all in-place strengths will easily be above that. This is not an economical way to design pavements.

Additionally, the matter of joints, or lack of joints, in RCC pavement also impacts on the rationality of these design methods. PCA design methodology assumes aggregate interlock or positive load transfer at all joints. It does that by requiring the pavements be continuously reinforced, or doweled, or be jointed with short spacings to assure good aggregate interlock at the working joints.

In RCC pavements, as presently being constructed, no joints are made. The pavement is allowed to crack randomly, and these have been occurring at 50 to 75 feet spacings. Some RCC pavements have had some spacings as long as 250 feet. This experience, however, is essentially with heavy-duty and therefore rather thick pavements. Little available data is obtainable from road or street pavement in the 5 to 8 inch thickness range. Furthermore, the sawing of joints in RCC is not being done in any present or past projects. Some experiments have been tried, but they were unsuccessful. The RCC material tends to ravel if sawing is attempted at a time considered early enough to control shrinkage cracking. What this means, then, is that if the RCC pavements are built without control joints the random cracking that will occur, will do so with rather long spacings. The individual cracks will open up quite widely, probably in the 3/8 to 3/4 inch range. All aggregate interlock is therefore lost, and the PCA design method then becomes unworkable. (Ref. 11,16,26)

Eventually a rational thickness design method will probably be developed for RCC street and highway pavements. Until then it is possible to use the current PCA method for conventionally place concrete pavements by assuming a very low flexural strength level which will reflect the worst case scenario for any given project. This will result in pavements initially one or two inches thicker than probably necessary, which should be considered acceptable for early trials & experimental projects.

VII

A Review of Recent State-of-the-Art Studies and Related Documents

Considering that the concept of roller compacted concrete is less than two decades old, the number of reports, research findings, and documents relating to this material is considerable. These writings cover the use of RCC in both dam and pavement construction. A listing of those documents which relate, essentially, to pavements is presented in Chapter XI (References). Inclusion of references which relate specifically to RCC's use in dam construction was purposely omitted. This decision is further justified by the fact that the evolution now taking place in RCC is being segmented into two distinct areas, dams and pavements. In this writers opinion the work underway in pavement applications has become so advanced and separated from the water resource application that pavement applications should be considered a separate entity and treated as such. From among the 63 listings in Chapter XI & XII, two documents occupy a particularly important role in deciding how and where RCC offers its greatest potential to the Arizona Department of Transportation. These are:

- The *proposed* ACI State-of-the-Art Report on Roller Compacted Concrete. This document is being developed by Committee 325-E of the American Concrete Institute,(ACI). It is currently going through its third draft (August 1989) and is expected to be published by ACI in 1990.
- The Guide Specification for Roller Compacted Concrete Pavement for Airfields, Roads, Streets and Parking Lots. This Department of the Army publication CEGS-02520 dated January 1988 is an excellent working document that can easily be modified for local use.

If the Arizona DOT considers building an experimental section of pavement using RCC, the data and material in these two particular volumes, in combination with the findings of this study, should be considered the main source documents. From these volumes, specifications and related details for an experimental road and/or street can be developed which will encompass the latest

experiences regarding this new paving material. However, with RCC pavement technology advancing as rapidly as it is, the writing of this or any related document becomes somewhat dated, even as it is printed and distributed.

VIII

RCC PROJECTS AND CONDITIONS SURVEY

Although the number of RCC pavements built in the United States has been comparatively limited, there is a sufficient number to study as a basis of making a performance review. In addition, the ongoing projects at Ft. Drum, N.Y. and at the Saturn plant facility in Tennessee, each of which includes over one-half million square yards of RCC pavements, adds to the evidence that some engineers seem convinced that RCC pavements are viable.

The following table entitled "R.C.C. Paving Projects in the United States" lists 30 projects with project sizes in excess of 10,000 square yards of pavement. Engineers from the Portland Cement Association have visited some of these over the past 2 years and have attempted to attach a performance rating to 12 projects. Although this analysis is admittedly somewhat crude, the ratings, on a scale of 1.0 (poor) to 4.0 (Excellent) is helpful in developing an overall concept of how some of the projects, built between 1982 & 1987, are performing.

