SPECIAL REPORT 91-25

CRREL

Environmental Monitoring and Performance Evaluation of Roller-Compacted Concrete Pavement

Conley Terminal, Boston, Massachusetts

Edel R. Cortez and Robert A. Eaton

December 1991

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U.S. Army Corps of Engineers
Cold Regions Research & Engineering Laboratory

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Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

PREFACE

This report was prepared by Edel R. Cortez, Civil Engineer, and Robert A. Eaton, Research Civil Engineer, Experimental Engineering Division, U. S. Army Cold Regions Research and Engineering Laboratory. Funding was provided by the Office of the Chief of Engineers under the FY85–89 Facilities Investigation Studies Program, Work Unit 101, *Monitor Roller-Compacted Concrete in Freeze/Thaw Areas*.

The authors thank James F. Murphy of Whitman & Howard, Inc., and Charles J. Korhonen and William F. Quinn of CRREL for their valuable input and technical review of this report.

Engineers and managers of the MASSPORT Marine, Engineering, and Maintenance Departments were involved in the construction management of this project. Whitman & Howard, Inc., of Wellesley, Mass., provided consulting services regarding the design and construction of this facility. J. F. White Contracting Co. of Newton, Mass., was the contractor of this construction project.

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Conley Terminal, Boston, Massachusetts

EDEL R. CORTEZ AND ROBERT A. EATON

INTRODUCTION

Roller-compacted concrete (RCC) is a construction material that combines the features of the cement-treated aggregate base, portland cement concrete (PCC) and asphalt pavement technologies. RCC is constructed by placing a zero-slump portland cement concrete mixture by means of a heavy asphalt paver, and compacting it with several passes of a vibrating roller. Large quantities of concrete can be placed quickly with a minimal amount of labor and equipment. No forms are needed and finishing operations are not required. These result in savings of approximately 30% over pavements built with conventional methods.

The Paul W. Conley Terminal, a shipyard owned by the Massachusetts Port Authority, is located at Castle Island, South Boston, Massachusetts (Fig. 1). The pavement at Conley Terminal is used for short-term storage of heavy freight containers mounted on trailer beds. The heavy load of the containers is typically transferred to the pavement through a tire tandem and two steel shoes. In the past, asphalt pavement was used because of its lower construction cost, but it did not last long enough. The load that is concentrated at each steel shoe was commonly large enough to cause the steel shoe to penetrate the asphalt pavement, leading to premature deterioration. One way of solving the problem was by using wood blocks under the steel shoes to distribute the load onto a larger area. This solution proved to be difficult to implement because it required the cooperation of every truck driver using the facility, increased the need for supervision and slowed down the operations. A second approach was to cast a strip of PCC at the expected location of the steel shoes, and to pave the rest of the area with flexible pavement. This option was tried at Conley but did not work as expected because the drivers frequently placed the steel shoes at the asphalt–PCC joints or totally on the asphalt pavement (Fig. 2), which led to joint and asphalt pavement damage.

RCC was selected because its bid cost was approximately 30% less than the equivalent asphalt option. However, the RCC freeze–thaw durability was questioned because of the absence of experimental data.

CRREL was at that time doing laboratory tests on the freeze–thaw durability of RCC and was asked to collaborate with Massport and its consultant on the Conley project. CRREL installed at the Conley RCC a system of sensors embedded in the RCC slab, base and subgrade, complemented by a weather station. The data were collected and recorded in electronic data loggers, and then retrieved with a computer.

PROJECT DESCRIPTION

The Conley Terminal RCC pavement area is approximately 53,800 m^2 (13.3 acres). One-third of the total area was built during October and November 1986 and the remaining area during April and June 1987. The thickness of the RCC slab is 0.457 m (18 in.) built in three layers. The bottom and the middle layer are 0.165 m (6.5 in.) thick each. The top layer thickness is 0.127 m (5.0 in.). The RCC slab rests on a dense graded, crushed stone base that is 0.203 m (8 in.) thick. The subgrade material is mostly composed of sand, silt and cobbles with a water table on the order of 1 m (3.28 ft) during the late summer. The average distance to the sea shore is approximately 100 m (328 ft). The RCC pavement is part of a freight ship terminal that serves the MASSPORT berths 11 through 17 where ships are loaded and unloaded. The freight containers are mounted on trailer truck beds and temporarily stored in a parking space on the RCC pavement.

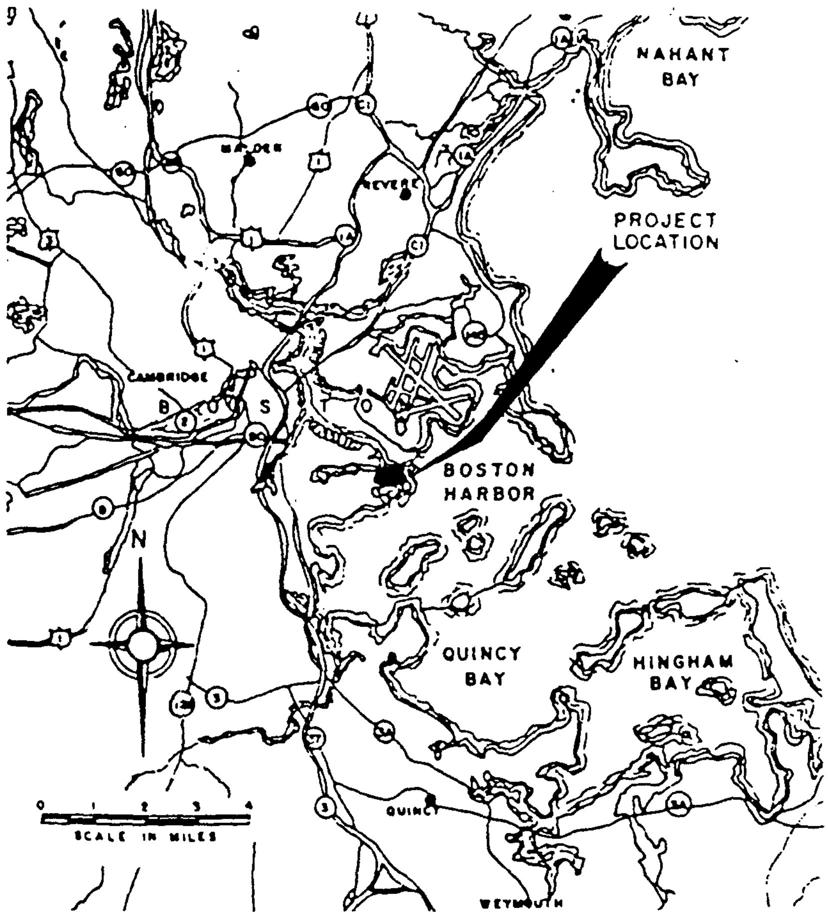


Figure 1. Location of the Conley Terminal, Castle Island, South Boston, Massachusetts.

Figure 2. PCC strip in asphalt pavement.

CONSTRUCTION

The mix proportions of the RCC per cubic meter were as follows:

Material	*Weight (kg)*
Portland cement type 2	296.7
Fly ash type F	59.3
Water	115.5
Combined aggregate	1940.1

The ratio of water to cementitious material was 0.41. No air-entraining agent or other admixture was used. The aggregate gradation was from 4–8% of the material passing the standard sieve number 200 to 19-mm (3/4-in.) maximum size. This mix satisfied the required 4.83-MPa (700-psi) flexural strength at 28 days of age.

The concrete was mixed in a continuous twin-shaft pug mill mixing plant temporarily installed at the facility. The zero-slump concrete was transported by dump trucks and delivered into the hopper of two heavy-duty pavers working in tandem to minimize cold joints. These pavers had a heavy, vibrating screed and dual tamping bars, which were able to obtain up to 93% of the target density at the back of the paver. A 10-ton dual steel drum vibrating roller followed the paver, compacting the concrete within 45 minutes after the addition of water to the aggregate–cement mixture at the plant. Four vibrating passes (one back-and forth-motion being two passes) were necessary to achieve the required density. Rubber-tire rollers were used to tighten and smooth the surface. The curing consisted of spraying a mist of water onto the RCC for seven days.

