ACT 64

Report No. FAA-RD-80-110

# POROUS PORTLAND CEMENT CONCRETE; THE STATE OF THE ART

MAJ Alfred Monahan

U. S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION
STRUCTURES LABORATORY
P. O. BOX 631, VICKSBURG, MISS. 39180

JANUARY 1981
FINAL REPORT

Document is available to the public through the
National Technical Information Service,
Springfield, Va. 22151

Prepared for

U. S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Systems Research & Development Service
Washington, D. C. 20591

**Technical Report Documentation Page**

1. Report No.
FAA-RD-80-110

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
POROUS PORTLAND CEMENT CONCRETE; THE STATE OF THE ART

5. Report Date
January 1981

6. Performing Organization Code

7. Author(s)
MAJ Alfred Monahan

8. Performing Organization Report No.

9. Performing Organization Name and Address
U. S. Army Engineer Waterways Experiment Station
Structures Laboratory
P. O. Box 631, Vicksburg, Mississippi 39180

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
DOT-FA79WAI-131

12. Sponsoring Agency Name and Address
U. S. Department of Transportation
Federal Aviation Administration
Systems Research and Development Service
Washington, D. C. 20591

13. Type of Report and Period Covered
Final Report
January to July 1980

14. Sponsoring Agency Code
ARD-530

15. Supplementary Notes

16. Abstract

This study investigates the current state of the art relating to the production and use of those porous portland cement concretes that may be suitable for the construction of porous portland cement friction courses. Porous concretes produced by gap grading or elimination of the fine aggregate fraction were found to have been used in both pavement and nonpavement applications with varied degrees of success. Nonpavement applications discussed include: porous draintiles and drains, porous concrete floors in greenhouses, and a porous concrete blanket placed on an earthfill dam.

Pavement applications discussed include: a no-fines pavement layer, porous portland cement concrete pavements, and porous pavement edge drains or porous hard shoulders.

Evidence as to the suitability of porous portland cement concretes for the construction of porous portland cement friction courses is inconclusive. The successful use of porous concretes in other pavement applications does, however, suggest that porous concretes may be useful in the construction of friction courses.

17. Key Words
Porous portland cement concrete
Porous concrete
No-fines concrete
Gap-graded concrete
Pervious concrete
Porous pavements

18. Distribution Statement
Document is available to the public through the National Technical Information Service, Springfield, Virginia 22151.

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
31

22. Price

**Form DOT F 1700.7** (8-72) Reproduction of completed page authorized

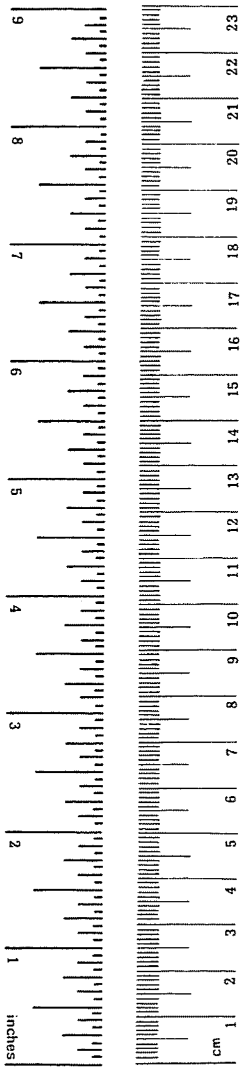
# METRIC CONVERSION FACTORS

## Approximate Conversions to Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | *2.5 | centimeters | cm |
| ft | feet | 30 | centimeters | cm |
| yd | yards | 0.9 | meters | m |
| mi | miles | 1.6 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 6.5 | square centimeters | $cm^2$ |
| $ft^2$ | square feet | 0.09 | square meters | $m^2$ |
| $yd^2$ | square yards | 0.8 | square meters | $m^2$ |
| $mi^2$ | square miles | 2.6 | square kilometers | $km^2$ |
| | acres | 0.4 | hectares | ha |
| | | **MASS (weight)** | | |
| oz | ounces | 28 | grams | g |
| lb | pounds | 0.45 | kilograms | kg |
| | short tons (2000 lb) | 0.9 | tonnes | t |
| | | **VOLUME** | | |
| tsp | teaspoons | 5 | milliliters | ml |
| Tbsp | tablespoons | 15 | milliliters | ml |
| fl oz | fluid ounces | 30 | milliliters | ml |
| c | cups | 0.24 | liters | l |
| pt | pints | 0.47 | liters | l |
| qt | quarts | 0.95 | liters | l |
| gal | gallons | 3.8 | liters | l |
| $ft^3$ | cubic feet | 0.03 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.76 | cubic meters | $m^3$ |
| | | **TEMPERATURE (exact)** | | |
| °F | Fahrenheit temperature | 5/9 (after subtracting 32) | Celsius temperature | °C |

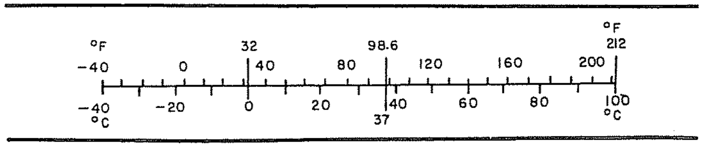
---

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



## Approximate Conversions from Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.04 | inches | in |
| cm | centimeters | 0.4 | inches | in |
| m | meters | 3.3 | feet | ft |
| m | meters | 1.1 | yards | yd |
| km | kilometers | 0.6 | miles | mi |
| | | **AREA** | | |
| $cm^2$ | square centimeters | 0.16 | square inches | $in^2$ |
| $m^2$ | square meters | 1.2 | square yards | $yd^2$ |
| $km^2$ | square kilometers | 0.4 | square miles | $mi^2$ |
| ha | hectares (10,000 $m^2$) | 2.5 | acres | |
| | | **MASS (weight)** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.2 | pounds | lb |
| t | tonnes (1000 kg) | 1.1 | short tons | |
| | | **VOLUME** | | |
| ml | milliliters | 0.03 | fluid ounces | fl oz |
| l | liters | 2.1 | pints | pt |
| l | liters | 1.06 | quarts | qt |
| l | liters | 0.26 | gallons | gal |
| $m^3$ | cubic meters | 35 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.3 | cubic yards | $yd^3$ |
| | | **TEMPERATURE (exact)** | | |
| °C | Celsius temperature | 9/5 (then add 32) | Fahrenheit temperature | °F |



# PREFACE

This study was conducted under authority of the U. S. Department of Transportation, Federal Aviation Administration, Inter-Agency Agreement No. DOT-FA79WAI-131, "Portland Cement Porous Friction Course."

