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TRANSPORTATION RESEARCH RECORD

Concrete Pavements

Harold Halm International Symposium on Concrete Pavement Construction and PIARC 18th World Road Congress—Construction and Maintenance of Rigid Pavements

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Contents

Foreword

If concrete pavement construction and maintenance techniques around the world are to continue to advance, the sharing and dissemination of knowledge are vital. To further this aim, this Record presents papers from the Harold J. Halm International Symposium on Concrete Pavement Construction.

Also included in this Record is General Report Question 3: Construction and Maintenance of Rigid Pavements from the 18th World Road Congress of the Permanent International Association of Road Congresses (PIARC). TRB and PIARC are taking special steps to share information of mutual interest. The PIARC report has therefore been included because of its direct relationship to the other papers in this Record. The combined scope of the papers and report should give the reader a good idea of the state of the art of concrete pavement construction around the world today.

Gordon K. Ray introduces the Halm Symposium papers with a description of the symposium's history and organization. He also provides an appreciation of pavement engineer Harold J. Halm, in whose memory the symposium was organized.

The introduction is followed by five descriptions of concrete pavement experience in various parts of the world. Both the history and the current state of the art are covered. The experience in South Africa is described by M. F. Mitchell and colleagues. Rupert Springenschmid and his coworkers present the situation in West Germany, and Carlos Jofré and his colleagues examine concrete pavement construction in Spain. Shigeru Iwama and Yutaka Anzaki cover Japan, and W. A. Yrjanson describes concrete pavement technology in the United States.

The PIARC report on concrete pavement technology provides an overview of the current state of the art in 28 countries around the world. The summarized national reports cover the five areas with which the PIARC Technical Committee on Concrete Roads was charged: design and behavior in service; materials; construction and control; maintenance and rehabilitation; and subbases and road bases treated with hydraulic binders (for both concrete pavements and semirigid pavements).

Introduction: The Halm Symposium

GORDON K. RAY

The Harold J. Halm International Symposium on Concrete Pavement Construction was sponsored by the Committee on Rigid Pavement Construction and Rehabilitation (A2F01). The committee includes four international members, who were added to the membership in 1986. This addition created an interest in concrete pavement construction techniques and equipment in other countries around the world. There were some committee members who felt that much could be learned by a session of papers from the different countries in which concrete pavements are built. As a result, all of the international members were invited to submit such papers for a symposium to be held in 1988.

The response from the members and contacts with other countries through the Technical Committee for Concrete Roads in the Permanent International Association of Road Congresses (PIARC) enabled the committee to organize this session. We are fortunate to have four foreign papers describing concrete pavement construction in South Africa, West Germany, Spain, and Japan, as well as a paper on the state of the art in the United States. The committee also felt that this international symposium, the first of its kind to be organized by a committee of TRB, should be dedicated to Harold J. Halm.

Harold had been a member of the committee from 1964 to 1983. He served as the committee secretary from 1973 to 1980. During Harold's time with the committee, he was a leader in encouraging new ideas, new methods, and new equipment, but he also always encouraged quality construction. He was a spark plug, always suggesting sessions, papers, and summer meetings in an effort to disseminate new information to engineers who worked with federal agencies or state, county, and city departments of transportation.

Harold was a pavement engineer with the Portland Cement Association from 1958 to 1964. He helped organize the American Concrete Pavement Association in 1964 and became its first executive secretary. Harold made sure that one of the association's principal objectives was the improvement of the quality of concrete pavement construction.

Harold Halm died of cancer in 1985. His death at the peak of his career was a big loss to the concrete paving industry. Harold's absence from the committee (he had been a "Friend of the Committee" since his departure from the committee proper in 1983) was felt by all of the members. The committee unanimously adopted a resolution at the 1987 TRB Annual Meeting to name this symposium for Harold in tribute to his many contributions to the committee and to the concrete pavement industry.

We are pleased that TRB has honored him by approving this session and planning this Record to include all of the papers presented so that they will be available to everyone who is interested in this subject.

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Experience with Concrete Highways in the Republic of South Africa

M. F. MITCHELL, L. R. MARAIS, AND C. R. FREEME

Before 1968 concrete pavements were used only in exceptional circumstances in the Republic of South Africa (RSA). They were constructed by means of hand methods and rudimentary plants that did not produce the longitudinal profile needed for modern traffic. As a result, the use of concrete pavements was discontinued during the 1950s and 1960s. The results of the AASHO road test, however, and studies and observations of modern concrete pavement performance, notably in the United States, stimulated interest in modern concrete pavements as a means of accommodating the rapidly growing traffic loading on South African highways. Construction of modern concrete pavements in the RSA, which commenced in 1968, has been accelerating since the mid-1970s. The technology that is currently being applied is based on that used in areas of the United States with similar climatic conditions. Because it is now recognized that existing concrete pavement designs are probably conservative for South African conditions, an extensive research and testing program has been initiated. The primary objectives of this program are to design more economical concrete pavements and to develop more economical methods for their rehabilitation.

The national and provincial road system of South Africa consists of ~185,000 km, of which 55,000 km are surfaced. The extent of the urban system is difficult to assess, but arterial roads in urban areas are estimated to total ~84,000 km. Traffic densities vary considerably: the more heavily traveled national intercity routes carry ~50,000 or more vehicles per day in the suburban areas, and some urban freeways carry 100,000 vehicles per day. The top end of the pavement axle-loading spectrum is about 2,500 equivalent 80-kN (18,000-lb) axle loads (E80s) per day, with a 20-year design life requirement of 50 million E80s.

Most modern surfaced roads in South Africa have pavements consisting of a 150- to 800-mm (6- to 12-in.) subbase of stabilized gravel, a 150- to 200-mm base, and a single-seal surface treatment. Some 900 km of national and provincial roads have an asphaltic concrete base and wearing course. "Modern" concrete pavements total some 890 km.

Before 1965, there was relatively little activity in the field of concrete pavements in South Africa. Isolated short lengths were constructed between 1927 and 1955 under special circumstances in certain locations by means of manual methods and the most rudimentary of plants. By today's standards, the riding quality of these pavements was unsatisfactory. The construction methods used were incapable of producing a longitudinal profile suitable for fast-moving vehicles. The wide transverse joints were formed manually, and they were sealed with bitumen, which tended to extrude and spread on the surface. The unevenness built into the joints resulted in a surface that caused regular bumping in moving motor vehicles.

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MODERN CONCRETE ROADS

The early use of concrete pavements was not continued during the 1950s and early 1960s. For sites where axle loads were in excess of the recognized capacity of the unbound crushed stone bases, road engineers used stiff asphaltic concrete to provide the additional strength required. However, the results of the AASHO road test, together with observations by South African road engineers during overseas visits (particularly to North America and, more specifically, California), resulted in a renewed interest in concrete pavements as a means of accommodating the rapidly growing pavement-loading requirements. At the same time, there was a move toward more flexible asphaltic concrete bases that could accommodate deflection of the pavement. Concrete pavements had the potential to provide a long-lasting, low-maintenance pavement.

Initially, concrete pavements were considered only for areas where low-height embankments were to be used. The misconceptions then prevalent prevented their use on embankments where excessive settlement could be expected. However, this assumption was changed in view of improvements in the application of geotechnical engineering techniques and the realization that concrete pavements could accommodate uniform settlement as effectively as any other type of stiff pavement. The environment for selection of pavement materials was expanded accordingly.

The first "modern" concrete pavement in South Africa was a 26-km dual-carriageway road constructed in 1968 near Cape Town. This was followed in 1978 by a 20-km section of similar road east of Pretoria. Initially, the type of pavement generally used was a short-joint spacing, unreinforced concrete pavement whose construction was mainly based on the Californian approach. To assess the construction and performance capabilities of other types of concrete pavements, an experimental pavement was constructed between Argent and Ogies in the eastern Transvaal in 1969. This sample segment incorporated various types of concrete pavement with numerous modifications, such as doweled and undoweled joints. The experiment not only resulted in general acceptance of plain concrete pavement with short joint spacing as the most appropriate type of cementitious concrete pavement for South African conditions but also yielded detailed information that permitted more definite judgments on matters such as cement-slag mixes and pavement thicknesses.

Construction of concrete pavements accelerated during the 1970s and has continued to do so during the 1980s. The most recent innovation in the use of concrete pavements has been their application in the rehabilitation of existing asphaltic pavements. Both unreinforced and continuously reinforced pavements have been used for this purpose.

PAVEMENT TYPE ECONOMICS AND POLICY

Many papers and articles aimed at justifying the selection of either asphaltic or cementitious concrete pavements in South Africa have been published during the 1960s and 1970s. Much of the information and data used (and hence the conclusions reached) have been spurious because they were based mainly on commercial interests.

In an attempt to introduce a degree of rationality into the process, a publication prepared by the Committee on Pavement Type Selection for the National Transport Commission was issued by the South African Department of Transport in 1980 (*1*). The economics of the process for selection of pavement type for major roads was analyzed, and all relevant factors were considered. In this document, the committee stated that for pavements carrying 12–50 million equivalent standard axles over its design life,

> . . . there is no significant difference on present worth of cost between bituminous and concrete pavements based on 1978/79 unit costs. The cheapest alternative will depend on the local factors prevailing at the time. The selection of an appropriate pavement to be used will depend on a number of factors among which local availability of materials, local knowledge, climatic conditions and performance of similar pavements in the area must be considered.

However, by 1985, the situation had changed, mainly as a result of better understanding of road user delay costs. Mitchell and Walker (*2*) demonstrated that

> . . . for heavy-duty pavements to carry up to 75 million E80s over a 80-year analysis period, a concrete pavement is more economical than a bituminous base pavement on a present worth of costs basis, particularly when road-user delay costs are taken into account. If the cost escalation trends of bitumen and tar continue to exceed those of cement, concrete pavements should continue to be more economical in the future.

Recent decreases in the price of bitumen mean that at present, concrete pavements are not necessarily cheaper than flexible pavements. The cost differences are sufficiently marginal, however, that major road authorities can base their selection on other considerations, such as technical performance, natural resources, experience and capability of contractors, and even public preference.

It is now recognized that concrete pavement designs that are based mainly on overseas methodology are probably conservative for South African conditions. An extensive program, using the Heavy Vehicle Simulator (HVS) (*3*), is currently under way. This plan has two primary objectives: to design more economical concrete pavements for various categories of roads and to develop more economical methods for the rehabilitation of concrete pavements. The HVS fleet will play a major role in achieving these objectives in a relatively short time. Trial test sections that include promising developments have been laid for HVS evaluation. The interim results of this research are discussed elsewhere in this paper.

DESIGN

Concrete Thickness

Modern concrete highways were introduced in the RSA in the late 1960s. Thickness design was initially based on the procedures of the Portland Cement Association (PCA) (*4*), AASHO (*5*), Road Research Laboratory in England (*6*), U.S. Army Corps of Engineers (*7*), and California State Highway Department (*8*). The thicknesses yielded by these methods were compared, and an appropriate design thickness was selected as needed.

Increased experience led to the adoption by what was then the Division of National Roads of a modified thickness design curve that was based on the 1970 edition of Road Note 29 (*9*). This modified curve did not take variations in subgrade or concrete strength into account. Pavement thickness was based on the estimated number of E80s in the design lane over the structural design life (usually 25 years) and an assumed concrete modulus of rupture of 8.8 MPa (550 psi) at 28 days, determined by third-point loading of 150 × 150-mm test specimens.

In practice, application of the various thickness design methods has resulted in thicknesses of 200 to 210 mm for highway pavements without tied concrete shoulders and 200 to 285 mm for pavements with tied shoulders. However, a thickness of 260 mm was used on one project, which traversed a mine slimes dump site.

Subgrades

The approach to subgrades for concrete pavements in South Africa requires awareness of the following considerations (*10*):

- uniformity in the composition, density, and moisture content of the subgrade during construction;
- adjustments, when feasible, in specified construction procedures and in thicknesses of selected materials at transitions of soils;
- proper procedures for backfilling ditches and trenches;
- road bed drainage; and
- procedures to prevent the undulations that are caused by compressible materials below fills.

Selected Subgrade

The subbase is typically supported on a 150-mm layer of selected granular material. Materials for selected subgrade have a minimum California bearing ratio (CBR) of 15 percent at 93 percent modified AASHTO density, a maximum swell of 1.5 percent at 100 percent modified AASHTO density, and a group index of 1. The required field density is 98 percent modified AASHTO.

Subbases

The cement-treated subbase is typically 100 mm thick and extends a minimum of 800 mm beyond the edges of the concrete slab. High-quality graded materials are normally selected, but cement-treated natural gravels have also been used. Current practice requires these to be strongly cemented [minimum 7-day unconfined compressive strength of 8 MPa (435 psi) at 100 percent modified AASHTO density].

The cemented material must also satisfy the durability requirements of a wet-dry durability test (*11*). These requirements take precedence over the unconfined compressive strength. The maximum loss of material permitted after 12 cycles of wetting and drying is 14 percent.

Shoulders

Most concrete highways incorporate tied, jointed concrete shoulders. However, asphalt-surfaced shoulders were used on two early projects.

Joint Design

The standard design is an unreinforced jointed pavement with transverse, skewed (1:6 clockwise) contraction joints at 4.5-m spacings and longitudinal weakened plane or construction joints at a maximum spacing of 3.7 m. The use of isolation joints is confined to locations adjacent to bridges.

Transverse contraction and longitudinal weakened plane joints are generally sealed. However, longitudinal construction joints are not sealed but are simply arris-rounded to a 5-mm radius. Preformed 11-mm-wide neoprene compression seals are used for longitudinal weakened plane joints, and 14-mm seals are used for transverse contraction joints. Recently, a 12.5-mm seal, suitable for both transverse and longitudinal joints, was introduced.

Materials

Cement

Ordinary portland cement (OPC), portland blast furnace cement (PBFC), portland cement with 5 to 15 percent slag (PC 15 SL), or a 50/50 mixture of OPC and milled granulated blast furnace slag (MGBS) can be used (*12*). PBFC is a cement that may contain 15–70 percent granulated blast furnace slag, but usually the slag content is 45 to 50 percent.

In practice, either OPC or PC 15 SL is commonly used. PBFC and 60/50 OPC/MGBS are not used because the lower rate of early strength development creates joint sawing problems.

Aggregates

Fine aggregates may be natural sands, crusher-produced sands, or blends of natural and crushed sands (*12*). To limit cement content and concrete shrinkage, maximum limits are imposed on the water demand of the fine aggregate (or combination of fine aggregates).

Coarse aggregates are usually supplied in two separate nominal sizes, 37.5 mm and (usually) 19.0 mm. In general, gap-graded concrete mixes are used; however, current practices tend toward the use of continuous gradings.

Admixtures

Water-reducing admixtures are used extensively. Air-entraining agents can also be used. It is likely, however, that the future application of the air-entraining admixtures will be limited to slip-formed paving or to paving concrete that is likely to exhibit excessive bleeding without such agents.

Requirements of Concrete

Concrete consistence is determined with due regard to the type of paving equipment to be used and the required characteristics of the mix (*12*). Once an optimum slump value has been established, however, variations must be limited to ~20 mm.

The specified cube (150 mm or 6 in.) compressive strength at 28 days is either 88 MPa (4,800 psi) or 0.85 times the compressive strength that corresponds to a 28-day modulus of rupture of 3.8 MPa (550 psi), whichever is higher.

CONSTRUCTION

Subgrades

Special techniques have been employed for weak or variable subgrades. For example, the dynamic substitution method was used to prepare the foundation for the 9-m-high embankment of a 1.2-km length of a road that traversed an area consisting of slimes, marsh, sediments and peat, with an average depth of 6 m.

Weak subgrades were also encountered on another project. Distributed steel and doweling of contraction joints had originally been specified, with retention of the normal contraction joint spacing of 4.5 m. These were later eliminated, however, in favor of an increase in pavement thickness from 235 to 260 mm.

On some projects, surface deflections were measured at the top of the subgrade before layer works were started. Where differential deflections were obtained, the cause was investigated and appropriate remedial work was carried out. Additional deflection measurements were then taken. A square or impact roller was also used successfully on some jobs to compact the area under fills before embankment construction and, subsequently, at every 2-m lift of the earthworks.

Cement-Treated Subbase

A cement-treated subbase is generally plant mixed and paver laid, using either asphalt or slip form concrete pavers. On a number of projects, the cement-treated subbase developed an unacceptable degree of cracking when it was cured under a black bituminous membrane and left for a long period before the concrete slab was placed. Measures were successfully implemented to control this cracking.

Concrete Mixing

Concrete is usually mixed at a central plant with dual 1.5-m^3 paddle mixers (capacity 120 m^3/h) and split drum mixers (capacity 150–180 m^3/h). Most side-formed projects have been built with paddle mixing equipment, whereas slip-formed projects generally use split drum mixers. A valuable feature of some split drum mixers is an automatic power demand recorder that permits the continuous monitoring of concrete consistency. On another project, the engineers used a 6-m^3 portable drum mixer that was equipped with an automatic print-out facility to provide details of date, batch number, time of mixing, and mix proportions.

Transportation of Concrete

The mixed concrete is usually transported to the road in rear-tipping trucks and dumped on the subbase in front of the paving equipment. Covers on trucks are essential as a protection against rain and when exposure to ambient temperatures above 25°C will exceed 20 min.

Paving Equipment

Two methods of paving are used: side form and slip form. Side form equipment is largely of German origin and typically consists of a compactor-finisher equipped with

- Rotary (paddle) or plate strike-off, vibrating compaction beam, and oscillating beam;
- Tie bar inserter;
- Diagonal leveling finisher:
- Texturing machine, to apply a longitudinal burlap, transversely grooved finish and white-pigmented membrane-forming curing compound; and
- On some projects, frame-mounted mobile canopies that cover up to 140 m of production.

Front-end loaders are generally used for spreading. On some projects, however, a German tracked paver (used principally for placing asphalt- or cement-treated base) was used. This device was attached to the leading unit of the "train."

Slip form equipment generally consists of Guntert and Zimmerman or McGregor pavers. These machines operate with guide wires (one on each side of the pavement) and include

- Transverse screws or a transverse plow (or both) for spreading and control of concrete surcharge;
- Immersion (poker) vibrators;
- Conforming plate; and
- An oscillating finishing beam.

Slip form pavers are also equipped with devices for automatic insertion of deformed tie bars. On projects in which wet-formed longitudinal joints used to be permitted, pavers had an attachment for automatic insertion of plastic strips. Attachments for the shaping and insertion of metal keyway strips have also been used.

A second machine, which also operates between guide wires, applies the final transversely grooved surface texture and the white-pigmented membrane-forming compound. For the initial burlap drag finish, the drag is attached either in front of the texturing-curing machine or behind a work platform that is towed by the slip form paver.

Paving Width

Generally, full-width paving of carriageways up to 11.1 m wide is required. A 15.0-m-wide carriageway is usually paved in two operations.

Surface Texture

The standard surface texture is obtained by applying a longitudinal burlap drag finish, followed by application of a transversely grooved texture that is achieved with a metal-tined grooving device. The tines are pieces of 0.6 $\times$ 3.0–mm flat spring steel, 100 to 125 mm long, spaced at random distances between 12 and 25 mm. The groove depth is 8–5 mm.

To reduce the traffic noise caused by grooving, a longitudinally grooved texture was provided on a concrete pavement in built-up areas in Natal. Subsequently, motorcyclists reported that they were having steering problems. Tests are now being arranged to investigate the relationship between noise levels and the frictional properties of surfaces, with the aim of reducing the noise factor.

Curing

Curing consists of the application of a white-pigmented, resin-based compound that complies with AASHTO standard M148, except that the water loss (as determined in the water-retention test) is limited to 0.040 g/cm^2. Because curing compounds have not always performed satisfactorily, certain aspects, such as specifications and field control of curing compounds, are being investigated by the Portland Cement Institute in Pretoria.

Joint Sawing

Although span saws have been used for sawing transverse contraction joints, the use of hand-guided saws is common on most projects. Hand-guided saws are also used for longitudinal weakened plane joints. In general, the optimum time for sawing has been between 0 and 24 hours after placement of the concrete.

Production

Production rates of up to 1,100 m^3/day have been achieved with side form pavers. With slip form pavers, the maximum has been 2,200 m^3/day, representing 1 km/day of 10.9-m-wide carriageway of 200-mm thickness.

Bridge Deck and Approach Slabs

Because concrete bridge decks and approach slabs provide insufficient space for the tracks of slip form pavers, full-width concrete surfacing (inclusive of concrete shoulders) for these features is not possible, and the work has to be done manually. This problem does not occur with side form pavers.

Trial Pavement

Before work begins on the main pavement, the contractor is required to lay a section of trial pavement to demonstrate that he is able to construct the pavement in accordance with the specified requirements (*12*). The trial pavement uses the same materials, concrete mix, and equipment as those intended for the main pavement. The contractor is also required to demonstrate the methods that he proposes to use for the application of the surface textures and the construction of joints, including installation of dowels, tie bars, and so on. The required minimum continuous trial length is 150 m.

Construction Problems

Numerous problems can be encountered during the concrete paving process (*13*):

- Inconsistency in the workability and proportioning of concrete mixes on some projects can cause variations in texture depth, time of texturing, finishing, and inconsistent timing of joint sawing.
- Inadequate protection of pavement against wind, sun, and rain can result in plastic shrinkage cracking and can affect texture and abrasion resistance.
- Delayed joint sawing, because of raveling of relatively fresh concrete, can cause shrinkage cracking.

Certain problems are specific to slip form construction:

- Because it has not been possible to form satisfactory day joints, this operation has had to be done manually, and panels infilled by hand have sometimes created poor ridability.
- When paving is done in two widths, poker vibrators have to be lifted. This step has affected concrete compaction near previously placed tie bars.
- If the mix is not carefully proportioned, unacceptable edge slumping will generally occur.
- Because it is impossible to repeat transverse tining, the achievement of the required texture depth presents a problem with stiffer mixes.
- The additional width of the earthworks (approximately 800 mm) required on both sides of the pavement can be costly with high fills.

Other problems are specific to side form construction:

- Unsatisfactory concrete spreading practices can lead to delays in finishing, texturing, and curing.
- Edge breaks that are caused by removal of side forms that have a keyway former cannot be satisfactorily repaired. This problem is aggravated when deformed tie bars are present.

Riding Quality

For the highest class of roads in South Africa, a Present Serviceability Index (PSI) of 4.0 is sought on newly constructed roads. The riding quality of roads has been measured with both the PCA roadmeter and the linear displacement indicator (LDI) riding quality car. In general, riding qualities measured by the LDI-type instrument have values below 4.0. This may, however, be due to a shift factor between the two types of instruments used to measure riding quality.

In general, slip-formed paving gives slightly better riding quality than side formed. When strict quality control is enforced, however, side-formed paving produces equally good results. Also, full-width paving produces better riding quality than does half width. The 8.9-m-wide paver used by some contractors produces low riding quality because most of the finishing is done manually. It may be necessary to provide finishing beams to suit the 8.9-m width.

The riding quality of 2.26-m- and 8.7-m-wide concrete pavements that are constructed manually to widen an existing concrete highway is low and is similar to the quality of the

8.9-m-wide paver-laid concrete. Finally, it should be noted that to achieve the best results, uniform concrete and a high level of dedicated and sustained supervision are essential.

Joint Seals

With a few exceptions, neoprene-type seals, with a life of 8–10 years, have been used.

RESEARCH

Research into concrete roads has recently received a new impetus in South Africa with the realization that the building of a sound concrete industry is necessary and that competition with other pavement types needs to be stimulated for economic reasons. There is an increasing demand for relatively maintenance-free roads close to urban areas, and concrete pavements have an important function to fulfill in this regard.

Experimental sections have been tested on two major roads, one involving an overlay to a distressed concrete pavement and the other including possible new designs. These are discussed in more detail in the following sections.

Overlays to a Distressed Concrete Pavement

Full-scale experimental overlays were constructed on an existing distressed pavement near Cape Town (*14, 15*). The distressed pavement consisted of a 200-mm jointed concrete slab with a 4.5-m joint spacing, a 100-mm cemented subbase, and a 75-mm natural gravel selected subgrade over a deep layer of sand. Some 5 years after construction, an unusually high incidence of hairline cracking was observed. It was established that this phenomenon was caused by an alkali-aggregate reaction. Traffic loading resulted in further deterioration of the cracks in the vicinity of the points and eventually resulted in punch-outs.

During 1986–1988, the road carried an average of 650 standard 80-kN axles per day in the slow lane. The experimental overlays were constructed on this road during the first three months of 1985, and an HVS test program on these sections began in June 1984. The layout of the experimental overlay sections is shown in Figure 1.

Bitumen-Rubber Premix Overlay

The 80-mm bitumen-rubber overlay (Sections A and N in Figure 1) comprised a semi-open grading. The primary distress mechanism was cracking in the overlay. These cracks reflected the block pattern of active cracks from the jointed concrete pavement. The cracks were located in the vicinity of the joints and extended to ~800 mm from the joints. The HVS testing indicated that this overlay could be expected to carry ~510,000 standard 80 kN axles (E80s) before the cracks would need to be repaired.

Gap-Graded Asphalt Overlay with Bitumen-Rubber Interlayer

This overlay (Section E in Figure 1) consisted of a 30-mm fine, continuously graded asphalt leveling course with 8.6 percent 150/200 pen bitumen. On top of this was a bitumen-

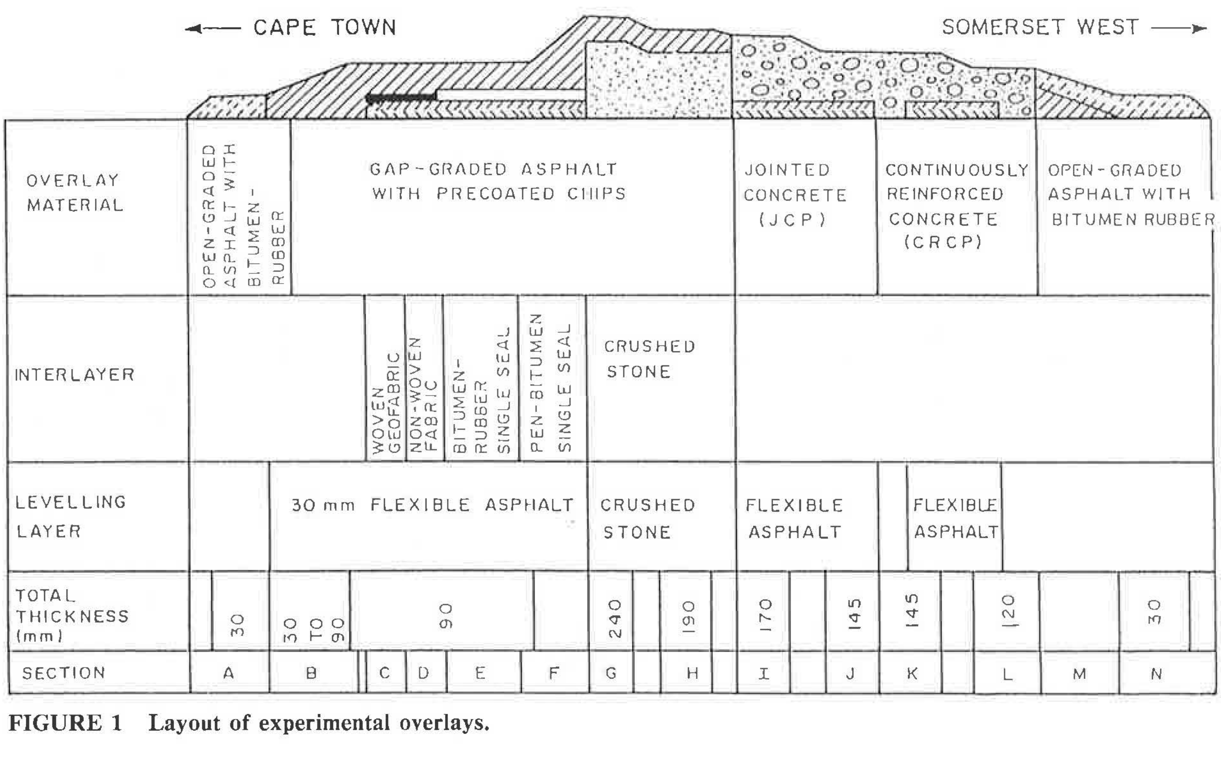

FIGURE 1 Layout of experimental overlays.

rubber single seal, topped with a 60-mm gap-graded asphalt layer.

The asphalt exhibited limited plastic deformation (7 mm) when asphalt temperatures exceeded 40°C. Faint longitudinal surface cracking was also observed. These cracks were not confined to the vicinity of the joints in the existing concrete pavement, where high load-associated crack movements (630 μm) were measured before overlay placement. Closer inspection revealed that the cracks originated in the gap-graded asphalt layer above the bitumen-rubber interlayer. The layer acted as a weak plane, and horizontal slippage contributed to the lateral movement of the gap-graded asphalt layer.

Gap-Graded Asphalt Overlay with Woven and Nonwoven Geofabric Interlayers

These two overlays (Sections C and D in Figure 1) comprised geofabric layers that were placed on top of an 80-mm leveling course, followed by a 60-mm gap-graded asphalt layer. Within 12–18 months after construction, both these sections reflected the joint pattern of the existing jointed concrete pavement in the form of fine cracks. All evidence indicates that the cracking was caused by thermal movements. These sections were not tested with the HVS.

Conventional Gap-Graded Asphalt Overlay (30 to 90 mm Thick)

This overlay (Section B in Figure 1) consisted of conventional gap-graded asphalt (with no interlayers) and varied in thickness from 80 to 90 mm. Within 10–20 months after construction, the joint pattern of the existing pavement reflected to the surface. Generally, longer periods without crack reflection were associated with thicker overlays. These cracks were also attributed to thermal movements and were not tested with the HVS.

Crushed Stone Overlay (150 to 200 mm Thick)

The crushed stone overlay (Sections G and H in Figure 1) carried the equivalent of ~30 million E80s without reflecting the crack pattern in the existing concrete pavement. However, a few cases were reported in which fine hairline cracks from the joints in the existing concrete pavement reflected through the overlay 3 years after construction. These fine cracks are not expected to lead to distress under traffic loading.