ENVIRONMENTAL INSTRUMENTATION SYSTEM

The set of sensors measured the following parameters: 1) air relative humidity, 2) precipitation, 3) barometric pressure, 4) wind speed, 5) wind direction, 6) direct solar radiation, 7) reflected solar radiation, 8) air temperature, 9) pavement surface temperature, 10) in-concrete temperature at several depths, 11) in-base/subbase temperature at several depths and 12) subgrade temperature at several depths

During the paving operation, one set of thermocouples was embedded in the concrete slab, base and subgrade at two representative locations. Figure 3 shows the depth of the temperature sensors in a cross section of the pavement. Temperature readings were taken every hour throughout the winter.

Figure A1 shows shows the hourly air temperatures 1.37 m (4.5 ft) above the pavement surface. Sixty-one

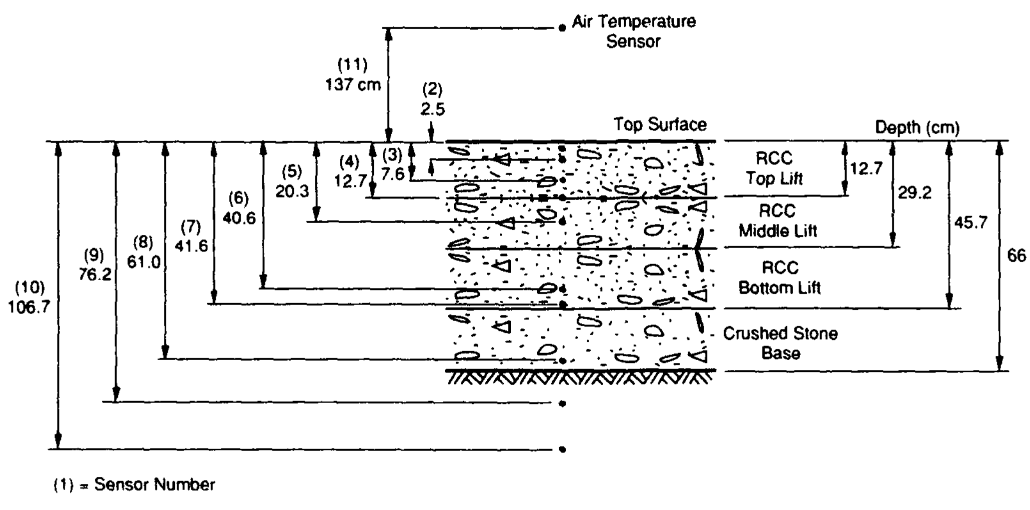


Figure 3. Thermocouple location.

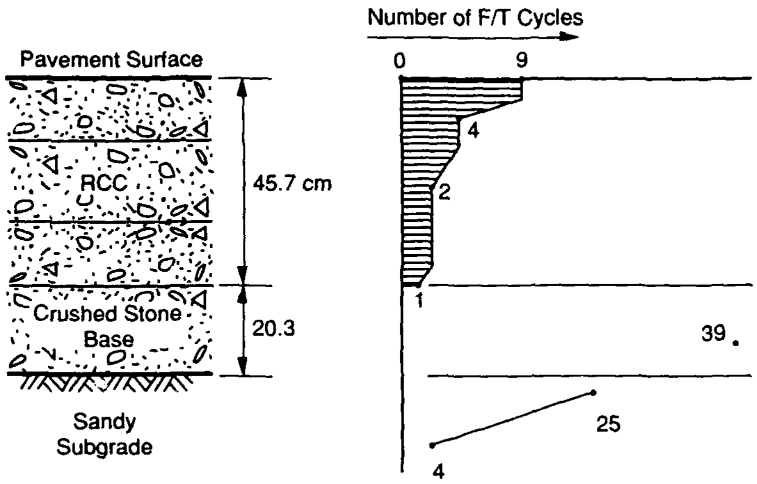


Figure 4. Conley RCC pavement freeze–thaw cycle profile, 1989–90 winter. (The number of freeze–thaw cycles in the air was 61.)

air temperature F/T cycles (when the temperature fell below 0°C, and then rose to above 0°C) were recorded from 15 November 1989 to 1 May 1990.

Figures A2 through A11 present the temperatures during the 1989–90 winter at several depths below the pavement surface. Figure A2 shows the temperatures at the concrete upper surface. The sensor was embedded in the concrete at only 3 mm from the pavement surface. Nine F/T cycles were recorded at this point during the 1989–90 winter. For the moisture inside the concrete, one F/T cycle occurs when the temperature falls below –5°C, and then rises to above 0°C.

Figures A3–A7 show the temperatures and number of F/T cycles at several depths inside the concrete during the mentioned winter. Figure A8 shows data from a temperature sensor embedded in the concrete at only 6 mm above the RCC/base interface. Only one F/T cycle was recorded at his point during the 1989–90 winter. Figure A9 shows data from a sensor embedded in the crushed-stone base course. For the moisture inside a granular soil, a F/T cycle occurs when the temperature falls below –0.5°C, and then rises to above 0°C. Thirty-nine F/T cycles were recorded at this point during the mentioned winter.

Figures A10 and A11 show data from temperature sensors located within the subgrade material at 76.2 cm and 106.7 cm from the pavement surface. For moisture inside a silty sand soil, one F/T cycle occurs when the temperature falls bellow –1°C (or lower in some cases), and then rises to 0°C. Twenty-five and four F/T cycles were recorded at these two depths, respectively.

Figure 4 shows a profile of the number of F/T cycles that occurred at several depths through the RCC slab, the base course and the subgrade. Notice that while 61 F/T cycles were recorded in the air, only nine cycles occurred at 3 mm below the pavement upper surface.

A distinction therefore must be made between two concepts of F/T cycles: 1) the air F/T cycle, and 2) the in-pavement F/T cycle. The first concept uses temperature data from sensors located at 1.37 m over the ground level (standard weather thermometer level). It is based on the freezing point of pure water at atmospheric pressure, where one F/T cycle occurs when the temperature falls below 0°C and then returns to above 0°C.

The in-pavement F/T cycle concept uses data from temperature sensors embedded in the pavement material at several depths. It is based on the temperature at which freezing of capillary water starts, approximately –5°C (Neville 1981). Moisture in concrete is an alkaline solution rather than pure water. If a sealed container having a small air release valve is filled with water to 91.7% of its volume and then subjected to a sustained subfreezing temperature, the ice will occupy 100% of its volume, the air being expelled as water changes to ice. If the same container is filled with water at more than 91.7% of its volume and then subjected to a sustained subfreezing temperature, the excess water will be expelled as the lower density ice fills the container. If the container is a concrete capillary void that is "critically saturated" (more that 91.7% of its volume is filled with moisture), and the release valve is a gel pore, the excess moisture will be expelled through the pores when the water freezes, causing high hydraulic pressure. If this pressure exceeds the tensile strength of

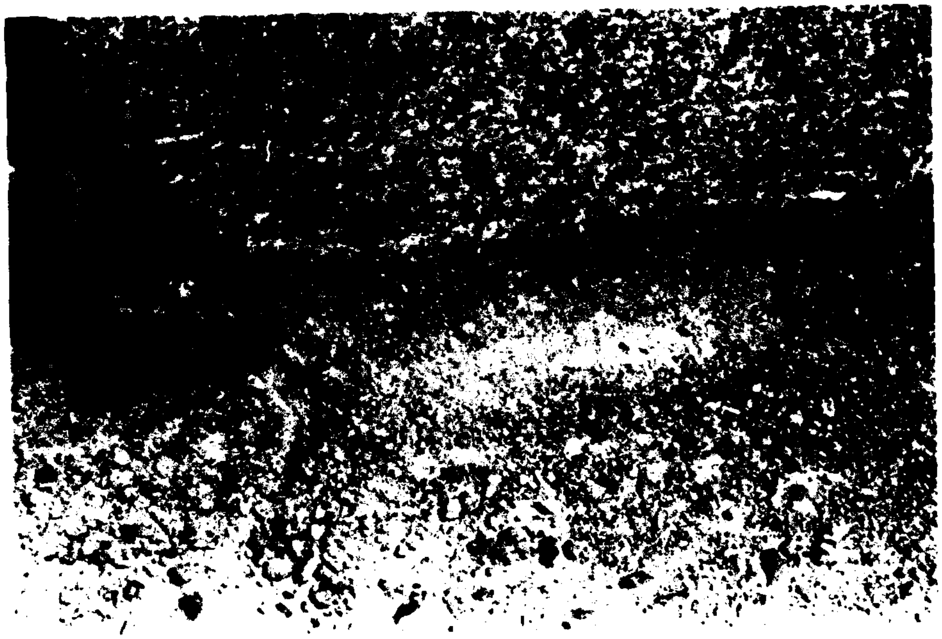


Figure 5. Loose pavement material at the vicinity of cold joints when opened to traffic.

the cement paste, a concrete breakdown occurs. For the in-pavement F/T cycle concept, a cycle is considered to occur when the temperature falls below –5°C and then goes above 0°C.

