# RCC PAVEMENTS IN SPAIN

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This paper deals with the design, construction and performance of roller compacted concrete (RCC) pavements in Spain.

The first known applications of RCC pavements in Spain took place around 1970. They were mainly pavements subjected to light traffic, located on housing developments, urban streets and rural roads.

A broad experience with RCC pavements has also been gained since 1984 in main highways and freeways, including new roads, strengthening stretches, rehabilitation and widening schemes.

From the experience acquired conclusions have been reached regarding different aspects of this technology: design standards, materials, mix manufacture, construction and control procedures during the work.

In the paper those aspects of the design, construction and performance of RCC pavements that concern the Spanish experience are described.

## 1. INTRODUCTION

The Spanish road network at present extends for 315,000 km (195,000 ml), of which 23,000 km (14,000 ml) form the State network under central Government management. The length of motorways is slightly more than 2,100 km (1,300 ml), of which 350 km (220 ml) have concrete pavements. One of the basic objectives of the Government's Road Plan for 1984-1991, which is in the course of implementation, is to upgrade more than 3,200 km (2,000 ml) of the trunk network to dual carriageway (expressway) standard.

In 1986 the Directorate-General of Roads published (1) an "Instruction for Expressway Pavement Sections" with the purpose of unifying the technical criteria used in the construction of the aforementioned expressway conversion program. The existing standards (6.1-IC and 6.2-IC, (2)) were published in 1976, and apart from being outdated in some respects, failed to contemplate the heavier traffic that would predictably be carried by such an expressway. The new "Instruction" deals with two traffic categories: T0, when the number of commercial vehicles/day on the design lane is over 2,000 during the first year of operation; and T1, when this traffic load is between 2,000 and 800. The "Instruction" includes pavement sections with asphalt concrete (AC) on a granular or cement treated base; with vibrated concrete; and with roller compacted concrete (RCC) covered with an AC wearing course, these being included for the first time in a Spanish official standard. Moreover, in the revision of the above-mentioned Standards 6.1-IC and 6.2-IC, which will be issued in 1989 covering all categories of traffic, RCC will also be considered.

It is important to say that many techniques succesfully developed in other countries require substantial modification before they can be succesfully applied in Spain due to the combination of the high legal limit for axle loading in Spain (13 t, 28.6 kips) and the extreme climatic conditions in the greater part of the country.

## 2. HISTORICAL DEVELOPMENT

As is well known, RCC is a mixture of aggregates, water and a binder, poured on site in the same way as a cement treated base, although the cement content is similar to that of vibrated concrete.

The use of RCC in Spain is now increasing due to some of the advantages that can be obtained with this material (3). One is the fact that it does not require any special equipment, since until recently there were only a few contractors suitably geared to construct quality vibrated concrete pavements. Another is, mainly bearing in mind its use in overlay works, the fact that RCC pavements can be opened to traffic immediately after completion as a result of the high stability achieved by the mineral skeleton formed by the aggregate once the material has been compacted. This eliminates one of the major disadvantages of the use of vibrated concrete for overlay purposes, which is the need to keep the finished stretch closed to traffic for a certain length of time. Furthermore, the stability of the mineral structure allows binders to be used with higher active addition contents than is usually the case with vibrated concrete pavements.

Obviously, the compacted concrete technique also has some limitations at the present time. The most important is, perhaps, the surface evenness achieved with the existing spreading and compacting procedures, which makes it necessary, with heavy traffic at high speeds, to add either a wearing course several centimeters thick made of AC, or, at least, a surface treatment to provide a suitable non-skid finish since the compacting rollers produce too smooth a finish. Only in low traffic roads has the concrete surface been left exposed, though with a textured finish obtained by mechanical trowelling. Another problem arises from the fact that the strength of the material is highly sensitive to loss of density if the compaction process is faulty. For this reason it is necessary to ensure that this operation is carried out energetically with a sufficient number of passes of the rollers and that the densities required are carefully controlled. The degree of moisture during pouring must also be checked to avoid either an excess of water or the material's drying out.

The first known applications in Spain took place around 1970 (4,5). They were mainly pavements subjected to light traffic, located on housing developments, urban streets and rural roads (Fig. 1). The

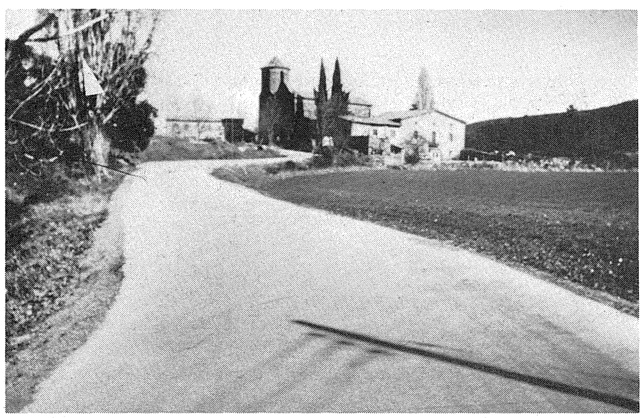

Fig. 1. Low volume road paved with RCC

technique was empirically developed by small local contractors who, through the experience obtained, (until now more than 4 million square meters laid), have achieved a technology totally adequate for those types of roads (Fig. 2 to 6).