The administration of this inter-agency agreement was accomplished by Messrs. Raymond Rollings and Harry Ulery, engineers of the Pavement Systems Division, Geotechnical Laboratory, U. S. Army Engineer Waterways Experiment Station (WES). Engineers of the Structures Laboratory (SL), WES, who were actively engaged in this investigation were MAJ Alfred Monahan and Mr. George Hoff. The work was performed under the general supervision of Messrs. John Scanlon, Chief, Concrete Technology Division, and Bryant Mather, Chief, SL. The report was prepared by MAJ Alfred Monahan.

COL Nelson P. Conover, CE, was Commander and Director of the WES during the conduct of this study and publication of this report. Mr. Fred R. Brown was Technical Director.

# TABLE OF CONTENTS

# BACKGROUND

The development and use of open-graded or porous asphalt friction courses in the last 15 to 20 years has served to greatly alleviate the problem of vehicular hydroplaning on wet highway and airfield pavements. Various methods of improving skid resistance and reducing hydroplaning on rigid pavements have been examined, resulting in the acceptance of grooving as the most feasible solution to hydroplaning problems. Little consideration to date has been given to the possibility of constructing friction courses with portland cement or any other hydraulic cements as the binder, probably because of concerns with durability. The rising costs for petroleum-based products will make portland cements more competitive with asphalt binders; thus the possibility of constructing porous friction courses using portland cement is being examined.

# POROUS CONCRETES

Porous portland cement concretes can be produced by at least three distinct methods. Cellular concretes are made by either introducing a preformed foam into the fresh mortar or causing the creation of gas bubbles in the mortar due to a chemical reaction. Lightweight aggregate concrete is made with either natural or synthetic aggregates, which are often extremely porous. The use of gap-graded aggregates or the total elimination of the fine aggregate fraction in the proportioning of concrete (no-fines concrete) can also result in a porous structure.

While all of these concretes are by definition porous, they possess differing void structures. Cellular and lightweight aggregate concretes can contain large percentages of voids, but these voids are relatively noncommunicating. Porous concretes produced by intentional gap grading or without fine aggregates can result in concrete with high percentages of interconnected voids.

Those porous concretes with noncommunicating voids may absorb small amounts of moisture, but they would not allow rapid passage of water through the concrete. For this reason, cellular and lightweight aggregate concretes are not given further consideration in this report. The remainder of this report will examine the state of the art relating to the production and use of porous concretes that may be applicable to the construction of porous portland cement friction courses.

# GAP-GRADED CONCRETES

Gap-graded concretes are produced by omitting particles of certain sizes from the aggregates when the concretes are proportioned. Proponents of gap grading claim that significant advantages result from its use including: more efficient packing, which produces greater compressive strengths by transferring stresses from particle to particle; lower possible water-cement ratios; lower required cement contents due to less specific surface; and lower creep and drying shrinkage.[1] Others suggest that evidence on the advantages of using gap grading is not substantial and point out that gap-graded concretes have a tendency to segregate at high slumps. Thus gap-graded concretes will often require additional internal vibration at the lower slumps used to prevent segregation.[2] The most common practice in proportioning concretes is to use the best available combination of aggregates to achieve a workable mixture with the desired compressive strengths. Economics often dictate degrees of gap grading to reduce the number of stockpiles required.

Concretes made with gap-graded aggregates are not necessarily porous. In fact, the majority of gap-graded concretes are proportioned to produce dense concretes with a minimum of voids. However, porous concrete can be produced using gap-graded aggregates. No-fines concrete is an extreme case of gap grading that results in a porous structure. Other porous concretes made using gap-graded aggregates are not correctly identified as no-fines concretes because they contain small amounts of fine aggregate. The advantages claimed for gap grading do not necessarily apply to porous gap-graded concretes since some of the advantages cited are based on the production of dense concretes.

# NO-FINES CONCRETE

No-fines concrete made with hydraulic cement (portland or blended),[3] coarse aggregate, and water has been used in building construction since at least the middle of the nineteenth century.[4] European countries have used no-fines concrete in different modes: cast in place load-bearing walls, prefabricated panels, steam-cured blocks, and limited pavement applications. Experience with no-fines concrete in North America seems to have been limited to laboratory experimentation[3] and small test projects such as the construction of a no-fines concrete building in 1939 at Coulee Center near Grand Coulee Dam.[5]

Aggregate gradings used in no-fines concrete are typically either single-sized coarse aggregate or gradings between 3/4 and 3/8 in. With the fine fraction omitted, no-fines concrete produces a lightweight porous concrete. Rounded and crushed aggregates, both normal and lightweight, have been used to make no-fines concrete.[6]

Mixture proportions are determined on the basis of the optimum water-cement and aggregate-cement ratios necessary to achieve a desired compressive strength. Lean mixtures with water-cement ratios of 0.35 to 0.50 are necessary to ensure that sufficient mortar is present to coat the aggregate particles but prevent the mortar from flowing off the aggregates. Aggregate absorption can significantly influence the desired water content. Optimum aggregate-cement ratios vary with types of aggregates, but higher ratios tend to produce lower compressive strengths.[7] Compressive strengths are much less than those of dense concretes with the maximum reported strengths slightly exceeding 2000 psi. As in cellular concretes, compressive strengths are closely related to unit weights. When proportioned with normal-weight aggregates, no-fines concrete will be approximately 70 percent the weight of dense concrete.

The high percentage of voids present reduces susceptibility to capillary action and increases the thermal insulation properties. Rapid drying due to the open surface texture and void structure also can result in the development of shrinkage cracks if proper curing techniques are not followed. For this reason, moist curing for periods up to seven days is recommended when using normal portland cements.

The absence of the fine aggregate fraction results in a discontinuous (noncohesive) mixture that requires little compaction and is often termed self-compacting. In fact, excessive compaction or vibration may result in removal of the mortar coating from the aggregate.

Drying shrinkage is much less of a problem with no-fines concrete when normal-weight aggregates are used. Thus the result is a reduced requirement for contraction joints in certain types of building construction.[8]

Tests conducted by Malhotra[3] have shown that the entrainment of air in no-fines concrete can result in significant improvements in resistance to freezing and thawing. No-fines concrete with a water-cement ratio of 0.41 and 3 percent entrained air was able to withstand 266 cycles of freezing and thawing (ASTM Standard Method C 666-73)[9] as compared with 73 cycles for a similar concrete without entrained air. Data on the reductions in strength that could be caused by air entrainment were not available.

Although various authors refer to the fact that no-fines concrete is very permeable and that water will very rapidly pass through specimens, few data are available on the mixture proportions or construction practices necessary to achieve varying permeabilities.

## NONPAVEMENT APPLICATIONS OF POROUS CONCRETES

In reviewing the available literature and discussing the subject of porous concretes with people involved in the field of concrete technology, several scattered applications of porous concretes were discovered. The use of porous concretes for their ability to pass or drain water could not be considered widespread. Experience has generally tended to make engineers strive to produce impermeable concretes, especially when the concrete is to be subjected to the actions of water.

The following three examples depict well-documented uses of porous concretes. Other examples were found, but documentation as to their mixture proportion or suitability was not readily available.