Typically, as occurred here, the density of an RCC pavement decreases gradually from top to bottom of each layer placed. It is interesting to observe in Figure 5 that the number of F/T cycles also decreases with depth. This means that, although the lower density at the lower levels reduces the material's F/T durability, the number of F/T cycles is also smaller at those depths.

PAVEMENT PERFORMANCE

As stated earlier, the Conley RCC pavement was constructed in two construction seasons. In both instances, the pavement was open to traffic one month after construction. At those times, no major distress was identified. Shrinkage cracks occurred naturally at intervals between 15–23 m (49–75 ft) along the pavement lanes. Fine cracks also developed along the construction joints between lanes. No joint was saw cut on this project. The width of the cracks ranged from 0.5 to 2 mm (0.020 to 0.079 in.). The surface texture was relatively rough and apparently sound. However, we observed that at the vicinity of the cold joints (i.e., the longitudinal construction joints between lanes where the last lane was placed 60 min or more later than the adjacent lane), there was a substantial quantity of loose material on the surface (Fig. 5). The loose material was always located on the side of the lane that was placed first.

After one year of service, the width of the shrinkage cracks increased. Some cracks were 4 mm (0.157 in.) wide. Deterioration of the RCC was observed along the cold joints. Figure 6 shows the same location as Figure 5 but one year later. The measured rutting was up to 30 mm (1.18 in.). At some spots the RCC material was so soft that samples were taken by scraping it with a regular spoon. Those samples were analyzed at CRREL by means of a scanning electron microscope (SEM) to determine whether a deicer material or any unusual chemical was present. The tests indicated that no chloride or any chemical foreign to concrete was present. Cores were also taken at both sides of the troubled joints at 0.15 m (6 in.) from the joint line, and at the center lane. The unit weights of these cores revealed that the relative density at the side of the lane placed first was only 90% of the density at the center of the lane. The relative density at the side of the lane placed last was 96% of the density at the center of the lane. These density proportions are explained by the fact that, when the first lane was placed and compacted, the edge was not confined, which resulted in lower density. At the time when the second lane was placed and compacted, the first lane was hard enough to provide lateral support and therefore the achieved density was higher. Figure 6 shows that the deterioration developed chiefly in one side of

Figure 6. Loose pavement material at the vicinity of cold joints after one year of pavement service.

the joint. The cores also revealed that the interlayer bonding was poor. The density was relatively high at the upper region of each layer and diminished with the depth. Figure 7 illustrates the density pattern through the slab section.

At two years of service, the shrinkage cracks were between 3 to 5 mm (0.12 to 0.20 in.) wide, and deterioration of the crack edges was observed at most traffic lanes. At relatively low temperature, the concrete contracted and the cracks became temporarily wider. Debris from the pavement surface fell and accumulated in the cracks. When the temperature rose, the concrete

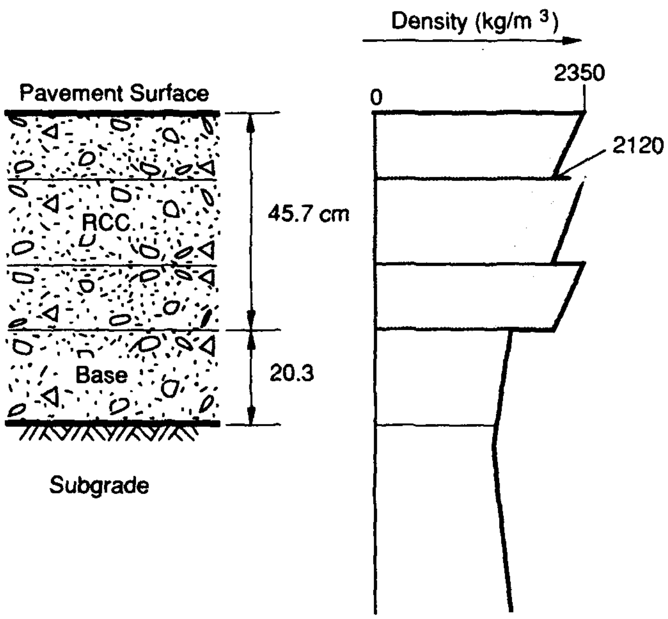


Figure 7. Typical density profile of the Conley RCC pavement.

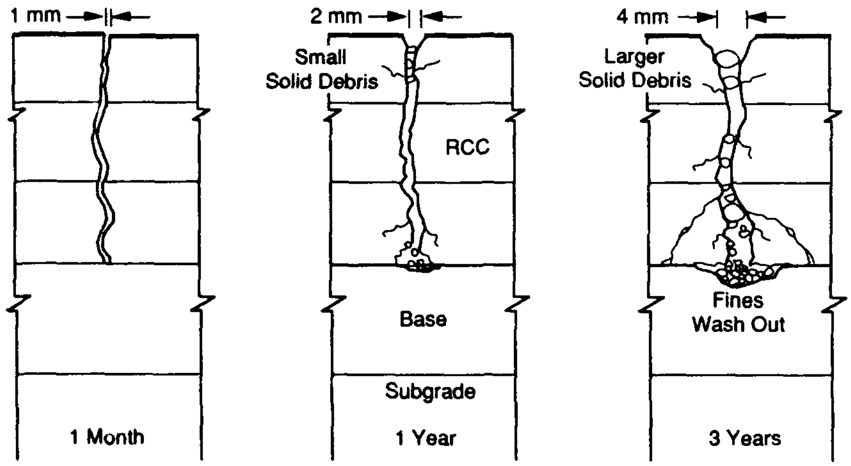


Figure 8. Typical shrinkage crack progression during the first three years of pavement service.

expanded. The hard debris in the cracks restrained the slab expansion, adding stress to the slab. This caused local fractures and contributed to the growth of the cracks. An asphalt sealer was applied to these cracks. This sealer did not penetrate into the cracks at regions where the cracks were less than 2 mm. The action of the traffic soon removed some of the sealer material from the cracks, but no further deterioration of the cold joints was observed.

After three years of service, the width of the shrinkage cracks appeared to be the same as that of the preceding year; however, the upper crack edges were now more deteriorated. Figure 8 shows a typical progression of the shrinkage cracks during three years of service. Very little growth of the shrinkage cracks was observed during the third year of service. The depth of deterioration measured at the cold joints remained unchanged. Apparently the poor material had been removed and now the exposed material was sound concrete. There was little additional deterioration at the pavement surface in the 1 m-strip along most of the cold joints subjected to traffic.

Despite the described localized pavement distress, the pavement serviceability has not been affected to date. The maintenance of the pavement has been limited to snow and ice removal without chemical deicers and spring broom cleaning. Only small repairs have been needed. No distress related to static loads has been observed. The abrasion caused by traffic has affected only those areas where the RCC density at the surface is deficient such as at the vicinity of cold joints. There is no evidence of any pumping problem at the joints of this pavement. No damage due to freeze–thaw cycles has been identified.

DISCUSSION AND CONCLUSIONS

The experience gained from the Conley Terminal RCC has been used to improve construction techniques and quality control methods for more recent projects. Density has been identified as the key quality control parameter for RCC pavements. New techniques have been developed to construct RCC joints and to control density (Cortez and Gerlach 1990). Interlayer bonding has also been identified as a potential problem in RCC pavements and the bonding techniques are being reviewed. RCC has been successfully placed in thicknesses up to 0.25 m (10 in.) in one single layer, which has eliminated the need for multiple layer construction in several recent projects. Shrinkage joints are now constructed by saw cutting the pavement to one-third its thickness at intervals of 18 m (59 ft) along the lanes. The slot left by the saw is then filled with an asphalt sealer up to 3 mm (0.118 in) from the pavement surface. This practice has proved effective in controlling most of the shrinkage cracks and also has enhanced the RCC appearance.

Despite the observed distresses described above, the pavement serviceability at Conley Terminal has not been affected and the overall condition of the pavement is good after three years of service. By building this pavement with RCC rather than with conventional concrete, the construction cost was reduced by approximately 30%. RCC has endured the heavy, concentrated loads that damaged asphalt pavements in the past and has served to date with little maintenance.