A wide experience using RCC has also been obtained on roads carrying heavier traffic (3,6,7,8). It is estimated that at the present time 600,000 sq.m (700,000 sq.yd) of road surface have been built with RCC both for new construction and for the widening, strengthening or improvement of existing roads. During the spring-summer of 1987 the first stretch

Fig. 2. Construction of RCC pavements for low volume roads: spreading with motor grader

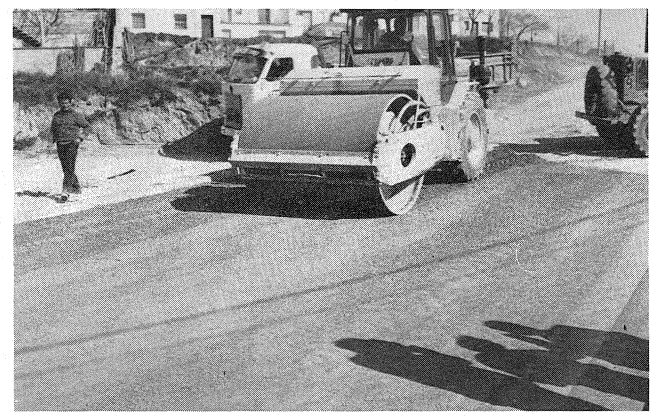

Fig. 3. Construction of RCC pavements for low volume roads: compaction with smooth drum vibratory roller

Fig. 4. Construction of RCC pavements for low volume roads: texturing with power trowels

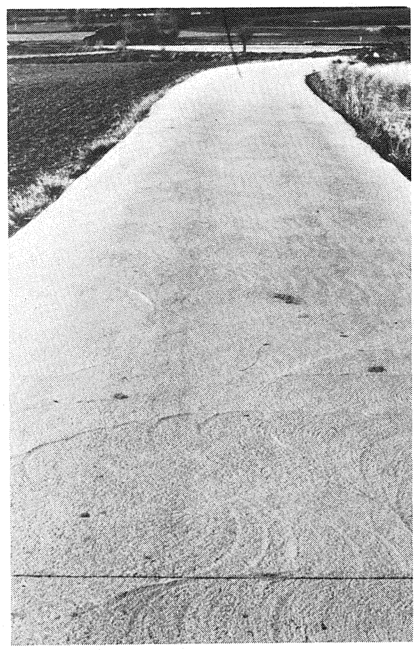

Fig. 5. RCC pavements for low volume roads: texture obtained through mechanical trowelling, and sawed joint

Fig. 6. RCC pavements for low volume roads: sawed joint

of expressway pavement using this technique was built over a length of 22.5 km (14 ml) and a width of 7.5 metres (8.2 yd); whereas in the autumn-winter of the same year, in a section 30 km (48 ml) long of an existing expressway, a new lane with RCC pavement was added to both carriageways. Moreover, in 1989 a new carriageway will be added to an existing road in Andalucia, in the South of Spain, in order to transform it into a main artery of that region. A RCC solution has been chosen for more than 100 km of the new carriageway.

## 3. DESIGN STANDARDS

### 3.1. THICKNESSES AND STRENGTHS. BASES

Equal thicknesses have been habitually specified for traditional vibrated concrete and for RCC when no wearing course has been provided on top of RCC or, at the most, only a surface treatment with little or no effect on its structural features. This hypothesis can initially be made because both materials have similar mechanical stregths. However, where for the purpose of achieving a more even surface an AC wearing course several centimeters thick is to be added, a small reduction in the RCC thickness has been admitted, which is justified by the application of mathematical models based on the multilayer elastic theory. This approach has also been used by the official standards which consider the following structural sections as equivalent (1989 revision):

- For T0 traffic category (over 2,000 commercial vehicles/day on the design lane) and E3 subgrade (CBR greater than 20):

Either:

28 cm (11") of HP-45 vibrated concrete, with a characteristic flexural strength of 4.5 MPa (650 psi) at 28 days
15 cm (6") of vibrated lean concrete or erosion-resistant cement treated base

Or:

10 cm (4") of asphalt concrete
25 cm (10") of RCC
20 cm (8") of soil cement

- For T1 traffic category (between 800 and 2,000 commercial vehicles/day on the design lane) and E3 subgrade (CBR greater than 20):

Either:

25 cm (10") of HP-45 vibrated concrete
15 cm (6") of vibrated lean concrete or erosion-resistant cement treated base

Or:

10 cm (4") of asphalt concrete
22 cm (8.5") of RCC
20 cm (8") of soil cement

The above thicknesses, both for vibrated and compacted concrete, are the minimum for the design lane. In the case of T0 traffic category, the thickness of the RCC layer between shoulder edges varies lineally between 23 and 27 cm (9" and 10.5"), while for the vibrated concrete the thickness varies between 26 and 30 cm (10.25" and 11.75"). A similar variation (20 to 24 cm -8" to 9.5"- with RCC and 23 to 27 cm -9" to

10.5"- with vibrated concrete) is stipulated for the case of T1 traffic category. The other layers are of even thickness.

For lower traffics the Standards specify a RCC thickness equal to 20 cm (8"). Thickness of the wearing course is related to traffic category: 8 cm (3") of AC for T2 traffic (between 800 and 200 daily commercial vehicles); 4 cm (1.5") of AC for T3 traffic (between 200 and 50 daily commercial vehicles); and for traffic T4 (less than 50 daily commercial vehicles), either 4 cm (1.5") of AC or a surface dressing. A soil-cement subbase, 20 cm (8") or 15 cm (6") thick, is in general compulsory for traffic T2 and T3. For traffic T4, it is permitted to spread RCC on the non-treated granular subbase or directly onto the subgrade, when this has a CBR index greater than 20. Soil-cement is required to reach a compressive strength of 2.5 MPa (360 psi) at 28 days, or alternatively 3.8 MPa (540 psi) at 90 days, in accordance with the active addition content of the binder.

The official standards in force provide that the average splitting tensile strength of the RCC shall be 3.3 MPa (470 psi) after 28 or 90 days, depending on the greater or lesser amount of active additions in the binder. This is approximately equal to assuming an average flexural strength of 5.5 MPa (785 psi), or a characteristic strength of 4.5 MPa (650 psi). This latter is the strength normally required for most vibrated concrete pavements subjected to heavy traffic. For less important works, lower values are allowed, i.e., a splitting tensile strength of 2.8 MPa (400 psi).

In the construction of secondary roads (4,5), 15 cm (6") thicknesses have usually been used, although in some pavements located in industrial areas this thickness has been increased to 20 cm (8"). No wearing course has been laid on top of RCC in pavements of this type (Fig. 1, 5 and 6). In these cases RCC has normally been laid directly onto the existing ground, after any organic top-soil, where this existed, has been removed.

### 3.2. JOINTS

Official regulations prescribe disposing transverse joints every 7 m (23'), arranged with a 1:6 skew in the same way as in conventional vibrated pavements. Longitudinal joints are not required.

In transverse joints, a distinction must be made between construction joints and shrinkage joints. In works where RCC has been topped by a wearing course, the most common practice has been not to saw any joints, allowing the concrete to crack spontaneously (Fig. 7). However, in more recent works there has been a tendency to dispose sawed joints (Fig. 5 and 6). In the different stretches constructed up to now the average distance between cracks has been found to vary widely between 10 m (33') and 25 m (83'). The weather conditions prevailing during the pouring and spreading of the RCC have a great influence on these variations. In this respect it is worthwhile mentioning that during the

Fig. 7. Spontaneous joint

construction of an expressway stretch in the summer of 1987, with a very low relative humidity level and a temperature occasionally going over 40 degrees centigrades (100 degrees Fahrenheit), where it was planned to make sawed joints every 15 m (50'), it became necessary to reduce the distance to 10 m (33') since if this was not done cracks appeared in-between. On the other hand, under these extreme conditions, the time span for cutting joints was almost as critical as that with vibrated concrete, as they had to be sawed within eight hours of laying the RCC.

In the case of low volume roads where, as noted earlier, RCC surfaces are left exposed, joints are customarily sawed every 10 or 15 m (33' or 50') for aesthetic reasons more than any other (Fig. 5 and 6).

There are not enough data available at this time to evaluate which of the two practices, joint sawing or spontaneous cracking in RCC, is more advantageous for heavy traffic roads.

### 3.3. TEXTURE AND SURFACE FINISHING

In order to obtain the adequate non-skid properties it is necessary to apply some surface treatment to the raw slab top left by the compacting rollers (3,9,10).

As has been already mentioned, official regulations specify an AC layer as a wearing course. Surface dressings are only admitted for lower traffic categories, because they do not offer the possibility of correcting the none-too-even surface left by the rollers. Both alternatives have been used in previous works where AC thicknesses from 4 cm (1.5") to 12 cm (5") have been employed.