Unbonded Jointed Concrete (JC) Overlay (115 to 145 mm Thick)

The unbonded JC overlay (Sections I and J in Figure 1) cracked after the equivalent of ~12 and 30 million E80s in the dry state for the 115-mm- and 145-mm-thick sections, respectively. The cracks were semicircular, ran predominantly in the transverse direction, and developed 600–700 mm from the joint.

The load applications that led to cracking, however, reduced markedly to 3 and 7 million, respectively, when water was allowed to seep into the joints. This was due to high relative vertical movement at the joints (~0.2 to 0.8 mm initially, increasing to about 1.1 mm before cracking) and resulted in severe pumping that, with time, created a void between the concrete overlay and the bond-breaking layer. The bond-breaking interlayer (a 30-mm fine, continuously graded asphalt) disintegrated in the vicinity of the wet joint. This degeneration was caused by the aggressive pumping action that stripped the binder from the asphalt and allowed the unbound fine material to be ejected. The crack mechanism was not related to the condition of the existing concrete pavement.

Thin Continuously Reinforced Concrete (CRC) Overlay (90 mm Thick)

In contrast to the jointed concrete overlays discussed previously, the thin CRC overlay (Section L in Figure 1) displayed no significant relative movements at the shrinkage cracks in either the wet or the dry states. Throughout the test the movements measured were generally below 30 mm, mostly in the horizontal direction. The equivalent of about 40 million E80s was applied, and no significant crack development occurred.

The relative crack movements of the pavement overlays discussed here are displayed in Figure 2. The marked differences in behavior between the CRC overlays and the wet joints of the thin JCPs are illustrated.

Other Experimental Concrete Sections

Additional experimental sections were laid in Natal near Pietermaritzburg (*16*). These sections are shown in Figure 3.

Thin Concrete Over a Thin, Strongly Cemented Subbase

A 150-mm JCP (Section 3 in Figure 3) displayed exactly the same failure mechanism as the thin JC overlays discussed previously, namely D-shaped cracking in the vicinity of the joints. In this case, the 150-mm gravel layer below the 100-mm cemented subbase was pumped out. Cracking at a wet joint occurred after only 1.5 million E80s using bidirectional loading. The number of repetitions needed until cracking occurred increased marginally to some 1.6 million E80s in the unidirectional loading mode. It was concluded that the difference between unidirectional and bidirectional loading was not significant when D-shaped cracking was the primary mechanism of failure (the dry joint was not tested to failure). This conclusion is substantiated by the D-shaped cracking that is currently developing in the fast lane next to these test sections, after a comparable number of E80s applied by normal traffic.

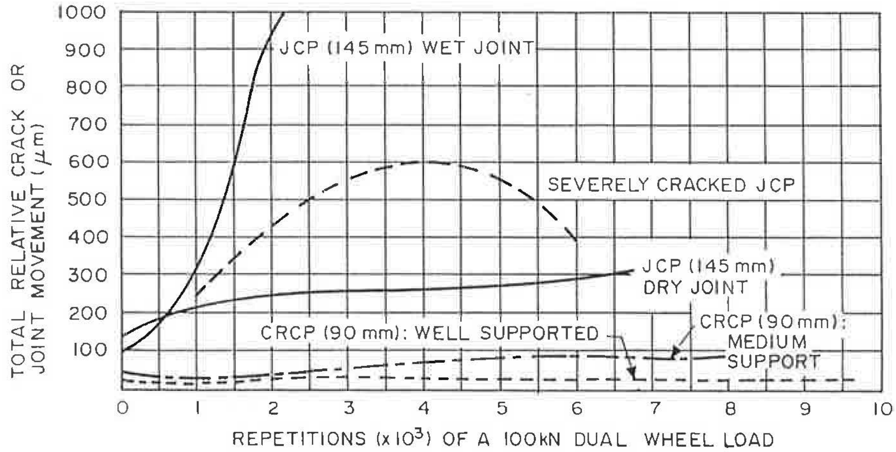

FIGURE 2 Typical crack or joint movements on rigid pavements [after Viljoen et al. (*14*)].

Thin Concrete Over a Thick, Strongly Cemented Subbase

A 150-mm-thick JCP (Section 5 in Figure 3) differed from the previous pavement only in the thickness of the cemented subbase (200 mm instead of 100 mm). The slab fatigue life of this section was significantly higher (some 12 million repetitions at the wet joint and some 88 million repetitions at the dry joint). The primary reason for this difference in performance was the non-erodible 200-mm cemented layer below the slab. No surface pumping was observed during either of these tests.

Thin Concrete Over a Weakly Cemented Subbase

Currently, tests are being carried out on a 150-mm JCP supported by two 125-mm weakly cemented (unconfined compressive strength between 0.7 to 8 MPa) layers (Section 4 in Figure 3). Pumping is occurring at the wet joint, and early D-shaped cracking is expected.

Thick Concrete Slabs (Greater than 200 mm) with Erodible Support

Two sections with concrete slab thicknesses of 230 mm were tested. The first section had a 100-mm strongly cemented non-erodible subbase supported by highly erodible subgrade material (Section 6 in Figure 3). This section exhibited a moderate pumping action throughout the test and had relative joint movements of about 0.55 mm when the test ended, after some 66 million E80s. A substantial amount of the granular subbase layer was pumped out during the test. No slab cracking occurred, but it was apparent that the slab was rocking. Bidirectional loading was used, and no step faulting occurred. However, all the results indicate that step faulting is likely to develop under normal traffic and under unidirectional HVS loading.

Thick Concrete Slabs (Greater than 200 mm) with Non-Erodible Support

The slab of the second section was supported by a 100-mm cold-recycled asphalt layer, followed by a 100-mm strongly

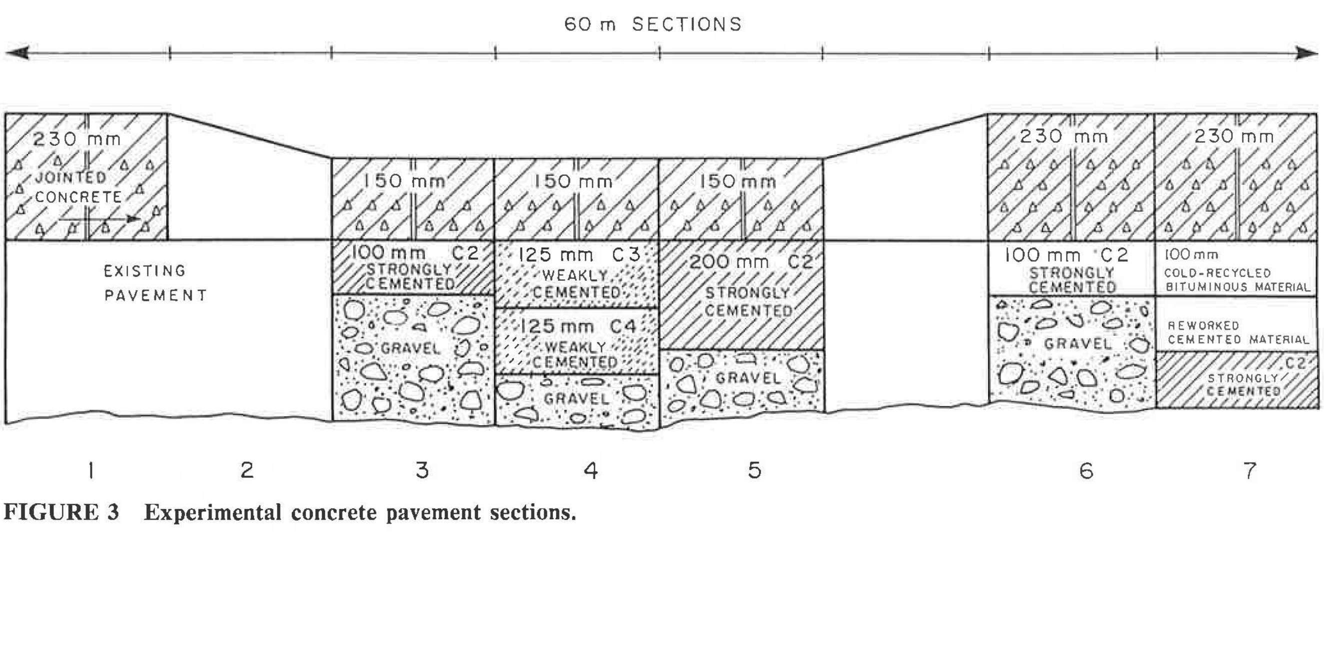

FIGURE 3 Experimental concrete pavement sections.

cemented layer and three granular layers (Section 7 in Figure 3). This section displayed no signs of distress after ~80 million E80s in the wet state. The deflection levels and the relative point movements increased only marginally during the test and were as low as 0.04 and 0.02 mm, respectively, at the end of the test. The good performance is ascribed to the apparently non-erodible 200-mm supporting layers.

Research Findings from Concrete Pavement Testing

The major findings and reconfirmation of existing knowledge to date can be summarized as follows. Slab cracking in the vicinity of the joints is the primary mechanism of failure of thin, jointed concrete pavements (up to 150 mm in thickness), whereas step faulting is more likely to cause failure in thick slabs (greater than 200 mm in thickness). Slab cracking generally occurs when the maximum tensile strain in the concrete reaches levels of 100 $\mu\epsilon$. These levels are not likely to be reached in thick slabs.

When water is present below points, the supporting layers in the close vicinity of the bottom of the slab are often eroded away, creating a void below the slab. The value of initial supporting layers, however strong, can be effectively destroyed in this manner.

Pumping can be a severe problem even with thick concrete slabs. To minimize the problem, cemented subbases need to be non-erodible and require a thickness of at least 200 mm to support thick slabs under high traffic rates. The slab fatigue life of 150-mm-thick jointed concrete pavement can potentially increase by a factor of 10 when non-erodible slab support is increased from 100 to 200 mm, and by a factor of 30 if water can be prevented from seeping into the joints. The cold-recycled asphalt that was evaluated proved to be an effective supporting layer for concrete.

More economical concrete pavements can be designed by using reduced slab thicknesses. A key element is the quality and thickness of the supporting layers close to the bottom of the slab.

The difference in behavior between unidirectional and bidirectional loading is not significant when D-shaped cracking is the primary mechanism of failure. The number of repetitions until cracking occurs under traffic compares well with that of HVS trafficking in both loading modes.

Thin, continuously reinforced concrete pavements can carry heavy traffic when well supported. The key to good performance lies in good load transfer at transverse cracks in CRC pavement, resulting in low relative movements.

CONCLUSIONS

Several important conclusions can be drawn from experience with concrete highways in the Republic of South Africa. It has been noted that modern concrete pavements constructed since 1968 are generally performing well, and their use is expected to increase in the 1990s, particularly for highways carrying heavy traffic. To achieve best results with concrete pavement, however, skilled field personnel and a high level of dedicated and sustained supervision are essential. The defects that have occurred in certain projects are believed to be caused by construction and construction-associated defects, substandard concrete, adverse weather conditions, and unfavorable roadbed characteristics.

Work with experimental sections has demonstrated that economical concrete pavements can be achieved with thinner jointed concrete slabs on erosion-resistant subbases that are 200 mm thick. Also, thin, continuously reinforced concrete pavements can perform well under heavy traffic when well supported. Because pumping can present a problem even with thick concrete pavement, cemented subbases need to be non-erodible, and they require a thickness of at least 200 mm for heavy traffic conditions.

The use of cementitious concrete pavements has also tended to stabilize the cost of pavement construction in South Africa through competition created by having a viable alternative to asphaltic concrete pavements in the heavy axle loading spectrum. A need exists for accelerated progress in the development of economically viable low-volume concrete roads for South African conditions. It is also considered necessary to examine riding characteristics of the various types of pavement over time, as well as operational aspects such as skid resistance, road noise generation, and visibility for night driving conditions.

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Construction of Concrete Pavements in West Germany

RUPERT SPRINGENSCHMID, BERND REIMER, AND WALTER FLEISCHER

In West Germany, the concrete pavements of the "autobahns" are generally constructed by the slip form method, usually on top of a hydraulic- or bituminous-bound base. The thickness of these pavements has recently been increased from 22 cm (9 in.) to 24–26 cm (9.5–10 in.). To control the formation of cracks and to relieve the stresses caused by restraint of volume changes, these pavements are divided by joints into slabs 5 m (16.5 ft) long and 4.25 m (14 ft) wide. The slabs are not reinforced, and ordinary portland cement is used. The transverse joints are doweled, and the longitudinal joints are anchored. Both dowels and anchors are vibrated into the compacted concrete. The aggregates used within the concrete surface must have a high frost resistance, and at least half of the coarse aggregate has to be crushed. To withstand the effects of frost and deicing agents, the concrete must also contain entrained air. When damaged slabs are reconstructed, a high–early strength concrete containing superplasticizer is used. In summer, the reconstructed segments can be reopened to traffic in as little as 12–14 hr. When old concrete pavements are renewed, either the old concrete is broken and new pavement laid on it, or the old concrete is crushed by a breaker and used as an aggregate for the cement-bound base.

In 1888, the first concrete pavement was built in Germany in the city of Breslau (*1*). Today, the majority of the new "autobahns" in West Germany are constructed with concrete pavements. Airport runways, taxiways, and aprons are also built of concrete. In West Germany, there are 8,400 km (5,040 mi) of autobahns, of which 2,800 km (1,680 mi) are paved with concrete (Figure 1). All autobahns built before World War II have been repaved since that time. In general, the choice between an asphalt or concrete pavement depends on the cost. Because some 30 percent of the autobahns in West Germany are more than 25 years old, the maintenance and renewal of these roads has become increasingly important (*2, 3*).

PRINCIPLES FOR PLANNING AND CONSTRUCTION

The standard specification for the construction of concrete is the *Additional Technical Specifications for the Construction of Concrete Pavements* (*4*), which is currently under revision. For nearly 50 years, autobahn concrete pavements have been built with a thickness of 22 cm (9 in.). Under the standards that have been imposed within the European Common Market, the maximum axle load was increased from 10 to 11.5 metric tons (MT) (22.5 to 26 kips) in 1988. As a result, the standard thickness of the autobahn concrete pavement has been increased to 24–26 cm (9.5–10 in.), depending on the volume of truck traffic. Beneath the concrete surfaces of the autobahns is a hydraulic or bituminous-bound base and an unbound subbase.

The concrete pavements are divided into slabs to control the formation of cracks and to relieve stresses caused by restrained volume changes. During rapid cooling and heating, thermal gradients can reach 0.09 K/mm (4°F/in.), resulting in stress because the curling of the concrete slabs is hindered. The length of the slabs is limited to 25 times their thickness so that these bending stresses will not exceed the tensile strength of the concrete. Normally, the joint spacing is 5 m (16.5 ft).

Until a few years ago, all slabs were made as wide as a lane (3.75 m; 12.5 ft). Currently, the slabs are 4.25 m (14 ft) so that the outer wheels of trucks will not run too close to the edge of the slabs.

In most cases, contraction joints are used. The depth of the initial saw cut is 25–40 percent of the thickness of the concrete slab. The contraction joints are cut so that they are wider at the top, forming a reservoir 8–15 mm ($\frac{3}{8}$–$\frac{1}{2}$ in.) wide and 25–35 mm (1–1$\frac{1}{2}$ in.) deep. All joints are sealed (Figure 2). Expansion joints are only provided in special cases, such as between concrete pavements and bridge abutments.

During hot weather, the omission of expansion joints can cause compressive stresses. There are several advantages to this effect: tensile stress is reduced; the width of the joints

FIGURE 1 Autobahn with two lanes in one direction.

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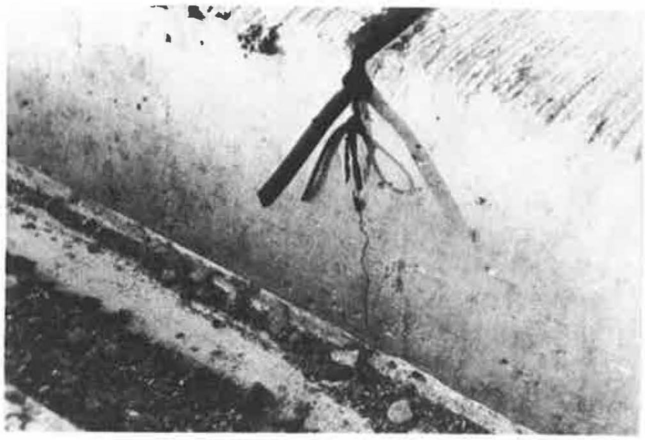

FIGURE 2 Sealed transverse contraction joint.

remains small; the stresses on the joint sealant are low; and because of aggregate interlock, the load transfer is higher (*5*).

Dowels are installed at all transverse joints to prevent faulting. The dowels used are round, smooth steel bars, 50 cm (20 in.) long and 25 mm (1 in.) in diameter. To prevent corrosion and bonding with the concrete, these bars are completely coated with a layer of plastic 0.3 mm (0.012 in.) thick. In the case of expansion joints, additional plastic expansion caps are inserted on one side to allow longitudinal movement of up to 15 mm (0.5 in.).

Tie bars are installed across the longitudinal joints to prevent joint opening. These anchors are ribbed bars, 80 cm (32 in.) long and 16 mm ($\frac{5}{8}$ in.) in diameter, with the middle 20 cm (8 in.) coated with plastic. Reinforced concrete is used only in a few special cases, such as when the length of the slab exceeds 25 times its thickness or if uneven settlement of the road base is expected.

CONCRETE TECHNOLOGY AND REQUIREMENTS

Ordinary portland cement, similar to the U.S. Type I cement, is used for all of the larger projects. Because slowly setting cements are preferred, retarding mixtures are unnecessary, even for large hauling distances. To ensure a low risk of irregular cracks before the initial saw cut, the portland cements that are used have a low zero-stress temperature and a low cracking temperature in the cracking frame test.

The aggregate used within the concrete surface must have a high frost resistance, and at least half of the coarse aggregate must be crushed. In areas in which such aggregate is too expensive, the concrete is poured in two layers. The specification for the aggregate of the lower layer is not as high as that for the upper layer. Washed natural sand, which is mainly quartz, is usually used as the fine aggregate.

The water-cement ratio of the fresh concrete is between 0.42 and 0.48, and the cement content is between 320 and 350 kg/m^3 (540 and 590 lb/yd^3). The workability of the concrete is low. Concrete used for autobahns must have an average cube strength at 28 days of at least 40 N/mm^2 (corresponding to a compressive strength of 4,440 psi for 6 $\times$ 12–in. moist-cured cylinders). A high resistance to alternate freezing and thawing and to deicing chemicals is required, so the fresh concrete must have an average of 4 percent entrained air.

Concrete for all autobahns is produced in on-site mixing plants (Figure 3). Modern mixing plants can be set up in 2–4 days without much excavating work (*6, 7*). The capacity of ready-mixed concrete plants is not usually large enough to produce the amounts of concrete necessary for the continuous slip form paving. Interruptions in the placement of concrete must be avoided to prevent unevenness in the pavement. The twin–pug mill mixers that are most commonly used have a production rate of 100–240 m^3/hr (130–310 yd^3/hr). If the pavement has to be constructed in two layers, the concrete for the upper and lower layers is usually mixed at two different mixing plants.

The cement is stored in silos and is measured by weight. A high degree of accuracy is necessary in proportioning the air-entraining agents. The aggregates are separated according to size and are stored at ground level. When needed, they are loaded into the silo compartments with wheeled loaders. From the silo, they fall onto a conveyor-type scale, and then they are transported to the feeder unit.

A concrete laboratory is located within each mixing plant. Every day, the aggregates, workability, and water content of the fresh concrete are tested, and the air content is tested every hour. Cubes for testing the compressive strength are made daily.

CONCRETE PAVEMENT CONSTRUCTION

The concrete is generally laid with slip form pavers (Figure 4). The maximum operating width of the largest slip form paver is 15.25 m (50 ft). For the construction of an autobahn with two lanes in one direction, the concrete shoulder is normally placed with the lanes. Two construction joints in the longitudinal direction are avoided, and the bending stress at the edges of the outer slabs is reduced. The concrete is transported from the mixing plant to the site in dump trucks.

FIGURE 3 Mixing plant for a concrete pavement construction site.

FIGURE 4 Complete paving plant train.

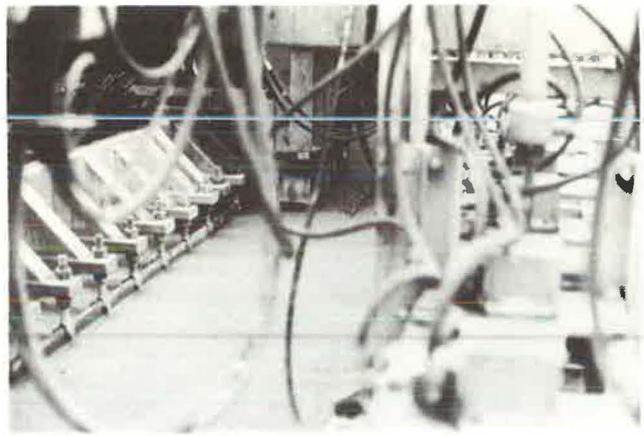

FIGURE 6 Anchor-vibrating device.

During the transport, the fresh concrete is covered with tarpaulins to prevent drying out and to protect against rain. The bound base serves as the construction site road.

Single-Layer Construction

The concrete is poured into one or two parallel moving concrete spreaders for distribution. These concrete spreaders are followed by the slip form paver, which compacts the concrete with internal vibrators.

In the chassis of the slip form pavers is a special device that vibrates the dowels into the concrete (Figure 5). The horizontal position of the dowels is guaranteed by fixing them with two or four bifurcated plates during vibration. To minimize the faulting of the concrete structure, the dowel-vibrating device stops moving while the dowels are being vibrated into the concrete, and the slip form paver itself moves on without pausing. Dowels are placed into the dowel-vibrating device either by hand or automatically. The anchors are vibrated into the concrete in a manner similar to that used for the dowels (Figure 6). The last parts of the slip form paver are the transverse and longitudinal smoother (Figure 7).

Slip form paving requires a certain consistency of concrete to obtain a perfect finish and prevent the pavement from edge slumping after the finishing transition. A self-propelled working deck follows behind the slip form paver, from which the broom finishing is carried out (Figure 8) and the curing agent is sprayed onto the concrete surface. The broom finishing is still done by hand because even slight changes in the mortar content on the surface must be compensated for to achieve an almost constant roughness. The whole paving plant train is controlled by wires or laser beams.

Because studded tires have not been allowed in West Germany since 1975, the texture of fine mortar at the surface is decisive for skid resistance. High skid resistance is necessary because there is no speed limit for cars on the West German autobahns. A double-rowed spring steel broom is used to produce a roughness depth of 1–2 mm (0.04–0.08 in.). A larger degree of roughness is avoided to prevent a corresponding increase in noise.

The finished pavement is protected by a tent draft. The protective tents are not necessary if a film-forming curing agent that protects against heavy rain is used as required.

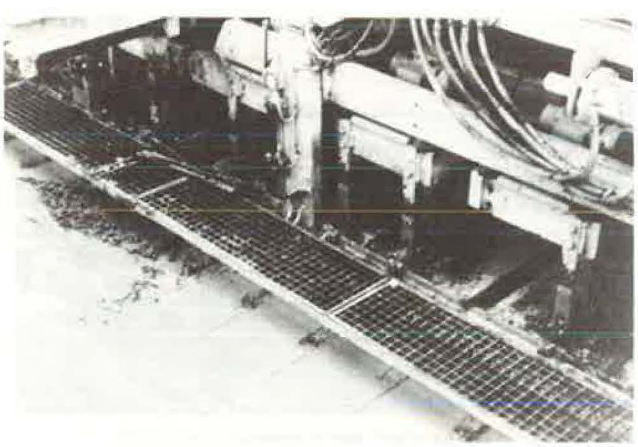

FIGURE 5 Dowel-vibrating device.

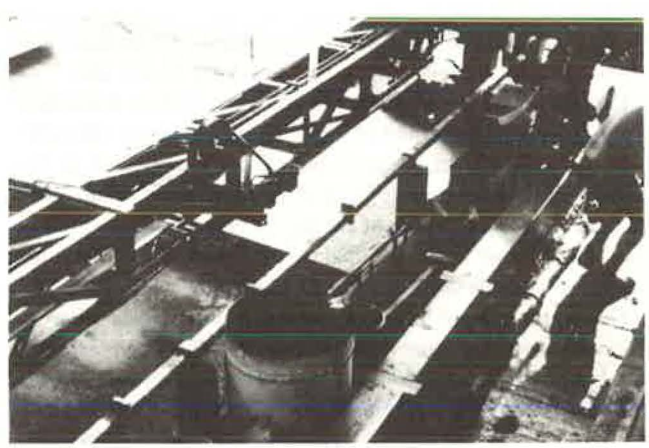

FIGURE 7 Transverse and longitudinal smoother.

FIGURE 8 Broom finishing.

Double-Layer Construction

Two slip form pavers are needed for the construction of a double-layer pavement. The concrete of the lower layer is spread and compacted by the first slip form paver, as described previously for a single-layer pavement. The lower layer, however, is 10 cm (4 in.) narrower on each side than is the upper layer. The edges of the pavement therefore consist only of the upper layer.

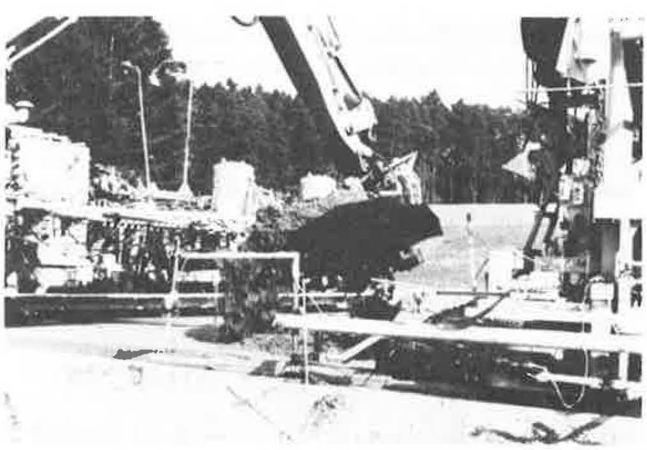

FIGURE 9 Backhoe placing the concrete of the top layer on the compacted concrete of the bottom layer.

FIGURE 10 Cutting transverse and longitudinal contraction joints with saws.

The anchors and dowels are vibrated into the concrete lower layer, as mentioned previously. Until a few years ago, the concrete of the top layer was poured by a side feeder. Today, a backhoe is used to take the fresh concrete from the dump truck and place it on the compacted lower layer (Figure 9). The transverse spreader of the second slip form paver spreads the upper layer of concrete across the entire width of the pavement.

The concrete of the upper layer is also compacted by internal vibrators. The finishing and protecting of the concrete are similar to those used in single-layer construction (*5, 8, 9*).

Joint Construction

The transverse and longitudinal joints are normally saw cut with water-cooled diamond blades (Figure 10). All of the joints are cut wider at the top to form a reservoir and are then cleaned and dried. A rope is inserted into the bottom of the cut, the sides of the joint are primed, and then the joint is sealed.

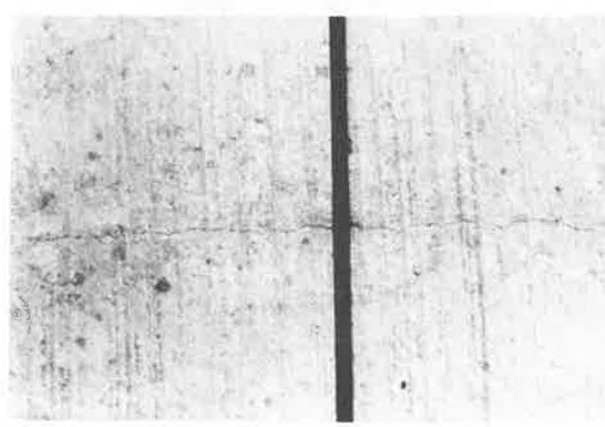

FIGURE 11 Longitudinal contraction joint placed in the compacted fresh concrete (crack), with sealed transverse contraction joint.

Longitudinal contraction joints can also be produced in the compacted fresh concrete by a vibrating metal strip fixed on the slip form paver. A small crack appears in the hardened concrete above this cut (Figure 11). No additional sawing or sealing of these joints is necessary.

In some cases, contraction joints are not sealed because the sealing of the joints is only waterproof for a short time (a maximum of 1 year) and the maintenance of the joints is expensive. On the other hand, unsealed joints require a bituminous base underneath. Road sections with drainage pipes underneath the joints or with geotextiles are now being tested (*9, 10*).

Evenness

Compliance with evenness requirements is determined by using a profilograph. In West Germany, a maximum unevenness of 4 mm (0.16 in.) within a 4-m (13-ft)-long beam is allowed. If this limit is exceeded, a fine must be paid. Large unevennesses are leveled with a bump-cutter.

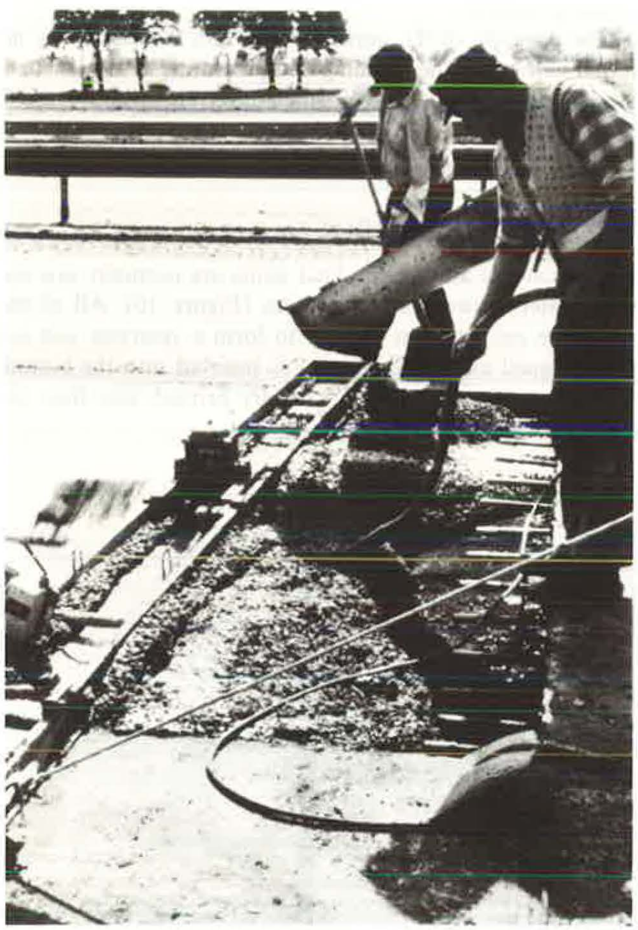

FIGURE 12 Paving and compacting of high–early strength concrete for 1-day reconstruction of concrete slabs (fast track concrete paving).