Concretes used to produce porous pipes are not discussed because they are normally steam cured.

### POROUS DRAINTILES AND DRAINS

Porous concretes have been used in the past by the Water and Power Resources Service (WPRS, formerly the U. S. Bureau of Reclamation (USBR)) to construct porous draintiles as well as drains beneath hydraulic structures to relieve uplift pressures, and to drain groundwaters from beneath sewer pipes. These concretes are produced by using gap-graded or single-sized aggregates, between No. 4 to 3/8 in. or 3/8 in. to 1/2 in., low-water cement ratios, and a minimum cement content only sufficient to bind the particles together. Type V cement is recommended where sulfate attack is an expected problem. The USBR _Concrete Manual_ indicates that concretes for porous concrete drains beneath sewer pipes should have compressive strengths in excess of 1000 psi and should be able to pass water at a rate of at least 10 gal/min/sq ft when a 4-in. water depth is maintained on a 12-in.-thick slab.[10]

A study conducted by the USBR on no-fines concretes similar to those cited for draintiles or drainage bases concluded that porous concretes had low resistance to freezing and thawing when tested by accelerated methods using saturated specimens. The specimens tested failed within 9-16 cycles by breaking through the middle.[11] It was pointed out that because of the rapid drainage characteristics of porous concretes, such saturated conditions were not likely to occur. This suggests that actual resistance to freezing and thawing could be greater than that produced in the laboratory. Test specimens with a 0.33 water-cement ratio and a 5.5 aggregate-cement ratio achieved a 28-day compressive strength of 2610 psi. Test results do not contain any indication on the use of entrained air.

Two problems cited from recent work by the WPRS were the failure due to leaching of a porous concrete beneath the spillway on the Fresno Dam, California, and difficulty with achieving field porosities equal to laboratory results for a porous concrete placed beneath the Welton-Mohawk Canal in New Mexico.[12]

## POROUS CONCRETE FLOORS IN GREENHOUSES

Researchers at Rutgers University have used a porous concrete floor in plastic greenhouses as part of a solar heating system.[13] The floor system, which is capped with 3 in. of porous concrete, serves as a storage area and heat exchanger for the solar-heated greenhouse. A cubic yard of the porous concrete contained 6 bags (564 lb) of cement, 2800 lb of 3/8-in. aggregate, and 20 to 25 gal of water. Expected compressive strengths were between 500 and 600 psi. Data on the permeability of this mixture were not available.

## POROUS CONCRETE BLANKET--SANTEE COOPER DAM

Use of a porous concrete was reported in an investigation conducted to determine the reasons for deterioration of a porous concrete blanket, 10 in. thick, placed on the upstream face of Santee Cooper Dam, South Carolina.[14] The concrete blanket was constructed of rounded quartz aggregate approximately 3/4-in. nominal maximum size with what appeared to be type I portland cement. When investigated nearly two years after placement, the concrete blanket, which extended below the waterline, had been eroded approximately 1/2 in. because of wave action and water flow. Cores taken from above the high-water mark indicated that the concrete was generally sound. Compressive tests conducted on these cores revealed average compressive strengths ranging from 1325 to 1560 psi. Cores taken from below the high-water mark were often found to show signs of deterioration and discoloration. It was determined that the deterioration of the porous concrete was caused by a combination of acid attack from the soil, possible sulfate attack, wave action, and water flow.

# PAVEMENT APPLICATIONS OF POROUS CONCRETES

Investigation into applications of porous portland cement concretes in the field of pavements revealed attempts to use porous concretes in three areas: (1) pavement edge drains or shoulders, (2) porous pavement layers, and (3) completely porous pavements. With the exception of porous concretes used by the French Laboratoires des Ponts et Chausees all experimentations or commercial applications have been extremely limited. Efforts were made in the United Kingdom to develop skid-resistant, freely draining no-fines concrete pavements, but this approach has been dropped in favor of using grooved pavement surfaces. Two developers in the United States are currently promoting completely porous pavements, and the California Department of Transportation has recently installed an edge drain section of porous concrete on an interstate highway. By far the most experimentation appears to have been done by French engineers, who are routinely using porous concrete in highway construction for drainage purposes.

## NO-FINES PAVEMENT

Engineers in the United Kingdom have experimented with the monolithic casting of a no-fines surface pavement layer over a conventional rigid pavement to take advantage of the drainage properties of no-fines concrete.[15] The 600-ft-long test road section constructed in Nottinghamshire consisted of a 2-in.-thick surface layer cast on top of 8 in. of wire mesh reinforced dense concrete. The no-fines concrete, which had an expected density of 90 lb/cu ft, was made using single-sized, 3/8-in. crushed granite, an aggregate-cement ratio of 4:1, and a moisture content of 6 to 7 percent. Anticipated compressive strengths at 28 days were 2000 psi.

Placement of the no-fines layer occurred within 30 min after the materials were mixed, and compaction of the base slab was completed. A layer, 2-1/2-in. thick, was placed and leveled by hand to result in a compacted layer of 2 in. Compaction was accomplished with six passes of a 12-in.-diam pipe (30 lb/ft minimum) although mechanical rolling was considered feasible for larger projects. Polyethylene sheets were used to cover the surface for seven days.

Transverse doweled contraction joints were placed at 33-ft intervals. Grooves, 1-in. wide and 3-1/2-in. deep, were formed in the composite pavement and partially filled with a bituminous sealing compound. The completed joint extends through the no-fines surface layer into the base slab approximately 1-1/2 in.

Early reports indicated that the test section was performing well; however, the project was not considered a long-term success.[16] Because the pavement had been constructed in a rural area, farm machinery entering from field access roads caused the pores of the no-fines concrete to fill up with soil. These areas tended to pond water, and surface deterioration was noted. Damage may have been due to freezing and thawing action, hydraulic pumping, or a combination of the two factors. Further research into the use of no-fines concrete roads in the United Kingdom has been abandoned. Other applications for roof pavements (parking garages) and tennis courts have evidently continued.[17]

## POROUS PAVEMENTS

In an apparent response to local ordinances prohibiting the development of increased runoff flows from new pavements constructed in the Sarasota, Florida, area, two developers are experimenting with and promoting the construction of porous portland cement concrete pavements. These pavements would allow drainage of water vertically through the pavement. Similar pavements using asphalt cement have been developed and have received limited application for parking lots and service roads.[18] None of the porous asphalt pavements were constructed to withstand heavy high-speed wheel loads.