In Arizona, aside from the RCC dam on Lower Chase Creek mentioned earlier in this report, and a small RCC water control structure at Ahwautukee, there is little experience to evaluate. A small repaving project in which RCC was used to reline an evaporation pond at City of Phoenix Waste Water Treatment Plant is apparently performing well. Also, experimental sections 8 inches thick placed with blade & roller at the Phoenix Redi-Mix plant in Southwest Phoenix also seem to show good strength and durability after 3 to 4 years of "yard" traffic. Nowhere in Arizona has RCC been placed under street or highway vehicular traffic.

R.C.C. Paving Projects in the United States

1.0 - poor
4.0 - best

Const. Period	*Project*	*Thickness (inches)*	*Performance Rating*
1984	Tank hardstand Ft Hood, TX	10	2.2
1985	Burlington Northern Intermodal Yard Houston, TX	18	1.5
1985	Port of Tacoma South Intermodal Yard Tacoma, WA.	12 & 17	
1985	North Plant Ready Mix Yard Colo. Springs, CO	8	2.5
1985	Port of Tacoma North Intermodal Yard Tacoma, WA	12 & 17	
1985	Portland Airport Aircraft Parking Portland, OR	14	3.0
1985	Multnomah Co., Or S.E. 99th St. (Portland)	7	3.5
1986	BN Rennick Yard Intermodal Terminal Denver, CO	15 & 20	3.2
1986	BN Parking Lot Denver, CO	6	3.0
1986	Tracked Vehicle Hardstand Ft. Lewis, WA	8.5	

R.C.C. PAVING PROJECTS IN THE UNITED STATES

CONST. PERIOD	*PROJECT*	*THICKNESS (INCHES)*	*PERFORMANCE RATING*
1986	Expanded Maint. Facility Ft. Benning, GA	7.5	
1986	Western Farmers Coal Yard Hugo, OK	13	
1986	Koch Industries Coke Pad Joliet, IL	10 & 14	
1987	Applied Instruct. Facility Aberdeen, MD	8.5	
1987	Socorro High School Parking & Entrance El Paso, TX	2.0	
1987	Tactical Equip. Shop Ft.Campbell, KY	7	
1986-87	Mass. Port Auth. Conley Terminal Boston, MA	18	
1987	Motor Park Hardstands & Tank Trail Ft. Bliss, TX	8 & 10	3.5
1987	Equipment Shop Ft. Hood, TX	8	4.0
1988-90	Equipment Shop & Helicopter Pad Ft. Drum, NY	7 & 10	

R.C.C. PAVING PROJECTS IN THE UNITED STATES

CONST. PERIOD	*PROJECT*	*THICKNESS (INCHES)*	*PERFORMANCE RATING*
1988	Central Wash Facility Ft. Hood, TX	9	
1989	HWy. 36 (Haz. Waste) Last Chance, CO	5.5, 7, 10	4.0
1987	Tuscany Way Austin, TX	7"	4.0
1987	Central Freight Terminal	7 & 7	4.0
1988-89	GM Saturn Plant Nashville, TN		
1989	Tank Trail. & Wash Facility Ft. Benning, GA	9	
1989	PorTAC Log Yard Tacoma, WA	9 & 15	
1989	Ft. Hood, TX AEB & Patriot	9	
1989	Camp Lejeune. NC	8	
1989	Gibbons Creek Power Plant, TX Haul Road	22	

IX

ANALYZING COST BENEFITS

By definition, roller compacted concrete can be considered a low-cement content concrete which is often made with marginal quality, unwashed aggregates. In combination with high production rates and reduced labor costs, this can result in savings of one-third to one-half that conventional concrete. Viewed from RCC's use in dam construction, ample proof of this is documented from a sizeable number of such projects in the United States over the past seven (7) years. A review of those projects ranging in size from 18,000 cubic yards to 1 million cubic yards indicates contract bid prices ranging from $17.00 per cubic yard to $37.00 per cubic yard. Cement and fly ash contents varied widely in these projects, and were not necessarily the major factor in the cost breakdowns.