FIGURE 13 Finished section of 1-day reconstruction.

ONE-DAY SLAB CONSTRUCTION ("FAST-TRACK" CONCRETE PAVING)

During warm weather, up to four slabs of concrete pavement can be reconstructed with high–early strength concrete. The concrete is transported to the construction site in truck mixers (Figure 12). The cement is placed in forms, and the surface is smoothed with a finishing screed. Dowels are placed in dowel baskets before the concrete is poured.

Joints are cut 6 hr after pouring, and the lanes are opened to traffic again (Figure 13). To achieve the required high strength of 10–12 N/mm^2 (1,111–1,333 psi) at 6 hours, a cement content of 360–400 kg/m^3 (607–674 lb/yd^3) is necessary. A superplasticizer makes a low water-cement ratio possible. The cement, superplasticizer, and air-entraining agent must be compatible so that the correct consistency is achieved and enough small air bubbles are produced (*9, 11*).

RENEWAL OF OLD CONCRETE PAVEMENTS

Many different techniques have been tested for renewing old concrete pavements. If the width of an old pavement is insufficient, the old pavement is broken into pieces smaller than

0.7 m (2.25 ft) and a strip of lean concrete is used for the outer lane. A new pavement is placed on top of the existing one. Unevenness is smoothed out with mortar as necessary. The new pavement is at least 22 cm (9 in.) thick and is constructed without a separating layer. If the design of the road has been changed, the old concrete is crushed by a breaker and used as an aggregate for the cement-bound base (*3, 12*).

SUMMARY

In West Germany today, the concrete pavements used on autobahns and at airports are usually constructed by the slip form method. The concrete pavement is divided into slabs by doweled transverse joints and anchored longitudinal joints. No reinforcement is used.

For the reconstruction of as many as four damaged slabs, a high–early strength concrete with superplasticizer is used (fast-track concrete paving). During warm weather, closure to traffic may be as brief as 12–14 hr with this technique.

When old concrete pavements are renewed, one of two procedures may be followed. Either the old concrete is broken and the new pavement is placed on top of it, or the old concrete is crushed by a breaker and used as an aggregate for the cement-bound base.

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Concrete Pavement Construction in Spain

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The development of concrete road pavements in Spain is described. Traffic and climate impose severe constraints in Spain, so design and construction procedures developed in other countries usually must be adapted to make them suitable for Spanish conditions. Although the first concrete pavements in the nation date from 1915, mechanized construction was not applied until the 1960s. In 1971, slip form pavers were introduced, along with the Californian approach. This technique has undergone considerable modification since the 1970s. Recent work indicates that to avoid faulting at the joints (caused by heavy traffic, which is common in Spain), the joints must be fitted with dowels, and this practice has been made compulsory in the most recent standards. Several contractors now have paving machines that can insert dowels into fresh concrete without halting. The characteristics of the longitudinal surface textures used in Spain are described because Spanish roads represent the only large-scale application of such textures in Europe. Finally, some observations are made on the use of roller-compacted concrete pavements, which are primarily used on secondary roads but have recently been used on some main roads.

Spain is part of the Iberian peninsula, which is located at the southwestern corner of Europe. The nation has an area of ~505,000 km^2 (~195,000 mi^2), and its 1988 population was ~40 million people.

The country's physical geography is dominated by a large central plateau known as the Meseta. The location, extent (more than two-fifths of the country), and significant altitude (650–700 m or 2,100–2,300 ft) of the plateau have a distinct effect on the country. Except at its eastern edge, the Meseta is surrounded on all sides by a group of prominent mountain chains with peaks more than 2,600 m (8,500 ft) tall. Outside the Meseta there are a number of other mountains. With an average altitude of 660 m (2,165 ft), Spain is the second-highest country in Europe (after Switzerland). Lowland plains cover a relatively small area of the country, and the mountain chains reach right down to the coastline.

Two climatic zones, known as "wet Spain" and "dry Spain," can be distinguished. Wet Spain, with average annual precipitation of more than 800 mm (32 in.), consists of a relatively narrow band in the northern part of the country, plus some isolated mountainous areas. In dry Spain, a distinction can be made between the coastal region, which has a mild Mediterranean climate, and the Meseta, which has a continental climate (cold winters and torrid summers). The Meseta region not only has large temperature variations over the year but also frequently produces great changes from day to night (sometimes more than 30°C, or 54°F). These extreme shifts cause high temperature gradients in road pavements.

The Spanish road network is currently 315,000 km (195,000 mi) in length. Some 23,000 km (14,000 mi) of this length form the state network, which is under central government management. There are some 2,100 km (1,300 mi) of freeways, of which 360 km (225 mi) have concrete pavements. One of the basic objectives of the government's 1984–1991 road plan (which is currently under way) is to add a second carriageway to more than 3,200 km (2,000 mi) of national highways. It is expected that ~1,000 km (620 mi) of this second carriageway will have concrete pavement.

Currently, the number of vehicles registered in Spain is of the order of 12 million, including 1,600,000 trucks and 45,000 buses. Road transport is vital and accounts for 73 percent of interurban freight in ton miles. The legal limit for axle loadings is among the highest in the world: 13 T (28.6 kips) for a single axle and 21 T (46.3 kips) for a twin axle. Although the percentage of overloaded axles above those limits is decreasing, the most recent weighings with dynamic scales have demonstrated that 4 percent of all axles are above the legal limit. There have been some loadings of 20 T (44 kips) on a single axle and 30 T (66 kips) on twin axles.

Clearly, this combination of climatic and traffic factors makes the stresses that occur on the pavements of Spanish roads that carry heavy traffic much higher than those on similar roads in most other countries (*1*). As a result, many techniques that have been developed and used successfully elsewhere must be adapted to make them suitable for use in Spain.

DEVELOPMENT OF CONCRETE PAVEMENTS IN SPAIN BEFORE 1970

The first sections of concrete pavement in Spain were built in 1915, but use of concrete remained uncommon for many years. At that time, it was mostly laid by manual methods. Vibrated concrete was applied to a road pavement for the first time in 1937.

After the 1936–1939 Civil War, some short sections of concrete roadway were constructed in different parts of Spain. Although the performance of these pavements was satisfactory, they were not used on a large scale because they were more costly than alternative solutions and because there was a shortage of cement.

Modern mechanized construction was introduced in 1960–1965. The first site was an experimental road on the outskirts of Madrid, built in 1963. This road supported a heavy traffic

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flow, with an average daily truck traffic rate (ADTT) of more than 2,500 in each direction. The concrete pavements were 4 km (2.5 mi) long, and fixed form methods were used in their construction. Except for some prestressed concrete sections, in which different problems occurred, the various methods that were tested performed well up to 1981. At that point, difficulties arising from road widening caused the concrete sections to be overlaid with asphalt, even though their condition was still acceptable for traffic (*2*).

For each type of pavement, several combinations of thickness, joint spacing, and other factors were tested. Plain concrete slabs, 25 cm (10 in.) thick and 5 or 6 m (16 or 20 ft) long, with dowelled joints, gave excellent results with few cracks, even though they were laid on a sand subbase. These slabs were therefore used as an empirical model for later works.

In 1968 the first section of freeway with a concrete pavement was built, close to the test section just described and on the same route (*3*). This section is 8 km (5 mi) long, with two carriageways 7 m (23 ft) wide. The carriageways have a plain concrete pavement with a uniform thickness of 25 cm (10 in.). The pavement is divided into slabs 6 m (20 ft) long with dowelled joints and was laid on a 15-cm (6-in.)–thick cement-treated base (with a 5 percent cement content) and a 10-cm (4-in.)–thick sand cement subbase. The shoulders are 6 cm (2.4 in.) of asphalt concrete and 19 cm (7.6 in.) of sand cement and natural aggregate. All joints were sealed with preformed neoprene profiles.

This section of pavement has supported the passage of about 30 million heavy vehicles in each direction and is still in good condition, with no significant structural defects (*4*). The satisfactory status of this pavement is probably the result of two elements that are currently considered fundamental to any lasting solution to the problem that heavy traffic poses for concrete pavement in Spain: the use of nonerodible bases and shoulders and, especially, the use of dowels to guarantee adequate load transfer at joints.

It should be stressed that the use of dowels has proved to be effective even though it was later determined that the machine that was used to insert the dowels into the fresh concrete had not worked correctly. The dowels had been placed only 5 to 8 cm (2 to 3 in.) from the surface, and many cracks had appeared over them. No harmful effects on the performance of the pavement were detected, however.

USE OF THE CALIFORNIAN APPROACH: 1970–1986

In 1971, slip form pavers were introduced, and thereafter equipment for fixed forms was generally restricted to applications other than highways (airports, industrial areas, etc.). The start of the National Freeway Program in 1967 involved the construction of long sections, so the investment in high-performance machinery was justifiable.

Most of these freeways are toll operated. The concessionary company is responsible for the design, construction, and operation of the freeway throughout the period of the concession. This company therefore chose the type of pavement to be laid, subject only to the technical approval of the Ministry of Public Works.

For a number of reasons (including the possibility of asphalt rutting due to overloads, availability of materials, and in particular, consideration of overall costs during the 20-year concession period), a concrete pavement was adopted for some sections of the Seville-Cádiz freeway, in southern Spain. The Californian approach was selected not only for its economic advantages but also because it has been developed in a region where many areas have a similar Mediterranean climate. The only apparent differences stemmed from the higher Spanish axle loads, which required an increase in the thickness of the slabs.

To assure the success of its initiative, the concessionary company decided to adopt the whole technique (both material specifications and equipment) that had been used in California in the early 1970s. Initially, the company had the assistance of U.S. experts and personnel. These workers were replaced with Spanish technical staff shortly thereafter.

The freeway consists of two 7-m (23-ft)–wide carriageways, with a plain concrete pavement that is uniformly 25 cm (10 in.) thick, on a 15-cm (6-in.)–thick cement-treated base with 3 to 4 percent binder. In those places where the subgrade is not adequate, the base, in turn, rests on a subbase of nonplastic granular material. The joints in the concrete pavement were set with a 1:6 skew and were spaced according to the following sequence: 3.5 – 4 – 6 – 5.5 m (11.5 – 13 – 20 – 18 ft). The shoulders are granular material covered with an asphalt layer.

The same pattern was followed for the 1974 construction of the first sections of the Tarragona-Valencia-Alicante freeway, along the Mediterranean coast (*5*). The traffic on that freeway, however, soon began to cause problems, even though it was not particularly heavy (1,000–1,400 trucks per day in both directions). Transverse cracking of the longer slabs, initiation of faulting, and degradation of the shoulders developed in spite of the careful construction, which had produced a pavement with a smooth surface. The initial pattern was therefore slightly modified on subsequent sections. Certain precautions were taken, such as stabilizing the granular materials of the shoulders with cement.

After 1977, in light of the experience in California that was reported at the First Purdue Conference, significant modifications were introduced to avoid faulting. These changes included provision of longitudinal trench drainage through pipes that were placed in the shoulders and surrounded by porous concrete, increasing the binder content in the cement-treated base up to 5 percent, and the use of a variable cross section for the pavement, with the thickness varying between 22 and 28 cm (8.6 and 11 in.) over the 7-m width of the section. At the same time, a rehabilitation program was started to install longitudinal drains on the sections in which these drains had not originally been included. Today, all of the concrete pavements in this freeway have lateral drainage. This measure has proved to be beneficial and has succeeded in controlling the faulting process.

For the last freeway section, constructed during 1983–1984, the following important innovations were introduced (Figure 1):

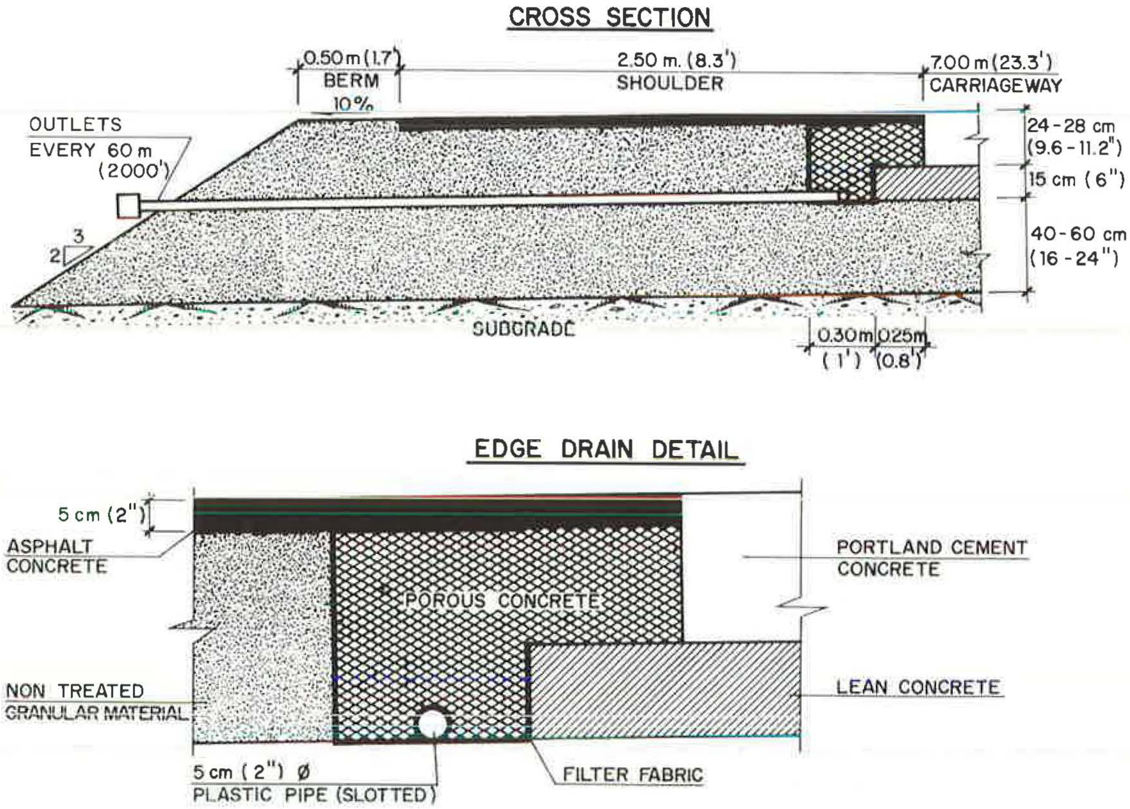

FIGURE 1 Pavement drainage, Tarragona-Valencia-Alicante motorway (Jeresa-Ondara section, 1985).

- a slight increase in the slab thickness, which now varies between 24 and 28 cm (9.4 and 11 in.) over the width of the cross section, together with a reduction of the joint spacing: 3.7 – 4.6 – 4 – 4.3 m apart (12 – 15 – 13 – 14 ft);
- replacement of the cement-treated base by one of vibrated lean concrete, laid by the same slip form paver used for the pavement; and
- improvement of the pavement drainage system by placing the slotted pipe deeper and fitting it with suitable outlets so that it can be cleaned out periodically by high-pressure water jets.

Given the traffic and climatic conditions on this freeway, these features are considered to be adequate to counteract faulting (*6*).

The recent development of slip form pavers with automatic dowel inserters on the run, so that neither the output nor the surface evenness is impaired, has changed the design policy. Currently, dowels are considered appropriate for traffic exceeding 800 trucks per day in the design lane during the first year of operation. The use of dowels was therefore made compulsory in the *1986 Instruction on Pavements for Dual-Carriageways* (Autovías) (*7*). The Californian approach is now used only for roads with medium and light traffic flows. Continuously reinforced concrete pavements (CRCP) are also included in the recent instruction (*7*), but for economic reasons their application has been limited in Spain, and their use is only anticipated for special cases in which there is extremely heavy traffic.

USE OF CONTINUOUSLY REINFORCED CONCRETE PAVEMENTS IN SPAIN

Excluding a 125-m (410-ft) long experimental slab built in 1963, the only CRCP application in Spain to date has been the 43-km (27-mi) long Oviedo-Gijón-Avilés (Asturias) freeway (*8*). This roadway, located in northern Spain, is the main artery of an important complex of industry, mining, and port facilities that generates heavy traffic (ADTT more than 4,500). Moreover, the freeway runs through a rainy, hilly region that has poor soils.

The two carriageways, built in 1975, are 7.5 m (25 ft) wide. The pavement consists of a 22-cm (8.7-in.)–thick CRCP, a 16-cm (6.3-in.)–thick cement-treated base (with 4 percent cement), and a 22-cm (8.7-in.)–thick granular subbase. The amount of reinforcement is 0.85 percent. In one test section this amount was reduced to 0.73 percent, with no noticeable change in the pattern of cracking in the pavement, so this level of reinforcement could probably have been adopted for the whole freeway without any problem. Two slip form pavers were used in the construction. The reinforcing bars had been placed on supports previously.

The performance of the pavement has been excellent so far. There has been little maintenance work, and the work that has been needed is confined almost entirely to reconstructions in a few areas where landslides had occurred.

PRESENT PRACTICE: DESIGN AND CONSTRUCTION OF CONCRETE PAVEMENTS IN SPAIN

As mentioned earlier, the Ministry of Public Works published the *Instruction on Pavements for Dual Carriageways* in 1986 to establish technical criteria for projects included in the National Road Plan, 1984–1991. The earlier standards had been published in 1975 (*9*) and needed revision, particularly for the heaviest types of traffic. The instruction deals with two categories of traffic, T0 and T1. The categorization depends on whether more or less than 2,000 trucks per day will use the design lane during the first year.

The instruction describes methods that use asphalt concrete on granular or cement-treated layers, roller-compacted concrete with an asphalt surface course, and vibrated concrete. The minimum thickness of the plain concrete pavement for the design lane in the vibrated concrete case is 28 cm (11.2 in.) for the T0 traffic category, with a 26–30-cm (10.2–11.8-in.) tapered cross section (Figure 2). For the T1 traffic category, the minimum thickness for the design lane is 25 cm (10 in.), with a 23–27-cm (9–10.6-in.) taper. In both cases the pavement rests on a nonerodible vibrated lean concrete or cement-treated base 15 cm (6 in.) thick. The base may be laid directly on the subgrade if it is in the E3 category, that is, if its California bearing ratio (CBR) is more than 20. When the base falls into the E2 category, with a CBR between 10 and 20, a granular subbase 20 cm (8 in.) thick must be used. Subgrades with CBRs less than 10 are not acceptable for major trunk roads.

At 28 days, concrete must attain a characteristic flexural strength of 4.5 MPa (640 psi) under the third-point loading test. Concrete with 4.0 MPa (570 psi) flexural strength may also be used, but in that case the thicknesses given previously must be increased by 2 cm (0.8 in.).

The instruction also permits the use of continuously reinforced concrete pavements, for which the relevant thicknesses of plain concrete may be reduced by 4 cm (1.6 in.). In contrast, jointed reinforced concrete pavements are not considered.

Longitudinal joints must be sealed and fitted with tie bars. Transverse joints should be equipped with 18 dowels per joint. These dowels are not placed at regular intervals but are instead concentrated underneath the wheel paths of heavy vehicles (Figure 3). The dowels must be perpendicular to the carriageway axis and must be placed 5 m (16.2 ft) apart. In rainy areas (with a mean annual rainfall more than 800 mm – 31.5 in.), the dowels must be sealed like longitudinal joints, but in areas of low rainfall, they may be left unsealed.

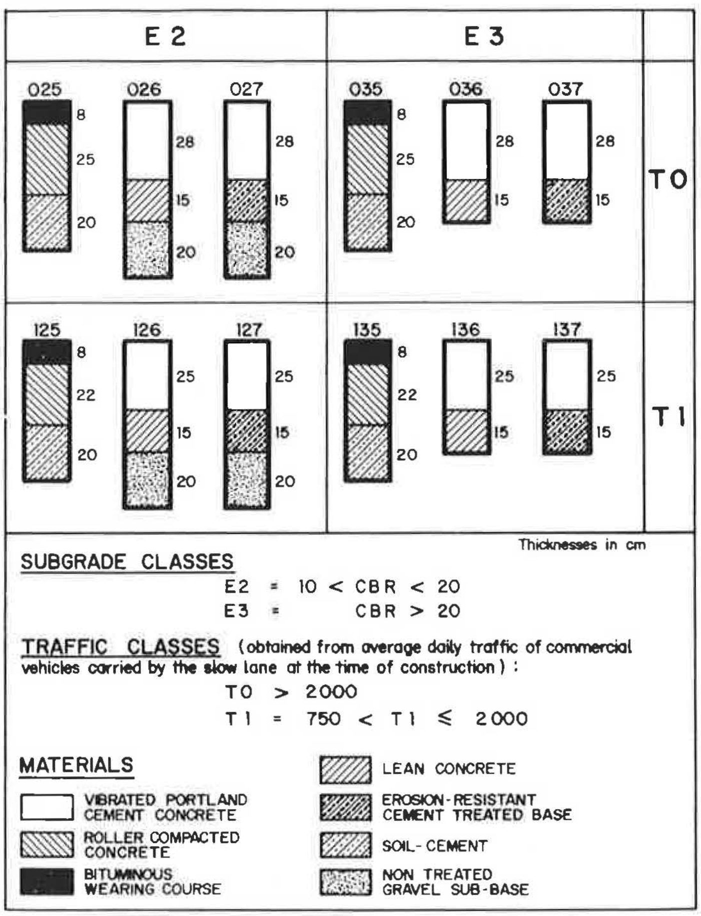

FIGURE 2 Structural sections of pavements with layers of vibrated or rolled compacted concrete (*7*).

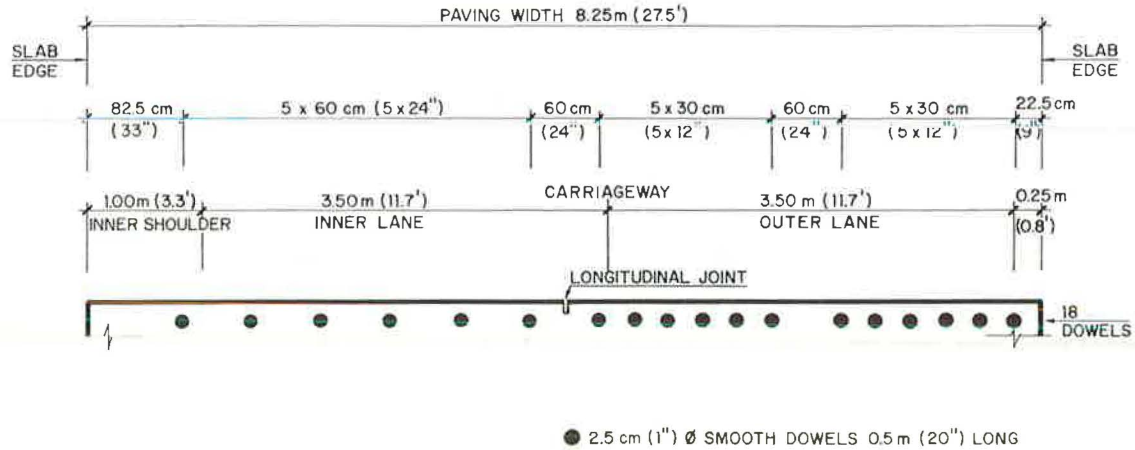

FIGURE 3 Dowel distribution at joints of concrete pavements (*7*).

Materials for use in the concrete of the pavement generally remain as prescribed by the Specifications PG-3/75 of the Ministry of Public Works (*10*). It should be noted that the use of crushed limestone as coarse aggregate in most of the projects has proved beneficial, yielding concretes that have low shrinkage and good flexural strength and facilitating joint sawing. The requirement that at least 30 percent of the fine aggregate should be composed of siliceous particles has produced pavements that do not have the skidding problems associated with texture wear. Sand patch testing of some pavements under heavy traffic reveals a texture depth of 0.55 mm (0.02 in.) after nearly 20 years in service. It has also been demonstrated that if an acceptable surface evenness is to be obtained, it is essential to restrict the fines content of the sand to 5 percent passing the No. 200 sieve, a limit that can be allowed to reach 7 percent if crushed limestone sand is used.

To avoid settlements at the edges when slip form pavers are used, the practice has usually been to employ concretes with a slump between 2 and 4 cm (0.8 and 1.6 in.). The usual water:cement ratios have been between 0.44 and 0.50; plasticizers have been used with the drier mixes. Air entrainers have also been employed to improve the thixotropy of the concrete, even in areas where frosts are not expected (e.g., along the Mediterranean coast). Cement content has usually varied between 300 and 350 kg/m^3 (500 and 590 lb/yd^3); 330 kg/m^3 (555 lb/yd^3) is a common quantity.

In general, Category 35 cements have been used, that is, cements with a 35-MPa (5,000-psi) compressive strength in standard mortar at 28 days. However, on one project where low temperatures were expected, a Category 45 cement was used. The trend toward the use of blended cements with a high proportion of active additions, usually fly ash, has been enforced by a recently signed agreement between the Ministry of Public Works and the Spanish Association of Cement Manufacturers. For major trunk road construction, the latter have agreed to supply Category 35 cements with a proportion of active additions of about 35 percent, which are more appropriate for pavement concretes, at a cost well below the normal market price. Category 25 cements with an active addition content of about 50 percent, which are definitely suitable for roller-compacted concretes, are also included in this agreement. Changes recently introduced into the Spanish Standard UNE 80-301-85, regulating cements (*11, 12*), have reduced the early strengths required for these binders with high addition contents, making their development possible. Finally, it has been demonstrated that under high temperatures and low relative atmospheric humidity it is essential to use high-quality curing compounds that are based on organic resin solutions.

Both cement-treated granular material and vibrated lean concrete have been used as base layers. To assure sufficient resistance to erosion, a minimum binder content of 5 percent for the cement-treated materials is specified. For vibrated lean concrete the cement content should be not less than 140 kg/m^3 (230 lb/yd^3). Both materials are required to have a minimum compressive strength of 8 MPa (115 psi) at 7 days or, alternatively, not less than 12 MPa (170 psi) at 90 days. The latter requirement permits the use of cements that have high active addition contents and consequently have slower development of strength. For practical reasons related to the use of the same equipment to lay both pavement and base, a trend toward using lean concrete bases has emerged. A second application of a paraffin-based curing compound has been sufficient to prevent the shrinkage cracks of these bases from being reflected in the pavement. More frequently, however, a plastic sheet is laid on top of the base.

There are several possibilities for the shoulders. A granular base may be used, for example. Alternatively, to avoid having many different units on site, one of the same materials that was used as the base of the pavement may be used with an asphalt surface course. Another choice is to lay a vibrated concrete shoulder that is tied to the pavement. This last option has been adopted for some recent projects without any reduction in the thickness of the pavement. In addition to increasing the bearing capacity of the pavement, the use of concrete shoulders allows effective sealing of the longitudinal joint between shoulder and traffic lanes, as well as the possibility of creating ridges in the concrete to act as audible warnings (rumble strips) to drivers whose vehicles inadvertently leave the carriageway. Ridges have been deliberately placed only in the central part of the shoulder so that it can be used as an emergency traffic lane. Moreover, if concrete shoulders are used, it is possible to eliminate the lateral pavement drainage that is recommended for rainy areas.

The main problems that have occurred during construction have stemmed from the use of concrete mixing plants that had insufficient output to keep pace with the pavers. This limitation forced the pavers to make frequent stops, resulting in an uneven surface. Another source of difficulty has been the occasional use of dowel-inserting equipment that requires stopping the paver. A number of contractors have therefore equipped themselves with paving machines that are capable of inserting dowels into fresh concrete without halting. These machines are also fitted with a longitudinal finishing screed. Their use on several recent works has proved that these devices are able to achieve excellent riding quality.

Another problem that has occasionally occurred has been longitudinal cracking during the first night after the pavement has been laid. These cracks are caused by large warping stresses produced by extreme temperature variations between day and night. It was therefore necessary to saw the longitudinal joint at the same time as the transverse joints, instead of delaying its cutting, as is the usual practice.

TEXTURING OF CONCRETE PAVEMENTS

Since the time that slip form pavers were introduced, almost all concrete road pavements in Spain have been given longitudinal texture, which has not been applied on a large scale in any other European country. Use of this technique has achieved surfaces with excellent antiskid qualities, combined with noise levels below those normally obtained with the textures used in other countries.

The first application of this type of texture on Spanish roads was during the construction of the Seville-Cádiz freeway in 1971. The texture was obtained by passing a piece of burlap dragged by the slip form paver along the top of the concrete surface. Later, the small textural depth obtained by that method led to its replacement by a plastic-bristled brush, a system that made it possible to achieve textures with an initial mean depth of the order of 1 mm (0.04 in.). In 1977 the plastic brush was exchanged for a metal-tined comb, but that in turn quickly gave place to the use of plastic brush and metal comb together. This combination created both a microtexture (with the brush) and a macrotexture (with the comb), with initial grooves of the order of 1.5 mm (0.06 in.) deep. However, a smoother texture is sought in the most recent projects.

Measurements of skidding characteristics and rolling noise, taken on a number of roads after several years of operation, demonstrated that these surface designs have excellent skid resistance. The transverse coefficients of friction obtained with SCRIM ranged from 0.55 to 0.75. Noise levels for vehicles rolling at 80 kph (50 mph) with the engine off displayed peak levels ranging between 72.5 and 78 dBA. These levels are 2 to 4 dBA below those obtained on concrete pavements with an equal depth of texture in other countries. The other nations use either transverse textures or random patterns that are obtained by chipping or stripping of the fresh concrete (*13*).

Transverse textures have been used only on the Oviedo-Gijón-Avilés freeway, which is located, as stated earlier, in a rainy area. To facilitate surface drainage, the pavement was transversely grooved with a mechanical rake. In a mountain pass that has steep gradients, a combined texture was obtained by the transverse application of a plastic-bristled brush, followed longitudinally by a metal-tined comb.