The first of these porous concretes is patented as a "porous pavement."[19] The pavement structure consists of a porous concrete layer constructed over successive layers of compacted aggregate and porous fill. The porous concrete is proportioned with portland cement, medium-sized crushed aggregate, and a liquid adhesive mixture. Aggregate-cement ratios of 3:1 are used. Gradings of the aggregate are usually between 1/4 and 1/2 in. Other mixtures with larger aggregates would incorporate small amounts of sand. Admixtures used include an air-entraining agent and a "single component water-base epoxy vinyl acrylic emulsion." Other polymer admixtures may be used to achieve specific strength requirements. The mixtures are proportioned for low slumps between 0 and 1-1/2 in. Type I portland cement is used. Laboratory testing is necessary to determine the specific component volumes required to achieve the desired porosity. Accordingly, unit weights vary with porosity.

The only test data available on the strength and durability of these porous concretes are contained in test reports presented in literature published by Porous Concrete, Incorporated.[20-22] These reports indicate that 28-day compressive and flexural strengths of 4000 and 650 psi, respectively, may be achieved. Other reported test results indicate improvements in resistance to freezing and thawing, abrasion, and scaling. Actual numerical test data are not available, however, since the reports only quote precentage improvements based on ASTM standard tests when compared with similar concrete mixtures without admixtures. Tests for skid resistance are not known to have been conducted.

The polymer admixture referred to in the patent (single component water-base epoxy vinyl acrylic emulsion) appears to be a proprietary modification of a vinyl acrylic polymer. Polymer portland cement concrete made with such latex emulsions can exhibit increased durability and adhesion.[23] As an emulsion, the admixture probably has a positive effect on resistance to freezing and thawing due to the air that would be entrained by the emulsifier. These emulsions are commonly used in combination with defoaming agents to prevent an unintentional entrainment of air. Controlled mixing may be necessary to prevent excessive entrainment of air if defoaming agents are not used. It should be pointed out that some latexes are pH sensitive and could hydrolyze because of the alkaline environment of portland cement, resulting in a strength loss with time. Compression tests on saturated specimens are recommended to determine whether this is true for a particular polymer.[24]

Actual construction of porous pavements using this patent has been limited to test strips and construction of a church parking lot in Sarasota, Florida. At least one of the test strips was placed using commercially available paving equipment. Materials for the test strip were mixed on site, spread by a paving machine, and rolled with a steel wheel roller. The church parking lot, which has been the only commercial application to date, was placed and rolled by hand primarily because the parking stalls were to be delineated by inserting pressure-treated lumber in the pavement. Approximately 40 cu yd of concrete were placed in a 4-in.-thick unreinforced layer over an existing crushed shell base. The mixture contained a crushed limestone, graded from 3/8 in. by No. 16, and unspecified amounts of cement, water, and admixtures.

A visit to the church parking lot approximately one year after completion (Figure 1) found the lot in excellent condition. No raveling or deterioration was evident. However, it had not been subjected to high-speed, heavy vehicle loads or a significant number of cycles of freezing and thawing. Despite heavy rains the day previous to inspection, large quantities of leaves from an overhanging tree still littered the pavement indicating that sheet flow had not occurred or the debris would have washed off the lot. The rain evidently passed directly

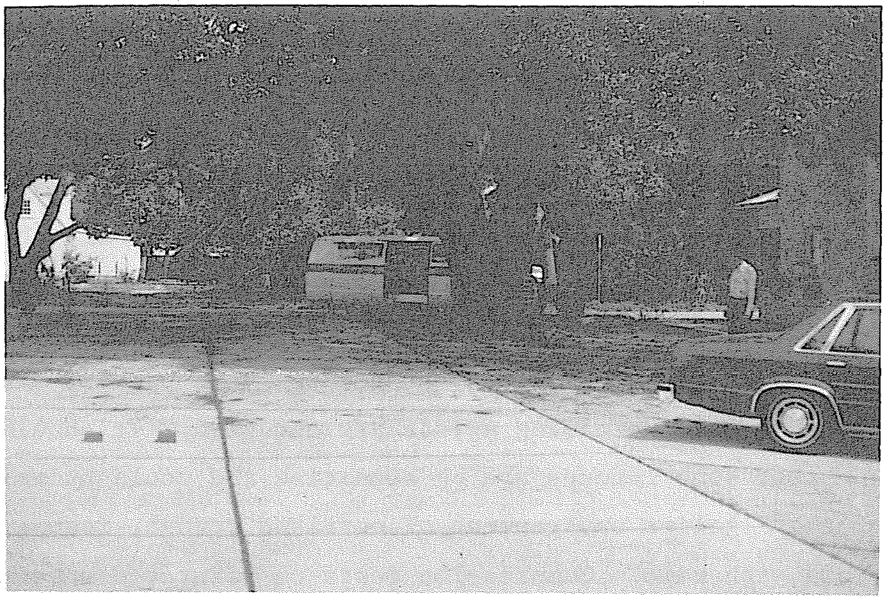


Figure 1. One-year condition of a porous concrete parking lot

through the pavement and was dissipated by the crushed shell base. A garden hose was discharged onto the pavement to confirm its permeability. Initially, the water had a tendency to flow on top of the pavement (Figure 2), but after wetting an area it began to drain rapidly (Figure 3). To ensure the pavement per se was permeable, care was taken not to place the hose near a pavement joint. The surface texture was fairly smooth (Figure 4) but open. Smoother textures may be obtained by overlaying the surface with a finer aggregate mixture (as shown by the block in Figure 5).

Further commercial applications of porous pavements are planned for subdivisions to be constructed in New Jersey and Pennsylvania during 1980. These projects may provide the cost data that are now lacking for construction using commercial equipment. Cost data cited in the brochures are based on projections rather than actual experience.

From discussions with the inventor, it was learned[25] that (1) air curing was adopted to prevent surface raveling which had occurred on an early test strip; (2) when the porous concrete was moist cured, the polymer admixtures settled causing a weakening of the top surface of the pavement; (3) neither contraction joints nor reinforcement have been used in the work to date; (4) a possible solution to corrosion of reinforcement in a porous material is the use of coated reinforcing; (5) patching methods other than overlay techniques have not yet been developed; and (6) the overlay method could be used to construct a porous friction course although the inventor favors a porous pavement.

The other porous concrete being promoted in Florida is termed "pervious concrete" and is made with single-sized aggregate, normal portland cement, and water (no admixtures are used). The production of this concrete differs in a number of ways. Mixing of the concrete is accomplished in two stages. First, the grout is mixed in a high-speed mixer, and then the grout and aggregate are combined in a conventional mixer. The concrete is placed using a paving machine developed to place and compact the zero-slump concrete, and the concrete is moist cured by covering with polyethylene sheets.