If RCC pavements are to find a place in the alternatives available to a highway department's design team, the cost must not only be acceptable, but advantageous. Few meaningful pavement project cost records are available, yet many engineers feel such pavements can be built for 30% less than comparable asphalt designs. Most U.S. paving projects built to date have been experimental, and have been built with a variety of engineering features. The 3-1/2 acre unsurfaced tracked vehicle hardstand area built in Ft. Lewis, Washington in 1986 cost $58 per cubic yard and is somewhat indicative of the cost savings available from the use of RCC as a pavement alternative. The Corps of Engineers estimated the cost of conventional slip-formed concrete would have been in the $95 - $100 per cubic yard range. They felt the 30% cost savings were real and could easily be 50% on a larger sized project.

In order to develop a meaningful cost for a hypothetical RCC paving project in Arizona, we can extrapolate from two sources of data. First, the RCC dam built in 1988 by Phelps Dodge Corp. at Morenci. The in-place cost of 26,000 cubic yards of RCC was $34.00 per cubic yard. If we equate that number to a hypothetical project involving one-half mile of RCC pavement in a rural location in the same county (Gila), we should assume a probable cost of $51.00 per cubic yard. In

a half-mile road, an 8 inch thick RCC pavement 34 ft. wide will then cost $100,000 or $10.00 per square yard as a bid item estimate for the raw material cost.

Another cost calculation can be developed for an urbanized area by taking proposed "ready-mixed" RCC costs provided by local companies in the Phoenix area. Assuming a haul of 15 miles and/or 30 minutes from their central-plant mix facilities, they estimate a delivered cost of RCC material at $ 36 per cubic yard. This can be translated to the material cost of an 8 inch thick RCC pavement in central Maricopa County of $ 8 per square yard. Placement, compaction and curing will probably add 25% to that estimate.

Costs will be very much affected by aggregate source and the size of any particular project. It seems very possible, however, that as a general rule RCC will in all probability cost less than conventionally place paving concrete.

X

CONCLUSIONS AND RECOMMENDATIONS

As a engineering material, roller compacted concrete has been shown to have several distinct advantages in terms of costs, ease of construction and inherent structural strength. It seems logical to conclude that RCC should find some application in building pavements within Arizona's system of streets & roadways.

Despite the rather significant use of RCC pavement in heavy duty applications, there is no widespread use of this pavement material by state or local public works agencies in the United States. Among the states, only Montana's Department of Transportation has made a firm decision to build an RCC pavement. This roadway is designed with a plant-mix asphalt surface. Their engineers feel this is necessary to assure surface smoothness for 55 mph traffic.

There has been no apparent encouragement from the Federal Highways Administration to the various States regarding the use of RCC in experimental pavements. Conversations with several members of that agency does indicate interest in the material, however, and they are presently synthesizing information on the subject. They have also recently sent personnel to Spain to review the work being done by engineers and roadbuilders in that country. Additionally, while there is no investigation of RCC under presently funded SHRP programs, there is opinion from engineers at the FHWA's Turner-Fairbanks Research Center predicting possible inclusion of RCC in future SHRP studies.

The wisdom of the Montana decision to use an asphalt surface to assure smoothness is epitomized by two large RCC pavement projects presently under construction; the 420,000 sq. yd. project at Fort Drum, New York, and the 1/2 million sq. yd. project at the new Saturn plant in Tennessee. In the N.Y. project the U. S. Corps of Engineers, reflecting current attitudes of engineers in the United States, is using RCC for all heavy-duty pavement designs, but has not elected to use any RCC for the street system within that large military base construction project. At the Tennessee site, the engineers for General Motors will use the RCC as an exposed pavement, without an asphalt surface. They will however, limit speeds on these residential streets to 35 mph

in recognition of anticipated surface irregularities. In both of these projects the engineers have shown they are unconvinced that RCC can be placed with presently available construction equipment to the surface tolerances required for high speed urban or rural traffic.

This reluctance is not, however, shared by either equipment manufacturers in the United States, or by road designers in Europe and Australia. The Pav-Saver Manufacturing Company of East Moline, Illinois is convinced they can place an RCC road and achieve a surface profile. They have a prototype machine available for trial projects and hope to prove that fact in the near future.