ROLLER-COMPACTED CONCRETE PAVEMENTS

Roller compacted concrete (RCC) is a homogeneous mix of aggregate, water, and binder that is laid on site in a manner similar to that for a cement-treated base, although the RCC cement content is similar to that of a vibrated pavement concrete. This material has certain qualities that have made it attractive for use in Spain. First, it requires no specialized machinery. This is an advantage because until recently, only a few contractors were suitably equipped to construct high-quality vibrated concrete pavements. Also, and particularly relevant to its use in overlays, use of RCC permits the road to be opened to traffic immediately because of the stability provided by the granular structure after the material has been compacted. This characteristic eliminates one of the main disadvantages of vibrated concrete for overlaying pavements, that is, the need to close them to traffic for a certain period. This need for closure significantly limited the use of concrete for overlays in Spain, where suitable diversions are not common. The stability of the granular structure also permits the use of cements with higher addition contents than those of the ordinary cements used for vibrated concrete pavements.

The first modern RCC applications in Spain were performed about 1970. The projects were pavements basically designed for light traffic, such as roads in housing estates, urban streets, and minor country roads (*14*). The technique was developed by some local contractors on an empirical basis. Although the contractors did not monitor the execution thoroughly on site, the performance of these pavements proves, on the basis of more than 4 million m^2 (6,400,000 yd^2) of experience, that a technology entirely adequate for the types of roads mentioned has evolved.

Experience has also been acquired with the use of RCC on highways with heavy or medium traffic levels. The first project carried out in this field was the pavement of a tunnel, laid in 1984, where it was mandatory to keep the road open to construction traffic. Since then the method has been used on new roads, on widening schemes, and on overlays (*15*). In all, some 300,000 m^2 (480,000 yd^2) of road pavement has been constructed with RCC (*16*). This figure will undergo a substantial increase in the near future because, as mentioned earlier, RCC pavements are now included in the *Instruction on Pavements for Dual Carriageways*. Several sections of roadway are currently under construction with this method (Figure 4).

The instruction includes the first official specifications for RCC. The maximum aggregate size for materials is limited to 20 mm (0.8 in.), or even to 16 mm (0.6 in.), to avoid

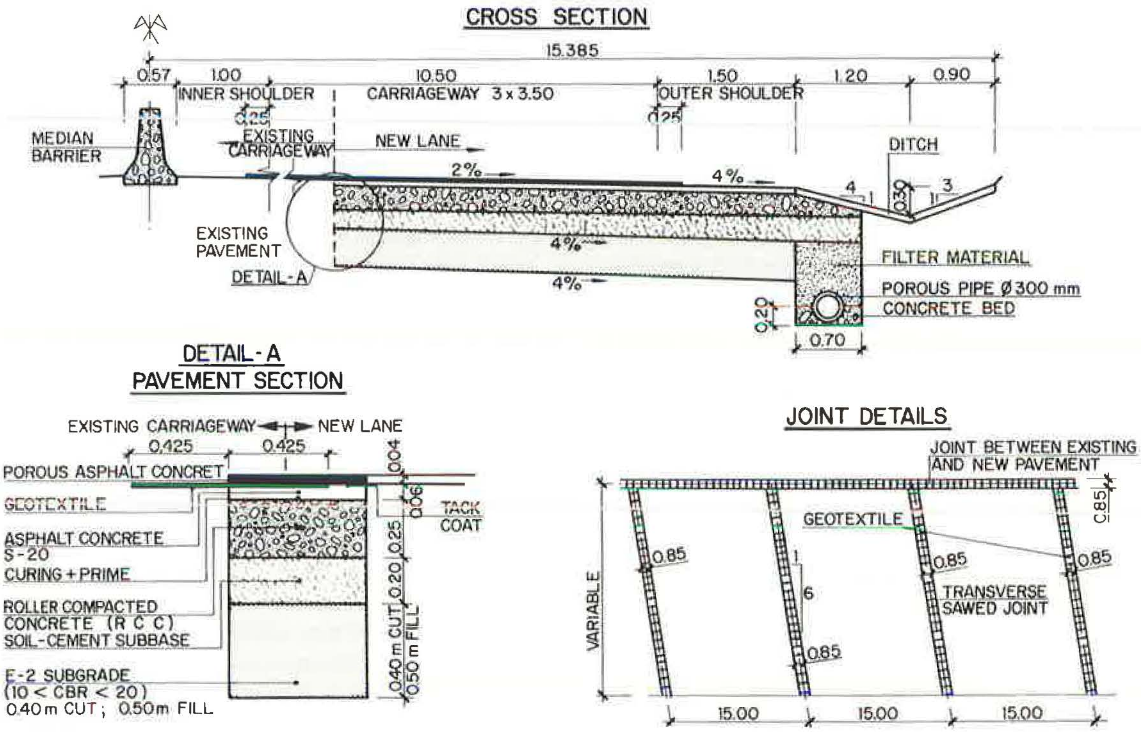

FIGURE 4 Use of rolled compacted concrete in dual-carriageway roads: addition of a new lane to the existing carriageways (National Road IV, Villaverde-Seseña section, 1987).

segregation. A high proportion of crushed material is required to obtain an aggregate stability that is sufficient to allow the road to be opened to traffic immediately. Blended cements with high proportions of additions (~50 percent) have been most frequently used, although cement and fly ash have been mixed in at a plant for some projects. Binder content usually ranges from 280 to 330 kg/m^3 (470 to 555 lb/yd^3) to reach the 3.3 or 2.8 MPa (470 or 400 psi) splitting tensile strength that is usually required. Samples are tested at either 28 days or 90 days, depending on the type of binder used. Water content usually ranges between 5 and 6 percent.

To allow compaction of the material to be carried out safely before setting begins, so that future performance of the pavement is not endangered, minimum periods of workability are prescribed. These periods vary between 5 and 9 hours, depending on the type of work involved. To achieve these minimums, it is usually necessary to use retarders.

Materials are usually produced in continuous mixers, although batch mixers and even occasionally truck mixers have also been used on some sites. Spreading has been performed by motor graders, especially on urban sites, or else by asphalt finishers. On some recent projects, high-powered finishers have been used, making it possible to achieve a substantial precompaction of the material.

Compaction operations should be carried out to assure an average concrete density of at least 97 percent of Modified Proctor and a compaction at the bottom of at least 95 percent. As the compaction depends to a large extent on the rigidity of the underlayer, a subbase of soil-cement is frequently provided in new roads designed for heavy traffic. It is important to make sure that the densities meet the specified criteria because one of the main disadvantages of RCC is the sensitivity of its performance to lack of compaction, which could result in a sharp drop in its strength. Frequent monitoring must therefore be carried out on site, preferably with nuclear gages.

The equipment normally used to compact the material consists of a smooth-wheeled vibrating roller and a heavy pneumatic-tired roller to seal the surface. The number of passes is of the order of 8 with the vibrating roller and 15 with the pneumatic-tired roller.

Another precaution that must be adopted during compaction operations is the avoidance of surface drying. The surface must be kept damp, and a fine spray of water should be used if necessary.

The compaction of a layer whose final thickness will be between 20 and 25 cm (8 and 10 in.) generally results in a surface that is not particularly smooth, even when asphalt finishers are used, for these devices are probably working at their limits in these cases. To obtain a road surface suitable for high-speed traffic, it is usually necessary to lay an asphalt surface course on top of the RCC. The instruction includes the following structural pavement sections for compacted concrete pavements (Figure 2):

- asphalt concrete 8 cm (3.2 in.) thick,
- RCC 25 cm (10 in.) thick for T0 traffic,
- RCC 22 cm (8.6 in.) thick for T1 traffic, and
- soil-cement 20 cm (8 in.) thick.

The RCC must have a splitting tensile strength of 3.3 MPa (470 psi).

Occasionally, a surface treatment has been laid on the top of the RCC to improve its antiskid properties. On secondary roads, where a high standard of surface evenness is not necessary, the RCC is left uncovered and is finished with power floats to obtain a texture that is adequate for moderate traffic speeds.

Like any material that is bound with cement, RCC cracks. However, because the water:cement ratio is much lower in RCC than in a cement-treated base, cracks appear at much greater intervals. Spacings have been observed to vary greatly (between 7 and 50 m, or 23 and 160 ft), but 20 m (65 ft) may be considered an average value. It is a moot point whether RCC should be left to crack freely or whether saw cuts should be made to obtain more regular and durable cracks. Both methods have been followed in Spain, although it should be noted that recently, on the pavements of secondary roads where compacted concrete is usually left uncovered, joints have been systematically sawed every 10–15 m (32–50 ft).

Under present conditions, the cost of RCC is, on average, 20 percent lower than that of vibrated concrete. Therefore, even considering its present limitations, it is reasonable to agree with the statement made at the Third Purdue Conference on Concrete Pavement Design (*17*): "It is doubtful whether any pavement technology has ever had the potential both for such significant savings and for such varied uses" as RCC has.

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Concrete Pavement Technology in Japan Today

SHIGERU IWAMA AND YUTAKA ANZAKI

In this paper, the current state of road pavement technology in Japan is described. The traffic and weather conditions that affect pavement design and the methods of pavement selection used are examined. Attention is drawn to the type and structure of portland cement concrete (PCC) used, as well as its performance and construction methods. Future trends in development of PCC pavement technology in Japan are also described.

Currently, most road pavements in Japan are made of asphalt. Concrete pavements were used first, however, and there is a rich accumulation of technological data. These many years of study have served as the basis for a recent compilation of standards for design and construction of concrete pavement in Japan, the *Manual for Cement/Concrete Pavement* (*1*), and are recognized as proof of the high level of concrete pavement technology in Japan. In addition, records of the construction of major roads, including national expressways, have been added to the data base of study results yearly. Although the compilation of these records is still small in volume, the contents indicate a positive attitude toward the development of new techniques through actual construction. This paper summarizes the background and present condition of the design and construction of concrete pavements in Japan. Problems that have yet to be solved and the directions of future studies and developments are also described.

DEVELOPMENT OF PAVEMENT USE IN JAPAN

History of Pavement Use

The types of pavement used in Japan, as well as changes in their use, are summarized in Figure 1 for three representative years (1965, 1975, and 1984).

Traffic Conditions, Weather Conditions, and Special Problems

Traffic Conditions

Roads in Japan are classified into six groups for pavement design, according to the amount of heavy vehicle traffic that is carried. Table 1 presents the current distribution of design classifications by type of road.

Weather Conditions

Weather conditions in Japan include high annual precipitation, extremely large seasonal and diurnal temperature differences, and large amounts of snow over about half the country. The annual rainfall is 60–440 cm (24–170 in., averaging 80 in.). The depth of snow accumulation in cold regions reaches a maximum of 3.8 m (13 ft) and averages 1.0 m (3 ft).

The annual temperature difference on pavement surfaces is 50–55°C (90–100°F) for concrete pavement and 60–65°C (110–120°F) for asphalt pavement. The daily temperature change of the surface during fine weather can range from 20°C to 22°C (36–40°F) for concrete pavement.

Special Considerations

The wear that accompanies the ongoing growth of traffic volume and the recent increase in the use of spiked tires is a serious problem, particularly in the cold, snowy areas. Another matter that needs special attention in Japan is the problem of roads that carry large traffic volumes near houses in many metropolitan areas. The construction, maintenance, and control of the pavement surface in these areas must include thorough consideration of the effect of noise and vibration on the roadside environment.

Role of Concrete Pavement

In direct contrast to the usual progression of road technology improvement, the use of concrete pavement in Japan has actually decreased. Many factors are involved in this unusual development. For example, asphalt pavement is attractive to road administrators because of its lower initial investment cost. Asphalt pavement can also be used to construct a wide range of structure types, from low cost to high cost. Each type of structure satisfies a particular set of road requirements, so the most economical structure for a given situation can be used.

Another factor in favor of asphalt involves closing roads to traffic, which is necessary for curing concrete. Because

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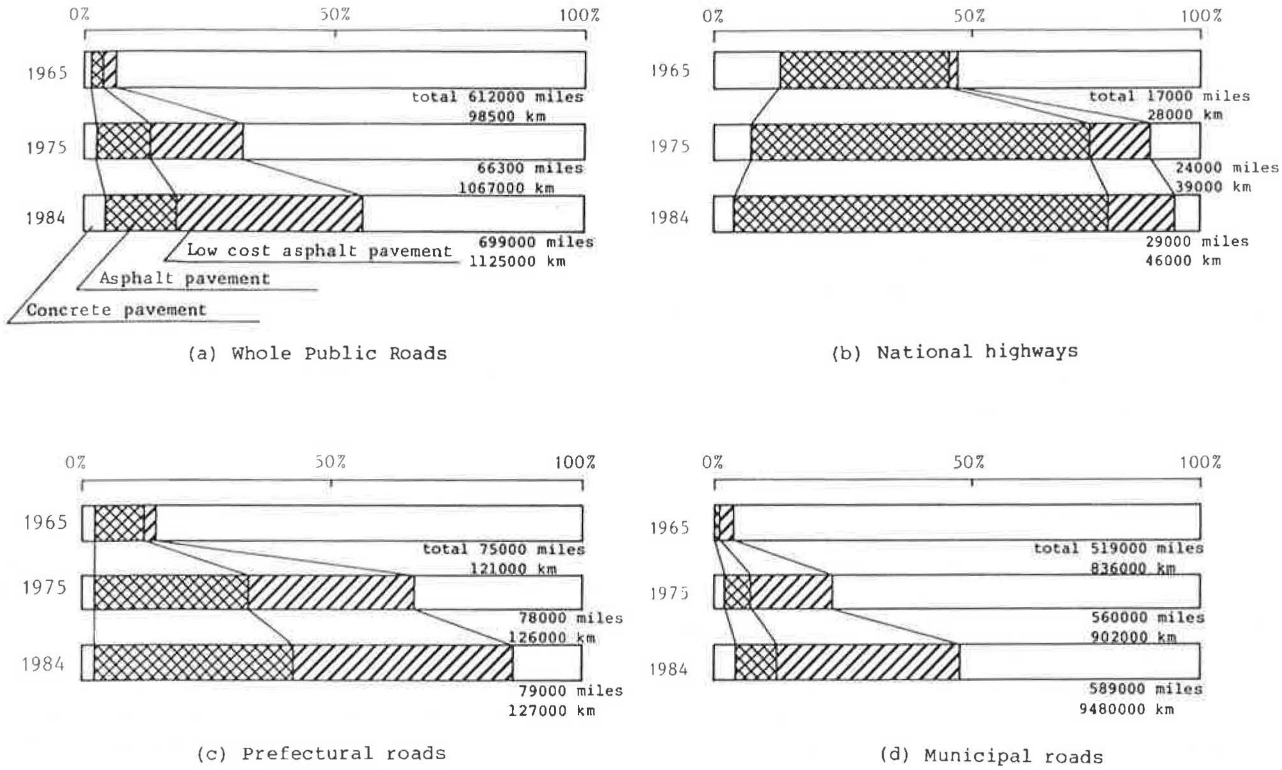

FIGURE 1 Types of pavements used in Japan and relative proportions of use, 1965–1984.

most of the pavements constructed during the past few decades were replacing existing gravel roads that were vital to local transportation, this was an important disadvantage of concrete. In urban areas, the repeated excavation work required for underground utilities was considered to be another disadvantage of concrete pavements.

The construction equipment for asphalt pavement, including plants and finishers, had been introduced at the beginning of Japan's road modernization process. Depreciation of the equipment was required first, allowing construction of asphalt pavements to precede other types.

Concrete pavement was considered to be inferior, albeit only slightly, in terms of ride, running performance, and the influence of noise and vibration on the roadside environment. In addition, repairs to damaged concrete pavement are technically more difficult than those to asphalt, even though the costs are similar.

It is apparent that the delay of concrete pavement use in Japan was the result of all these reasons combined. In addition, as the volume of concrete pavement work that was performed decreased, improvements to and documentation of construction techniques were also delayed, resulting in higher construction costs and additional disadvantages in application. Concrete pavement construction in Japan thus entered a vicious cycle.

Despite these problems, concrete pavement is expected to be increasingly important for Japanese roads. This is especially true for roads carrying heavy traffic, where rutting caused by flow of asphalt pavement is extreme; for roads in snowy, cold areas, where deterioration caused by spiked tires is severe; and for local roads that may have small traffic volumes but still require maintenance-free pavements. For all of these roads, asphalt pavement is not sufficient. In view of the new roles expected for concrete pavement in Japan, the

TABLE 1 DISTRIBUTION OF PUBLIC ROADS IN JAPAN BY TRAFFIC CLASSIFICATION, 1979

	Traffic Classification (% of total road length)				
Road Type	*L* (ADTT < 100)	*A* (ADTT 100–250)	*B* (ADTT 250–1,000)	*C* (ADTT 1,000–3,000)	*D* (ADTT 3,000+)
National (urban) expressways	0	3.6	39.0	32.4	25.0
Ordinary national highways	11.4	19.9	39.3	24.0	5.5
Prefectural roads	56.9	23.7	15.9	3.2	0.3
Subtotal	45.3	22.8	21.8	8.4	1.6
Major municipal (city, town, and village) roads	78.6	12.0	7.7	1.6	0.1
Total	49.5	21.4	20.1	7.6	1.4

technical problems and considerations involved in concrete pavement construction should be studied and solved as soon as possible. In addition, the appropriate methodology should be more widely distributed.

Selecting Pavement Type: Comparison of Life Cycle Cost

Comparison studies between asphalt and concrete pavements have been carried out for trunk roads and rural expressways. These comparison studies usually include consideration of the advantages and disadvantages for given ground and subgrade conditions, an average daily truck traffic (ADTT) estimate, regional weather conditions, the availability of material for the base course and of aggregate, and so on. The most essential part of this comparison is the life cycle cost.

The most typical case, the selection of portland cement concrete (PCC) pavement, occurs when the life cycle cost of concrete pavement is less than that of asphalt pavement, even though the initial construction cost of the concrete pavement is higher by a certain percentage. The difference in life cycle cost is sometimes as high as 30 percent because the design lifetime of asphaltic concrete pavement is only about 10 years. Concrete pavement is usually preferred in tunnels because significant reductions in the lighting cost are possible.

STRUCTURE AND PERFORMANCE OF CONCRETE PAVEMENTS

Types of Concrete Pavement

Long doweled slabs, reinforced with steel mesh, have been almost exclusively used for expressways, national highways, and prefectural roads (administratively equivalent to state roads in the United States). Continuously reinforced concrete and prestressed concrete pavements are being applied in certain exceptional cases, and the former now accounts for scores of kilometers of expressways, as well as national highways. For municipal roads, plain undoweled concrete slabs are widely used because of the reduced requirements of the lighter traffic and because of the increased ease of construction.

Concrete Slab Thickness

The concrete slabs used for road pavements in Japan are the thickest in the world (see Tables 2 and 3). They can be as much as 30 cm (12 in.) thick when the bending strength of the concrete is 45 kg/cm² (650 psi).

TABLE 2 THICKNESS OF CONCRETE SLAB

Road Classification[a]	Thickness of Concrete Slab
L Traffic	15 (20) cm [6 in. (8 in.)]
A Traffic	20 (25) cm [8 in. (10 in.)]
B Traffic	25 cm (10 in.)
C Traffic	28 cm (11 in.)
D Traffic	30 cm (12 in.)

NOTE: For roads other than expressways. Figures in parentheses for *L* and *A* traffic are for concrete bending strength of 40 kg/cm² (570 psi), instead of the commonly used strength of 45 kg/cm² (650 psi).

[a] See Table 1.

TABLE 3 THICKNESS OF DESIGNED CONCRETE PAVEMENT SLAB, EXPRESSWAYS

Designed Traffic Volume[a] (10^6 vehicles)	Thickness of Pavement Slab
Less than 13	25 cm (10 in.)
13–24	28 cm (11 in.)
24 or more	30 cm (12 in.)

[a] 20-year accumulated traffic volume of heavy vehicles.

Base Course Structure

In the case of national highways, a 10–50-cm (4–20-in.)–thick base course is provided in accordance with the magnitude of the California bearing ratio (CBR). An asphalt cushion course, ~4 cm (1.6 in.) thick, is often provided on top. For expressways, 15-cm (6-in.)–thick cement-treated granular material with an unconfined compressive strength of 20 kg/cm² (330 psi) has always been applied when the CBR of the 30-cm (12-in.)–thick subbase course or uppermost subgrade exceeds 10.

Performance of Concrete Pavement

Figure 2 shows the relationship between the accumulated volume of large-vehicle traffic, the thickness of the concrete pavement slab, and slab condition. The data were derived from an investigation carried out by the Public Works Research Institute, Ministry of Construction in 1981–1982.

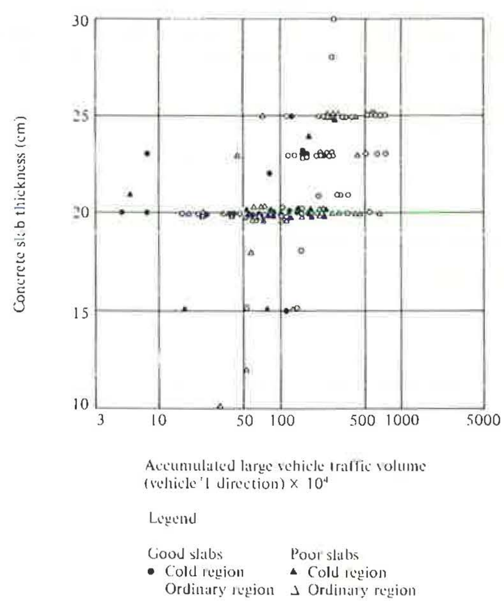

FIGURE 2 Relationship between accumulated large-vehicle traffic volume, concrete slab thickness, and slab condition.

TABLE 4 PAVEMENT DESIGN CATEGORIES, CORRESPONDING ACCUMULATED LARGE TRAFFIC VOLUME, AND SLAB THICKNESS

Category	ADTT	Accumulation of 20 years (thousands)	Standard Design Thickness of Slab
L	< 100	< 730	15 cm (6 in.)
A	100–250	730–1,820	20 cm (8 in.)
B	250–1,000	1,820–7,300	25 cm (10 in.)
C	1,000–3,000	7,300–22,000	28 cm (11 in.)
D	3,000+	22,000+	30 cm (12 in.)

Those sections with no cracks or few cracks are marked either with a solid circle (in cold regions) or an open circle (other regions). Those sections with many cracks, which had almost reached the end of their service life, are marked either with an open triangle (cold regions) or a solid triangle (other regions). It is clear that cracks generally appear earlier in cold regions.

The general relationships between pavement design categories (refer to Tables 1 and 2) and accumulated volumes of large traffic in 20 years are presented in Table 4. From the evidence presented by Figure 2 and Table 4, it can be concluded that a design life of 20 years is usually achieved.

CONSTRUCTION METHODS FOR CONCRETE PAVEMENT IN JAPAN

When viewed in terms of the scale of construction, Japan's recent PCC pavement works can be generally classified as follows:

- expressways, for which the unit work area is 10–15 km (6–10 mi) in length and 170,000–250,000 m^2 (180,000–260,000 yd^2) in area, and
- national highways and major local roads, for which the construct unit is 1–2 km (0.6–1.3 mi) in length and 7,500–35,000 m^2 (8,000–37,000 yd^2) in area.

The side form system is being used for both classes of construction. The slip form method was used once by the Kanto Regional Construction Bureau of the Ministry of Construction, using a slip form paver imported from the United States. The volume of works was four lanes, 60 km (38 mi) of paved roads in length, or 210,000 m^2 (250,000 yd^2) in area during 1969–1972, but no further construction was performed. The major reasons were the difficulty of achieving large increases in the production and transportation capacity for the concrete, as well as the presence of too many bridges, viaducts, and culverts.

Construction Methods Applied in National Highways and Major Local Roads

Base Course

The materials listed in Table 5 are generally used for the base course. The base course materials that are preferred are marked with double plus signs. The most mechanically stable material, crushed stone, is generally used for national highways, and soil cement is used for expressways.

TABLE 5 MATERIALS USED FOR BASE COURSE OF PCC PAVEMENTS

Material	Used as Subbase Course	Used as Single-Layer or Base Course
Granular Materials		
Pit run gravel, crusher run, sand, or slag	++	–[a]
Crushed stone for mechanical stabilization	–	++
Slag for mechanical stabilization	–	++
Hydraulic slag for mechanical stabilization	–	++
Stabilized Base Course Materials		
Cement stabilization	+	++
Lime stabilization	+	–[b]
Bituminous stabilization	–	+
Dense graded asphalt concrete	–	+[c]

NOTE: Double plus signs indicate frequently used materials. Single plus signs indicate materials used less frequently. The mixing system of crushed stone for mechanical stabilization, cement-stabilized base course material, lime soil–stabilized base course material, and bitumen–stabilized base course material includes the plant mixing system and road mixing system.

[a] Can be used when the modified CBR is 80 and over, and when the PI (plasticity index) of the material passing a 0.4 mm (No. 40) sieve is 4 or less.

[b] Can be used when the asphalt intermediate layer is provided as part of the base course.

[c] Asphalt intermediate layer.

Machine Formation and Paving Capability

The typical machine formations that are employed are shown in Figure 3. The selection of machine formations is based on factors such as the daily extension of pavement required, whether the concrete paving (spreading and compacting) is of the single-layer or double-layer type, whether the concrete can be supplied from outside the lanes to be paved, and the type and number of usable machines.

Paving Procedures

Mixing and Transportation Concrete is supplied by ready mix concrete plants. There are some 4,000 of these plants nationally. The mixed concrete is transported by dump trucks (rear dumps, not side dumps).

Form Setting and Form Removal Generally, steel forms are used, as described at the beginning of this section.

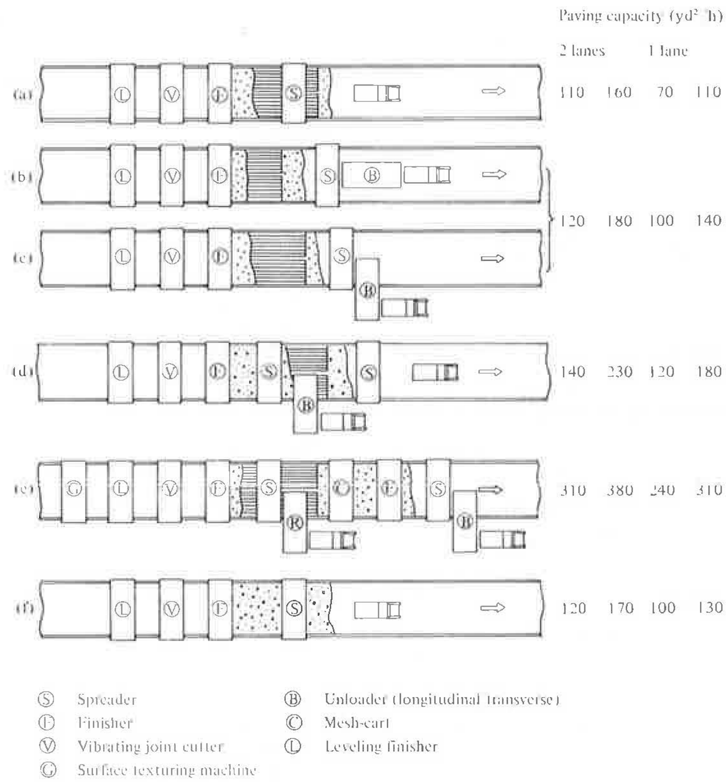

FIGURE 3 Typical paving machine combinations.

Spreading In principle, concrete spreading is performed separately for the lower layer and upper layer. The wire mesh is used as a boundary, with a spreader that may be of the blade type, box type, or screw type.

Installing Wire Mesh and Edge-Reinforcing Bar The wire mesh and reinforcement are loaded beforehand on mesh carts or at suitable intervals along the roadsides. They are placed manually on the spread lower concrete layer.

Compacting In principle, compacting is carried out for the whole layer of concrete, or in two layers. Compacting is usually performed with the surface vibration–type finisher, but sometimes an inner vibration–type machine is used along side forms.

Surface Finishing Surface finishing is performed with a finisher, followed by a float machine and then by a surface texturing instrument.

Joint Execution

For joint construction work, particular attention is paid to obtaining a structurally suitable and smooth finish. A method that involves placing a thin temporary insert into fresh concrete and then cutting the top 1.6 in. with a diamond cutter is usually used at the rate of one in three dummy joints. Simple joint cutting after the concrete has hardened is usually performed on the remaining two-thirds of the dummy joints on the next day of paving.

Curing

For curing, sunlight and a wind-protecting tent or the membrane curing method is used for the initial couple of hours. Sponge, hemp cloth, straw matting, or similar materials are then spread, and water is sprayed periodically. The curing period required to obtain a flexural strength of 500 psi is generally 2 weeks in the case of ordinary portland cement, 1 week for high-early strength portland cement, and 3 weeks for moderate heat portland cement and fly ash cement.

Construction Methods for Expressways

The first concrete pavement work for an expressway in Japan was performed in three work areas between Yaita and Shirakawa (a distance of ~48 km) on the Tohoku Expressway during October 1973–October 1974. The machine formation used for this work is shown in Figure 4. It is a set form system formation with an 8.5-m (28-ft) slab width.

This work sets the standards for large-scale mechanical work in Japan. The large-scale concrete pavement projects for expressways constructed after this work, up to the current time, are presented in Table 6.

For an expressway, a special type of cement is commonly used. Its specifications are given in Table 7. One of the special features of PCC pavement construction on expressways is the use of tine grooving to obtain a higher skid resistance immediately after the road is opened to traffic. Another is the use of mix design at 91 days. This procedure also provides better skid resistance, in this case through the intentional difference between the strengths of the mortar and the aggregate.

Construction of Special Types of Pavement

Special Pavement Structures

Continuously Reinforced Concrete Pavement The reinforcement in this type of concrete pavement consists of a steel content of 0.6 percent in the longitudinal direction. The pavement has D16 bars placed at 60-cm (24-in.) spacing in the transverse direction. The reinforcement may be installed by either of two methods. In the first procedure, the reinforcement is assembled on the ground and then set in the embedment position by using chairs. In the second, reinforced wire meshes weighing ~150 kg (330 lbs) each are installed. Bars are then arranged in a staggered pattern so that the lapped portions are transversely diagonal. Construction joints are prepared with stop forms, using timber blocks that are placed to clamp the longitudinal bars. In this case, the longitudinal reinforcement is enhanced by applying reinforcement bars of the same diameter, 100 cm (40 in.) long, to every third bar.