Test data on the properties of this no-fines concrete are not

Figure 2. Initial surface ponding of water after rapid flooding

Figure 3. Drained surface of parking lot shortly after flooding

Figure 4. Reasonably smooth, open texture on parking lot

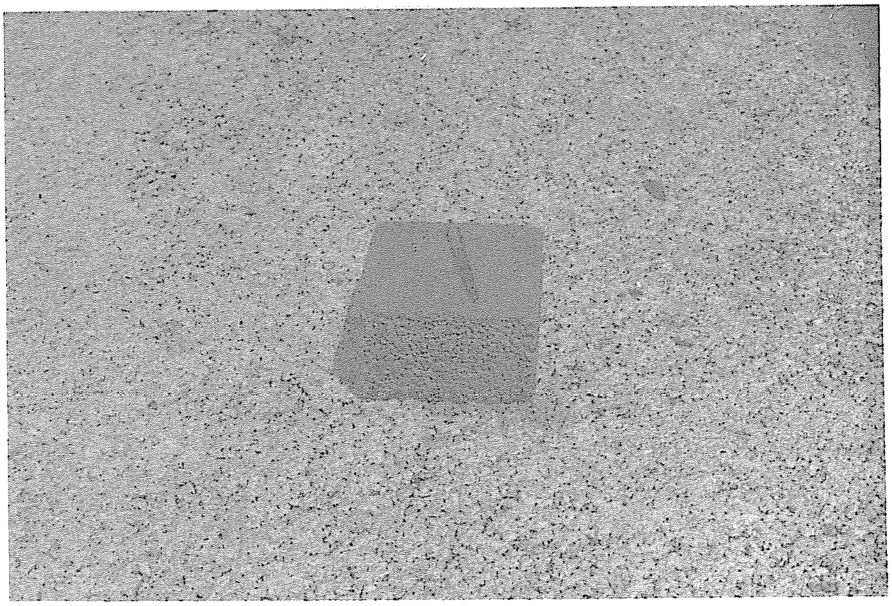


Figure 5. Smoother surface textures resulting from overlays of finer aggregate mixtures (as shown by block)

available other than a claimed drainage capacity in excess of 10 in. of rainfall per minute. Although the developers have produced different mixtures to alter porosity and surface texture, standard ASTM tests have not been conducted. The mixing of the grout in a high-speed mixer is reported to give improved concrete strengths. Reports on programs to determine if high-speed slurry mixing does improve concrete strength properties have given conflicting results.[26] The most recent results suggest that high-speed slurry mixing may not be responsible for increasing concrete strengths.[27]

One test strip, 3-1/2 in. thick, has been constructed using the small-scale equipment developed to validate the concept of placing the low-slump concrete. The mixture used 3/8-in. crushed gneissic granite aggregate, a 0.43 water-cement ratio, and 2800 lb of aggregate. This strip was approximately six months old when observed and was in excellent condition. However, because of its location and size, the strip had received little traffic other than vehicles used to test its skid resistance (Figures 6 and 7). A stream of water directed from a hose onto a section taken from the pavement demonstrated the relative permeability of the concrete (Figure 8).

The paving machine (Figures 9 and 10) has a triangular cross-section hopper (Figure 11) that is raised and dropped to extrude concrete. Tamping action is applied by the bottom of the hopper and a series of pneumatic tampers arranged across the rear of the paver (Figure 10). As presently configured, the tamping feet produce slight ridges at their interface. The paver travels at about 4 ft/min. According to the inventor, the special equipment was developed because of the difficulty experienced in using conventional paving equipment to place very low-slump concrete.

During further discussions with the inventor, the following areas were addressed.[28] Air entrainment is thought to be unnecessary since the concrete drains so rapidly. Overlays to produce porous friction courses may be possible, but he favors porous pavements. Repairs would be accomplished by overlays. Reinforcement and contraction joints are considered unnecessary. Construction cost figures, while not

Figure 6. Overall view of skid resistance test strip of pervious concrete

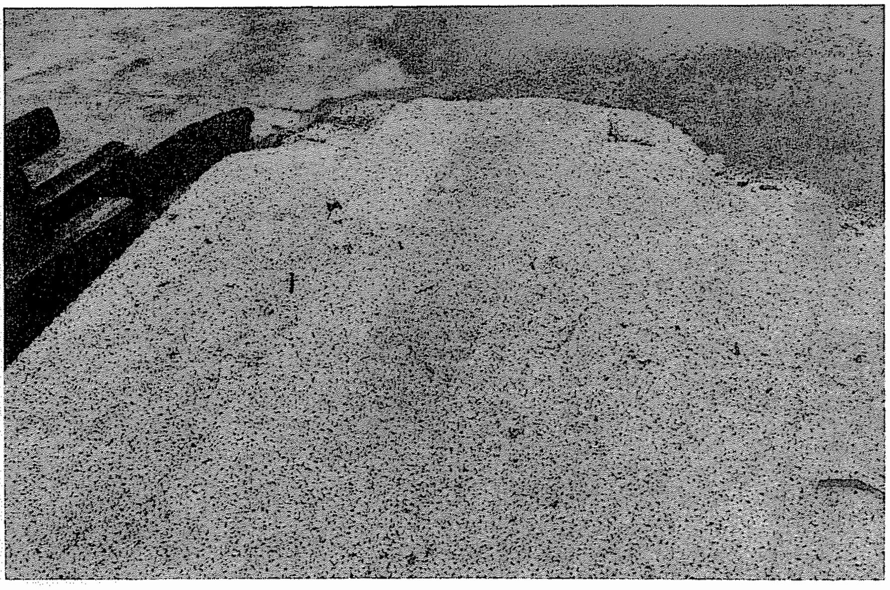


Figure 7. Close-up of skid resistance test strip of pervious concrete showing surface texture