Experimental roads & streets using exposed surface RCC should & will be built in the near future. Australia is a good example of this and their efforts should be considered a model for review in this regard. They have completed two trial projects and an abbreviated list of details, by project, includes:

1. - Wells Road at Aspendale, Australia
   - Major pubic arterial road
   - Traffic speeds to 100 km/hour (62 mi/hour)
   - Expected traffic: 30 years = 1.4×10^7 equivalent standard axles (ESA)
   - RCC pavement thickness 200 mm. (7.9 inches)
   - Cement stabilized base 100 mm. (3.9 inches)
   - Joints sawed at 24 hours using experimental spacings of 10,12, 15, 20 and 100 meters
   - All sawed joints sealed.
2. - Cashmere Estate Housing Roads near Brisbane
   - Streets in major housing development
   - Traffic speeds: Less than 50 km/hour (31 mi/hr)
   - Light residential traffic
   - RCC pavement thickness 150 mm. (5.9 inches)
   - Joints sawed at 24 hours using "regular" Australian PCCP spacings
   - All joints sealed

Arizona should also build experimental pavements using RCC. They should include both exposed & bituminous surfaced RCC. In that regard this author recommends the design & construction of the following two (2) projects.

1. A rural state or county highway

   - Low to moderate traffic mix
   - Site above 4500 feet elevation to induce some freeze-thaw stresses to pavement
   - Select two design thicknesses, with a 1 1/2 inch differential, depending on traffic data
   - Mix design to incorporate locally available aggregate with a 3/4 in. MSA
   - Mix design to achieve a minimum 7- day compressive strength of 3500 psi and a comparative flexural strength of approx. 600 psi
   - Design density of 100% (minimum)
   - Add a retarding admixture to the mix design
   - Build two (2) one-mile contiguous sections
   - First section to be exposed RCC with joints sawed (1/3 d) at 50, 75, & 100 ft. intervals for first section only. No sawing on 2nd section. All joints sealed with neopreme sealant.
   - Second section built without sawed joints, but overlaid with relatively thin bituminous surface (3/4 to 1 1/2 inch), possible incorporating asphalt-rubber.
   - Both sections cured with *continuous fog* (water) spraying for first 24 hours; then double application of white pigmented curing compound on exposed section. A bituminous curing seal applied to section that will receive overlay.
   - Traffic to be held off of exposed section for 72 hours; but placed on bituminous surface section after 24 hours.

2. An urban area, high density street, preferably near a ready-mix concrete plant capable of central-mixing RCC & delivering that material in dump trucks.

   - One design thickness, dependent on traffic data
   - Mix to be designed using locally available aggregate normally used in 3/4" hot mix asphaltic concrete
   - Same design strengths as above
   - Design density of 100% (minimum)
   - Add a retarding agent to mix design

- Build a 1 or 2 city block project, entirely unsurfaced
- Cure with continuous fog (water) for 48 hours. On this moist, but unponded surface, apply a chlorinated rubber membrane curing compound (clear). Allow to air-dry for 24 hours
- Open to traffic after 36 hours
- Build the pavement to within 3/4" at gutter section elevation. If pavement proves to have a surface unacceptable for 40 mph traffic, place a 3/4" to 1 1/2" hot mix asphalt surface on it at an appropriate future date.
- Saw cut at 24 hours at 1/3 d. Seal with neopreme sealant. Saw cut joints should be spaced at 50, 75 & 100 ft. spacing on entire length of project

In these first experimental projects there is no need to include monitoring devices to measure pavement stresses or related engineering properties. The essential aim of the experiments is to prove that it is or is not possible to build an acceptable riding surface in an RCC pavement. Secondarily, a determination can be made as to how early such pavements can be opened to regular traffic.