Prestressed Concrete Pavement This method is the same as the ordinary method, except for the installation of steel members for prestressing [~20 kg/cm^2 (300 psi) by effective prestress] and the prestress introduction work. The method of introducing the prestress was formerly either the pretension system or the posttension system, but currently the posttension system is applied in most cases.

The steel members that are inserted into the sheath are arranged by chair in a mesh form, both transversely and longitudinally, so that they are installed at middepth of the slab [usually 15 cm (6 in.) thick]. High-quality concrete, except for a slump of 5 cm (2 in.) or so, is conveyed by agitator trucks and spread and compacted in a single layer. Roller finishers are used in many cases because of the significantly higher consistency and the thinner slab. The quantity of standard daily work by mechanical construction is some 130 m^2 (160 yd^2).

To introduce the prestress, preliminary tension is generally applied by using special jacks, 3 to 7 days after paving. Final effective prestress is then obtained at 14 to 28 days.

In all, 33 projects during the past 10 years have used this method. The work amounts to ~100,000 m^2 (120,000 yd^2), including projects other than roads.

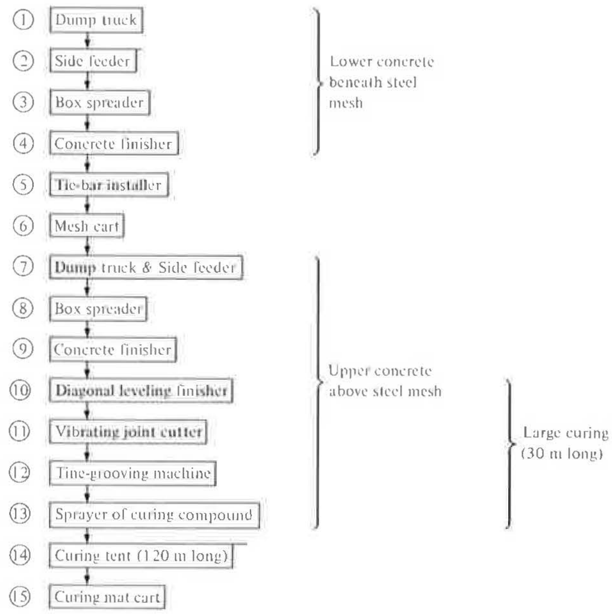

FIGURE 4 Paving machine formation for expressway construction.

Pavements in Special Sites

Tunnels The execution method for tunnels is nearly the same as that applied to ordinary projects. The exceptions are that the form is not installed on the base course but uses the drainage structure on the shoulder in many cases and that because of the tight clearance in the tunnel, the concrete is conveyed by agitator trucks.

Approach Zones for Other Structures The execution method is the same as for ordinary pavement, except that double reinforcement is arranged beforehand and the concrete is spread and compacted in a single layer. A distinctive feature of work performed in Japan is that slabs of this type are included in the pavement work for each contract.

Pavements Constructed of Special Materials

Plasticized Concrete This material is used for concrete pavement repair work on existing roads when an early return to traffic flow is required. The material used for pavement is continuously reinforced concrete. An 8-cm (3-in.) slump is set as the target value for consistency at the job site, and a superplasticizer, as 2 percent of the volume of the cement used, is added at the plant. In addition, if slump adjustment is required during placement because of the loss of slump during conveyance, the superplasticizer is added to the agitator truck and agitated at the job site. Continuously reinforced concrete pavement with plasticized concrete was used for a total of 65,000 m^2 (78,000 yd^2) of roadway during a period of 3 years.

TABLE 6 CONCRETE PAVEMENT WORK ON EXPRESSWAYS IN JAPAN

Expressway	Tohoku Expressway	Chuo Expressway	Sanyo Expressway	Trans-Kyushu Expressway	Tokai-Hokuriku Expressway	Joban Expressway
Work area	Yaita, Tochigi pref. - Shirakwa, Fukushima pref.	Nirasaki, Yamanashi pref. - Fujimi, Nagano pref.	Ako, Hyogo pref. - Bizen, Okayama pref.	Sagayamato, Saga pref. - Nakahara, Saga pref.	Gifu, Gifu Pref. - Mino, Gifu pref.	Sekimoto, Ibaraki pref. - Taira, Fukushima pref.
Work period	1973. 7 - 1974. 12	1975. 11 - 1977. 5	1981. 3 - 1982. 6	1983. 10 - 1985. 2	1984. 11 - 1986. 3	1986. 12 - 1988. 4
Extension of work (km)	48.1 30 miles	35.2 22 miles	9.5 6 miles	16.3 10 miles	19.2 12 miles	26.5 17 miles
Extension of concrete pavement (km)	46.7 29 miles	34.0 21 miles	9.5 6 miles	14.2 9 miles	11.3 7 miles	23.8 15 miles
Pavement width (m)	8.5 x 2 28.5' x 2	8.0 x 2 26.5' x 2	8.0 x 2 26.5' x 2	8.5 x 2 28.5' x 2	8.0 x 2 26.5' x 2	8.5 x 2 28.5' x 2
Slab thickness (cm)	30 12"	30 12"	30 12"	28, 30 11", 12"	25 10"	25, 28 10", 11"
Flexural strength in pavement design (kg/cm^2)	45 (51.8) 640 psi (740)	45 (51.8) 640 psi (740)	45 (50) 640 psi (714)	45 (50) 640 psi (714)	45 (50) 640 psi (714)	45 (50) 640 psi (714)
Age (day)	28	28	91	91	91	91
Unit cement content (km/m^3)	340 573 lbs/ yd^3	350 590 lbs/ yd^3	280 472 lbs/ yd^3	280 472 lbs/ yd^3	270 455 lbs/ yd^3	280 472 lbs/ yd^3

Note) A special type of cement is used for expressways. Its specifications are shown in Table 7.

TABLE 7 SPECIAL SPECIFICATION OF PORTLAND CEMENT FOR EXPRESSWAY PAVEMENT

		Japan Industrial Standards	
	Specification Pavement	Moderate-Heat Type	Normal Portland Cement
Fineness by Blaine	3,000 ± 100 cm^2/g (480 $in.^2/g$)	2,500+ cm^2/g^a (400 $in.^2/g$)	2,500+ cm^2/g^a (400 $in.^2/g$)
Flexural strength at 28 days	65+ kg/cm^2 (900 psi)	30+ kg/cm^2 (410 psi)	40+ kg/cm^2 (550 psi)
Hydration heat, 7 days	65− cal/g	70− cal/g	None
Sulfuric anhydride	2–3 percent	3− percent	3− percent
Tricalcium silicate	40–50 percent	50− percent	None
Tricalcium aluminate	5− percent	8− percent	None

[a] Actually, 3,200–3,300 cm^2/g.

Steel Fiber–Reinforced Concrete Concrete with ~ 100 kg of steel fiber added per 1 m^3 (290 lbs/yd^3) of concrete is often used. This material is frequently applied during maintenance and rehabilitation projects, such as concrete overlays in thin layers (5–10 cm, or 2–4 in.).

Concrete with slumps of 2.5 cm (1 in.) and 8 cm (3 in.) or so are available, with the former being conveyed by dump truck and the latter by agitator truck. For cases in which the work volume is small and an extra high early strength cement is used, steel fiber–reinforced concrete is mixed with other concrete in agitator trucks or by other methods at job sites. Sometimes special pavers that spread, compact, and finish concrete in one sweep or asphalt finisher–type spreaders are used, but otherwise the execution method is nearly identical to the ordinary method. Some 30 projects have been reported during the past decade, amounting to ~50,000 m^2 (60,000 yd^2). This count includes the rigid reinforcement of the floor slabs of steel bridges.

Porous Concrete Porous (permeable) concrete pavement is used for the low-traffic pavement of residential roads, squares, pedestrian areas, and parking lots. Porous concrete pavement has air voids of 25 percent, a coefficient permeability of ~10^{-1} cm/s (0.04 in./s), and a bending strength at 28 days of 25 kg/cm^2 (350 psi) and up. General mix proportion (in weight) consists of 60 percent coarse aggregate, 20 percent fine aggregate, 14 percent cement, and 6 percent water (including rubber latex, 6 percent water).

Manufacturing is done at ordinary concrete plants, and the material is conveyed in dump trucks. In the case of mechanical paving, asphalt finishers or special pavers (improvements of the former) are used for spreading and compaction. The other parts of the work, namely the curing, joint cutting, filling of joint sealing material, and so on, are nearly identical to those of the ordinary method. The slab thickness is 8–15 cm (4–6 in.), depending on the application site.

A major example of construction by this method is the pedestrian pavilion square at the Tsukuba International Scientific Exhibition grounds.

Other Materials Pavements made by using precast slabs can be found in harbor and airport facilities. Records for the past decade include some 45 projects with this method, amounting to ~110,000 m^2 (130,000 yd^2). Precast prestressed slabs are hoisted by large, special cranes and installed. The distinctive feature of this method is that after the height is set, continuous support is provided by filling the voids between the slab bottom and the base course with grout. There is also a method of slab joint connection in which steel bars are inserted into the hollow tubes that were embedded beforehand into the slabs and then moved by compressed air. Grout is then filled in to fix the bars, as shown in Figure 5. Use of this method for the replacement or repair of concrete pavement has been increasing recently because it minimizes the period of closure to traffic.

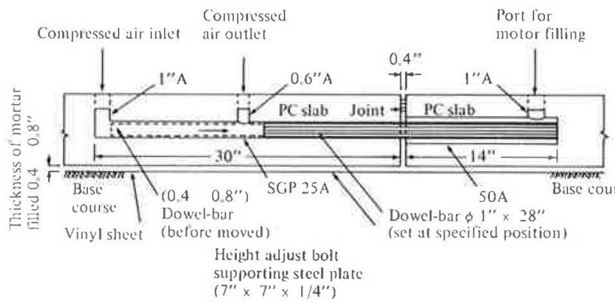

FIGURE 5 Precast concrete slab joint.

TRENDS IN THE DEVELOPMENT OF CONCRETE PAVEMENT TECHNOLOGY

Although concrete pavements have the disadvantages of high initial cost, difficult maintenance and repair procedures, and high noise and vibration in comparison with asphalt pavement, they also have the benefits of higher durability, less rutting, and better visibility, among others. It is therefore reasonable to expect that concrete pavement will be used more frequently in projects for which these characteristics are important. A few examples of current Japanese research and development into the extended application of concrete pavement, with these points in mind, are the following.

Roller-Compacted Concrete

This method allows concrete pavement to be placed by machines used for asphalt pavement. There is also a remarkable reduction of the curing period, which has thus far been a major disadvantage of concrete pavement. In Japan, roller-compacted concrete methodology is now at the basic study stage. Ongoing work includes mix design and structural design.

More Efficient Maintenance and Repair Methods

Even though concrete pavement offers far better durability than does asphalt pavement, its use has not prevailed because of the difficulty and cost of repair. To develop more efficient and economical maintenance and repair methods for concrete pavement, researchers in Japan are examining thin concrete overlays, faster execution methods using precast concrete, and concrete block pavements.

Small-Scale Concrete Pavement Construction

In the past, concrete pavements constructed in Japan were of the high-quality construction designed for use in trunk roads. More recently, the use of concrete pavement for small-scale projects has been growing through the construction of local municipal roads by this method. Local engineers have discovered that the material can be worked easily on this scale without any special machines and that the materials are readily available, even though these points have not been the focus of many technical studies. For these local roads, concrete pavement can be considered essentially maintenance free. Studies with these small-scale concrete pavement projects as the main focus are being conducted so that technical standards can be compiled for the execution of such work.

REFERENCE

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Concrete Pavements U.S.A.: State of the Art

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In this paper, the current state of the art of concrete pavement construction in the United States is described, and changes in pavement design that have been made to accommodate the increase in traffic volume and loading are examined. The history of traffic development on the Interstate and other major highways is discussed, and the tremendous increase in traffic loading that accelerated the deterioration of the Interstate and primary highway system is noted. This deterioration required some type of rehabilitation strategy to preserve the existing system, and thus a new era in highway construction began, with emphasis on preservation of the highway system through resurfacing, pavement restoration, reconstruction and recycling. The various types of concrete overlays are discussed, along with typical highway projects, and the different kinds of pavement designs used on the Interstate and heavy duty primary system are examined. Typical designs used for the major hub, civil, and general aviation airports are considered, and concrete paving for container ports, parking lots, and truck terminals is discussed also. Developments in equipment over the past 30 years have resulted in major changes in PCC pavement construction methods that increased production to meet the needs of massive road-building programs during this period. Design changes that improve performance of PCC pavements are reviewed, along with examples of innovative technology.

The transportation system of a nation is the lifeline of its economic and cultural development. The development of a system of pavements represents a major investment of public funds. Concrete pavements make up a significant portion of the pavement system in the United States, which includes highways, civil airports, streets, military airfields, and port facilities.

In this paper, the state of the art of concrete pavements in the United States will be discussed. First, the history of the U.S. pavement system as it influences the type of work available to contractors will be examined.

HIGHWAY SYSTEMS

In 1957, the United States began one of the most monumental public works road-building programs in its history. The Interstate network, which connects major urban areas, is now nearly complete, and many miles of the primary system have been upgraded. The program has been a success, and the improved highway transportation has contributed to the development of the U.S. economy.

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The Interstate system is the hub of the U.S. national highway network. Although the Interstate system accounts for only 1 percent of the total highway mileage, it carries more than 21 percent of all vehicle miles traveled. Certain other major primary highways, constituting 9 percent of the total highway mileage, carry an additional 50 percent of all vehicle miles traveled. In combination, the Interstate and primary highway network carries more than two-thirds of the vehicle miles travelled in the United States.

Total U.S. travel in 1985 reached 1.77 trillion vehicle miles (*1*), an increase of 7.6 percent since 1983. Urban travel increased by 10.1 percent during the same period and now represents 58.9 percent of total travel. This significant increase in traffic has resulted in an increase in congestion on the Interstate system and on other arterials in both rural and urban areas. The percent of peak-hour travel in urban areas that occurs under congested conditions has increased over the past few years. In response to the unusually rapid growth of traffic in urban areas, funding levels have increased for these areas. The result will be projects to increase the capacity of existing urban routes by lane additions, reconstruction, and related strategies.

During the early stages of Interstate construction, historical data were used to project future traffic volume and loading. As a result, the volume of traffic was grossly underestimated, as was the growth rate of truck traffic and changes in truck type due to the increased use of trucks in hauling the nation's commodities. Studies have demonstrated that actual traffic loadings have consistently exceeded the forecast values, often by as much as 5 times. As a result, some new facilities experienced their 20-year design traffic within a few years of entering service.

From 1966 to 1980, total traffic increased 100 percent. Truck traffic, however, increased 600 percent during the same period. The average daily traffic composition has changed significantly during the past several years. A comparison of the traffic composition in 1970 with that in 1983 displays significant changes in truck traffic. The greatest change has been in the percentage of trucks with five or more axles, which grew from 9 to 17 percent. This was an increase of almost 100 percent in the 13-year period. Many routes now carry 25–30 percent trucks with five or more axles in the daily traffic volume.

Not only have traffic loadings increased, but the legal load limit on the Interstate system and certain routes on the primary system (totaling 181,000 mi) has also been increased. The limit for five-axle tractor-semitrailer trucks has been raised to 80,000 lbs from the previous 72,000-lb gross vehicle weight limit.

Because the traffic composition has changed through the years, the Equivalent Single Axle Loads (ESALs) representative of the traffic composition have changed significantly. For example, in 1970, trucks with five or more axles produced 69 percent of the ESALs, whereas in 1983, because of the increase of such trucks in the traffic mix, they produced 91 percent of the ESALs on rural Interstate routes. The trend is similar on urban Interstates and other primary routes.

The forecast range of ESALs for a 20-year design life for rural Interstate routes during the early 1960s was 8–15 million. The range of actual ESALs was 15–32 million. Truck tire pressure has also increased significantly in the past few years, so that tire pressures of 120 psi are not uncommon.

Traffic studies indicate that truck traffic on rural Interstate routes amounts to ~29 percent of the total traffic. Tractor-semitrailer volumes of 2,000–6,000 per day are not unusual on many rural Interstate routes. Some urban Interstate routes, such as the Stevenson Expressway in Chicago (I-55), carry high volumes of trucks. The average daily truck traffic (ADTT) is 32,000 units, of which 23,000 are tractor-semi-trailer trucks (five axles). With this increase in traffic loadings, highway engineers have had to take a new look at design standards to meet the needs of future traffic for new pavement construction and rehabilitated pavements.

Overall, the U.S. Interstate and primary network has performed far better than anticipated, considering the traffic loadings experienced. Many of the pavements have far exceeded their design traffic loadings and, as a result, are showing their age. They require rehabilitation to restore their serviceability.

NEW ERA IN HIGHWAY CONSTRUCTION

Now that the Interstate system is essentially complete, the emphasis has been changed to preservation of the Interstate and primary system. The type of work presently available to paving contractors has changed considerably in recent years. On the Interstate and primary systems, new construction has been essentially replaced by preservation work, such as resurfacing (overlays), pavement restoration, recycling, and reconstruction. Although there is a considerable amount of new construction on various highway systems, the bulk of future expenditures on the Interstate and primary systems will be for system preservation. The construction of new urban expressways, however, will be a continuing program as urban areas expand.

Financing

The U.S. Congress recognized the need for additional funds to preserve these systems and passed federal aid highway acts to help solve the problem. The "4R" program, which covers resurfacing, restoration, rehabilitation and reconstruction, is dedicated to improve the existing Interstate system.

The 1982 Surface Transportation Assistance Act, which increased the federal gas tax by 5 cents/gallon and increased other fees, has generated additional funds that can be used to provide more lasting solutions to these problems. This act increased the federal gas tax to 9 cents/gallon. The states have also increased their gas taxes to provide funds for preservation of the highway systems. Total highway revenue collections and disbursements have increased substantially over the past few years. Total dollars collected for highway purposes by all units of government exceeded $63 billion in 1986 (*1*).

This new era has provided the concrete pavement industry with new opportunities to expand their markets, which currently include the following areas.

Concrete Pavement Restoration

Concrete pavement restoration (CPR) is used to correct problems on existing concrete pavements so that their service life is extended. CPR is an engineered approach to restoring concrete pavements in cases where much of the pavement remains in good condition, with only limited areas of deterioration and loss of ride quality due to problems at joints and cracks. This approach involves a system that includes a number of repairs or other techniques designed to prolong the life of the pavement. Among the methods used are full-depth repair, slab stabilization by grouting, partial-depth or spall repair, diamond grinding to restore ride and skid resistance, cleaning and resealing joints and cracks, restoration of load transfer, shoulder restoration, and installation of a subdrain system. The techniques used are selected on the basis of the pavement needs.

CPR techniques, applied at the proper time, provide a cost-effective solution that adds many years of service life to the existing pavements. Since 1976, the state of Georgia has conducted an effective concrete pavement restoration program on its Interstate highways. The state highway engineers have applied various CPR techniques as needed and have extended the life of their concrete pavements by several years.

Resurfacing (Overlays)

The resurfacing of concrete and asphalt pavements with concrete is not a new concept. Such resurfacing has been designed and installed for many years. Experience has demonstrated that these resurfacings provide excellent service on many heavy-duty routes. A 1982 NCHRP synthesis (*2*) on the evaluation of design, construction, and performance of concrete resurfacings, placed both on concrete and asphalt pavements, attests to this fact. The report states that "performance data indicate that a relatively low maintenance service life of twenty years can be expected and many resurfacings have provided thirty to forty years of service."

Types of Overlays

Several different types of concrete resurfacings are used to rehabilitate a pavement. The exact type selected will depend on the condition of the existing pavement. Concrete overlays on existing concrete pavements can be either bonded (monolithic), partially bonded (direct), unbonded (separated), or concrete over asphalt pavement.

Overlay Designs

Various overlay designs are used, depending on the condition of the existing pavement and the engineer's choice. These designs include plain concrete (with or without dowels), nominally reinforced concrete (dowel-mesh) pavement, continuously reinforced concrete, and (at a few projects) prestressed concrete overlays. Because of the need to increase the structural capacity of many of the pavements on the current heavy-duty system so that they will meet the needs of future traffic, concrete overlays are a rapidly developing market.

Unbonded Overlays

The predominant type of concrete overlay being used to rehabilitate heavy-duty concrete highway pavements is the unbonded overlay. A bond breaker is applied to the surface of the existing pavement to prevent reflective cracking from joints or cracks in the old pavement. This technique will permit a change to be made in the joint pattern between the existing pavement and the overlay. Among the bond breaking media used are a hot mix asphalt layer, usually 1–1.5 in. thick; an asphalt emulsion with sand or chip cover; or a slurry seal.

Among the states using this type of overlay is Pennsylvania, where several unbonded overlays with thickness of 10–13 in. have been constructed. A project was recently bid on I-80 for a 10-in. plain, unbonded overlay with skewed, doweled joints at 20-ft spacing and concrete shoulders. The project involves about 1,000,000 yd^2 of pavement and will be built during 1988.

Minnesota has constructed unbonded overlays with a 1–1.5-in. asphalt bond breaker on its Interstate and primary routes. These overlays are in the 8–8.5-in. range and have been designed as either plain-doweled pavements with skewed joints at an average spacing of 15 ft or dowel-mesh pavement with a skewed joint at 27 ft. This state also pioneered the use of a lime slurry "whitewash" on the black asphalt bond breaker to reduce the temperature during the hot weather. During hot, clear days, the surface temperature of the "whitewash" section has been reported to be 20–25°F lower than the untreated asphalts. This will have a significant effect on the heat buildup in the overlay pavement, particularly at the interface between overlay and bond breaker.

Texas has a continuous program of constructing unbonded overlays with plain doweled pavements and CRCP (continuously reinforced concrete pavement) overlays. The thickness of these overlays usually ranges from 9 to 12 in.

The thickness of unbonded overlays varies from 6 to 12 in. nationwide, depending on projected future traffic and existing pavement conditions. Tied concrete shoulders are used on many of the unbonded overlays to strengthen the overlay by providing edge support, resulting in a significant reduction in deflection and a corresponding increase in pavement life.

Bonded Overlays

Bonded overlays are, as the name implies, bonded to the existing pavement. The surface of the old concrete is prepared by different methods to assure a clean surface for bonding. The two methods commonly used are cold milling and sand blasting or shot blasting with steel shot. A bonding grout of portland cement and water or portland cement, sand, and water is generally used. On portions of some projects, however, the concrete has been placed directly on the old pavement without a bonding grout, and bond strengths in these cases have been equivalent to or better than those in sections with a grout. When the bonding grout is used, it is placed on a dry surface.

The concrete mixture that is used generally consists of 600 lbs of cement per cubic yard and a 50-50 combination of coarse and fine aggregate. A 0.375–0.5-in. top size aggregate is used for the 3–4-in. overlays, which are usually built on highway projects. A bonded overlay of 8 or 9 in. has been placed to strengthen the runway for heavier aircraft at the Champaign-Urbana Airport in Illinois. The 75-ft center section was constructed as a bonded overlay, and the outer lanes were constructed as direct overlays.

A number of bonded overlays have been constructed in various states. In Iowa, these overlays have been used on all classes of highways and streets, from Interstate routes to local roads. Iowa was the first state to construct a bonded overlay on an Interstate route, on I-80 in 1979.

Reconstruction and Recycling

Reconstruction and recycling are also developing markets. These procedures are used quite extensively in many areas of the United States. Reconstruction may be needed for a number of reasons, such as geometrics, advanced pavement distress, need for subgrade improvement, and similar causes. In many cases, reconstruction can be the most cost-effective solution. With reconstruction, bridge clearance can be maintained, roadway slopes do not have to be regraded, and other fixtures, such as guard rails, do not have to be replaced or adjusted.

Recycling of portland cement concrete (PCC) pavement is a technology that has made great strides in the past few years. New equipment has been developed to economically break, remove, and crush concrete pavements to produce aggregate for use in new PCC pavements. States including Michigan, Wisconsin, Minnesota, North Dakota, Iowa, and Wyoming have each launched several reconstruction and recycling projects.

Michigan Projects

Michigan has had 15 major recycling projects on its Interstate system since 1983. The state made recycling a requirement on several earlier projects (during 1983–1985) to develop experience with recycling of concrete pavements. Since that time, recycling and the reuse of the material have been at the option of the contractor. In every case the contractor has exercised the option to recycle. It is estimated that a savings of \$3.00 to \$5.00 per ton of coarse aggregate is realized by recycling. Before the 1987 work in Detroit (described next), Michigan had more than 425 lane miles of recycled aggregate pavement, or $\sim$3,000,000 yd^2.

In 1987, Michigan embarked on a landmark recycling project on a heavily traveled urban freeway in downtown Detroit. The John C. Lodge Freeway project was an 8.7-mi section of a six-lane freeway that carries 130,000 vehicles per day. The job involved complete reconstruction by removal, recycling, and replacement. The project had 463,000 yd^2 of new 10-in. pavement and 101,000 yd^2 of concrete shoulders that used recycled coarse aggregate.

An effective public relations campaign resulted in wide public acceptance and a minimum of complaints. The time schedule for completion of this work was specified as 3 months on the northbound roadway and 3 months on the southbound roadway. An incentive and disincentive clause of \$30,000 per day was included in the contract for early or late completion. The project was started on April 11, 1987, and was completed in mid-October. This project represents the type of work that will be needed in the future to relieve the congestion in U.S. urban areas.

Wyoming Projects

The Wyoming State Highway Department has constructed several recycling projects on I-80 from Pine Bluffs in the southeastern corner of the state to the Green River in southwestern Wyoming. The first U.S. project to recycle pavements subject to alkali-silica reaction was constructed near Pine Bluff, Wyoming. A joint long-term study by the Wyoming Highway Department and the Portland Cement Association on recycled concrete aggregate from these pavements was conducted. The assessment indicated that the pavements could be recycled as coarse aggregate for a new pavement if low-alkali cement (less than 0.60 percent as Na_2O equivalent) and an appropriate fly ash were used to counteract expansion due to the alkali-silica reaction. The state conducted a significant amount of in-house testing to select the proper fly ash for these projects.

The existing pavements were 8-in. plain concrete pavements on 6 in. of crushed aggregate base. The new pavement was a 10-in. plain pavement that included recycled coarse aggregate with skewed randomized joints on 4 in. of existing crushed stone base. The pavement was laid 38 ft wide in one pass, which included the 24-foot main-line pavement, a 10-ft outside shoulder, and a 4-ft inside shoulder. Several projects in the Cheyenne and Green River area have also used recycling.

Minnesota Project

Minnesota was the first state to recycle a "D" cracking concrete pavement. This 16-mi project involved U.S. Route 59 from Worthington to Fulda, Minnesota, in 1980. Extensive research and testing by the Minnesota Department of Transportation (DOT) was conducted before the decision was made to recycle this pavement. The pavement was crushed to 0.75 in. to reduce the top size of aggregate for improved performance.

Wisconsin Project

Wisconsin conducted the largest recycling project to date on I-90 and I-94, using recycled aggregate for building new pavements. The project involved a 32-mi section of four-lane Interstate from Madison to Portage, Wisconsin. The rehabilitation work involved constructing a six-lane facility with 10-ft concrete shoulders on each side of each roadway. A 4-mi section of 8-in. continuously reinforced concrete pavement was left in place and resurfaced with bonded concrete overlay. A 12-ft inside lane and concrete shoulders were added to this section. Traffic was carried through on both roadways during construction. A new 10-in. CRCP with epoxy-coated bars replaced the existing 9-in. dowel and mesh pavement.

Illinois Project

Reconstruction of the Dan Ryan Expressway in Chicago is planned for the near future. A 13-in. continuously reinforced concrete pavement will be built for this route, with 0.8 percent steel reinforcement. The Dan Ryan Expressway is the most heavily traveled roadway in the world, with a traffic volume in excess of 225,000 vehicles per day, including 14 percent trucks. The ESAL projection for 20 years is about 100,000,000 for the lane carrying the highest percentage of truck traffic.

Concrete Overlays and Inlays of Asphalt Pavements

These methods have also been used to rehabilitate worn asphalt pavements on a wide range of highway systems. Among the states using this type of overlay is Utah, where concrete resurfacing has been placed on several Interstate and heavy-duty primary pavements to renovate asphalt pavement that has deteriorated and become rough through repeated crack filling and patching. Pavement rutting is also a serious problem in many areas of the United States because of the increased volume and weight of traffic and increasing truck tire pressure. Concrete overlays have been used to rehabilitate many of these roadways.

Before rutted pavements are overlaid with concrete, the existing pavement is prepared by cold milling to profile the surface or by using an asphalt leveling course. In many cases the concrete overlay is placed directly on the rutted pavement, with a minimum thickness specified. Because of the surface variation in the asphalt pavement and the settlements that are present in some roadways, payment for the pavement is bid as two items. Concrete is paid for by the cubic yard, and placing, finishing, texturing, jointing, and curing are paid for by the square yard. This method of payment is equitable to both the agency and contractor because it is difficult for the contractor to estimate overruns. The state usually sets the grade for the pavement to meet minimum thickness requirements.

Concrete resurfacing of asphalt pavement on a heavy-duty road system ranges from 8 to 12 in. thick, depending on future traffic and pavement condition. For example, resurfacing designs on Interstate routes in Utah have used 9–11-in.-thick PCC pavement. These pavements are generally laid 38 ft wide in one pass of the slip form paver and include a 24-ft-wide main-line section and tied concrete shoulders of 10 and 4 ft.

On secondary road systems, several counties in Iowa have resurfaced failing asphalt county roads with concrete. Through 1986, there were ~176 mi of concrete overlays on these pavements. The thickness varies from 4 to 8 in., depending on the traffic. Some 135 mi of these overlays are 5–6 in. thick.

Oregon has placed several miles of continuously reinforced concrete pavement on old asphalt Interstate pavements. The overlays varied from 7 to 9 in. thick. These overlays are in excellent condition after several years of service.