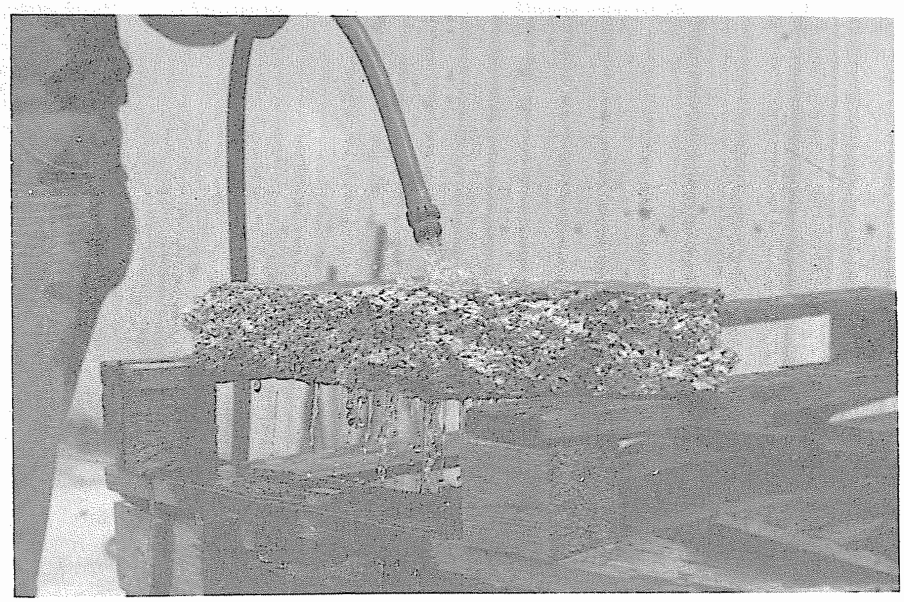


Figure 8. Demonstrated permeability of pervious concrete

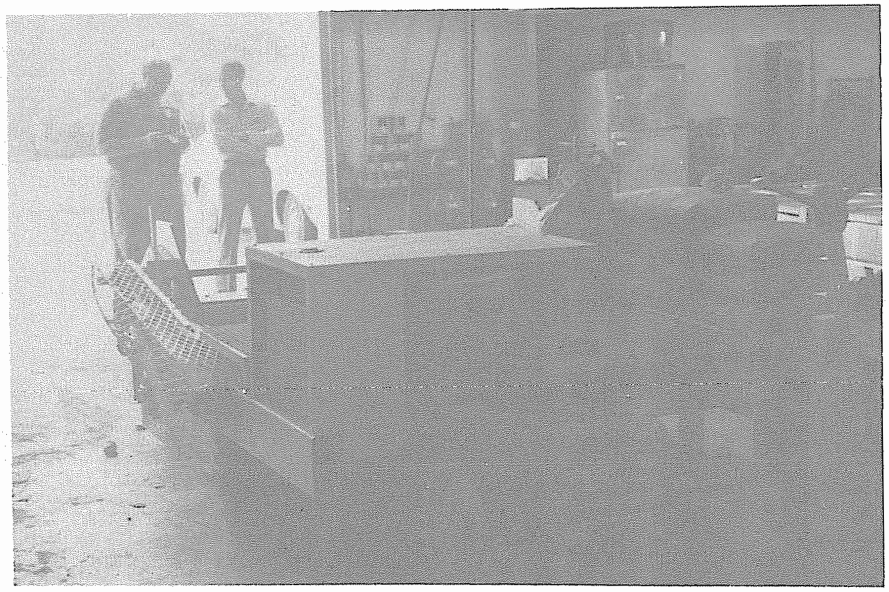


Figure 9. Paving machine used to place pervious concrete

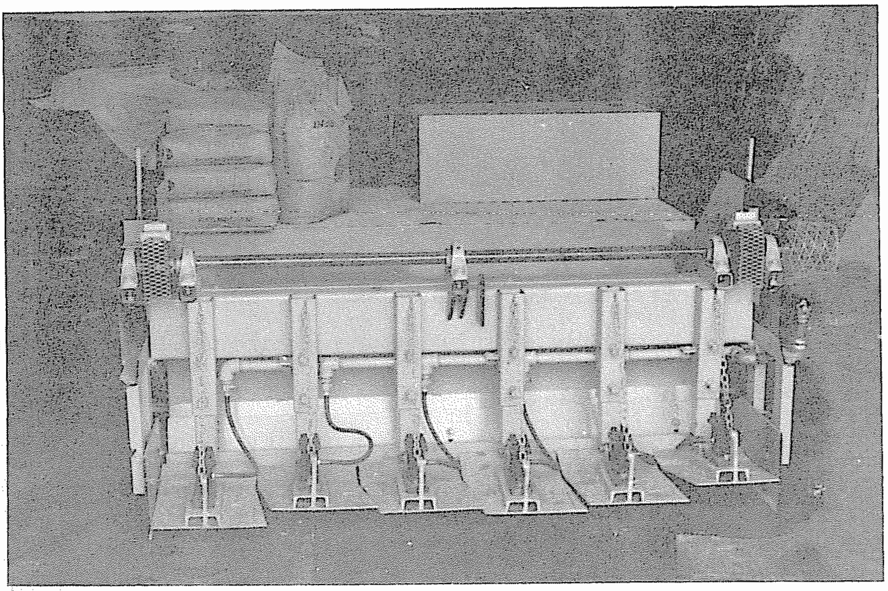


Figure 10. Rear view of paving machine showing pneumatic tampers

Figure 11. Triangular cross-section hopper used to extrude concrete from paving machine

available are thought to be reduced because finishing is unnecessary. Several patents on the equipment to mix and place pervious concrete are in the processing stages.

## PAVEMENT EDGE DRAINS OR POROUS HARD SHOULDERS

The most extensive experimentation with the use of porous portland cement concretes has been done in France at the Laboratoires des Ponts et Chausees. Efforts to reduce pumping beneath concrete pavements have led to the rather routine use of porous lean concrete layers in the shoulders of highways adjacent to concrete pavements as a means of rapidly draining water from the pavement structure. The shoulders constructed of porous concretes are not intended as wearing courses but are surfaced often with a bituminous mix.

Although various mixtures have been tried, a typical mixture would seem to make use of coarse crushed aggregate between 0.2-0.8 in. (5 and 20 mm), small amounts of sand weighing between 169 and 508 lb/cu yd (100 and 300 kg/$m^3$), and a cement content of approximately 270 lb/cu yd (160 kg/$m^3$) . Water-cement ratios have been found to vary between 0.36 and 0.55.[29] Air-entraining admixtures are used to increase the resistance to freezing and thawing of the mortar binder. Most mixtures were found to use either portland blast furnace slag cement or pozzolanic blast furnace slag cement. Cement choices are made based on the desired resistance to water and an appropriate rate of strength gain.[30]

Compressive strengths achieved by the differing mixture proportions are often less than 2000 psi at 28 days. Porosities between 15 and 25 percent have resulted in permeabilities of 6.84 to 9.5 $ft^3$/s/$ft^2$ (18 to 25 ℓ/s/$m^2$). These porosities have been found to nearly eliminate risk due to freezing, unless the concrete is allowed to become saturated. It has been suggested that the fatigue characteristics of porous concretes are similar to those of treated gravels.[30] Design compressive strengths take into account reduced fatigue strength due to porosity and possible chemical attack.

Satisfactory concrete placement has been accomplished using both side spreaders and slip-form machines. Side dumping from trucks or transit mixers results in uneven spreading and compaction problems. Selection of compaction equipment is dependent on the layer depth and leanness of the mixture. Care must be taken to ensure that the equipment selected can achieve proper densities at depths. A closed surface texture is desired. Curing is accomplished by coating the surface with emulsions within 15 to 30 min after placement. Failure to properly cure the porous concrete can result in rapid drying.