Roller compacted concrete is a new engineering material that has the potential of providing the Arizona Department of Transportation with a low cost pavement that can be produced from non-standard aggregates. If the resulting pavement can be constructed with tolerable surface profiles and can also allow earlier than usual openings to traffic, a new dimension will be added to A.D.O.T.'s choices in alternative pavement designs. The construction of the recommended experimental pavements, albeit a pioneering effort, will add measurably to developing knowledge of this new material, and also provide some immediate benefit in terms of pavement usage.

XI

REFERENCES

1. Hansen, K.D., Feb. 1987, "A Pavement for Today and Tomorrow," *Concrete International,* **Vol. 9.**, No. 2.

2. Adaska, W. D., July 1989, *Southwest Contractor*, pp. 33-38, "RCC Concrete Versatility."

3. RCC NEWSLETTER, No's 1 thru 7, date July, 1986 thru Spring, 1989, Portland Cement Association, Skokie, Illinois.

4. Schrader, E., Sept-Oct. 1977, "Roller Compacted Concrete," *Military Engineer,* The American Society of Military Engineers.

5. May 19, 1986, "Intermodal Terminal Paved with Roller Compacted Concrete," *Rocky Mountain Construction,* pp. 19-22.

6 July 1988, "Unique RCC Dam is First in Arizona," *Southwest Contractor*, pp. 19-20.

7. Piggot, R W., 1986, "Roller Compacted Concrete Pavement in British Columbia," ASCE Conference Proceedings on Roller Compacted Concrete, Denver, Colorado.

8. Keifer, Jr., Oswin, Oct. 1987, "Paving with RCC," *Civil Engineering,* **Vol. 57**, No. 10, pp. 65-68.

9. Piggot, R. W., 1986, "Roller Compacted Concrete for Heavy Duty Pavements: Past Performance, Recent Projects, Recommended Construction Methods." Concrete in Transportation, ACI SP 93, American Concrete Institute, Detroit.

10. Piggot, R. W., Feb. 1987, "Ten Years of Heavy-Duty Pavement in Western Canada," *Concrete International: Design and Construction,* **Vol. 9,** No. 2, pp. 4954.

11. Keifer, Jr., Oswin, March 1988, "Corps of Engineers Experience with RCC Pavements," Proceedings, ASCE Conference on Roller Compacted Concrete II, San Diego, CA.

12. Hess, J. R., 1987, "Roller Compacted Concrete Pavement for Tooele Army Depot, Utah," M.Sc. Thesis, California State University, Sacramento, CA.

13. Jofre, C., Josa, A., Fernandez, R., Kreamer, C., April 1989, "RCC Pavement in Spain." Proceeding, 4th Int'l. Conference on Concrete Pavement Design and Rehabilitation, Purdue University, pp. 587-599.

14. Murphy, H. W., 1987, "Highway Construction in Queensland (Australia): Roller Compacted Cemented Paving," ACI Compilation No. 8, American Concrete Institute, Detroit, Michigan.

15. January 1988, "Corps of Engineers Guide Specification, Military Construction," Roller Compacted Concrete Pavement for Airfields, Roads, Streets and Parking Lots." Dept. of the Army, CEGS-02520.

16. Hansen, K. D., Feb. 1987, "A Pavement for Today and Tomorrow," *Concrete International: Design and Construction,* **Vol. 9**, No. 2.

17. Tayabji, S. D., & Okamoto, P.A., 1987, "Engineering Properties of Roller Compacted Concrete," TRB Record 1136, Transportation Research Board, Washington, D.C.

18. Anderson, R. 1986, "Pavements of Roller Compacted Cohcrete-Physical Prperties," Nordic Concrete Research.

19. Larso, J. L., Feb. 1987, "Concrete Kaleidoscope-Roller Compacted Concrete; Projects and Equipments," *Concrete International: Design and Construction*, **Vol. 9**, No. 2, pp. 37-41.

20. Haque, M. N. and Ward, M. A., 1986, "Marginal Material in Roller Compacted Concrete for Pavement Construction," *Journal of the American Institute*, No. 4 Proceedings V83, Detroit, MI.

21. ACI Committee 211, 1975, "Standard Practice for Selecting Proportions for No-Slump Concrete," ACI 211, 3-75, *American Concrete Institute,* Detroit, Michigan.