Concrete Inlays

Concrete inlays have been placed on failing asphalt roadways. Generally, the asphalt pavement is trenched to the desired depth by milling, the concrete inlay is placed, and shoulder work is then completed. These inlays have varied in thickness from ~8 to 13 in., depending on traffic and subgrade conditions. Inlays have been laid 24–27 ft wide, and in some cases only the heavy traffic lane has been inlaid.

Concrete Shoulders

In addition to constructing concrete shoulders on new pavements, several states have replaced deteriorated asphalt shoulders on existing PCC pavements with tied concrete shoulders. The purpose of this work is not only to provide new shoulder pavement but also to supply edge support to the existing pavement, thereby reducing deflection for extended service life. South Carolina has constructed several miles of tied concrete shoulders as replacements for existing shoulder pavements. Recently, the state let a contract on a 19-mi project on I-95 in Dillon County for 312,000 yd^2 of PCC shoulders, combined with concrete pavement restoration involving 530,525 yd^2 of diamond grinding and joint resealing.

Drainage

Most of the older PCC Interstate highways were built without drainage systems. Where granular base courses were used, they were generally dense-graded, which did not allow rapid removal of trapped water. Some of the stabilized bases that were used were not erosion resistant. The use of dense-graded or stabilized material in the shoulders resulted in a "bathtub" design that trapped water between the pavement and the base and shoulder.

Performance studies of existing concrete pavements indicate that free water in the pavement structure is the principal cause of distress on pavements subject to heavy traffic. As a result, several states are providing drainage on both new pavement construction and routes that are being reconstructed. There is also a continuing program to provide edge drains on existing pavements. On new construction and reconstruction projects an open-graded base course is being used in several states, with an appropriate drainage system.

U.S. PAVEMENT DESIGNS: INTERSTATE AND HEAVY-DUTY PRIMARY SYSTEM

Plain Concrete Pavements

Plain concrete pavements are those without doweled joints, reinforcing steel, or mesh. This type of design is used primarily in the western United States. Many of the early Interstate pavements were built as plain pavements, with a cement-treated base (3–4 percent cement) and skewed, randomized joint spacing of 13, 19, 18, and 12 ft. These pavements were usually 8–9 in. thick. An asphalt surface with dense-graded base was used for shoulders on these early pavements.

The present pavement design in these states consists of an econocrete or lean concrete base and tied concrete shoulders. The econocrete base is used to improve erosion resistance of the base and to provide a stable, smooth track line for construction of the pavement with a slip form paver. The typical design of a four-lane Interstate pavement (two lanes in each direction) would be a 24-ft main-line pavement with tied 10-ft outside and 4-ft inside concrete shoulders of the same thickness as the main-line pavement. The thickness of these pavements ranges from 9 to 11 in. for heavy traffic routes. The pavement is placed on a 4–5 in. econocrete or lean concrete base laid 44 ft wide in one pass. The main-line pavement and shoulders are laid 38 ft wide in one pass of the slip form paver. In the past few years, joint spacing has been reduced in these states, to 11 – 12 – 17 – 16 ft in California and 10 – 11 – 15 – 14 in Utah. The Century Freeway in Los Angeles is designed with a 10-in. plain pavement laid on an 3-in. porous concrete or asphalt drainage layer over a 6-in. lean concrete base on 6 in. of untreated granular subbase course. Another example is the use of a 12-in. undoweled pavement with tied concrete shoulders on a well-draining sand subgrade for several construction projects on I-80 in Nebraska.

Plain Doweled Pavement

This type of pavement is being used more frequently for construction of heavy-duty Interstate and primary routes, both for new construction and for overlays. The joint spacing for this type of pavement is 15–20 ft, depending on local aggregates and environment. In some states a skewed, doweled joint is used. For new construction the pavement is placed either on a unstabilized base, an open-graded base, or a stabilized base, such as econocrete, ranging in thickness from 4 to 6 in. The pavement thicknesses vary from 9 to 12 in. for this type of design.

Dowel-Mesh Pavements

These pavements are reinforced with mesh and with dowels in the joints. The joint spacing of the conventionally reinforced (dowels and mesh) pavement is 26–40 ft. A few agencies, however, use a spacing of up to 60 ft, and one state (New Jersey) uses 72-ft spacing. Welded wire fabric (mesh) is embedded in the concrete, usually about 2.5 to 3 in. from the surface. The purpose of the mesh is to hold any midpanel cracks tightly closed to prevent spalling or faulting. This type of design is used primarily in the central and northeastern parts of the United States. The pavement thickness will vary from 9 to 12 in., depending on traffic.

Continuously Reinforced Concrete Pavements

Continuously reinforced concrete (CRC) pavements are reinforced with preformed steel bars, which are lapped to provide continuous reinforcement of the pavement. Generally, the steel percentage is about 0.7 percent. The continuous steel in the pavement restrains the shrinkage of the concrete and causes cracks to develop, usually at 4–10-ft centers. These cracks are held tightly closed by the steel. No transverse joints are used with this type of pavement, except for construction joints. This type of design has been used extensively in Illinois, Wisconsin, and Texas for both new construction and overlays. New pavement construction in Houston, San Antonio, and Galveston (all in Texas) consists of CRC pavements 13–14 in. thick with a double layer of steel. In Texas, CRC overlays on old PCC pavements are usually 8–10 in. thick on heavy-duty routes.

PAVEMENT THICKNESS DESIGN METHODS

Each state highway department uses its own design procedure. However, these are usually based on design procedures developed by AASHTO, the Portland Cement Association, universities, or other agencies.

The AASHTO guide for design of pavement structures was recently revised. The 1986 edition has been improved and expanded to consider several new factors in design of pavement structures. Among these are reliability, drainage, and tied concrete shoulders. Other considerations, such as life cycle costs, rehabilitation, and pavement management, are also included in the revised guide.

Municipal Streets and Low-Volume Roads

These structures are usually designed by city, county, or consulting engineers. In many cases the municipality or county may use state standards for design thickness and details when the street is eligible for funding from the state. The street system in a municipality can range from a lightly traveled residential street to a heavy-duty industrial roadway. Thickness can vary from 5-in. plain concrete for lightly traveled residential streets to 10-in. pavement with doweled joints in the heavily traveled industrial areas.

Low-Volume Roads

These routes are usually on the county highway system. In rural areas, they are the farm-to-market roadways. Traffic may vary from 100 to 2,000 vehicles per day. Iowa has made extensive use of plain concrete pavement on their farm-to-market roads, with ~5,500 miles of concrete in this system. More than 90 percent of these roadways are 6 in. thick. Where required, thicker pavements are used to accommodate the traffic volume and loads.

Civil Airports

The airport system in the United States is composed of 10,000 airports, ranging over general aviation, reliever airports, major hub airports, and military airfields. There are ~570 air carrier airports and 300 military airfields in the system, which represents more than 400,000,000 yd^2 of pavements. During 1985, some 4 billion dollars was spent on civil airports. This included Federal Aviation Administration funds, state and local funds, and bond issues. The projects included terminal structures, apron, taxiway, and runway pavements, as well as other work at these airports.

The pavements at the major hub civil airports such as Chicago, Illinois; Atlanta, Georgia; Los Angeles, California; New York, New York; Dallas and Fort Worth, Texas; and Denver, Colorado, are designed to carry a large number of the heaviest civil aircraft, such as the Boeing 747, McDonnell-Douglas DC-10, and Lockheed L-1011. Pavement thickness is generally in the range of 14 to 21 in. The stabilized base that is used under these pavements is usually a cement-treated base, econocrete (lean concrete), or occasionally an asphalt base. The thickness of the base is usually 6–12 in. Many of the airport pavements have been strengthened by overlays, which have given excellent performance in both civil airports and military airfields. Overlays and reconstruction of airport pavements will represent the major market area for airport pavements in the future. Additional runways and apron pavements will also be needed at existing airports to accommodate increases in passenger traffic volumes. There is also a continuing program of construction and enlargement of pavement facilities at airports for cargo and "overnight delivery" firms, such as the Flying Tigers, Federal Express, Purolator Courier, and others.

General Aviation Airports

General aviation airports are those designed to handle the lighter private aircraft, which have gross weights up to 60,000 lbs. Many of the smaller facilities are designed for gross weights of 12,500 to 30,000 lbs. Design thicknesses are usually 5 in. for aircraft under 12,500 lbs. and 6 in. for up to 30,000 lbs. Design charts are used to determine thickness for heavier aircraft. Concrete overlays of existing asphalt pavement are usually in the 5–6-in.-thick range for pavements at general aviation airports.

Military Airfields

There is a continuing program of overlaying or rebuilding pavements at military airfields. Concrete overlays and new pavements for runways, taxiways, and aprons are being constructed at a number of facilities for deployment of the B-1-B bombers. The overlay pavements vary in thickness from 10 to 12 in., whereas new pavements are up to 15–24 in. An example of this type of work is the Ellsworth Air Force Base (AFB) near Rapid City, South Dakota. A 12-in. unbonded overlay was used to strengthen the runway pavement, which is 13,500 ft long and 300 ft wide. Another example is the McConnell AFB at Wichita, Kansas, where runway, taxiway, and apron pavements have been overlaid. Many of the military airfield pavements are more than 30 years old and will require overlays or reconstruction to accommodate future aircraft traffic.

Container Port Facilities

Concrete pavements have been used on several container port facilities and intermodal transfer facilities. These pavements are designed to carry the heavy industrial vehicles that are used at container ports. The large forklift trucks, straddle carriers, mobile cranes, and wharf cranes can have wheel loads of more than 100,000 lbs. The concrete pavement thicknesses used are dependent on the type of operation, equipment used for loading, and other factors.

The Wando Terminal Facility at Charleston, South Carolina, is typical of one type of port facility. There are ~150 acres (725,000 yd^2) of 13- and 15-in. pavement at this facility. The 15-in. pavement is adjacent to the wharf, whereas the 13-in. pavement was used in the main storage area. An additional 100 acres of storage is planned.

Parking Lots

Concrete parking lots are a rapidly developing market throughout the United States. These parking lots vary in size from those needed at small businesses, apartment buildings, and fast food establishments to those at large shopping malls and manufacturing facilities that may need 25–30 acres (120,000 to 145,000 yd^2) of pavement. The pavements range in thickness from 4–5 in. for automobile parking to 6–8 in. for areas subject to truck traffic. The pavements are usually placed directly on the compacted soil, which is trimmed to proper grade before paving.

Truck Terminals

Terminal facilities for long-distance trucking firms, such as Yellow Freight, have provided an expanded market for concrete pavement within the past few years. The lot size can vary from a few acres up to 30–40 acres. One lot was recently planned for 70 acres. Because of the concentrated truck traffic, the pavement thickness is usually 8–10 in., depending on where the pavement is located in the lot. A granular base course is usually used, with doweled joints in the entrance and at the heavy traffic areas of the larger lots.

Equipment Developments

During the 1950s and 1960s, there were major changes and developments in construction equipment to meet the needs of the concrete pavement industry in building the Interstate System. During this period, the slip form paver came into widespread use. The central mix concrete plant replaced the small on-site mixer, to increase production and keep pace with the slip form pavers. Fine-grading equipment was developed to provide the finished grade for the paving equipment. These developments resulted in major changes in construction methods for concrete pavements, which increased production to meet the needs of the massive road building program during this period.

The challenge to the construction equipment industry during the "new" era of highway construction has brought about new equipment development to meet the changing needs of the industry. With the emphasis on preservation of the highway system, the type of work available has changed considerably and requires new equipment development. Concrete overlays of various types, reconstruction and recycling, lane additions, reconstruction of shoulders, concrete overlays on asphalt pavements, concrete inlays, and concrete pavement restoration all require new types of equipment or modification of existing equipment.

Manufacturers offer slip form pavers designed for all paving markets, from small parking lot projects to the largest highway and airport projects. Slip form pavers to produce maximum pavement widths from 12 to 60 ft are available. To minimize encroachment on adjacent lanes, a "zero clearance" slip form paver has been developed. The tracks of the zero clearance slip form paver are within the area being paved. The concrete is deposited in a hopper at the front of the paver and is conveyed by a belt through the paver. It is then deposited and spread by a screw auger at the rear of the paver. The consolidation and finishing are performed by a cantilevered rear unit. The width of the side form is the extent of encroachment into the adjacent lane. Concrete placer-spreaders have been developed for all categories of the concrete pavement market.

Equipment has also been developed and is in use for inserting dowels in transverse joints. With the increased use of dowels in pavements with short joint spaces (15–20 ft), the dowel inserter offers promise as a valuable tool for the rapid and economical construction of this type of pavement, particularly when the concrete can be hauled on the existing base or roadway.

Concrete Pavement Restoration

Pavement restoration is a developing technology that required new types of equipment. Diamond grinding to reprofile old pavements that have become rough through joint faulting has been used extensively through the United States. Since 1975 there have been major advances in diamond grinding equipment. Equipment development has progressed from the "bump" grinders to the large long–wheel base equipment that is capable of profiling old pavement to new pavement smoothness tolerances. Larger and more powerful concrete saws have been developed, and blade technology has been advanced to permit more economical grinding of hard aggregates and cutting of concrete for full-depth repairs. Hydraulic drills for drilling holes for dowels and tie bars are available, reducing the time required for this operation.

Reconstruction and Recycling

These processes required new equipment to economically recycle PCC pavements. The development of concrete breakers has had a big influence on the economics of recycling. Because all types of concrete (plain, reinforced, and continuously reinforced pavements) are being recycled, there was a need for breakers that would aid steel removal.

Among the breakers currently in use are the diesel pile hammer, the sonic breaker (vibrating beam), whip hammers, guillotine drop weight breakers, and other drop weight types. Crushing equipment was modified to handle concrete with embedded steel. The equipment developed for recycling PCC pavement has made reconstruction and recycling a viable option whenever a roadway must be reconstructed.

DESIGN CHANGES TO IMPROVE PERFORMANCE

In general, the original Interstate and heavy-duty primary system was built with a thickness of 8–10 in. The base and subbase were either granular materials or stabilized bases that were built with cement or asphalt. The joints were sealed with a variety of sealants. In many areas, plain PCC pavements without dowels were built on stabilized and unstabilized subbases. As noted earlier, little drainage was installed during the early construction of the Interstate system.

Thickness

Thicknesses for pavements on the Interstate and heavy-duty primary systems have been increased to the 10–14-in. range. The changes in the types of trucks that travel on these systems, which now include more tractor-semitrailer vehicles, will significantly affect the loads applied to U.S. pavements. Weigh-in-motion studies also indicate that there are more overloads than are normally considered in design. Increased truck traffic volumes and changes in truck type are now being included in design of pavements for the U.S. heavy-duty system.

Load Transfer

There is an increase in the use of dowels in PCC pavements in many areas of the United States. Because of the increased thickness of pavements, larger dowels are being used. More plain doweled pavements with joint spacings of 15–20 ft are being built. Dowels are also being used more frequently on stabilized bases and in overlays of existing pavements. The dowel bars used today are coated for corrosion protection, particularly when they are to be installed in areas where deicing chemicals are being used.

Slab Length

The panel lengths used in dowel and mesh pavements have been significantly reduced during the past 20 years. Panel lengths of 80, 90, or 100 ft were used in a number of states. The longest panels used today are usually 45 ft or less, with some down to 26 ft. Only a few states are currently using longer panels.

The longer panels used in the past had cracks within the panel. After several years of service, the mesh frequently ruptured because of the "lockup" of dowels. This phenomenon is caused by corrosion from deicing chemicals, which contributed to distress at the cracks and joints. Shortening the panels and using better joint sealant materials and corrosion protection on the dowels should materially improve the performance of these pavements.

Base or Subbase

A number of states, particularly in the western United States, placed cement-treated subbases under their PCC pavements. On earlier Interstate projects, these subbases were usually stabilized with 3–4 percent cement. After several years of heavy traffic, faulting developed because the subbase was prone to erosion and water had become trapped under the pavement. A lean mix concrete or econocrete subbase is now used in many states to provide an erosion-resistant surface.

Concrete shoulders are frequently placed with the mainline pavement to provide a stronger pavement. Dowels are normally not used in these pavements in the western United States. The joints are closely spaced, randomized, and skewed.

The combination of aggregate interlock in the pavements with short joint spaces and the lean concrete base is considered sufficient to provide load transfer at the joints. Tied concrete shoulders are also used, which will reduce deflections and significantly influence pavement performance.

Concrete Shoulders

Increased use of concrete shoulders on new pavement and retrofit of shoulders on old PCC pavement will provide better performance in the future. Tied concrete shoulders are equivalent to ~1 in. extra thickness on the main-line pavement, as far as load-carrying capacity is concerned. The joint between the shoulder and main-line pavement can also be effectively sealed to prevent water infiltration at this joint, which is normally responsible for most of the water that enters a PCC pavement system.

Drainage

There is an increased use of drainage systems in the PCC pavements built today. Drainage is usually installed on new and reconstructed pavements that are placed on granular or open-graded base courses. Drainage systems are also being installed on existing pavements to remove water trapped in the roadway section.

Joint Sealing

New and improved joint sealants are currently being used. During the early construction of the Interstate system, no attention was paid to providing the proper shape factor for the sealant used. Many of the sealants had short service lives, and the joints were usually not resealed. The performance of the improved sealants gives evidence of an extended service life when the sealants are properly installed.

"Fast-Track" Concrete Paving

The "Fast-Track" concept of concrete paving was developed in Iowa to provide a concrete pavement that could be opened to traffic the day that it was paved. The initial research involved formulating mix designs that would develop adequate strength to support traffic within 24 hours. Subsequent developments have resulted in adequate strength levels in 8–12 hours. With the new cements that are becoming available, this time could be reduced further.

The Fast-Track concept was used experimentally in its first major project on a 6.8-mi section of U.S. 71 in Buena Vista County, northwestern Iowa. The existing pavement, constructed in 1937, was 8 in. thick and 20 ft wide. The project involved widening the roadway to 24 ft and laying a 4-in. bonded concrete overlay to strengthen the pavement. Construction was completed in late summer 1986. A survey in May 1987 by Iowa DOT personnel indicated that pavement is in satisfactory condition and is expected to give good service for a number of years.

Several additional Fast-Track projects have been constructed since that time. Among these are a 1-mi section of roadway into a housing development near Des Moines, Iowa. This section was closed to traffic at 7:30 a.m. on a Monday and reopened to traffic, complete with striping and granular shoulders, on Tuesday at 5:00 p.m. Another interesting sidelight of this project was that the contractor received a check for 95 percent pay on Wednesday. The concept was also used at a general aviation airport in Osceola, Iowa, where the contractor paved the center lane of a 50-in.-thick, 75-ft-wide runway and alternate lanes on the ramp with Fast-Track concrete, reducing the time required to place the adjacent lanes. The 3-day flexural strength was 590 psi, which permitted equipment traffic to use the new pavement. The project was complete in 9 calendar days. More than 200,000 yd^2 of Fast-Track concrete pavement was laid in Iowa during 1986 and 1987.

The mixture design normally used in Iowa for Fast-Track is 640 lbs type III cement, 70 lbs type C fly ash, 1,413 lbs fine aggregate, and 1,413 lbs coarse aggregate. The type III cement must also have a compressive strength of the cement mortar cubes (2 in.) of at least 1,300 psi in 12 hours. A water reducer is also used. The Fast-Track concept is continuing to be improved and should find application in many paving situations where early opening to traffic is required.

CONCLUSION

What does the future hold for concrete pavement construction in the United States? The present emphasis on preservation of the highway system will dictate that rehabilitation will represent the major pavement market of the future. The concrete pavement industry is rapidly adapting to the new era in highway construction.

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PIARC General Report: Construction and Maintenance of Rigid Pavements

At the 18th World Road Congress, members of the Technical Committee on Concrete Roads of the Permanent International Association of Road Congresses (PIARC) were asked to consider five aspects of rigid pavements: design and behavior in service, materials, construction and control, maintenance and rehabilitation, and subbases and road bases treated with hydraulic binders (both concrete pavements and semirigid pavements). Representatives from 28 nations responded with reports on the state of the art in their countries. Concrete pavement construction techniques around the world continue to improve, due at least in part to the sharing and dissemination of knowledge and technology.

At the 18th World Road Congress of the Permanent International Association of Road Congresses (PIARC), September 13–19, 1987, in Brussels, 28 countries presented national reports on the construction and maintenance of rigid pavements: East Germany (GDR), West Germany (FRG), Australia, Austria, Belgium, Brazil, Bulgaria, People's Republic of China, Czechoslovakia, Finland, France, Hungary, India, Italy, Japan, Kuwait, Mexico, Morocco, Norway, the Netherlands, Poland, Portugal, Romania, Spain, Switzerland, Yugoslavia, United Kingdom, and the Soviet Union (USSR). We had requested the various countries to report in a concise manner on the new techniques and recent developments in the field of concrete roads, while selecting the most interesting points.

The 18th Congress program selected five main topics and also included certain specific points, so as to better classify the information. Following the instructions of PIARC Executive Committee, some members of the Technical Committee on Concrete Roads were given the task of analyzing and synthesizing each of the topics. Some conclusions had to be brought forward for the Congress and definite progress and facts had to be mentioned, as well as unresolved problems and desirable research.

The topics and reporters are as follows:

- Design and behavior in service—F. Verhee and M. Ray (France);
- Materials—H. Sommer (Australia);
- Construction and Control—T. Moss (Germany);
- Maintenance and rehabilitation—B. J. Walker (United Kingdom); and
- Subbase and road bases treated with hydraulic binders (concrete pavements and semirigid pavements)—M. Moraldi (Italy).

The reporters' work saves us from the need to add a general synthesis here. Such a presentation is envisioned at the Congress. It is hoped that national reporters will understand that it was only possible to summarize certain points in the attempt to stress the most interesting points at a general level. In any case, readers are encouraged to study the original reports after they are told about the contents, so allowing them to find the issues of concern to them more quickly.

It is opportune to recall that progress in this field is also collated in the report from the Technical Committee on Concrete Roads, which includes nine chapters:

1. Combating concrete road pumping;
2. Concrete overlays;
3. Cement concrete road—state of the art;
4. Monitoring and repair methods of concrete surfacings;
5. Use of compacted concrete in road construction;
6. Cracking of concrete surfacings;
7. Third International Conference on the Design and Rehabilitation of Concrete Pavements (Purdue University, West Lafayette, Indiana, 1985);
8. Fifth International Symposium on Concrete Roads (Aachen, West Germany, 1986); and
9. Workshop on the Theoretical Design of Concrete Pavements (Epen, Netherlands, 1986).

Although concrete road techniques have reached a very advanced stage, progress continues, due to research and experience. The diffusion of our knowledge is certainly an accelerating factor in this.

C. Kraemer (Spain)
President of the
Technical Committee on Concrete Roads

DESIGN AND BEHAVIOR IN SERVICE

Examination of National Reports

Present Concept and Design of New Pavements

GDR The new text *Compilation of the Uniform Technical Prescriptions on Construction* includes a pavement calculation of the limited state type. For heavy traffic there is a need to provide load transfer devices at the longitudinal and transverse joints of a cement-treated subgrade and to avoid expansion joints. The expected life duration, based on experience, ranges from 40 to 50 yr.

FRG The structures performed according to *ZTV Concrete 1978*, presenting an excellent short-term behavior. The new *Guidelines for the Standardization of the Roads and Runways Superstructures* (RST 086) provides for a 2-cm thickness increase for the slabs facing heavy traffic (22 cm for class II and possibly 24 cm for class I). A fully hydraulic binder–treated structure without a frost-free layer has been introduced.

In the case of a pavement without dowels, steps appear very quickly. For slabs up to 20 cm thick the length should not exceed 20–25 times the thickness.

Australia Since 1983 an important development has begun in New South Wales concerning the use of the short slab technique (even ultra-short slabs: 4 m long) with generally nondoweled joints on a subgrade made of lean concrete containing fly ash (resistance after 28 days: 5 MPa).

The continuously reinforced concrete pavements constructed in the 1970s behave well, but this technique has not been developed much because of the investment cost.

Belgium There is a design method for rigid pavements with heavy or low traffic. The resulting typical structures (life duration: 40 yr) are presented (continuously reinforced concrete on lean concrete, doweled concrete on lean concrete or on nontreated material, nondoweled concrete or nontreated material in case of low traffic).

A behavior forecast model has been established in order to manage the road network. It takes into account longitudinal evenness, slab deflection, stepping, adherence, and visual inspection.

Brazil The economic comparison between bituminous and cement concrete pavements shows identical costs. The use of lean concrete for subgrade, subbase layers, and wearing courses has been widely tested.

Roller-compacted concrete is being tested (cement ratio: 85 and 180 kg/m^3; resistance after 7 days: 5 to 7 MPa), especially as a subgrade layer for heavy and medium traffic urban pavements.

Spain One can note trends toward

- An increase in slab thickness;
- The improvement of the resistance to erosion through the use of lean concrete or through the increase of the cement ratio (5.5 percent);
- The systematized use of dowels on heavy-traffic pavements;
- The systematic use of a lateral drainage (porous concrete, drainage gravel, drainpipe); and
- If the emergency parking lane is made of concrete, it is linked to the lining with clamps.

At the end of 1986, new standard cross sections were published. Roller-compacted concrete is making its appearance as subgrade over a cement-treated gravel and with a bituminous mix wearing course.

Finland Concrete pavements are of special interest because of their resistance to tire spikes. However, and in spite of this, a 50-mm wear-off is expected over 30 yr. In order to take this fact into account, at the design level, one considers increasing the slab thickness to allow for two grindings of the pavement during the pavement life. Taking the structural improvement brought by this additional thickness, one considers only 70 percent of the wear. Globally, the construction and maintenance costs of the rigid and flexible pavements are estimated as comparable.

France The last few years have seen the introduction of continuously reinforced concrete:

- For the overlay of the old two- or three-lane cement concrete pavements with or without widening, after the preliminary crushing of the slabs, for very heavy traffic (2,000 to 3,000 trucks per day per direction: thickness of 20 cm).
- For the rehabilitation of old slow lanes with concrete slabs with conservation of the old existing treated gravel subbase (and reshaping with the bituminous mix layer). There are no connections between the remaining pavement slabs and the continuously reinforced concrete slab in order to prevent preferential cracks.
- For new pavements: the structure is made of a 35-cm-thick cement-treated sand layer, a 5-cm bituminous mix meant to prevent the erosion risk of the sand, and a 19-cm-thick continuously reinforced concrete slab, for a 400 trucks per day per direction traffic. In this case, the treated sand acts a foundation layer. It seems that it is within such a layout that continuously reinforced concrete may face competition.

One must outline the use of equipment that allows for, in most cases, construction without transverse support steel.

Japan The 1972 *Design and Construction Manual for Concrete Pavements* has been revised on the basis of an in-depth inquiry into the behavior of existing pavements. It now concerns heavy- and low-traffic pavements and should last for 20 yr. The thickness of the slab varies between 15 and 30 cm (concrete with a 40 kg/cm^2 resistance). The thickness of the subbase is generally taken from the CBR. The nontreated material seems to be widely used.

Morocco Morocco took an interest, in recent years, in the introduction of cement concrete pavements because of the price of oil-based products and problems raised by flexible pavements. Besides, Morocco has a very large cement production capacity. This approach has included

- The study of international experiences;
- The definition of a design method;
- The study of concrete;
- The setting up and studying of an experimental work site (RS 229); and
- The introduction of regulatory requirements.

The selection has been applied to short slab structures, with or without dowels (5 or 4 m if nondoweled), on nontreated gravel or eventually treated supporting soil. The provisional structures depend on the traffic level, the soil, and the climate (barren, semibarren, semihumid, and humid areas). The heavy-traffic pavement shoulders include a layer of draining material.

The technico-economical studies performed on the base of these structures show

- That the concrete pavement represents a lower investment cost for heavy traffic (> 2,000 veh/day) on bad soil;
- That concrete is competitive on bad soil if maintenance is taken into account;
- That concrete requires less energy; and
- That concrete requires less foreign currency.

According to this, the Director of Roads and Traffic carries on making efforts to introduce this technique. A 100-km pilot work site is planned for 1987.

Norway As with Finland, the concern about wear caused by tire spikes is important. In order to improve the resistance of concrete, high-resistance concretes are being researched (400 kg/m^3 of cement, 20 to 25 kg of silicium fume, and plasticizer agents). One thus obtains 65 to 75 N/mm^2. Thanks to this, the wear resistance is doubled.

The Netherlands A study on nonreinforced pavements over soils likely to settle has been performed. An S/T^2 parameter has been established where

- Settlement is compared with a sinusoidal function,
- S is the vertical maximum size of the settlement; and
- T is the half-period undulation.

On a special case, the analysis supplies, as admissible value, $S/T^2 = 25 \times 10^{-5}\text{mm}^{-1}$, which means that for a 10-m T, the admissible settlement range is 2.5 cm.

Italy Tests have been performed on the NARDO track, where the different modes are being tested: 18- and 24-cm slab thickness, 4- and 5-m slab length, doweled or nondoweled joints, all of it lying on 15 cm of cement-treated gravel. The use of dowels multiplies its life by 4.5. According to the overloads, which may reach 50 percent of the authorized weight in the case of heavy traffic, the pavement thicknesses should not be less than 24–25 cm.

Nonconventional and Experimental Pavements

GDR Ten test sections with a very short slab (1–3 m) pavement have been built on roads with very different traffic. Thicknesses vary from 10 to 18 cm because it is considered that these short lengths reduce the stresses in the slabs and improve the load transfer at the joints. The longitudinal and transverse joints have been realized through the introduction of a plastic film within the fresh concrete. These joints are not waterproof. These pavements could be compared with prefabricated concrete slabs pavements but with better bedding conditions and better evenness.

Some low-traffic roads and deck overlays have been realized with concrete including 30 km/m^3 of fabric waste (fiber length: 13–55 mm). There are no manufacturing or laying problems (finisher + compaction). These wastes supply a stability that permits immediate use.

FRG For the rehabilitation of old concrete pavements when an important reshaping is made of lean concrete, the layer is notched at the location of the future shrinkage flexion joints. Studies and tests have been performed on the possibility of constructing widening and emergency parking lanes on bituminous pavements with cement concrete. Theoretically, the thickness of the slab should be increased by 2–4 cm at the side of the bituminous pavement. The drainage of water, which could enter at this point, has to be carefully studied.

