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 km² (~195,000 mi²), 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):

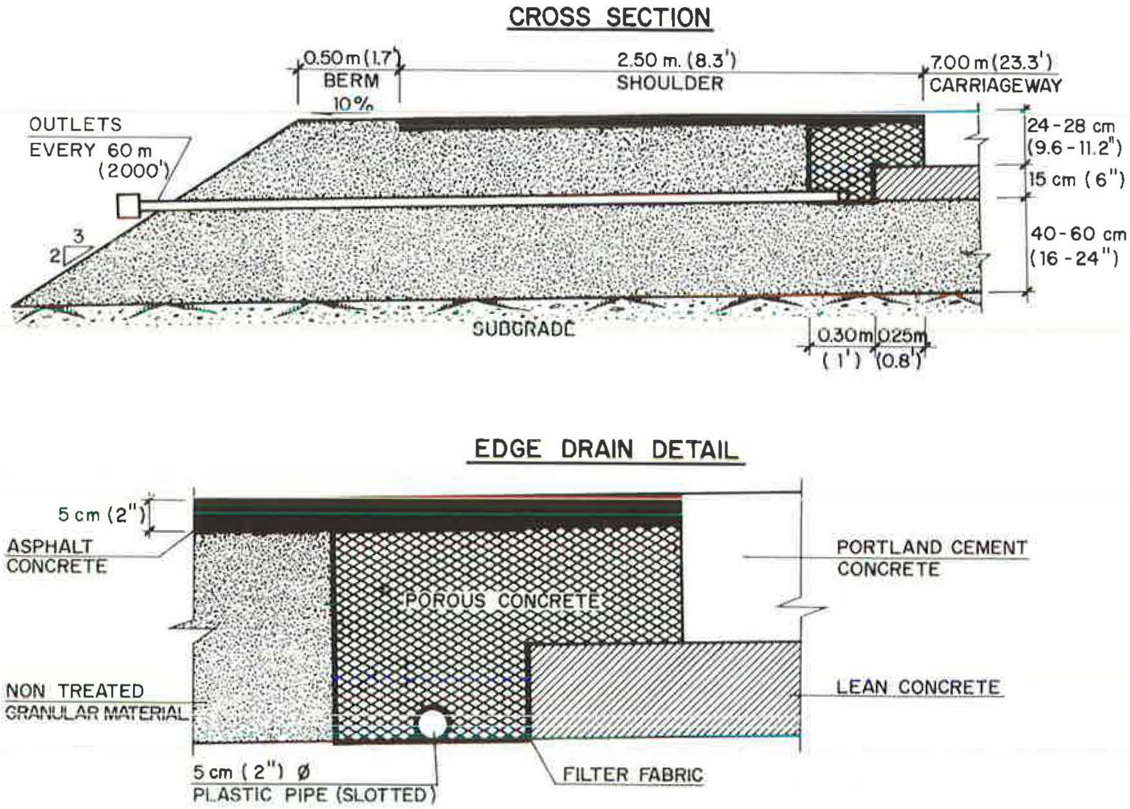

FIGURE 1 Pavement drainage, Tarragona-Valencia-Alicante motorway (Jeresa-Ondara section, 1985).

- 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.

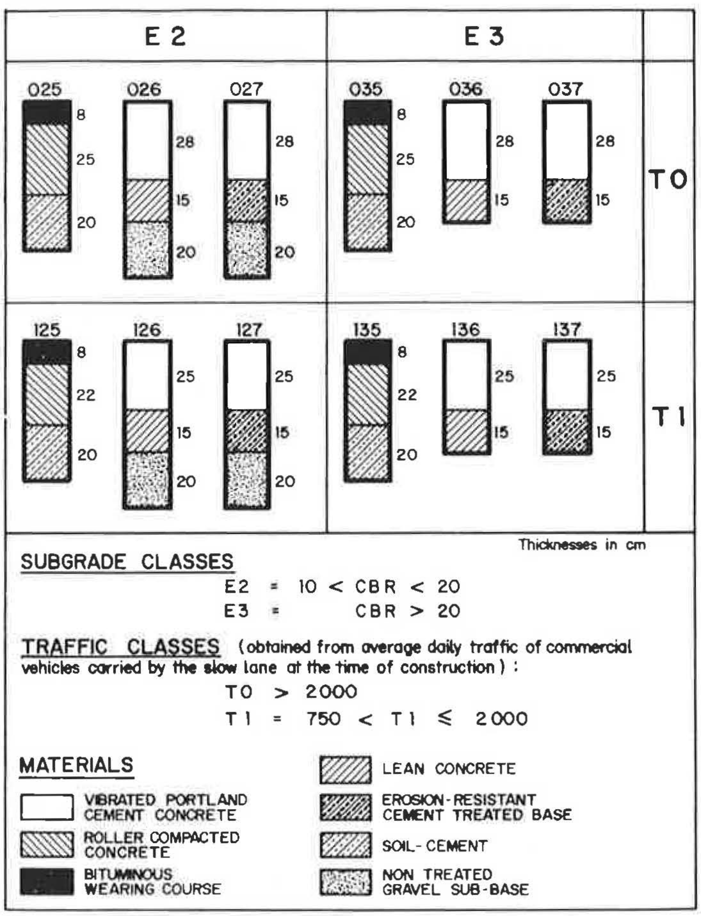

FIGURE 2 Structural sections of pavements with layers of vibrated or rolled compacted concrete (*7*).