22. Keifer, Jrl., Oswin, March 1986, "State-of-the-Art: Paving with Roller Compacted Concrete," *Concrete Construction,* pp. 287-297.

23. Ragan, S.A., March 1988, "Proportioning RCC Pavement Mixtures," Proceeding, ASCE Conference on Roller Compacted Concrete II, San Diego, CA.

24. 1987. Portland Cement Association, "Structural Design of Roller Compacted Concrete Industrial Pavement," IS 233.01 P.

25. White, T.D., 1986, "Mix Design, Thickness Design of Roller Compacted Concrete" TRB Record 1062, *Transportation Research Board*, Washington, D.C.

26. June 1989, "Roadnote 29, Roller Compacted Concrete Pavements," Cement and Concrete Association of Australia.

XII

ROLLER COMPACTED CONCRETE PAVEMENT

Bibliography

Abrams, J.M., et al, 1986, "Roller Compacted Concrete Pavement at Portland Int'l. Airport, *Transportation Research Record* **1062**, Transportation Research Board, pp. 20-24

Abrams, J.M. and Jacksha, J.L., Feb. 1987, "An Airport Apron and a County Road," *Concrete International: Design and Construction*, **Vol.9**, No. 2. pp 30-36.

Adaska, W. D., July 1989, *Southwest Contractor*, pp. 33-38, "RCC Concrete, Versatility."

ACI Committee 207, 1988, "Roller Compacted Mass Concrete," ACI 207.5R-88, American Concrete Institute, Detroit, Mich.

Allen, G., 1981, Project Fact Sheet, Performance of Canadian Heavy-Duty Pavements (Re: RCC), Canadian Portland Cement Association, Ottawa, Canada.

Andersson, R., Jan. 1986, "Roller Compacted Concrete," *Dynapac Research Bulletin* No. 8033

Andersson, R. Feb.1987, "Swedish Experience with RCC," *Concrete International: Design and Construction*, **Vol 9**, No.2
Bock, B., April 1989, " RCC Paving Record Set," *Concrete Construction.* pp 373 - 377.

Brett, M., March 1988 "RCC Pavements in Tasmania, Australia," *Proceedings, ASCE Conference on Roller Compacted Concrete II*, San Diego, CA.

Clark, D.E. & Oliverson, J.E., Sept. 1985, "Notes about the Roller Compacted Concrete Pavement at Burlington Northern Railroad's Intermodal Hub Facility, Houston, Texas," presented to Arizona Chapter Meeting of American Concrete Institute.

Colucci, B., 1988, "Roller Compacted Concrete Pavements," El Puente, Transportation Technology Transfer Center, University of Puerto Rico.

Delva, K.L., March 1988 "Renick Yard RCC Pavement Design and Construction," *Proceedings, ASCE Conference on Roller Compacted Concrete II*, San Diego, CA.

Hutchinson, R.L., Ragan, S.A. & Pittman, D.W., Feb.1987, "Heavy-Duty Pavements," *Concrete International: Design and Construction*, **Vol 9**, No.2

Jofre, C., Fernandez, R, Josa, A., & Molina, F. March 1988, "Spanish Experience with RCC Pavements," Proceedings, *ASCE Conference on Roller Compacted Concrete II*, San Diego, CA.

Josa, A., Jofre, C., & Molina, F.,1986, "An Experimental Overlay with Rolled Concrete, ACI SP 93-11, American Concrete Institute, Detroit, Mich.

Knickerbocker, K.L.,July 1987, "Roller Compacted Concrete for Repair of Sludge Lagoons," *Southwest Contractor,* Phoenix, AZ pp 19. 23, 53.

Koehi, Stefan, Oct. 1979, "New Dryland Sort at Port McNeill," British Columbia Lumberman, Vancouver, BC, Canada.

Logie, C.V., & Oliverson, J.E., Feb.1987, "Burlington Northern Railroad Intermodal Hub Facility," *Concrete International: Design and Construction*, **Vol 9**, No.2 pp. 37-41.

Malisch, W.R., Jan.1988, "Roller Compacted Concrete Pavements," *Concrete Construction*, pp 13-17.