Australia Reinforced concrete linings with crack inducers have been used and studied. As a consequence, the steel rates vary between 0.6 at the level of the crack inducers and 0.2 percent between them where, normally, any cracks should appear. In fact, cracks appear in the less reinforced sections, near the crack inducers, whereas the strongly reinforced zones stop the cracks. This type of test has now been rescinded.

Steel fibers are considered for operational usage, but they are not conventional. Use of them is mainly in the construction of industrial floors (18-mm fibers with bulging ends). The cost of the fiber concrete is twice the classical concrete's, but the thickness may be reduced by up to 40 percent. On roads, this type of concrete has been used at bus stops, toll stations, and for special shaped slabs.

The use of polypropylene fibers (no modification of mechanical characteristics) to curb growing cracks is being studied.

Belgium The excellent behavior of the PIARC experimental pavement is certainly due to its very stable support from the old pavement and to the efficient drainage system. It is possible to point out the following:

- No difference in the joint-sealing products;
- Very limited slab movements, those of the nondoweled joints being twice as great as those of the doweled ones; and
- The lack of sealing at certain joints is of no consequence (this effect is certainly due to the lateral drainage).

Spain Since 1984, dry roller–compacted concrete has been used on numerous new pavements and rehabilitation experimental sections ranging up to 4 km and accommodating medium to heavy traffic. The binder dosage is approximately 300 kg/m^3, the binder including a part of fly ash. A binder including 51 percent of crushed slab at 2 800 cm^2/g has also been used in order to increase the workability time. The laying is mostly performed with a finisher. The thickness ranges between 21 and 23 cm. The wearing course is made of bituminous mix (5–8 cm) for heavy traffic; otherwise a coating may be applied. The resistances obtained are at least equal to 3.3 MPa after 28 days; the behavior is generally satisfying.

In 1984, within the procedure of redesigning the 2 $\times$ 2 lane roadways, roller-compacted concrete structures were proposed.

Finland Since 1982, experimental two-layer concrete pavements have been constructed with a slip form machine. The two layers have comparable thicknesses, for a total thickness of 18–20 cm, which is a 2- to 3-cm increase compared to a single-layer structure. The cement part of the lower layer varies between 110 and 250 kg/m^3. The present behavior is comparable with that of classical concrete pavements. Roller-compacted concrete has also been used.

France For reduced size pavements (bicycle lanes, for example) in sand-rich areas, sand concrete was used that differs from mortar by the 250 to 300 kg/m^3 cement part. The structure and the laying are comparable to those of traditional concrete.

A recommendation for roller-compacted concrete pavements and an information note have been published.

India Test sections for vacuum-dried concrete have been realized. The process consists of the aspiration, under vacuum, of the fresh concrete in order to extract a part of the concrete's water, thus reducing the water-cement ratio and increasing resistance and other characteristics. It is best to treat a 10-cm thick layer for 20 minutes. The stiffness of concrete is considerably increased.

Italy The experimental pavement project presented in Sydney has been realized. The alternatives were whether to include dowels or not, to have a subbase made of cement treated gravel, lean concrete, or cement-treated gravel and mix. The shoulder is made of porous concrete. An adjacent short section has been reinforced with fiber concrete, the joints being then at distances of 15 to 20 m. The surface was then treated by chemical stripping. At present, it is behaving well.

Japan A continuously reinforced concrete pavement, approximately 3 km long, was constructed in 1985 with the following structure: 25 cm concrete, 4 cm bituminous mix, and 15 cm crushed stone subbase. The temperature variations are large (–15°C to +37°C), as are certain longitudinal gradients (up to 6 percent).

Sweden The use of roller-compacted concrete is increasing (1984: 10 000 m^2; 1985: 30 000 m^2). This material is used for pavements requiring resistant wearing courses and where traffic runs are reduced speeds (bus stops, industrial, and agricultural areas). The required compression resistance is at least 40 MPa. The design uses the same criteria as for conventional concrete. Soils likely to settle with frost-thaw cycles are not fit for roller-compacted concrete.

Czechoslovakia During 1984, the reinforcing of a 17-cm-thick continuously reinforced concrete airport pavement was realized. During the test, several reinforcement rates have been tried (from 0.567 to 0.737 percent longitudinally and 0.205 to 0.38 percent transversally) as well as interface types (mix coated plastic film). The most important effect on the cracking pitch has been the concreting temperature on the plastic film (the crack spacing is 12 to 14 percent higher than that on the bituminous mix). The average cracking pitch ranges from 2.9 to 6.5 m (but sometimes 0.1 m). The optimal reinforcement rate seems to be 6 percent. A large plastified concrete work site has been manually built on a "container area": 4300 m^3—14 500 m^2 in 84 hours; that is, an average output of 50 m^2/hour, with a daily peak of 830 m^3.

Technical and Economical Balance of Old Pavement Behavior

Belgium For medium to heavy traffic, the oldest pavements (20–25 yr) with long slabs (10 m) show damage at the transverse joints. On more recent ones (up to 20 yr) with short slabs (5 m), this defect is almost nonexistent.

France The behavior of the new pavements' draining shoulders—lean concrete, nondoweled, short slab structures—is good. The oldest one, the A1 motorway (accumulated traffic: 20 billion trucks), shows a good structural status.

The behavior of "thick slab" structures (general traffic 600 to 700 trucks per day per direction; accumulated traffic on the oldest one: 1.3 billion trucks) is hard to determine, because it's out of the usual frame. Slab movements are as high as those of classical structures, and movements (in the absence of tie bars) are higher at the level of the longitudinal joint than on the slab edge joint: this is linked to the thickness difference (trapezoid cross section 40–25 cm.)

The main question is the final behavior of the slab supporting layer (draining gravel of fine material under draining geotextile).

United Kingdom 36 nonreinforced concrete pavements, built from 1970 to 1979, have been studied. From that study a strong correlation may be drawn between transverse cracking and the slab length/width and length/thickness ratios. Slab movements were influenced by the thickness of the subbase and the length of the dowels. The twin-layer construction supplied a better evenness, a better surface texture, and less susceptibility to joint spalling. The quality of the execution also seems important.

Switzerland The introduction, in 1970, of enclosed air in the concrete has suppressed the effect of deicing salts. The use of sawed-off joints after 1975 and the suppression of reinforcement seems to have eliminated damage to the previous cast-in-place joints, as well as, of course, damage to the reinforcement corrosion. The pavements and the dowels have been realized with a nonstop working slip form machine and, after 4 yr, behave well (good positioning of the dowels).

Pavements for Residential and Low-Traffic Roads

GDR Prefabricated, large size slabs (from 1 m × 1 m to 1.5 m × 2 m) are sometimes used for low-traffic and reduced-length roads. The size is determined according to their use: residential street, path for cars, parking. The reinforcement is not part of the pavement structure but is part of the transportation and laying. This type of construction is used when there is no concrete plant available, when the pavement must be immediately used, or when it is not possible, for climatic reasons, to use classical concrete.

Australia To fight potential slab pumping on submergible roads in Queensland, the foundation surface (CBR 15) has been treated at the level of the joints and the slab edges through the laying of a waterproofing film made of emulsion and nonwoven fabric strips in 1-m widths. For residential roads the thickness of the concrete generally reaches 10 cm.

Belgium The low-traffic road slabs are 5 m long and generally 16–20 cm thick. On bicycle paths, the normal thickness is 15 cm, except where there are regular car crossings (then 20 cm).

Spain The Spanish experience in the use of roller-compacted concrete for this type of road is important. The first construction of this type goes back to 1969–1970. At present, 4 million m^2 have been laid, almost all of them in Catalonia. The thickness varies between 15 and 20 cm, directly laid on the platform. Over the last few years, the sawing off of the joints every 12–15 m has been introduced because cracks were developing every 18–22 m.

Cores show a good resistance (Rc: 35 MPa; Brazilian test: 3.3 MPa). These results and good behavior show this technique to be adequate for the purpose.

India An economical solution has been designed for "creteways" using cement concrete cobblestones for rural roads, made of portable prefabricated rectangular sections (10 × 60 × 90 cm) with dowels for the load transfer. These blocks are laid on a semi-rigid foundation. A test track built according to this method has given satisfying results.

Japan Up until now, one generally used bituminous mixes for low-traffic roads, especially open, because many roads are permeable in order to collect rain water, thus improving pedestrian comfort (walkways). A first porous concrete pavement was built in 1983, and its principle has been extended to the walkways and squares of the Tsukuba 1985 Science Exhibition. The characteristics of this concrete are the following:

- Porosity 25 percent and permeability 10^{-1} cm/s;
- 28-day resistance 25 kg/cm^2 (during this period);
- The only defect is that it is a long time before it is operational (composition: cement 14 percent, water 6 percent with 8 percent latex, passing to 2.5 mm < 20 percent).

The proposed structures are:

- Walkways: 8-cm porous concrete and 10-cm nontreated gravel;
- Parking areas, residential streets: 10-cm porous concrete and 15-cm nontreated gravel; and
- Residential streets, reservoir parking places, and low-traffic roads: 15-cm porous concrete and 20-cm nontreated gravel.

Poland The pavement width is 3.50 m and the shoulder 1 m wide, stabilized with lime material (most frequently), or 2 × 3 m. The slabs are 5–6 m long and have no dowels or reinforcement. The thickness ranges from 14 to 18 cm. The transverse gradient is 1.5 percent for the 3.5-m pavement. The foundation generally is a cement stabilization of the soil over 14 cm deep if no draining layer is required. The expansion joints are suppressed if the pavement is built between April and October. The joints are waterproofed.

USSR The use of concrete for rural roads (about 300 veh/day) is interesting because its life is long and it allows traffic to circulate all the year round. The rigidity of these pavements makes it possible to pass over limited bearing capacity soils and foundations. The operational cost of this kind of pavement is 2.2 times lower than that of the nontreated gravel–type pavements: the required work material and energy quantities are 10, 7.5, and 4.5 times lower, respectively. The thickness limits are 12 and 18 cm. In order to determine the thickness and the length, one takes the risks of settlement of the foundation into account.

Urban Pavement

Australia In New South Wales the trend is to use concrete for urban pavements regardless of whether the pavement is rigid or flexible, when the soil has a low bearing capacity. One uses a fly ash concrete (28 days Rc mini: 5 MPa) as foundation layer or work site platform.

A concrete layer with higher resistance is cast over it after a separation layer (usually a wax emulsion) has been poured in between. Sometimes this concrete layer is covered by a bituminous mix layer. In order to prevent the reflection of the cracks, one has to lay a geotextile between the two.

Another solution is the laying of a thick bituminous mix layer over the foundation concrete (at least 15 cm). A third solution is to insert a nontreated gravel layer between the foundation layer and the bituminous mix (the thickness of which may then be lowered to 10 cm).

Spain In this field, roller-compacted concrete is also being tested.

Czechoslovakia In the future urban road pavement catalog there will be a structure with a concrete subbase and bituminous mix wearing course. The subbase slabs will have the following size: 3.5 × 3.5 m to 4 × 4 m and a 15- to 25-cm thickness (wearing course: 10 to 12 cm).

Concrete Block Pavements

GDR The development of block production is steady (export not included): 232 000 m^2 in 1983, 400 000 m^2 in 1984, 575 000 m^2 in 1985, and 795 000 m^2 in 1986. The use of this technique is made possible by the mechanization of laying.

Thus the use of the "pince de décalage" (staggering clamp) has allowed for a 70 m^2/hr productivity increase. These blocks are used on small and irregularly shaped areas, as well as for aesthetic reasons. The thickness ranges from 50 to 100 mm. They are laid on 40-mm sand bedding.

Australia The concrete block pavement structure has been the object of a great deal of research that ended with the design curves of the Cement and Concrete Association of Australia (CCAA). The drawback of these curves was that they only took into account the upper foundation CBR values over or equal to 16.

Additional research has been carried out by the Australian Road Research Board (ARRB) on clayey soils with a 2–4 CBR. The main conclusions are

- It is necessary to take the "immersed" CBR into account if the soil is clayey and the subbase made of nontreated gravel;
- The subbase should be made of high-quality nontreated gravel and be at least 10 cm thick; and
- The subbase should be stabilized if the CBR is less than 4.

Also, the external noise level of the concrete blocks pavements is identical to that of the bituminous mix; the low-frequency noises are covered by the noise of the vehicle motor.

If the ARRB research leads to a higher cost for concrete block structures, this should be globally profitable, as it makes this type of pavement comparable to the flexible structures through the design approach and its behavior.

Belgium The design approach is empirical. A study performed by the CRR shows that if the constraints at block level in continuous and noncontinuous (blocks) pavements are different, at the lower level they are comparable.

United Kingdom During these last 10 yr, the increase in the use of concrete blocks has been huge (a 40 percent yearly increase). They are used for playgrounds as well as for major urban road design and bulk plants. This technique has a good overall behavior and is competitive and good looking.

It is important to ensure a long-term life duration and a good skid resistance. There are few cases of discrepancy. To achieve good skid resistance, adequate aggregates are selected.

Some structural failures on nontreated subbase were due to water-receptive materials (reduction of the "immersed" CBR). The immersed CBR of the subbase has to be at least 70. This is possible through a good selection of material or through its treatment. It is advisable to make the surface waterproof.

The circular depressions (30 to 100 cm) that have been observed on the traffic path of bus lanes made of concrete block pavement on treated foundations seem to be due to the granular degradation of the laying sand, which, once transformed into powder, is squeezed out in the form of a paste by the traffic, at the level of the joints. To prevent this, the sand is selected after testing with a small ball mill.

The stated defects are few, and the future of this technique seems encouraging. The laying is often manual, in spite of mechanical means, even for areas as large as 180 000 m^2.

Japan Since 1978, the year when concrete blocks were introduced in Japan, the number of block-paved pavements has increased steadily. The concrete block pavements are mostly used for decoration. At present, paved surfaces cover about 2.5 million m^2, only 5 percent of which are on roads open to traffic.

There is presently no specific design method. The method used consists of assimilating the "relative resistance coefficient" to that of the bituminous materials. Studies are in progress on the theoretical behavior of such structures under heavy traffic (using finite element methods).

Furthermore, the concrete blocks are tested for their anti-wear ability for roads in mountainous regions, where spikes and chains are used. High-resistance concrete blocks (low e/c ratio through the use of plasticizers) and concrete blocks containing polymers (PIC) have been tested, with a wear rotation system. The wear is a direct function of the concrete resistance. The PIC blocks that present a 150-MPa resistance to compression show the best resistance (5 times that of the bituminous mixes). An experimental section of those PIC blocks has been realized in 1981 in Sapporo. The maximum rut depths were 4.2 mm after the first year, 7.7 mm after the second, and 9.9 mm after the third. The high cost of the PIC blocks may be balanced by their usage in the sole traffic paths. The blocks are also used for pedestrian ways at intersections for contrast and for their anti-skid properties.

The Netherlands Concrete blocks are very much appreciated on urban roads, but they are also well adapted to heavy-traffic areas (like container-handling areas).

Since 1980, studies have been in progress to elaborate a design method for this type of pavement. These studies are performed by various bodies. A finite elements model is used. This program supplies results that correspond well with on-site deflection measurements. Rutting is also an important design criterion. The results of 10 rutting and deflection test experimental sites have led to the drawing up of a provisory chart, with the final chart published about 1987.

In the 1980s a high-output laying machine has been produced, to be operated, for example, on the E.C.T. container facilities (800 000 m^2). Other systems are being developed, in particular, vacuum lifting.

USSR For prefabricated pavements, besides reinforced and prestressed concrete slabs, slitted and lightly reinforced slabs are used. The nonreinforced slabs 2–2.4 m long develop cracks due to traffic. Making slits that divide the slabs into smaller elements reduces the bending movement down to values admissible for nonreinforced slabs. The reinforcement is calculated only to allow the construction of the pavement and to act as tie bars. This technique also facilitates fabrication and does away with using heavy metal molds and steam curing (which lowers the resistance of concrete to frost).

Concrete Slabs on Soils with Low Bearing Capacity or Subject to Large Variations in Volume

Australia The report outlined the necessity of either using a treated subgrade or treating the soil, especially where there is a risk of swelling.

India The document reported on the experiment on pavements subject to heavy traffic where the soil, sensitive to water, has been enclosed to a 1.20-m depth by a prefabricated bituminous lining. Analyses 20 yr later show the efficiency of this method in curbing water content variations.

Taking the Effects of Very Heavy Vehicles into Account in the Design of Pavements

In the GDR, because the mechanical reservation of the pavement under exceptionally heavy loads is limited, heavy traffic has to take into account the hour of the day or the season in order to comply with the temperature of the slab. In FRG, the RSTO 86 takes the trend in the axle load increase into account, adding 2 cm to the thickness for the heaviest traffic class.

Pavements in Severe Climates

Czechoslovakia reports temperature measurements on an experimental motorway pavement section in Irak. The pavement presented the following structure: 20 cm nontreated subgrade + 20–30 cm of lightly reinforced cement concrete (51 MPa, 28-day resistance). A model for thermic flow has been established from these measurements. The thermic gradients appear to be less dangerous than in the rest of Europe: maximum positive gradient 0, 53°C mm^{-1}; maximum negative gradient 0, 43°C mm^{-1}.

The constraints due to thermic gradients are about the same order of magnitude as those due to loads.

Other Applications of Concrete

FRG A new guideline for concrete pavements on airfields has been published. Most of the runways and parking areas are made of cement concrete. The subgrade is often treated with an hydraulic binder. The thickness of the slabs may reach 40 cm; no length or width exceeds 30 thicknesses (maximum 7.5 m); and where possible slabs are square shaped. The runway longitudinal joints are doweled, except where the slabs are too short (< 5 m), and more than 30 cm thick. If the foundation is treated, the longitudinal joints are just fitted with connection irons. The key system is not satisfactory.

Belgium The pavements and new strip structures of the New Brussels National Airport are mostly made of concrete. One deals here with 5 m × 5 m × 35 cm slabs on 20 cm of lean concrete and 20 cm of cement-treated sand. In 1983 and 1985, tests were performed to replace 35-cm-thick slabs by 18-cm-thick steel fiber concrete slabs (40 kg/m^3 of 60/80 fibers) in order to eventually use this material for pavement reinforcement. Up until now the behavior has been satisfactory.

On the Zeebrugge bridge, the following structures have been used to support a 100-ton load on four wheels: either 23-cm nonreinforced slab (6 × 3.75 m) on 15-cm reinforced lean concrete laid on 15-cm granular stone base, or concrete blocks (22 cm × 11 cm) 12 cm thick on 3-cm treated sand, 20-cm lean concrete, 15-cm granular stone base, or cement-treated sand. Drainage is carried out by closed metal fiber cement ducts. The laying sand of the blocks is made of crushed limestone 0/2-2/4, granulated slag, and lime that remains workable for several days and becomes as resistant as cement-treated sand.

United Kingdom The increasing number of heavy vehicles and the increase in the maximum admissible weight from 32.5 to 38 tons require the design of new barriers. Metallic and concrete barriers designed by the TRRL (British Safety Barrier) have been tested. The concrete barrier has the following characteristics:

- 3-m prefabricated elements;
- Longitudinal tenon-mortise assembly; and
- Ground fixing through six dowels on a lean concrete base.

Tests consisted of 15-degree impacts supplied by cars traveling at 110 km/hr and by two trucks (16 and 30 tons) traveling at 80 km/hr. The conclusions are as follows:

- The cars and the 16-ton truck are retained by both barriers.
- The 30-ton truck is retained by the special metallic barrier, but the concrete one is broken.
- The gravity of the "accident" is the same for the people involved in both cases.

Conclusions for Approval by the Congress

Improvements and Points Considered Established

Since the Sydney Congress, several national specifications have been published (GDR, FRG, Japan, Spain, Belgium, Morocco). These and the trends stated in other countries show that for medium- to high-traffic pavements, there is a strong tendency to increase the structural capacities at the design stage for concrete pavements, because of the increase in traffic (volume–axle load) (FRG, Morocco) or because of work performed on old pavements (Japan); or on experimental sections (Italy, FRG). These structures are joint structures. This structural capacity increase is supported by the following points, as stated in 1983:

Improvement of the Subgrade Mechanical Characteristics, Especially Resistance to Erosion Through the increase in the binder content for treated gravel (Spain, GDR) or through a switch to lean concrete (Spain, Australia, Brazil).

Doweling of the Transverse Joints Spain retains doweling for heavily trafficked roads; so does GDR. France uses dowels for the very heavily trafficked roads around Paris. Italy outlines a 4.5 multiplication of the life of a doweled pavement as compared with a nondoweled pavement. The FRG states a slab level difference on nondoweled pavements. The United Kingdom points out the influence of dowel length.

Increase in Slab Thickness This is used for heavily trafficked roads in Spain or FRG. One must note the isolated case of Finland, where the slab thickness increase (35 cm) is considered with the goal of grinding the pavement twice during its life in order to suppress rutting due to spiked tires.

Shortening of Slabs The risk of cracks building in too long a slab is known and has been mentioned several times (United Kingdom, Japan, FRG). A 5-m length for slabs 20 cm thick seems a good compromise. In order to improve mechanical behavior through better load transfers and reduced bending stress, a trend toward shorter slabs can now be seen (Australia: 4 m; Spain, Morocco).

The case of an experimental pavement with 1- to 3-m-long slabs is mentioned in GDR, the thickness ranging from 10 to 18 cm. This trend toward short slabs is certainly worth noting for the future (cf. the states of Washington and California).

Drainage Systematic implementation for heavily trafficked roads in Spain and Morocco, as has been done in France since 1975. In the follow-up performed on pavements containing such features as short slabs (5 m), lean concrete, or dowels, eventually lateral drainage showed good behavior (Belgium: 20 yr experience; Spain, France, FRG; PIARC's comparative site on the N4 in Belgium).

Continuously Reinforced Concrete Behavior is satisfactory (Australia), but utilization seems to be limited by cost. France alone has started to use it since 1983 for specific works like the reinforcement of slow lanes or for overlay of old concrete roads. It has also been used for new pavements on a treated sand subgrade. The erosion risk of the sand is checked by the insertion of a 5-cm-thick bituminous mix and lateral drainage.

Roller-Compacted Concrete As a material it is now well defined. France has issued a recommendation on its realization and a technical notice on its design. Although Brazil is still at the experimental stage, Finland, Sweden (100 000 m^2 in 1986), and Spain have seen a rapid development in its usage.

In Sweden it is used for areas of slow traffic (bus stops, industrial, and agricultural areas). The required resistance to compression is at least 40 MPa.

In Spain it has been used since 1984 on numerous sites for heavy-medium trafficked pavements, including reinforcements, where its quick readiness is very much appreciated. The laying is performed with a finisher. The layer thickness ranges from 21 to 23 cm. For medium to heavy traffic, a bituminous concrete wearing course (5–8 cm) is recommended.

Concrete Blocks These have been an important aspect of cement pavement technique in recent years. Almost all countries report significant development in the usage of this technique (GDR, Brazil, United Kingdom, Japan) and where this increase is not reported, its usage is still important (FRG, Netherlands, etc.). For example, in the United Kingdom, the average yearly increase has reached 40 percent. Concrete blocks are used in all countries for low trafficked areas (playgrounds, pedestrian areas) due to the ease of implementation on small areas with odd shapes and their appearance (cf. GDR). They are also used in many countries for heavy slow and channeled traffic lanes or areas (harbor bulk plants, bus lanes): Belgium, France, Netherlands, Brazil. Their usage on fast lanes is very limited.

Metal Fiber–Reinforced Concrete This is mentioned by several countries (Australia, India, Italy, Belgium) and is considered an operational technique. However, its usage remains limited in the road field. In fact, although the improvement of the mechanical characteristics has been noted, the decrease in thickness that it allows does not make it competitive. It is thus reserved for special usage, often on heavily used areas.

Concrete In general, concrete is confirmed as a material with a good resistance to wear due to spiked tires (Finland, Japan). Norway expects an improvement in its wear resistance by an increase in the concrete's resistance. It may be doubled through the use of 400 kg/m^3 of cement plus silicium additive and plastifiers.

Use of Nonreinforced Prefabricated Slabs Such use is confirmed in USSR and GDR. These slabs do not exceed 2 m length in order to curb cracks. They include a small reinforcement for handling purpose (transportation and laying). In the USSR, in order to prevent cracks, the nonreinforced slabs that are too long are cut. These cuts act as crack starters that reduce the length of the slabs to the required length.

Use of Different Concretes Laid Together After 5–13 yr experience, the United Kingdom and, after 3 yr experience, Finland confirm the good behavior of pavements made of two different concretes (laid together). In Finland, the tested cement dosages range from 110 to 250 kg/m^3, and the total thickness of the structure is increased by 2–3 cm.

Unresolved Problems: Desirable Research

It has been seen that for medium and heavily trafficked roads, the previously recommended solutions (erosion-free subgrade, extra width in certain countries, drainage, dowels) are increasingly used, sometimes even simultaneously. These solutions are adapted to the existing problem, thus maintaining the competitiveness of the structures, while integrating investment and maintenance.

For example (although it has not been mentioned here), maintenance normally includes waterproofing joints. In the case where a pavement is fitted with an erosion-free subbase and efficient drainage, is the maintenance of waterproofness absolutely required (cf. PIARC's experimental site, where the waterproofed and the nonwaterproofed sections show the same behavior)?

Among the structural dispositions mentioned, some present an easily measured and then controlled efficiency (dowels, erosion-free subbase). In contrast, the efficiency of the newly installed lateral drainage and its continued efficiency are less easy to quantify directly. It is, however, a crucial point. It is important to know the development in time of this efficiency and the precise reasons for this development, in order to optimize, if required, the retained solutions. One must note that the solutions may be different from one country to the other, if not within the same country. This represents an even more interesting data base.

These two research directions aim to prove the urgency of a common examination of national experiences in order to follow up the realized structure, a follow-up that has already been started at a national level in many countries. This could lead to a data base available to all. Why shouldn't it be possible to consider the usage of a system like that, already operational, and performing well, which has been developed in the United States (COPES)?

The question of the risk of upsurge of cracks from the hydraulic-treated subbase to the concrete wearing course is not exactly new. It remains present, however, especially when lean concrete is used. In FRG the foundation is therefore obviously preslauted.

The structures with ever shorter slabs should be watched closely, as they may be an economical way of improving behavior. Excellent operational results are reported from the United States, from Washington State and more recently from California.

Roller-compacted concrete is now a well-defined material, but questions remain on certain behavioral and technical aspects:

- *Evenness*: If the traditional equipment (grader, finisher) allows for a good evenness on low- and medium-trafficked lanes, they are not satisfactory for heavy traffic (the only unused means up to now is "autograde" with final grinding). This could lead to bituminous wearing courses, which, economically speaking, are less interesting than surface coating.
- *Behavior*: The behavior with regard to crack building seems very variable, even on a short-term basis. One can note that joints are realized (Spain: low traffic; France: heavy

traffic). The follow-up on construction should lead to information on whether this material behaves like a concrete pavement with joints, with the attached consequences (drainage, erodibility of the foundation, etc.) or like a semirigid pavement. It is most likely halfway in between, and construction procedures will have to be stated accordingly.

A general interest in concrete blocks may be noted, as well as the search for models that will allow the representation of the structures in which they are used, in order to design them. A common examination and synthesis of these efforts could lead to a statement on when to use this technique.

Subjects Proposed for Discussion by the Congress

- The establishment of a data base on the behavior of medium and heavily trafficked pavement structures;
- Extra costs linked to the different construction processes that better ensure pavement life (extra slab thickness, lean concrete, drainage, shorter slabs, dowels, concrete emergency lanes, waterproof joints, etc.) and the definition of coherent fields of application of these processes;
- Fields of application for concrete block pavements and limits of suitability for medium or heavily trafficked pavements; and
- Curbing the upsurge of shrinkage cracks from the subgrade.

MATERIALS

Examination of National Reports

The information contained in the 21 national reports received was divided into three groups:

- Questions of general interest, reported on by many countries;
- New developments from one place that should be of general interest; and
- Detailed information that may be of interest in special cases.

Questions of General Interest

Pulverized Fuel Ash (PFA)

PFA for Bases and Subbases (AUS, B, E, FRG, GDR, I) PFA, used for many years (e.g., in the United States and France), has found interest and application in a number of other countries.

Granular material mixed with PFA and lime hardens slowly and behaves initially like an unbound base. Well-graded aggregates are necessary, as well as protection against rain and frost for a relatively long time.

Mixtures of PFA and portland cement harden more quickly and can be used even for stabilizing uniformly graded sand in more severe climates. The slow hardening process of bases and subbases containing PFA is expected to result in more closely spaced cracks that are less liable to reflect through bituminous surfacings but without the inferior long-term performance normally connected with low strength mix design.

PFA for Pavement Concrete (AUS, FRG, GDR, India, NL) Considerable amounts of PFA would reduce the effect of air-entraining agents and superplasticizers and increase early shrinkage cracking, creep, and curing requirements. PFA is therefore not generally used for replacing cement in pavement concrete. The Netherlands, however, reports satisfactory test results with portland cement containing 10–30 percent PFA, both in the laboratory and in the field.

Recycling of Concrete (B, F, FRG, GDR, NL)

Crushed concrete is being used extensively for bases and subbases. If not mixed with cement, the material may be somewhat inferior to natural aggregate at the beginning, but this is usually offset by some sort of a hardening process later on.

In France, crushed concrete was used instead of coarse aggregate together with 25 percent natural sand for making new pavement concrete of satisfactory strength and durability. Problems with skid resistance were overcome by applying a surface dressing a year later.

Thin Bonded Overlays (A, CSSR, GDR, I, Japan, N)

Bonded overlays with a thickness of only 2–8 cm have performed very well in a number of countries, though they have been used only to a limited extent. To ensure a durable bond, the old concrete has to be scarified, sand-blasted, and prewetted. A slurry of fine mortar has to be brushed into the prepared concrete surface. The overlay mix is designed with a very low w/c (e.g., 0.35, using a superplasticizer) and for very small thicknesses with a suitable latex addition.

Early Opening to Traffic (AUS, CSSR, F, Japan)

Super-plasticized concrete with a w/c < 0.40, first reported by Australia and FRG, is now routine in a number of countries. Opening to traffic can be possible the same day the concrete was placed.