At the Conley Terminal, no freeze–thaw related distress has been identified. In addition, the conceptual distinction between the number of F/T cycles that moisture in air undergoes and the number of F/T cycles of the moisture inside the concrete was shown to be important. The number of F/T cycles experienced by the moisture in the concrete pavement was substantially smaller than the number of F/T cycles that occurred in the air above the pavement.

Surface smoothness was not a relevant issue at the Conley RCC because the traffic speed is usually low. Further research and development of the RCC technology is needed prior to any high-speed pavement application.

Confidence in the use of RCC in cold climates has been substantially increased. Large new RCC projects have been built in Massachusetts and northern New York in the last three years and all of them are performing satisfactorily. New pavers have been developed for more productively placing RCC in wider lanes and at higher compaction efforts. The RCC technology should be able to take advantage of new developments in the concrete industry, such as fiber-reinforced concrete, fast track concrete, crack-and-seat rehabilitation, latex-modified concrete, admixtures, etc.

LITERATURE CITED

Cortez, E.R. and R.A. Eaton (1990) Freeze–thaw tests of full-scale roller-compacted concrete test sections. U.S. Army Cold Regions Research and Engineering Laboratory, Special Report 90-25.

Cortez, E. R. and J.A. Gerlach (1990) Roller-compacted concrete pavement construction at Fort Drum, New York. Transportation Research Record 1282, Transportation Research Board, Washington, DC.

Neville, A.M. (1981) Properties of concrete. Harlow, Essex, England: Longman Scientific and Technical Publishers, p. 31.

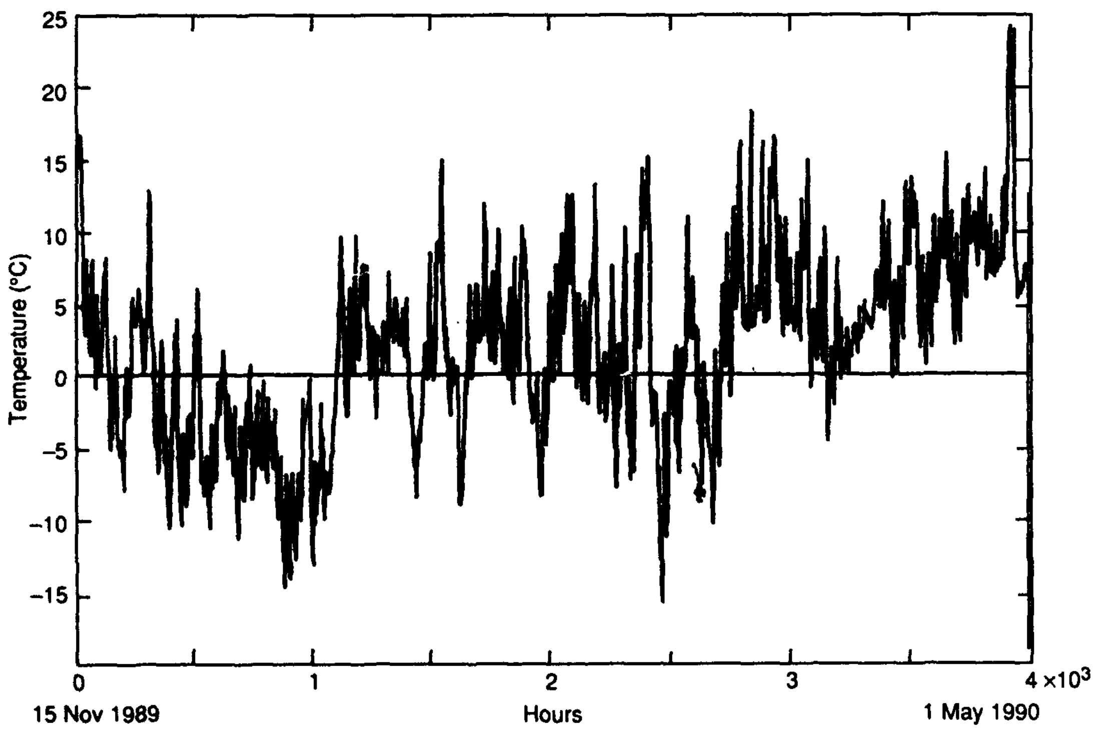
Tayabji, S.D. and P.A. Okamoto (1987) Engineering properties of roller compacted concrete. Transportation Research Record 1136, Transportation Research Board, Washington, DC.

U.S. Army Corps of Engineers (1988) Engineer Technical Letter 1110-1-141, Washington, DC.

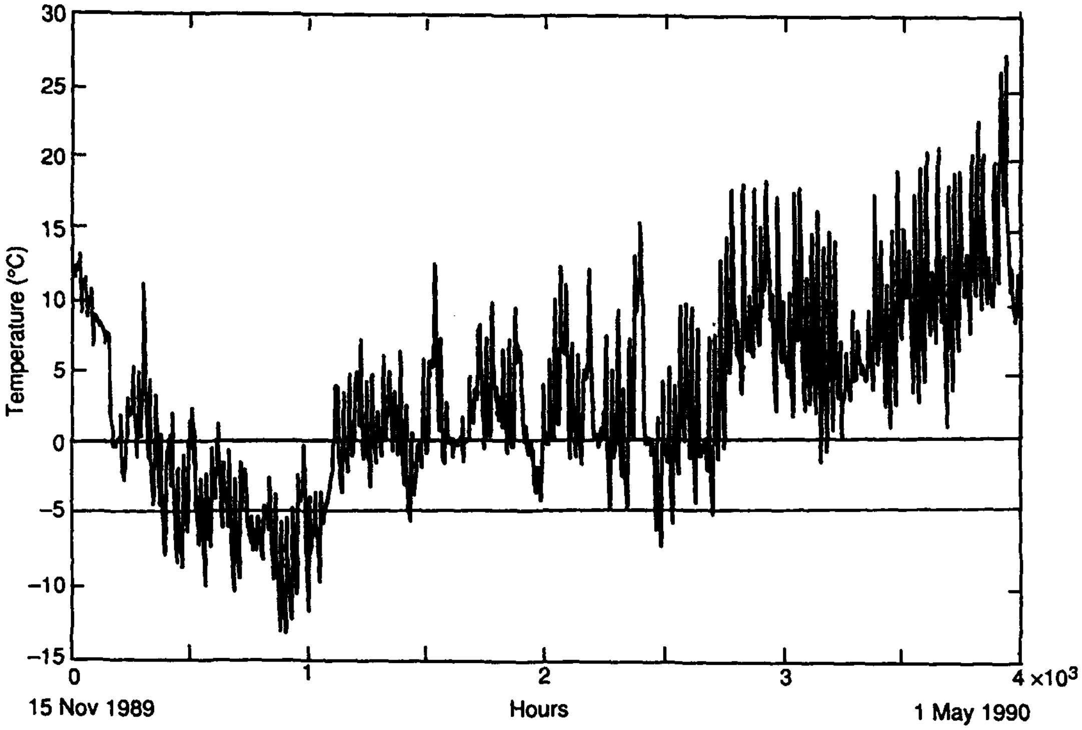
White, T.D. (1986) Mix design, thickness design, and construction of roller compacted concrete. Transportation Research Record 1062, p. 2, Transportation Research Board, Washington, DC.