Mueller, Paul E., Oct. 1986, "An Introduction to Roller Compacted Concrete', *Arizona Roads Newsletter*, Center for Advanced Research in Transportation, Arizona State University

Nanni, A., May-June 1988, Limestone Crusher-Run and Tailings in Compaction Concrete for Paving Applications," *American Concrete Institute, Materials Journal*, pp 158,163

Nanni, A. & Johari, A., March 1989, "RCC Pavement Reinforced with Steel Fibers," *Concrete International: Design and Construction*, pp. 37-41.

Palmer, W.D., Feb. 1987, "One Tough Pavement," *Concrete International: Design and Construction*, **Vol 9**, No.2 pp. 25-29.

Pittman, D.W., March 1988, "RCC Pavement Construction and Quality Control," *Proceedings, ASCE Conference on Roller Compacted Concrete II*, San Diego, CA.

Pittman, D.W. & White, T.D., April 1985, "Roller Compacted Concrete Pavements," *Proceedings, Third Int'l. Conference on Concrete Pavement Design and Rehabilitation.*, Purdue University, Lafayette, Ind.

Ragan, S.A., 1986, "Evaluation of the Frost Resistance of Roller Compacted Concrete Pavements," *TRB Record 1062*, Transportation Research Board, Washington, D.C.

Rollings, R.S., Mar.1988,"Design of Roller Compacted Concrete Pavements," *Proceedings, ASCE Conference on Roller Compacted Concrete II*, San Diego, CA.

Schrader, E., Sept-Oct. 1977, "Roller Compacted Concrete," *Military Engineer,* The American Society of Military Engineers

Schrader, E.,Paxton, J., & Ramakrishnan, V., 1985, "Composite Concrete Pavements with Roller Compacted Concrete," *TRB Record 1003*, Transportation Research Board, Washington, DC

Schweizer, E & Raba, G.W., March 1988, Roller Compacted Concrete with Marginal Aggregates". *Proceedings, ASCE Conference on Roller Compacted Concrete II*, San Diego, CA.

Schmidt, Michael, April 1989, "Experiences and New Developments in Concrete Road Construction in the Federal Republic of Germany," Proceedings, *4th Int'l. Conference on Concrete Pavement Design and Rehabilitation*, Purdue University, pp 301-310.

Stetzer, S.W., & King, R., Jan.23, 1986, "Smoothing Out the Bumps in RCC," *Engineering News Record*, pp 106-107.

Stewart, R.F. & Schexnayder, C.J., 1986, "Construction Techniques for Roller Compacted Concrete," TRB Record 1062, Transportation Research Board, Washington, DC.

Tayabji, S.D., & Okamoto, P.A., 1987, "Bonding of Successive Layers in Roller Compacted Concrete," Report to the US Bureau of Reclamation by Construction Technology Laboratory, Skokie, Illinois.

Tayabji, S.D., & Okamoto, P.A., 1987, "Engineering Properties of Roller Compacted Concrete," *TRB Record 1136*, Transportation Research Board, Washington, DC.

August 1976, "Compaction Study of Zero-Slump Concrete," *Misc. Paper S-76-16*, US Army Waterways Experiment Station, Vicksburg, Miss.

1983, "Roller Compacted Concrete for Pavements, Canadian Portland Association, Vancouver, B.C.

1986, "Aircraft Parking Apron Paved with Roller Compacted Concrete," Concrete in Transportation - *Job Report No. 33*, Portland Cement Association, Skokie, Ill.

1984, Portland Cement Association, "Thickness Design for concrete Highway and Street Pavements," EB109.01P.

January, 1986, "Smoothing Out the Bumps in RCC," *Engineering News Record*, pp 106-107.

July 1986, "First Use of RCC in Arizona," *Southwest Contractor*.

January 1987, "Roller Compacted Concrete Pavement at Portland International Airport - Fact Sheet," Port Of Portland, Oregon.

January 1988, "Roller Compacted Concrete Pavements," *Concrete Construction*, pp 13-17.

October, 1988, "Paver Builds Concrete Business with Asphalt- Derived Equipment," *Concrete Products*, pp 50-52.