New Developments

Curing Compounds (A)

Superplasticized concrete and slip-formed concrete are rich in fines and therefore prone to early shrinkage cracking. Curing compounds are available that can be sprayed onto the fresh concrete surface immediately and are very effective in preventing the evaporation responsible for cracking. Another curing compound (also available in GDR) forms a relatively thick sheet that can protect the fresh concrete against damage by rain. Protective tents required by regulations in many countries have become unnecessary.

Permeable Pavement Concrete (Japan)

A latex-modified permeable concrete (with a porosity as high as 25 percent) has been used since 1983 for sidewalks, parking areas, and more recently also for low trafficked roads. The concrete is placed 8–15 cm thick by means of a normal asphalt paver on a granular subbase. Contraction joints are sawn.

Sundries

Because of inadequate compaction, slip-formed concrete performed poorly in Australia and USSR. New regulations require a high content of well-graded sand, which was also found to improve strength, durability, and the air-void system of the concrete.

In Norway (where studded tires are also used by trucks but deicing chemicals are generally not used), concrete is made very wear-resistant by choosing high-strength (75 N/mm^2, no air entrainment) and carefully selected aggregate. In a region lacking coarse aggregate, concrete made of sand only has proved satisfactory for minor roads and cycle paths.

In the Netherlands, foam concrete was used as a base on a subgrade of extremely low load-bearing capacity.

Summary and Suggestions

- PFA is used increasingly for bases and subbases but is not used for pavement concrete in general.
- Crushed concrete has been used extensively for subbases. It is suggested by the reporter that a code of good practice be drafted.
- Thin bonded cement-bound overlays perform very successfully if constructed very carefully.
- Scarifying and sand-blasting the old concrete and curing the overlay are as essential as its mix design.
- New curing compounds are available in order to protect the concrete against early shrinkage cracks. Spray-on sheets for protecting fresh concrete against rain are also obtainable.
- A permeable pavement concrete has been used successfully in Japan for sidewalks, parking areas, and minor roads. Further development is highly desirable.

CONSTRUCTION AND CONTROL

Examination of National Reports

New Equipment and Construction Methods

Placement of Conventional Concrete The use of slip form pavers for roads of any type and width is being adopted increasingly. Various countries (Belgium, Brazil, France, Poland, Switzerland, and the USSR) reported on their successful use. A slip form paver of a width of 15.25 m has been employed for the first time in the Federal Republic of Germany. Austria is also envisioning slip form pavers of up to these widths. The construction of concrete paving by means of slip form pavers has been developed so far that it has been possible to overcome defects occurring due to structural measures. Thus the USSR reported on an edge design of slabs with reinforcement ensuring sufficient evenness of adjoining strips made by slip form pavers. Satisfactory results are obtained with a single-layer placement of up to a thickness of 30 cm; two-layer placement is selected for thicknesses exceeding 30 cm (USSR).

The incorporation of dowels and anchors causes no difficulties (Federal Republic of Germany, Belgium, France). Continuously reinforced paving can also be made by means of slip form pavers (France). The construction method with slip form pavers may be better than the construction method with multipart paving trains (Austria). A special form work used for multipart paving trains has been developed by Belgium.

Dowels are either fixed on the base course with the aid of dowel baskets or directly vibrated into the fresh concrete. A device for vibrating joint nicks into the fresh concrete has been developed in the German Democratic Republic. The results, as well as those for completed pavings, are satisfactory. In the case of the slip form construction method, it has also been possible to discover methods for placing foils to separate concrete in longitudinal joint areas (France).

Placement of Rolled Concrete Spain, Norway, Poland, and Sweden report on roller-compacted concrete (RCC). The Swedish and Spanish reports describe concrete engineering prerequisites and placement techniques in detail. Rolled concrete, that is, with a very low water content, can be placed in thicknesses of up to 25 cm by means of simple spreaders, for instance graders or bituminous mixture finishers, and compacted by flat steel rollers. Precompaction by means of the bituminous mixture finishers tamping or vibrating beams will reduce the use of rollers. The operating speed ranges from 1.0 m/min (Sweden) to 1.5 m/min (Belgium). The concrete is immediately capable of bearing wheel loads. The evenness achieved depends considerably on the uniformity of composition and particularly on a constant water content. Joints are either nicked into the fresh concrete (Spain) or the concrete is permitted to crack at random, since a few cracks occurring will not impair the quality of the layer (Sweden).

Concrete with Special Properties

- *Composition of Concrete for Low Temperature*: Concrete work has had to be carried out at –5°C for operational reasons in Austria. High–early strength concrete with plasticizer has been successfully used for this purpose. Mixing water and aggregates have been heated. The surface has been covered in a way that an air cushion has provided adequate protection from cold weather.

- *Vacuum Treatment of Concrete*: The vacuum treatment of concrete has been tested in the Netherlands. The vacuum concrete's adhesion to the supporting medium and its bond are better than those of conventional concrete. Vacuum concrete is also less susceptible to the attack of natural weathering agents. The additional cost is compensated for by economies in other areas.
- *Facilitation of Concrete Placing Methods with Addition of Pulverized Fuel Ash*: Romania reports on the addition of pulverized fuel ash to concrete, considerably improving the fresh concrete's workability with otherwise equal qualities.

Provisions for Slab/Support Interface

On the one hand, achieving a bond between the concrete paving and the hydraulically bound supporting medium is attempted but, on the other hand, it is deliberately interrupted. Thus the reports from France and the Federal Republic of Germany refer to the use of layer textiles separating the bond between the concrete paving and the supporting medium, while also causing drainage of the water that has penetrated through the concrete paving's joints.

In Poland, a separating diaphragm between the concrete paving and the supporting medium is selected in the form of polyethylene sheeting. However, this type of sheeting has not proved suitable in Australia for reasons of climate, but rather asphaltic emulsion or penetration-grade asphalt filled with mineral matter is employed for continuously reinforced concrete paving (CRCP), and polish emulsion is used in the case of nondowelled concrete paving, so that cracking will occur at the spacings desired in each case.

Dowels, Placing Methods, and Tolerances

Dowel and anchors are either placed on dowel baskets, which, in turn, are immovably connected to the base course, or they are vibrated into the fresh concrete. For constructing concrete pavings, slip form pavers have been developed so that the equipment does not need to be stopped for incorporating dowels (Federal Republic of Germany, Belgium, Spain). Spanish investigations have shown that dowels fulfill their functions if their ends do not deviate more than 15 mm from their theoretical locations. The Federal Republic of Germany and Switzerland refer to investigations according to which dowels can be placed into their final positions with sufficient accuracy. The Australian report emphasizes that the difficulties encountered in accurate incorporation of dowels have led to concrete pavings with no or only few dowels.

Methods of Achieving Evenness and Surface Texture, Performance

Evenness Proper evenness is obtained by expedient and constant concrete composition and by steadiness of placement by conventional multipart equipment and slip form pavers. Reference has been made to this by the German Democratic Republic, Australia, Belgium, Spain, and the USSR. Uniform concrete consistency and uniform conditions of placement are primarily important for the slip form paver construction method. The United Kingdom and the USSR reports especially deal with these questions. In the Swedish report, reference is made to questions of evenness in rolled concrete construction; two-layer placement might become necessary. The Japanese report describes a newly applied method for attaining sufficient evenness of concrete pavings in railroad tunnels.

Texture Various contributions on how to achieve an adequate texture that promises a lasting skid-resisting property have been submitted. The freshly placed concrete surface is provided with the texture desired by means of brooms, burlaps, and plastic grooving (Australia, France, India). The texturing of surfaces with the acid of chemical agents is described in the French report. This, however, requires sufficiently hard aggregate in the top course concrete. Sands that are resistant to polishing and that are still supposed to maintain adequate skid-resisting properties when the superficial mortar layer has been worn out by traffic are used in the Federal Republic of Germany. Subsequent texturing is possible by cutting grooves (Federal Republic of Germany) or by the milling of rolled concrete (Sweden).

Control Methods, Equipment, and Control Tests During Construction

Control of the fresh concrete composition is important for the quality of the hardened concrete and finished concrete paving. The analyses apply to the individual ingredients of concrete and its properties (German Democratic Republic). It has been possible to indirectly ascertain the fresh concrete's consistency with the aid of the mixing machines' power consumption (Belgium). Data processing systems are used to collect the properties of materials and also of the vibrators' power requirements and the finishers' operating speeds (France). Concrete compaction can be carried out with the help of radiometric measuring instruments (Australia). The Polish testing program includes full testing of concrete and finished concrete paving and of random samples taken at a minimum of one-fifth of every stretch of road. The Swedish report gives extensive instructions for checking rolled concrete.

Nondestructive methods, with their advantages and disadvantages, as well as their accuracy for determining the location of dowels, have been investigated in detail in the United Kingdom. Australia also reported on them. Brazil is now conducting nondestructive tests for controlling the concrete paving to be constructed and the hardened concrete paving. The Indian Central Authority for Public Structures has worded acceptance criteria for cracks.

Conclusions

Progress Made

The use of slip form pavers for constructing high-grade, even, and nonskid concrete pavings for heavy traffic is quite possible. A prerequisite, however, is a sufficient design of mixing installations capable of producing amounts of concrete to permit continuous operation of slip form pavers. Dowels can also be vibrated in subsequently without interrupting the slip form paver's travel.

Rolled concrete construction is simple, involving a technique perfected in its type. However, rolled concrete is very sensitive to fluctuations in consistency. Dowels can be vibrated into their final locations with sufficient accuracy. Sufficient evenness can be achieved by placing concrete in the usual way or by using slip form pavers, if the technical machinery requirements are met. The usual texturing of the freshly placed concrete paving's surface will result in adequate skid resistance.

Unresolved Problems

Although rolled concrete construction is simple, the conditions under which it constitutes an economical construction method should be ascertained. The economy of continuously reinforced concrete pavings (CRCP) as compared with unreinforced concrete pavings has not been sufficiently commented on. Maintaining consistency is important for achieving a sufficient evenness. Methods for continuous, simplified, and fast checking are missing.

Desirable Research

Research should deal with the concrete quality for mixing and placing in order to obtain adequate information on the quality to be expected of the hardened concrete paving. This comprises influencing concrete composition, mixing installations, and laying machines. Pertinent testing procedures exist to some extent or are still to be developed. Further research is required on the necessity of separating concrete pavings from or bonding them to subjacent layers.

The use of different types of concrete pavings, such as unreinforced concrete pavings, continuously reinforced concrete pavings (CRCP), or the use of conventional concrete and rolled concrete should be investigated from the economical viewpoint. Research should show from what viewpoints the individual types of concrete paving are selected.

Subjects Proposed for Discussion at the Congress

- Ascertainment of the fresh concrete's quality with regard to the finished concrete paving.
- Nondestructive testing procedures applied to newly finished concrete paving with regard to the possible direct improvement of properties.

MAINTENANCE AND REHABILITATION

Examination of the National Reports

Maintenance Strategies, Pavement Condition Assessment, Nondestructive Monitoring, Intervention Threshold, and Costs

Austria This report considers not only road pavements but pavements for container freight traffic. For operational reasons, repair of concrete pavements must be simple and quick to perform.

Belgium The Roads Administration carried out systematic surveys of state roads on a regular basis (2–4 yr) to afford a rational management of the road system. Surface evenness, skid resistance, stepping, and faulting are measured on a routine basis, together with visual inspections of the road system.

Brazil The maintenance and rehabilitation program is based on pavement inspections.

Czechoslovakia Because maintenance, repairs, surface renewal, and reconstruction operations impose considerable demands on resources, the development and use of computer models have been initiated. Serviceability of airfield runways is being assessed using multicriteria techniques.

France Maintenance strategies are based on pavement condition surveys. The systems used include GERPHO (photographic survey), APL (longitudinal profile analyses), SCRIM (friction coefficient), DMDB (slab pumping), and COLLOGRAPHE (load transfer).

Federal Republic of Germany Since 1980 a pavement management system has been under development and use. The assessment of concrete roads is currently based on visual measurements and inspections, together with operational reports. Problem diagnosis has proved to be a difficult subject, and further research is necessary. A detailed survey of a motorway in Lower Saxony is reported.

In Lower Saxony the whole Federal 47 motorway has been evaluated. A systematic random sample of 10 percent of the whole area has been examined for crack length, crack width, edge and corner fractures, stepping at joints or cracks, foundation state, and surface condition.

German Democratic Republic Pavement condition is assessed using a practicability meter (BM2). Details of intervention thresholds are given. These data supplement visual surveys.

India Pavement condition is assessed by defect survey and deflection tests for structural capacity. Maintenance cost yardsticks have been evolved. Nondestructive testing and functional evaluation measurement are undertaken.

Netherlands A brief description is given of the use of a visual inspection system for concrete pavements and the evaluation connected with it.

United Kingdom Strategies adopted for the maintenance of concrete roads may be either reactive or proactive, although the latter is considered to be the better long-term approach. If concrete roads need major repairs, a number of different options are available, and in order to make the most effective use of expenditure, the whole life costs of these options should be evaluated. Two items of equipment which may be of assistance in the condition of concrete road pavements are the High-Speed Road Monitor and the Falling Weight Deflectometer.

Maintenance Methods and Techniques, Local Repairs, Resurfacing and Retexturing, and Long-Term Assessment

Belgium Experimental full-scale work has shown that surface dressing provides effective protection for concrete pavements subject to scaling. A 5–8-year life is estimated, depending on the type of binder used. Deep transverse grooves (4 mm) have been used at 19-, 25-, 31-, and 37-mm spacing pattern to retexture old surfaces.

Czechoslovakia Stress analysis has been used in models describing thin (3–10 mm) overlays bonded as a surface renewal.

France Surface dressing is used on concrete road pavements. A life of 7–8 yr is obtained with a traffic level of about 35,000 vehicles a day (15 percent heavy vehicles). Reconstruction work has been undertaken since 1976.

Federal Republic of Germany Treatments to surfaces include sand (and steel) jet (blasting), flame jet, milling, and groove cutting to improve the surface characteristics. Each method displays a different long-term effect. The application of surface layers up to 1 cm thick in the form of coatings containing cement or resin mortar or bituminous protection layers is used to improve surface characteristics.

Preventive maintenance is considered in addition to normal maintenance. A Code of Practice includes joint and crack filling, edge damage repair, dowelling and anchoring cracked or displaced slabs, supporting slabs, improving drainage, treating surfaces, impregnating, applying surface layers, and renewal by various methods.

German Democratic Republic The careful maintenance of joints takes precedence. Defects shown on short sections of road pavement are often due to local features or construction errors.

For local repair of surface damage, the use of thin coatings is employed. The report details the treatment method.

India Equipment has been developed for the correction of settlement using jacking techniques. Resins are used for local repair work to surfaces and edges. A study of resins has been undertaken.

Japan Precast, prestressed concrete slabs have been used to replace old concrete tunnel paving damaged by studded tires. A unique method of placing dowels and tie bars was used. Details are reported.

Italy A concrete road built in 1971 has been treated for joint faulting by milling the surface, rocking slabs have been replaced, and drainage has been provided along the shoulder.

Netherlands A description is given of a method developed for the very rapid renewal of broken slabs in an unreinforced concrete pavement. Prefabricated units are used for this cost-competitive system.

Norway A new strategy for maintenance of concrete pavements has been introduced. Pavement thicknesses are increased by 30–70 mm, depending on traffic volume. When rutting (due to studded tires) develops, the surface is restored by grinding. Thin overlays reinforced with steel or plastic fibers have been used.

Spain A report is given on the rehabilitation of a pavement that has undergone premature degradation as a result of improper design and construction.

Switzerland During the rehabilitation of parts of the runway at Basle-Mulhouse, a concrete with a tensile (flexure) strength of 3 N/mm^2 at 5 hr was used to speed the opening time. The runway repair work was trafficked by aircraft after this short hardening time.

United Kingdom The Department of Transport and the Cement and Concrete Association have jointly produced a *Manual for the Maintenance and Repair of Concrete Roads.* The manual is a practical guide to those engaged in maintaining all types of concrete roads, from motorways to minor roads, in a good serviceable and structural condition.

USSR One method of preventing concrete road scaling is the use of a hydrophobizing liquid applied as a water emulsion. The reported treatment also increases the corrosion resistance of concrete test specimens.

Overlays on Old Concrete Pavements

Belgium Between 1982 and 1985, seven experimental sites were constructed for thin overlays, amounting to a total of 137,000 m^2, of which 104,000 m^2 was in concrete reinforced with steel fibers and 33,000 m^2 in thin CRCP. Details are reported.

Brazil Studies have been started to assess the behavior of several rehabilitation solutions. These include bonded, part bonded, and unbonded options.

France Total pavement costs are determined, including maintenance and traffic disruption, before selecting the type of overlay. Very high work output is then required. For example, an 18-km two-lane overlay completed in 6 weeks; a 30-km overlay and widening to 3 lanes completed in 7 weeks.

Federal Republic of Germany Rehabilitation techniques using bituminous construction have been used satisfactorily. Concrete overlays are an accepted method today.

German Democratic Republic Overlays are an economical method of rehabilitation. Use is made of direct overlays (the parameters are reported), as appropriate, and overlays with leveling courses. Old slabs are reduced to pieces 1.5–2.0 m edge length and support conditions made reliable. Leveling courses (BK 12.5) can vary between 80 and 250 mm in thickness. They are provided with joint notches to correspond with the new concrete pavement joint module or a separating layer to avoid unwanted reflection cracks.

India In general, concrete overlays have not been used.

Japan Bonded overlays to concrete pavements currently involve slab milling (2–3 cm). The surface is then generally steel shot–blasted. A bond coat (epoxy or cement) is used, and the overlay concrete is spread, compacted, and finished. Joints are matched over old joints. The pavement is generally opened to traffic after 5–7 days' curing. In-service performance is being assessed.

Italy Thin (3–4 cm) bonded overlays are used, particularly on airport pavements. Concrete with a 25 N/mm^2 compressive strength is used. A shear (bond) strength of 2–3 N/mm^2 is needed. Good curing and temperature control is also essential.

Concrete Overlays on Flexible Pavements

Belgium Two thin CRCP overlays have proved to be satisfactory. Details are reported. The tests have shown the importance of strict thickness control. Variations have important effects on crack pattern. A longitudinal reinforcement requirement of 0.60 percent appears to give the test results.

France The overlaying and strengthening of flexible pavements by means of a hydraulic concrete slab can involve the use of either a rolled concrete or traditional vibrated concrete. Rolled concrete has been in use since 1976, and the technique practically allows the work to be performed under traffic. The traditional concrete overlay dates from 1976 also, but local roads were treated as long ago as 1973. Overlays on old concrete pavements tend to be CRCP. High-output paving is the normal target for such work; for example, 30 km of 3-lane overlay completed in 7 weeks.

Federal Republic of Germany The renewal of concrete carriageways should be carried out using concrete methods without removing the existing subgrade. This is an accepted method today.

The Netherlands The results are given of an in situ investigation into the behavior of concrete overlays on an asphalt paving. Two test sections were built in 1977, one using 21-cm unreinforced concrete with unsealed transverse joints and the other using 16.5-cm CRCP.

Romania Concrete overlays (18–20 cm thick) have been used for heavy and congested road strengthening.

United Kingdom Some rust staining has been observed on a continuously reinforced concrete road after only 6 yr of service. In case corrosion of reinforcement in this type of pavement does become a problem, a trial of epoxy-coated reinforcement has been incorporated into a 225-mm-thick continuously reinforced overlay that has been constructed to strengthen an existing bituminous pavement.

Drainage of Existing Pavements

Belgium Porous cement concrete was first used in 1979. Since that time it has been used in hard shoulders and as overlays and new pavement construction. The proportions of the best mix (15-MPa compressive strength at 28 days) are reported.

France Effective drainage is essential for any pavement. Work is undertaken to provide older roads with good drainage if this provision was not included initially.

Federal Republic of Germany The improvement of pavement drainage is a part of the standard maintenance system. Studies by the Federal Institute of Highways (BASt) have shown that premature pavement damage was nearly always due to water penetration into the pavement structure. In recent years the improvement of drainage on existing roads has also received increased attention. This involves sealing edges, improving runoff, and the provision of retrofitted drainage systems.

German Democratic Republic The need for pavement structure drainage has long been accepted. Experience shows that clogging of drains is a problem, especially when filter layers have been inadequate.

Recycling of Pavement Concrete

Belgium A study has been undertaken of crushed road concrete aggregate as an unbonded base material. Recommendations are reported.

Federal Republic of Germany In the past, when the renewal of roads involved the removal of the existing material, the broken old pavement was considered rubble that was subject to disposal. More recently, increasing attention in concrete road construction circles views this material as reusable after suitable treatment. Several contracts on the Federal A7 motorway have already used recycled concrete. Old concrete is broken, crushed, and processed as a 0/45-mm mineral mixture that is spread and hydraulically bonded (stabilized) in situ.

German Democratic Republic Recycling is used now more than ever before, and the method is important. Old concrete is crushed (0/60 mm) and used for hydraulically bound road bases.

India Studies have been conducted on the use of crushed concrete as recycled aggregate. Accepting a loss of strength, compared with a conventional aggregate concrete, a cost economy of some 3 percent is still attainable.

Conclusions

Progress Made and Points That Can Be Considered as Established

- The need for pavement conditions survey work and a central data base appears to be an accepted goal.
- The need for pavement maintenance intervention thresholds and the establishment of maintenance strategies is generally accepted.
- The prevention of water ingress into pavement structures is an important design and maintenance requirement.
- The value and reliability of concrete overlays (thick and thin) over old concrete and flexible pavements continues to increase. This form of treatment is now widely accepted.

Unresolved Problems and Desirable Research

- Although it is essential, few countries have a central pavement condition data base. This would be more readily introduced if cheaper and quicker survey systems were available. Photographic (including video) and other automated electronic pavement condition assessment systems need further research and development.
- The retrofitting of effective drainage provisions for existing road structures requires further research.
- Detailed technical and economic studies are needed to identify the full potential of concrete pavement recycling options.

Congress Discussion: Proposed Subjects

- The establishment of a central pavement condition data base, problems and solutions, access to data and data use;
- State of the art covering concrete overlays to old concrete and flexible road pavements;
- Concrete pavement recycling; and
- The role of roller-compacted concrete for pavement rehabilitation work.

SUBBASE AND ROAD BASES TREATED WITH HYDRAULIC BINDERS (CONCRETE PAVEMENTS AND SEMIRIGID PAVEMENTS)

Examination of the National Reports

Such layers have assumed great importance in the subbase and base courses of heavily trafficked roads and motorways, both under concrete and bituminous pavements in rigid and semirigid pavements, respectively. This is evident from an examination of the reports in this section of this Question.

In Australia, to avoid cracking of the layers treated with hydraulic binders, curing methods are adopted that protect them from changes in temperature, especially during the night. Second, between the subbase and the subgrade, a bituminous layer roughened by means of chipping is adopted, so as to increase friction between these layers.

In Belgium the Road Research Centre has experimented in the laboratory and in situ the use of PFA and lime mixtures as a subbase course and adding 0/20 mm aggregates as a base course. The setting time of these binders is much slower than the corresponding setting time of cement mixtures. This is an advantage, but they require protection from rain and frost early on. On cores, compressive strengths from 2.8 to 4.0 MPa and tensile strengths of 0.2 to 0.4 MPa with moduli of 3,000 to 4,000 MPa have been obtained. In the long term, strengths of 15–17 MPa and 1.3–1.5 MPa, respectively, have been obtained. Lime content greatly influences the resistance.

In Brazil, lean concrete is the most frequently used material for subbase layers in portland cement pavements subject to heavy traffic or resting on poor soils.

In France, because the subbase layer of portland cement pavements for heavy traffic roads is made of lean concrete without joints, the problem arises that such layers should not crack, or should crack only slightly, to avoid reflection cracks in the young concrete pavement. This result is obtained by limiting the flexural strength to 2.5 MPa and consequently the value of the modulus.

The erodibility of material used in subbase layers, following the data published in previous Congresses, has continued to be the object of study. Five classes of erodible materials and three types of drainages (depending on traffic and climate), have been established and are reported in Table 2 of the report.

The German Democratic Republic employs sand cement base course layers with cements having a high pulverized fuel ash PFA content; 7.5 to 12 N/mm^2 strengths are thus obtained. Good results have also been achieved by using, as aggregate 0/32 mm Siemens-Martin slags.

In the Federal Republic of Germany, subbase layers treated with hydraulic binders are built without joints, provided that a network of fine cracks can be obtained so as to assure a good load transfer across cracks. This can be achieved by requiring a 28-day strength not over 12 N/mm^2. This is sufficient when the thickness of the layer is 150 mm, which is the normal case. When the thickness exceeds this value, transverse crack inducers are necessary. Such crack inducers are also required whenever the compressive strength is higher than the above-mentioned value or when the bituminous cover is less than 140 mm. The distance between such crack inducers should be less than 5 m, or even 2.5 m if the bituminous layer is thin. The aggregate is generally of high quality and is mixed in plant and laid by means of a finisher.

The use of natural marginal aggregates, with friable grains, has been studied, as well as aeolian sands, industrial byproducts, and garbage waste materials. In such cases the frost resistance should be assessed when the percentage of fines passing the 0.063 mm sieve is higher than 5 percent. When laying it is advisable to compact at a water content below Proctor optimum if the material is coarse grained and above optimum if it is rich in fines.

In Lower Saxony, good results have been achieved using recycled concrete aggregate mixes. The material laid on the subgrade is penetrated in situ by a cement mortar. This allows a draining layer under the hard shoulders to be obtained. All these requirements are stated in *ZTVT Standard St6-86*.

In India, the adoption of semirigid technologies has given complete satisfaction. Base bound layers are replacing unbound layers more and more.

In Italy, an experimental study on a mixture of gravel, PFA, cement, and lime has made possible the establishment of the fatigue curve of the material. The modulus varies between an initial value of 4.000 and a final value of 2.000–2.500 N/mm^2.

In the Netherlands, two new procedures of construction have been experimented with to reduce reflection cracking. The first one consists of laying the bituminous pavement layer immediately after compaction of the sand cement base course layer, without waiting for initial setting. The second is to open the lean concrete base course layers to construction traffic as soon as possible. A new material, foam concrete, has been experimented with as a foundation material in road pavement structures. It is a concrete containing air bubbles and having a mass density that can be varied between 600 and 1 800 kg/m^3, as required. In a series of diagrams the mechanical resistance and the moduli of the material are given in relationship to the mass density. The advantages of the use of such a material in pavements built on compressible soils of lower bearing capacity have been assessed.

In the Saragossa region of Spain (because of the very high summer temperatures), to avoid reflection cracks in the concrete slab, below this and the base course, it was necessary to provide a sheet of polyvinyl to ensure complete separation between the layers. In another case in the lean concrete of the base course, covered by only 12 cm of bituminous concrete, a special cement composed of 80 percent PFA and 20 percent clinker has been used. The mechanical resistances obtained have been entirely satisfactory (17 MPa on cores at 28 days), and a greater ease of compaction has been achieved.

In the United Kingdom an exhaustive study concerning reflection cracking in semirigid pavements has been performed by a working group of the Road Research Laboratory and the Cement and Concrete Association. This group has examined more than 700 km of heavily trafficked lanes, opened to traffic since 1960, and the conclusions that have been reached are the following. The percentage of pavements affected by this type of cracking, both transversally and longitudinally, is not very relevant; at least 50 percent of the length of lanes examined have cracks and only 5 percent have close cracks. On the other hand, very few cement-treated base course layers have been subject to complete repair.

Only a third of the pavements open to traffic in 1971 composed of a base course layer 175 mm thick and covered by a bituminous concrete layer of equal thickness, with a traffic of 20 million standard axles, have needed structural repair. These conclusions have served to place the problem in perspective.

Important technical conclusions have been the result of such a study. First, it is not possible to predict the probable life of a pavement on the basis of transverse cracks, and second, that it is advisable to use very resistant cement-treated layers together with thick bituminous layers.

In the Soviet Union, a particular type of structure is used for road bases. This is a layer, 15 to 25 cm thick, of crushed aggregate, penetrated from the surface for a depth of 25 to 75 percent of its thickness by a mixture of sand cement which, in some cases, is mixed with the upper part of the aggregate. An appreciable reduction of road base thickness is thus realized, as well as other technical and economical advantages.

Conclusions, Trends, and Innovations

From the examination of the papers presented, it is evident that composite pavements, having a base or subbase course layer treated with hydraulic binders, continue to be universally employed with success, although differences in the techniques applied in various countries are evident. It is undeniable, however, that as more time elapses, this type of structure continues to reveal its aptitude to support very heavy and intense traffic.

The problem of transverse cracking, which reflects itself on the surface due to shrinkage and thermal stresses, which are considered inevitable, is a concern to all those who adopt this type of pavement but in different measure. Some use low-shrinkage cements (with a high content of fly ash) or even setting retarders. Others place crack inducers under the layer when there is an obvious tendency toward erratic and wide cracks. Others insert a layer of unbound aggregate or a plastic foil over the bound layer. Others promote microcracking by delaying compaction. However, an extensive and exhaustive study, performed by TRRL and the Cement and Concrete Association in the United Kingdom, has shown that such cracks should not be a major concern because they are not related to the beginning of the end of the service life of the pavement, which can continue to be efficient for many years. Naturally, this is true if the pavement design is correct, that is, if the thickness of the bituminous layers is adequate (not less than 120–200 mm thick). Otherwise the pavement life will be short. On the other hand, the appearance of longitudinal rutting and cracking is a sign of the end of the pavement life.

Whether it is necessary to seal transverse surface cracks depends on the climate, the water sensitivity of the lower layers, and crack width. In many countries, cracks are left unsealed; in others a procedure called "crack bridging" is successfully and economically adopted.

Innovations include the use of marginal and waste aggregates (the former, however, not yet on an operative scale). France has systematically introduced the evaluation of erodibility measures on the treated layer when this is laid under a concrete pavement.

The Soviet Union is currently adopting the system of constructing the layers by penetrating the uncompacted aggregate from the surface with a mortar of sand and cement. This is a revival of the "cemented macadam" pavement proposed many years ago.

An interesting question that will be examined and discussed at the workshop dedicated to composite pavements at the next Brussels Congress is the convenience of hydraulic bound layers in local low trafficked roads. A different point of view is expressed by those who rely on theoretical design methods (Belgium) and those who rely on experimental methods (United Kingdom). It is hoped that the participants in this workshop will be called on to express an opinion on this subject.