APPENDIX A: AIR, CONCRETE BASE COURSE AND SUBGRADE TEMPERATURES, 15 NOVEMBER 1989 TO 1 MAY 1990

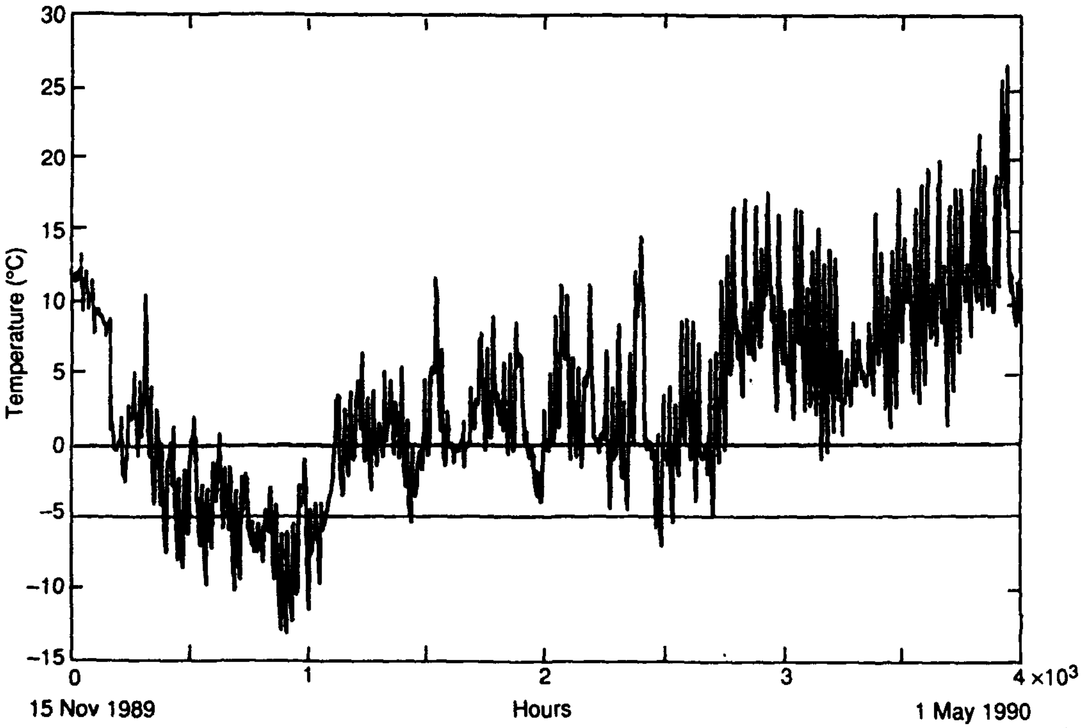
Each graph in Figures A1–A11 shows data points corresponding to 4,000 temperature readings taken every hour from 15 November 1989 to 1 May 1990. The following figures are an expansion of the horizontal axis to show more detail and to allow direct accounting of the number of F/T cycles. Each one of the figures in Appendix A includes 1,000 hours of data.



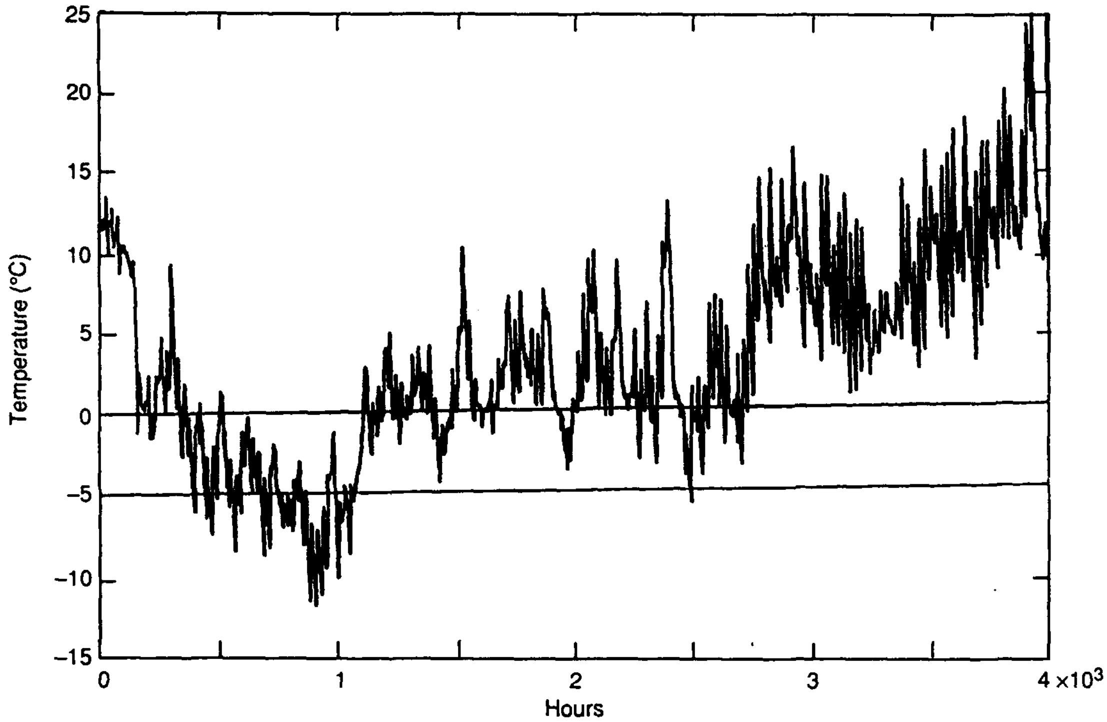
A1. Air temperature at 1.37 m above the RCC pavement



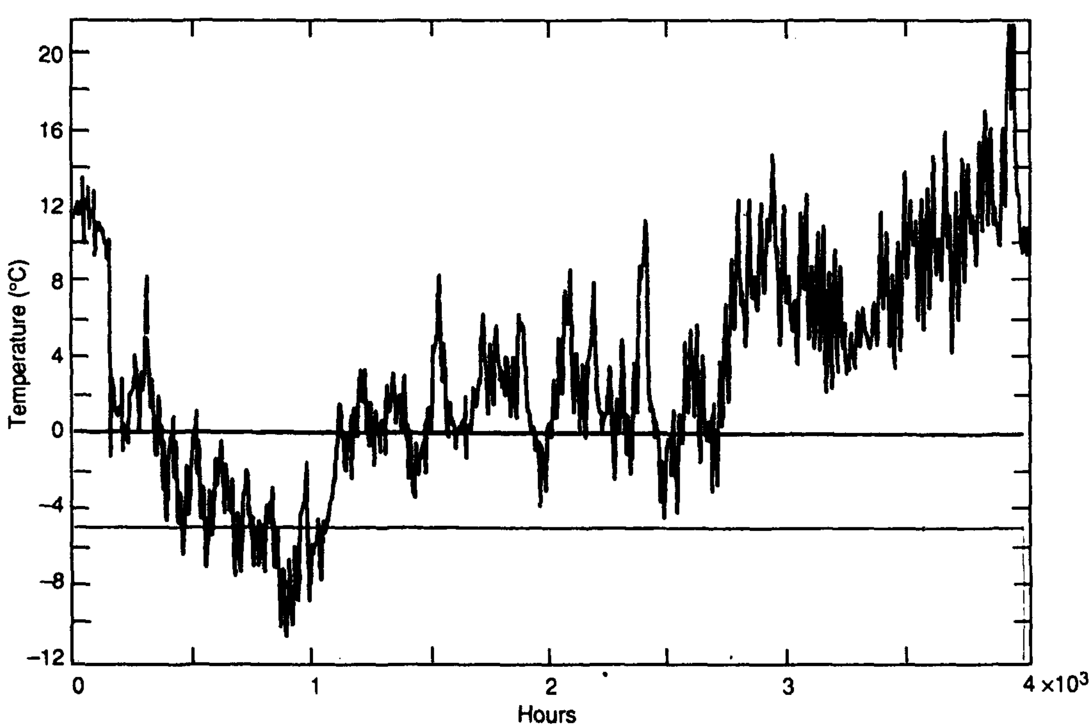
A2. RCC surface temperature.