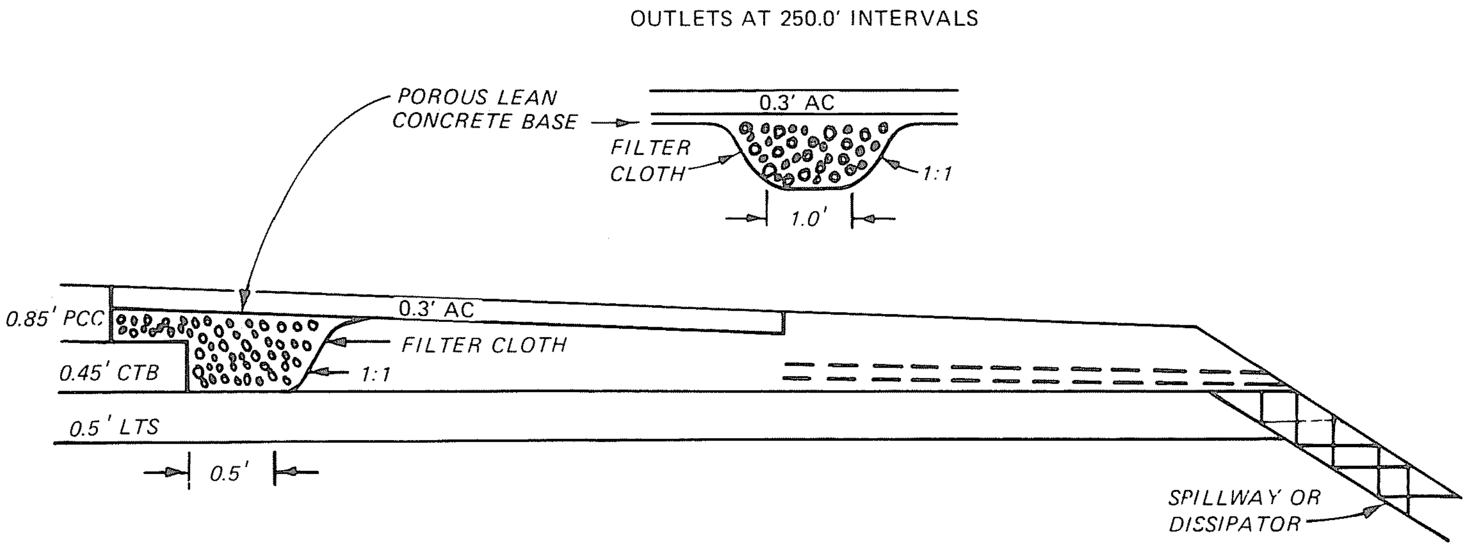
Extensive quality controls are suggested[31] for this type of construction, such as laboratory testing for minimum compressive strengths and porosities, and field check of materials, proportioning, equipment, and methods of construction. Acceptance tests to measure the drainage effectiveness are also conducted.

## PAVEMENT EDGE DRAINS (UNITED STATES)

Construction of a porous, lean concrete edge drain similar to the French designs has recently been completed by the California Department of Transportation.[32] The permeable concrete was installed on a section of Interstate 5 near Sacramento, and engineers report that the concrete is performing well to date. Figure 12 depicts a cross-sectional view.

Prior to installation, laboratory mixtures were tested using both a crushed (3/4 in. to No. 4) and a rounded (1 in. to No. 4) aggregate with water-cement ratios and aggregate-cement ratios between 0.35 and 0.41 and 6:1 and 8:1, respectively. Compressive strength and permeability tests were conducted to select optimum mixture proportions. Admixtures were not used in laboratory mixtures. Laboratory results showed 28-day compressive strengths and vertical permeabilities as high as 2400 psi and 15.8 gal/min (taped 12-in. cylinders), although not in the same mixtures.

The mixture proportion selected for use consisted of rounded aggregate graded from 1 in. to No. 4, an aggregate-cement ratio of 8:1, and a water-cement ratio of 0.36. Laboratory tests indicated a



NOTE: POROUS LEAN CONCRETE OUTLET TO EDGE OF ASPHALT CONCRETE WITH TWO PVC LONGITUDINAL OUTLET DRAINS FROM EDGE OF ASPHALT CONCRETE TO THE SPILLWAY.

Figure 12. Cross section of pavement edge drain, Interstate 5, near Sacramento, California

possible 28-day compressive strength of 2210 psi and a permeability of 8.2 gal/min.

The concrete was mixed on site in 5-cu-yd batches in an 8-cu-yd capacity central mixer. Bottom dump trucks were used to transport the concrete that was spread by the trucks as they straddled the trench. Laborers leveled the concrete with shovels, and a steel-wheel roller was used for compaction.

# CONCLUSIONS AND RECOMMENDATIONS

## CONCLUSIONS

From the review of the state of the art of porous concretes, it was concluded that:

- _a_. Efforts to produce porous, freely draining concretes have been scattered with variable results.
- _b_. Either gap-graded or no-fines concretes can be proportioned to produce freely draining concretes with permeabilities suitable for porous friction courses.
- _c_. Strengths expected of porous concretes are generally much less than those of dense concretes.
- _d_. Mixtures are proportioned by water-cement and aggregate-cement ratios. Lean mixtures are necessary to prevent filling of the voids by mortar.
- _e_. Resistance to freezing and thawing will be satisfactory if the porous concretes are not saturated when frozen.
- _f_. Air entrainment appears to significantly improve the resistance to freezing and thawing of no-fines concrete.
- _g_. Porous concretes have received some application in highway construction largely as drainage layers. Data on the suitability of porous concretes for surface courses are inconclusive.
- _h_. Polymer-modified portland cement concretes may be capable of producing porous concretes of superior strength and durability.
- _i_. Cost data for placement of porous pavements are not available due to limited commercial application.

## RECOMMENDATIONS

Based on this review of the state of the art of porous portland cement concretes, the following recommendations should be considered:

- _a_. Laboratory testing should be conducted to determine whether either no-fines concretes or other processes can satisfy the strength and durability requirements for porous friction courses.
- _b_. If the laboratory testing yields satisfactory results, controlled field tests should be conducted to verify the test results and develop recommended construction practices.
- _c_. Any future commercial applications of porous concretes should be closely monitored for cost and performance data.