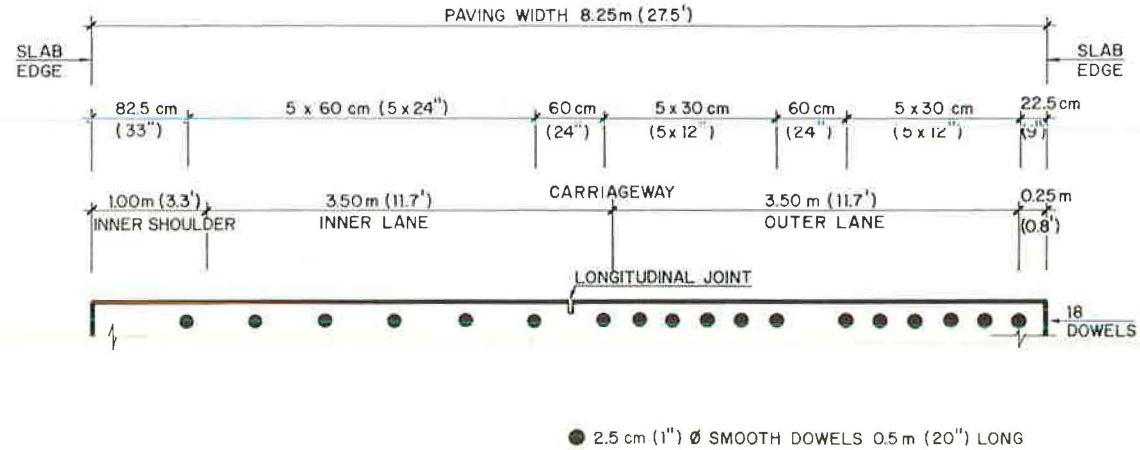

FIGURE 3 Dowel distribution at joints of concrete pavements (*7*).

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

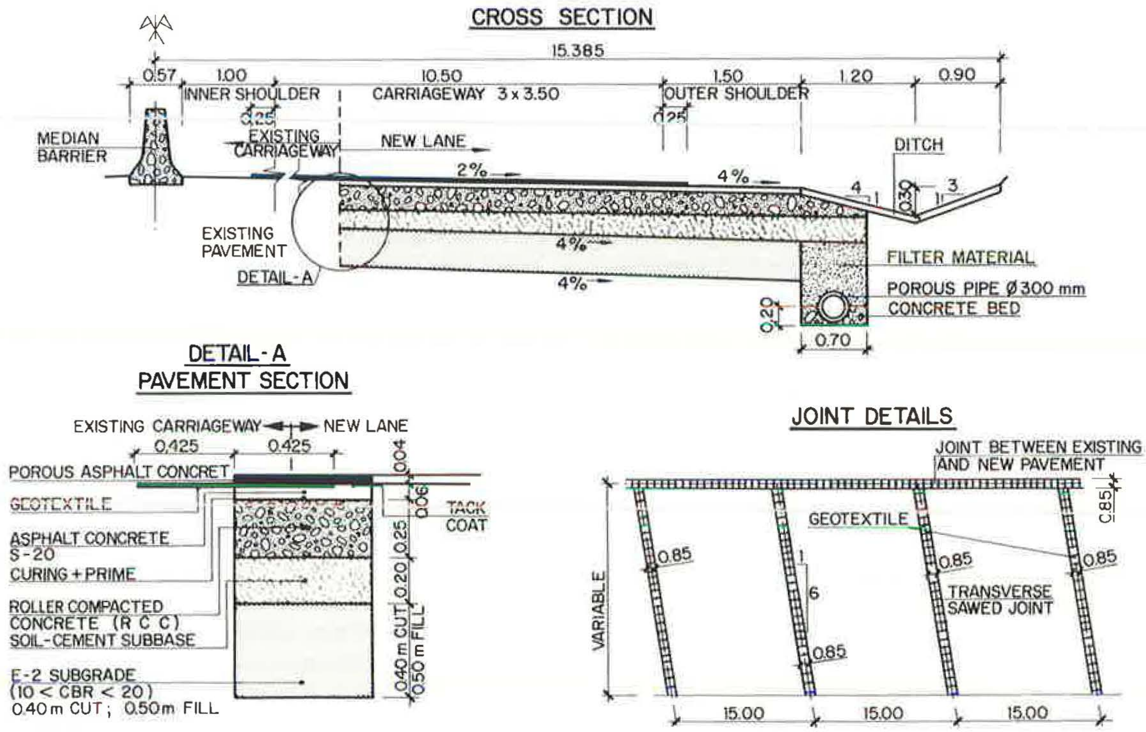

FIGURE 4 Use of rolled compacted concrete in dual-carriageway roads: addition of a new lane to the existing carriageways (National Road IV, Villaverde-Seseña section, 1987).

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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