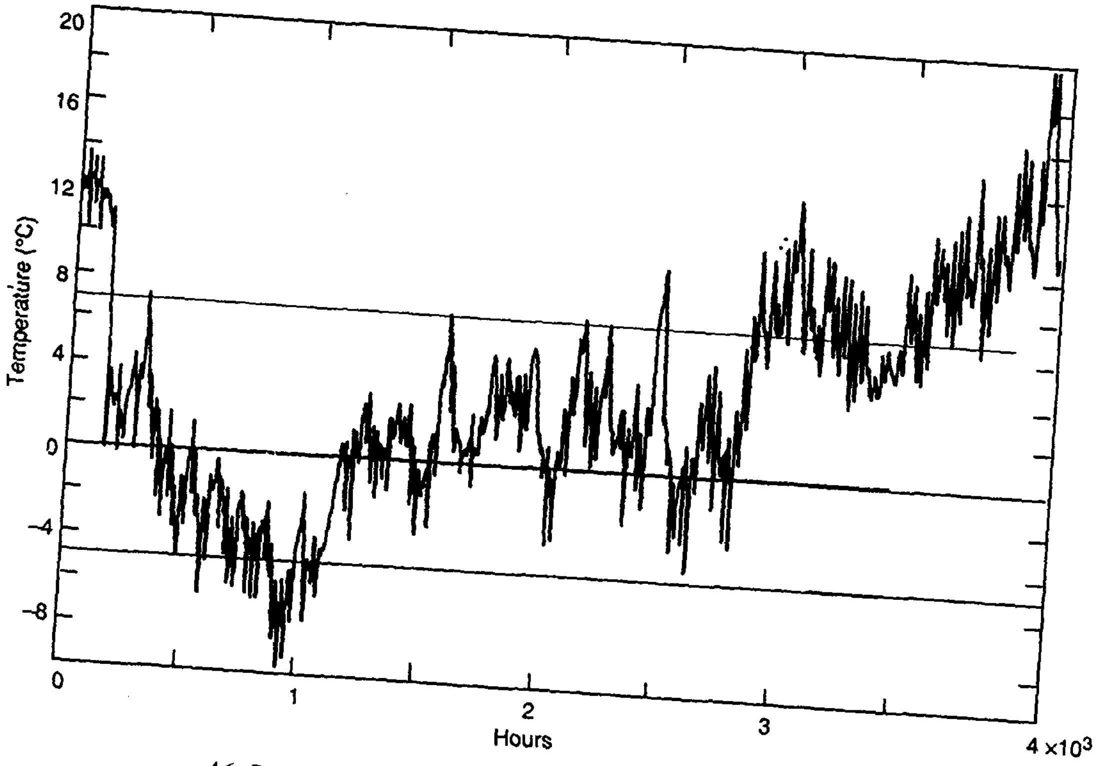
A3. Pavement temperature at 2.54 cm below upper surface.



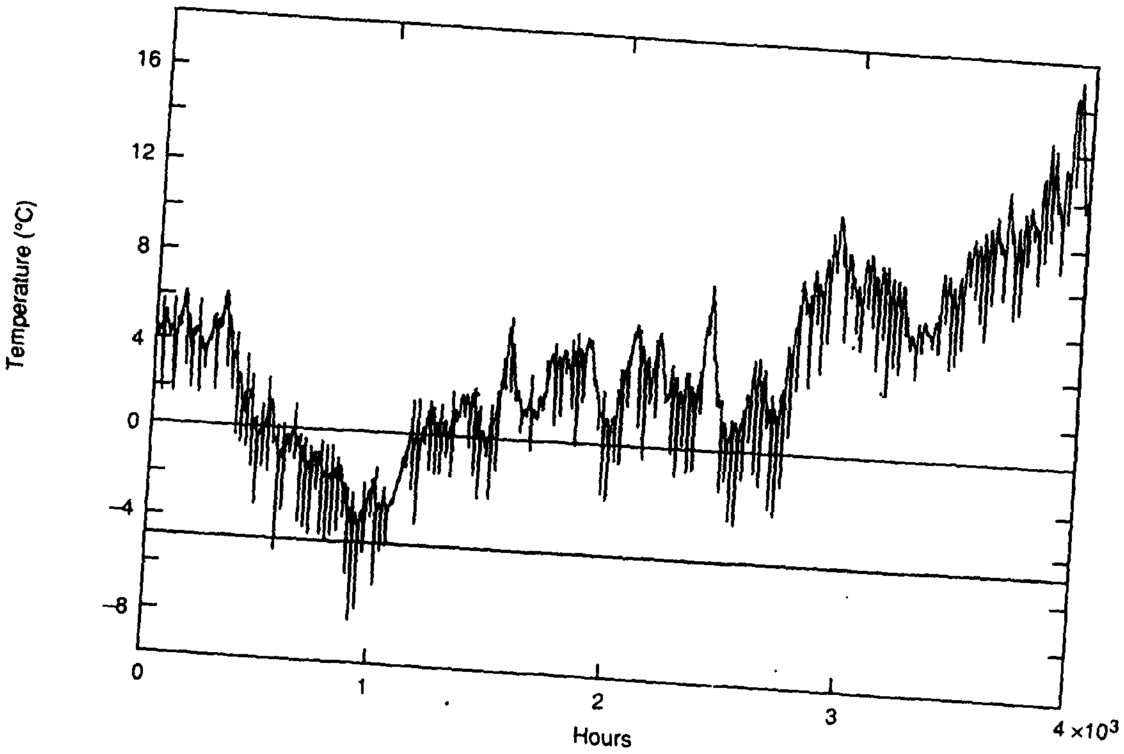
A4. Pavement temperature at 7.6 cm below upper surface.



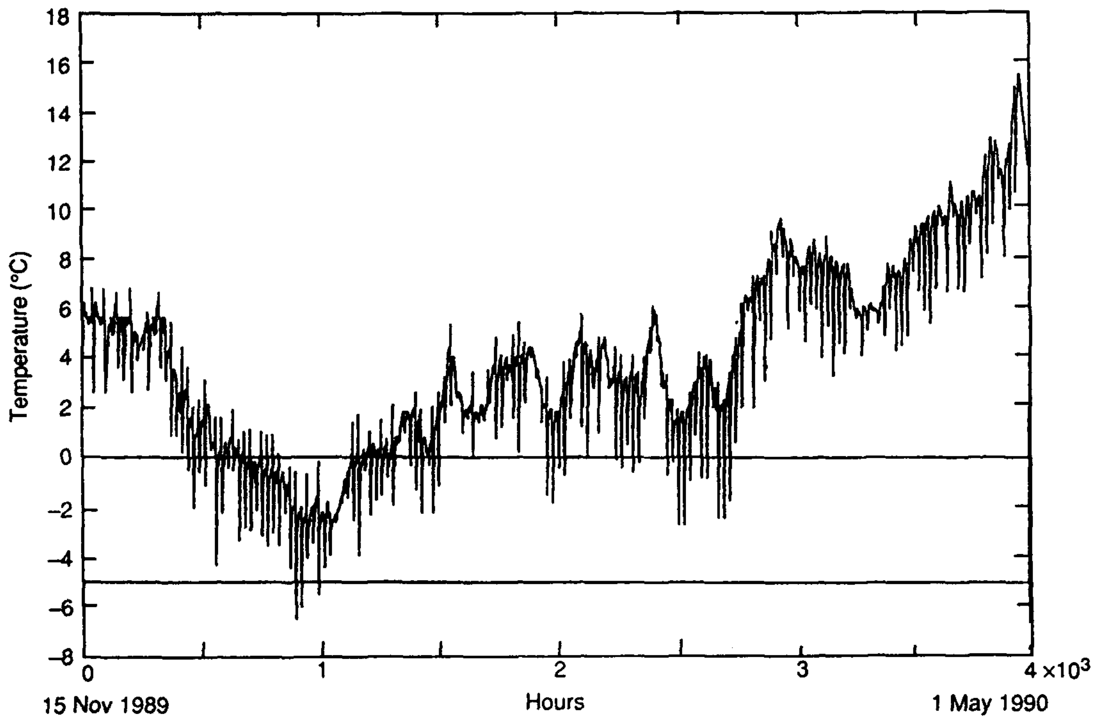
A5. Pavement temperature at 12.7 cm below upper surface.



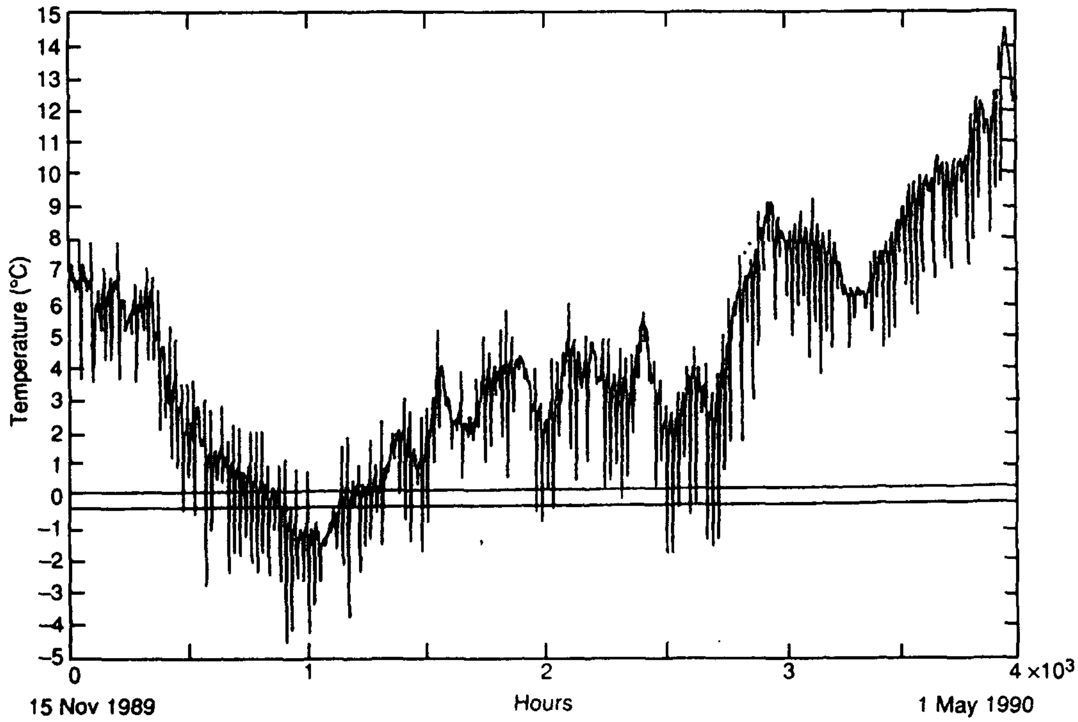
A6. Pavement temperature at 20.3 cm below upper surface.