# REFERENCES

1. Li, Shu-Tien, "Proposed Synthesis of Gap-Graded Shrinkage Compensating Concrete," Journal of the American Concrete Institute, No. 10, Proceedings, Vol 64, 1967, pp 654-661.
2. Neville, A. M., Properties of Concrete, Chapter 3, John Wiley and Sons, New York, 1973.
3. Malhotra, V. M., "No-Fines Concrete--Its Properties and Applications," Department of Energy Mines and Resources Mines Branch, Ottawa, Canada, 1974.
4. Francis, A. J., "Early Concrete Buildings in Britain," Concrete and Constructional Engineering (England), Vol 60, 1965, pp 73-75.
5. Malhotra, V. M., "A Low-Cost Concrete Building," Engineering News Record, 1939, pp 62-63.
6. Orchard, D. F., Concrete Technology, Chapter 4, Vol 1, John Wiley and Sons, New York-Toronto, 1973.
7. Raju, K. N. and Basavarajaiah, B. S., "Experimental Investigations of No-Fines Concrete," Journal of Institute of Engineering (India), Vol 55, 1975, pp 137-140.
8. Short, A. and Kinnibargh, W., Lightweight Concrete, Chapter 7, John Wiley and Sons, New York, 1963.
9. American Society for Testing and Materials, "Resistance of Concrete to Rapid Freezing and Thawing," Designation: C 666-73, 1974 Annual Book of ASTM Standards, Part 14, Philadelphia, Pa., 1974.
10. Bureau of Reclamation, Concrete Manual, Chapter VIII, Eighth Edition, U. S. Department of the Interior, Washington, D. C., 1975.
11. Bureau of Reclamation, "The Durability of Porous Concrete," Materials Laboratories Report No. 3-369, U. S. Department of the Interior, Washington, D. C., 1947.
12. Telephone conversation between author and Mr. Ed Harboe, Concrete Section, Water and Power Resources Services, Denver, Colo., 18 April 1980.
13. Mears, D. R. et al., "The Rutgers Solar Heating System," Presentation at Annual Meeting of American Society of Agricultural Engineers, 1977.
14. "Investigation of Porous Concrete Santee Cooper Dam," Letter Report from North Atlantic Central Concrete Laboratory to Office, Chief of Engineers, Washington, D. C., 1945.
15. Maynard, D. P., "A No-Fines Road," Concrete Construction, Vol 15, No. 3, 1970, pp 116-117.

16. Letter to author from Mr. D. P. Maynard discussing long term performance of No-Fines Road (Reference 15), 9 April 1980.

17. Personal communication between Mr. George Hoff, Waterways Experiment Station, and Mr. D. P. Maynard at Cement and Concrete Association, United Kingdom, April 1980.

18. Thelen, E. and Howe, L. F., "Porous Pavement," The Franklin Institute Press, Philadelphia, Pa., 1978.

19. Medico, J. J., Jr., "Porous Pavement," U. S. Patent 3,870,422, 1975.

20. Porous Concrete, Inc, "Porous Concrete Paving Specifications and Uses, 1979.

21. Medico, J. J., Jr., "The Story of Porous Concrete Pavement," Porous Concrete, Inc., 1979.

22. Medico, J. J., Jr., "Research and Development of Porous Concrete Paving," printed by J. J. Medico, Jr.

23. Concrete Society, "Polymer Concretes, Report of a Concrete Working Party," Technical Report No. 9, The Concrete Society, London, England, 1975.

24. Personal communication between author and Dr. Joseph Lavelle, Rohm and Haas Research Laboratory, Springhouse, Pa., 8 April 1980.

25. Personal communication between author and Mr. John J. Medico, Jr., 3 April 1980 at Sarasota, Fla.

26. MacInnis, C. and Thomson, D. V., "Special Techniques for Producing High-Strength Concretes," Journal of American Concrete Institute, No. 12, Vol 76, pp 996-1002.

27. MacInnis, C. and Kostenuik, Paul W., "Effectiveness of Revibration and High-Speed Slurry Mixing for Producing High-Strength Concrete," Journal of American Concrete Institute, No. 12, Proceedings, Vol 76, pp 1255-1260.

28. Personal communication between author and Mr. Harry Hodson, inventor of Pervious Concrete at Sarasota, Florida, 3 April 1980.

29. Ray, M., "Recent Developments in the Design of Rigid Pavements in France, Study of Performance of Old Pavements and Consequences Drawn from New Highway Construction," Proceedings, International Conference on Concrete Pavement Design, Purdue University, 15-17 February 1977, pp 265-277.

30. Nissoux, J. L. and Merrien, P., "Emergency Stopping Lanes of Porous Concrete; Study of the Material," Bulletin de Liaison des Laboratoires des Ponts et Chausees, No. 92, 1977, pp 142-148.

31. Ray, M., "Concrete Pavement Design, Present Options in France," International Colloquium on Concrete Roads, Cembureau, 1978, pp 44-104.

32. Letter to author from Mr. James H. Woodstrum, California Department of Transportation.

# BIBLIOGRAPHY

Boyd, A. F., "Report on Tests Carried Out on No-Fines Concrete for Compressive, Transverse, and Torsional Strength," Duplicated Document No. 12, Sydney, Commonwealth Experimental Building Station, 1946, 6 pp.

Cedergren, H. R., *Drainage of Highway and Airfield Pavements*, Chapter 10, John Wiley and Sons, New York, 1974.

"Engineering Developments in the USSR," *Civil Engineering and Public Works (England)*, Vol 53, No. 621, 1958, pp 273-320.

Eyman, K. H., "Method of Proportioning Normal and No-Fines Concrete Mixtures," *Journal of the American Concrete Institute*, 1963, pp 927-943.

Federal Highway Administration, "Unique Concepts and Systems for Zero Maintenance Pavements, State-of-the-Art Report," Report No. FHWA-RD-77-76, Department of Transportation, Federal Highway Administration, Washington, D. C., 1978, pp 74-108.

Forlani, R., "No-Fines Concrete," *Journal of the American Concrete Institute*, LR 46-49, 1959, pp 477-479.

Hadlev, W. O., "An Evaluation of Gap-Graded Concrete," Research Report 73-1, Materials Research Laboratory, Louisiana Tech University, Ruston, La., 1977.

Hoff, G. C. et al., "Identification of Candidate Zero Maintenance Paving Materials," Miscellaneous Paper C-77-14, Vols 1 and 2, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss., 1977.

Macintosh, R. H., Bolton, J. D., and Muir, C. H. D., "No-Fines Concrete as a Structural Material," *Proceedings, The Institution of Civil Engineers*, Vol 5, 1956, pp 677-694.

Parker, F., Jr., Gunkel, R. C., and White, T. D., "Observations of Portland Cement Concrete and Porous Friction Course Pavement Construction," Miscellaneous Paper S-77-76, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss., 1977.

Peterson, P. H., "Properties of a Porous Concrete of Cement and Uniform Sized Gravel," Report BMS96 National Bureau of Standards, The Superintendent of Documents, U. S. Government Printing Office, Washington, D. C., 1943.

Simons, L. G., "The Behavior of No-Fines Concrete Panels as the In-Fill in Reinforced Concrete Frames," *Civil Engineering and Public Works Review*, Vol 62, No. 736, 1967, pp 1245-1250.

Valore, R. C. and Green, W. C., "Air Replaces Land in No-Fines Concrete," *Proceedings, American Concrete Institute*, Detroit, Vol 47, 1951, pp 833-846.

Washa, G. W., "Properties of Lightweight Aggregates and Lightweight Concretes," *Journal of the American Concrete Institute*, 1957, pp 375-382.

White, T. D., "Porous Friction Surface Course," Miscellaneous Paper S-75-12, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss., 1975.

White, T. D., "Field Performance of Porous Friction Surface Course," Miscellaneous Paper S-76-13, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss., 1976.

Wimpey Company, "No-Fines Concrete Housing System," Wimpey, Toronto.

* U.S.G.P.O. 725-808/1302-1216