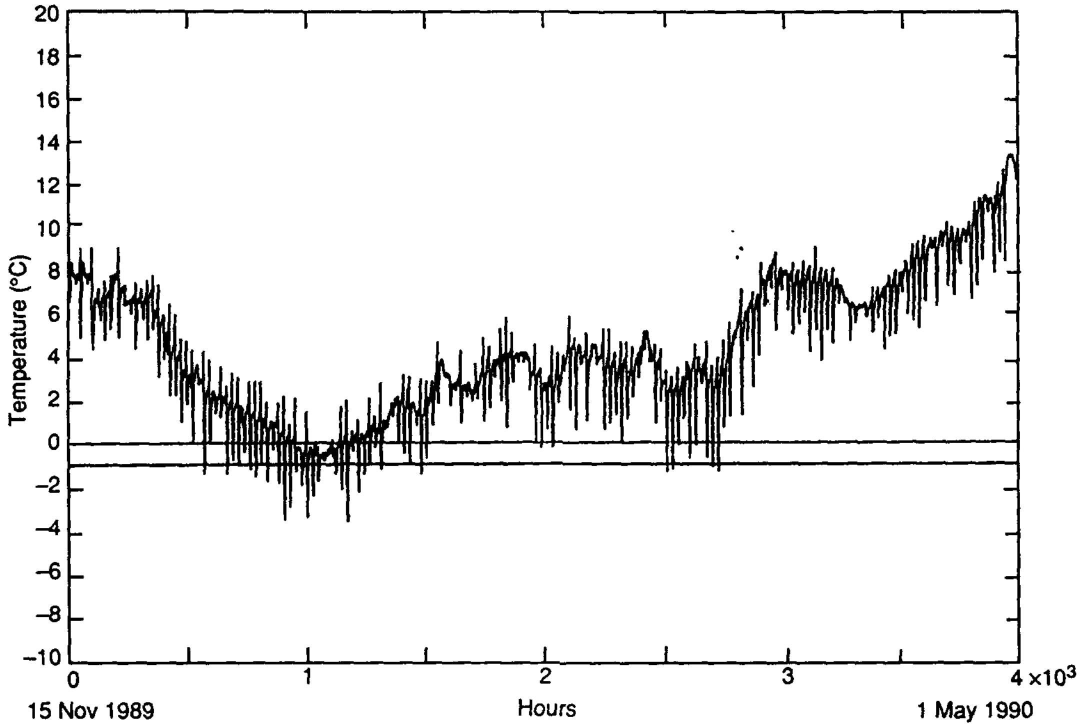
A7. Pavement temperature at 40.6 cm below upper surface.



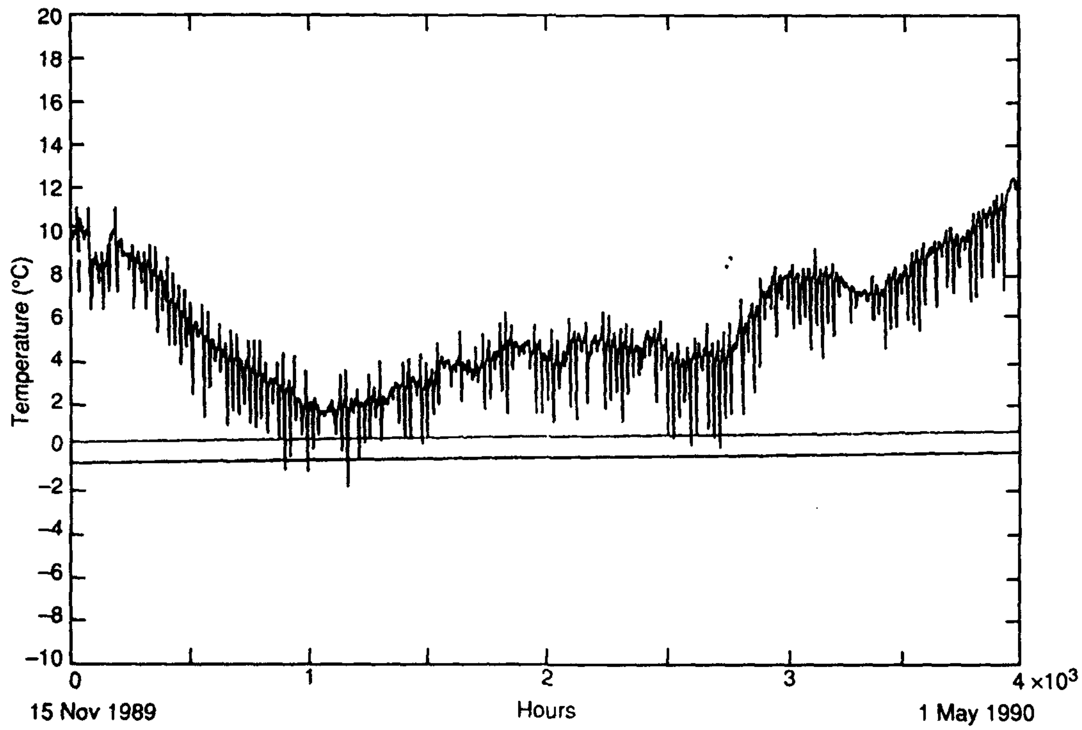
A8. Pavement temperature at the bottom of the RCC slab.



A9. Temperature at the crushed-stone base course.



A10. Subgrade temperature at 76.2 cm from the RCC pavement surface.



A11. Subgrade temperature at 106.7 cm from the RCC pavement surface.

APPENDIX B: WEATHER SUMMARY DATA

The figures in Appendix B present monthly average values of the relative humidity, total water-equivalent precipitation and temperature at the Conley Terminal from October 1986 to March 1990. The number of F/T cycles in air = 61 (at 1.37 m above pavement).

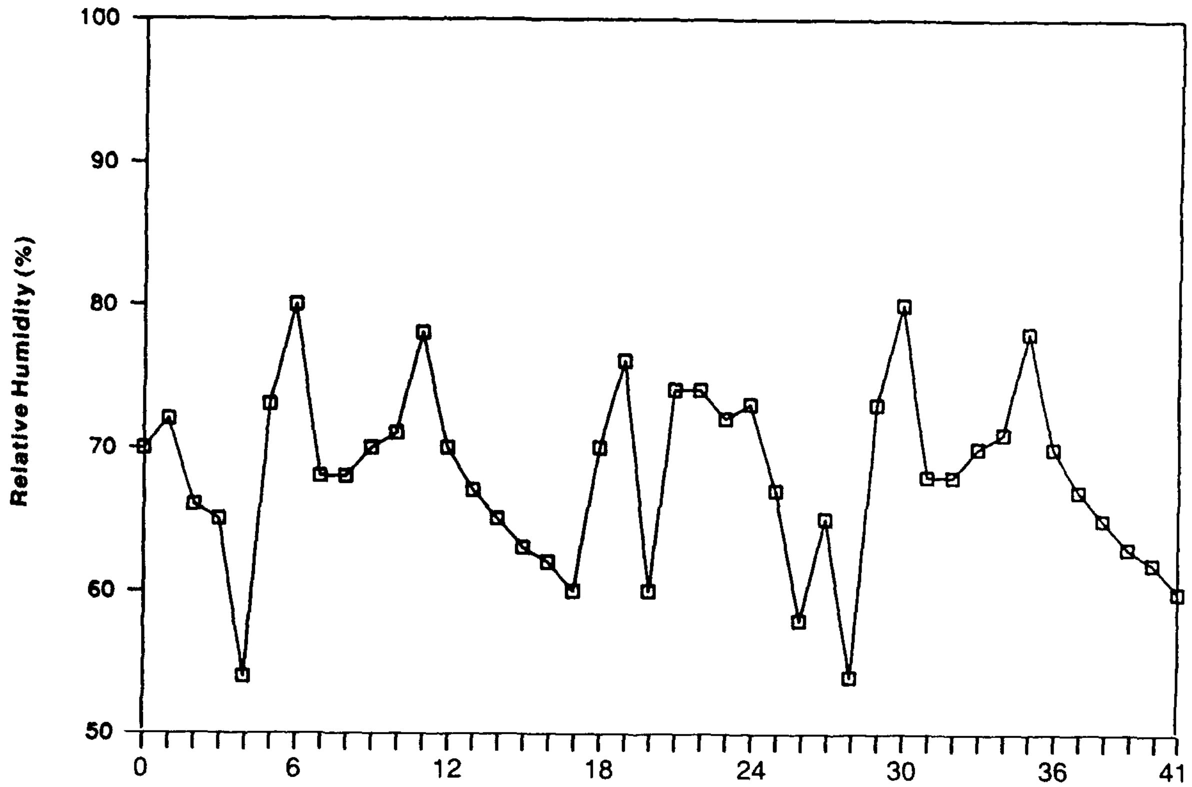


Figure B1. Monthly average relative humidity.

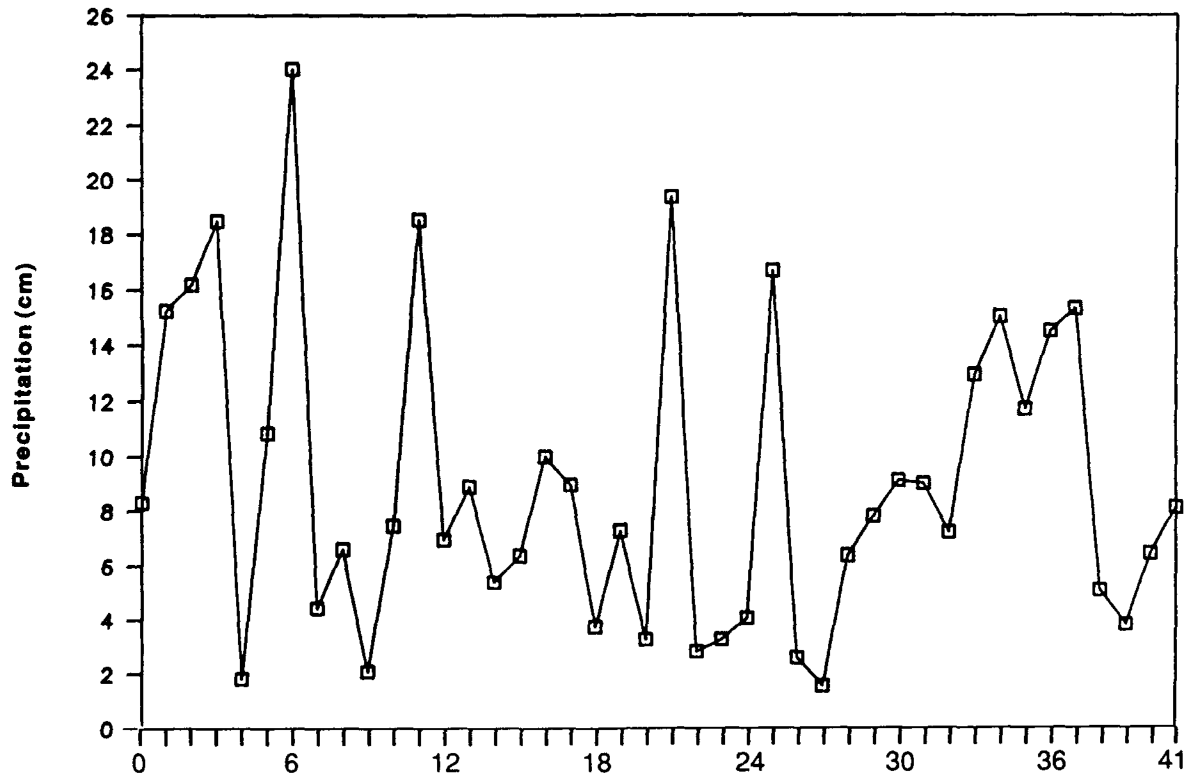


Figure B2. Monthly total precipitation.

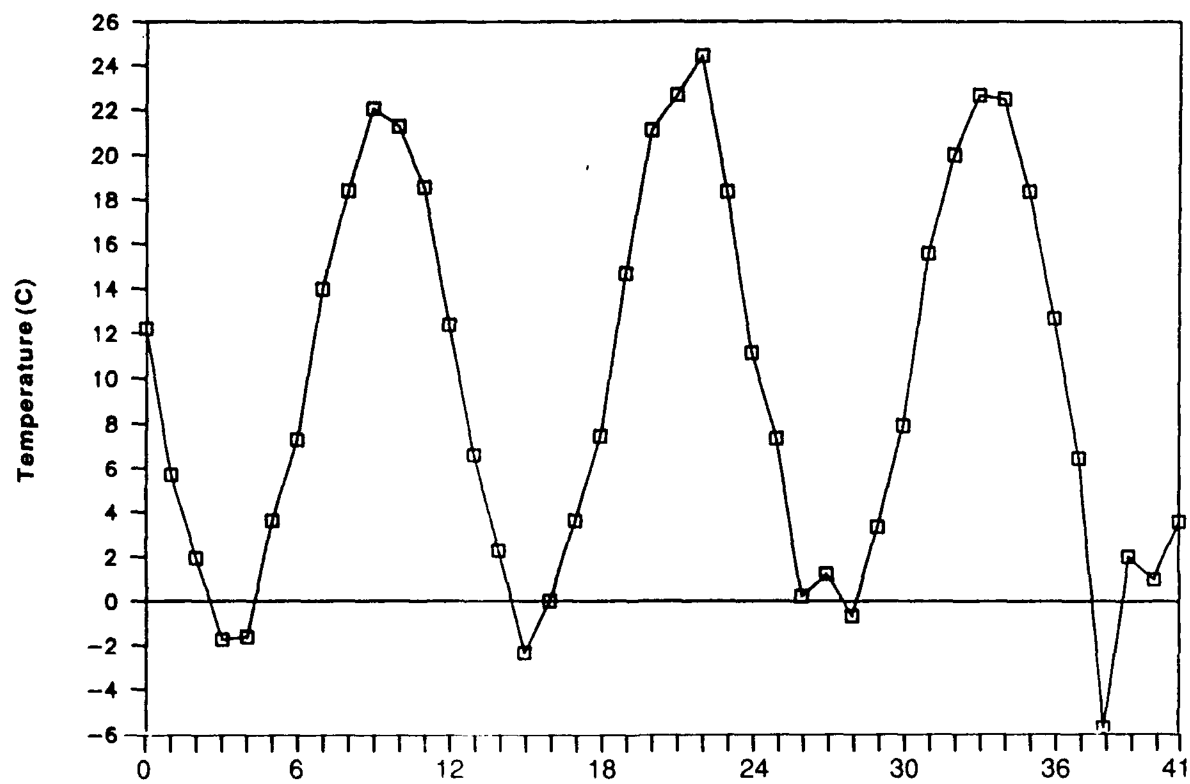


Figure B3. Monthly average temperature.

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13. ABSTRACT (*Maximum 200 words*)

The Massachusetts Port Authority (MASSPORT) built 53,800 m^2 (13.3 acres) of roller compacted concrete (RCC) pavement at the Paul W. Conley Terminal, Castle Island, South Boston, Massachusetts, during the 1986 and 1987 construction seasons. This was the first time an RCC pavement was built in the multiple freeze–thaw environment of the northern United States. A system of sensors was installed at this project to monitor the main environmental parameters that affect pavements. This report describes the instrumentation system, presents a summary of the recorded data, and discusses cause-and-effect relationships between construction procedures and pavement performance.

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