In low traffic roads the most usual solution has been, as previously said, to leave the RCC untopped. In order to give the pavement some texture, RCC is compacted with a slight moisture excess and the newly laid concrete receives a mechanical trowelling (Fig. 4). The finish obtained in this way (Fig. 5) is not recommended for speeds over 40 km/h (25 mph), but is adequate for residential streets, industrial parking lots, etc. In these cases vehicles are not allowed to drive over the pavement until some hours have elapsed, to avoid erasing the soft texture obtained by trowelling.

## 4. MATERIALS

### 4.1. AGGREGATES

The specifications to be met by aggregates are, in general, the same as those required for each category of design traffic for cement treated bases (3,9,10). It should be noted in this respect that the experience obtained with the latter over more than 20 years has been very useful for the subsequent development of RCC pavements. To avoid the risk of segregation, and to obtain a better surface quality, aggregates with a maximum size of 20 mm (3/4") and even 16 mm (5/8") are being used, which, at the same time, has made the mixing of the material easier. However, in low traffic applications, maximum sizes of up to 38 mm (1.5") have been used, although in this case the mechanical trowelling commonly used to finish the pavement enables the gaps created by the surface segregation to be filled in. In every case continuous gradings have been used.

The official specifications (1) determine the grading limits for maximum aggregate sizes of 20 mm (3/4") and 16 mm (5/8") respectively (Table 1). They also include the binder contents with the purpose of limiting the total proportion of fines (excesive fines can cause compacting problems with fluffing of the material).

Both siliceous and limestone type aggregates have been employed. Generally speaking, crushed aggregates are used, supplied in three, two or even one size (0-20 mm or 0-3/4"), depending on its grading.

It has already been mentioned that one of the main advantages of RCC, particularly when used to strengthen existing roads, is the possibility of opening the stretch to traffic right after completion. This demands that the mineral skeleton formed by the compacted aggregate achieve a sufficiently high stability or have an "inmediate bearing capacity". It is then necessary to make a compromise between its compactability, which increases with the rounded aggregate content, and its stability which, conversely, increases with the percentage of crushed particles it contains. It is usually necessary for two thirds of the aggregates used to be of the crushed type to obtain an adequate bearing capacity.

### 4.2. BINDERS

Another advantage of RCC derives from the fact that, owing to the aforementioned stability of its mineral skeleton, it is possible to use binders with a high content of active additions, of which, in the medium and long run, the strength achieved is equal to or even greater than the values of cements with a lesser proportion of additions. On the other hand, binders with a high proportion of active additions possess some other properties which make their use in road construction very attractive, such as a low hidration heat, lower shrinkage and a noticeable delay in the start and finish of the setting process, which in turn facilitates the spreading and compacting operations. A number of changes in the Spanish cement Standards (last revision in 1988, (11)) allowing a lower strength ratio at 7 and 28 days than the one previously required, has made it easier to develop these cement types than before. An agreement made between the Ministry of Public Works and Urban Development and the Spanish Association of Cement Manufacturers, by which the latter agrees to supply these types of cement for the construction of roads included in the Expressways Program at prices 20 to 25 % lower than those prevailing in the market, has doubtless contributed to their extensive use.

| | % Passing | |
|---|---|---|
| Sieve Size | Maximum Size:16mm(5/8") | Maximum Size:20mm(3/4") |
| 25 mm (1") | --- | 100 |
| 20 mm (3/4") | 100 | 85 - 100 |
| 16 mm (5/8") | 88 - 100 | 75 - 100 |
| 10 mm (3/8") | 70 - 87 | 60 - 83 |
| 5 mm (Nº4) | 50 - 70 | 42 - 63 |
| 2 mm (Nº10) | 35 - 50 | 30 - 47 |
| 400 µm (Nº40) | 18 - 30 | 16 - 27 |
| 80 µm (Nº200) | 10 - 20 | 9 - 19 |

Table 1. Grading limits for RCC

The binder content used (3,9,10) has fluctuated from 260 to 330 kg/cu.m (440 to 555 lb/cu.yd), which means, aproximately, between 11.5 and 14.5 % of total weight of dry materials. Both, mixes in plant of portland cement and fly ash as well as blended cements, have been used (and in the most recent works the active additions content has been as high as 50-55 % of the total). In this case, additions have usually consisted of the fly ash which is much more abundant in Spain (about 9 million metric tones or 9.9 tons produced per annum) than natural pozzolan or blast furnace slag. Up to now, only in one RCC work has blast-furnace slag been used as an active addition. With regard to mixes in plant of cement and fly ash, these have usually been of the silica-alumina type (class F in accordance with ASTM standard C 618), which are the most commonly found in Spain.

The use of high additions contents in the binder produces a considerable increase of concrete strengths from 28 to 90 days. This increase can even be of 45 % with an addition content of 50 %. For this reason, to demand tests with these materials only after 28 days, means underestimating their potencial, and it is convenient to do these tests after 56 or 90 days. Table 2 shows, as an example, the results obtained with laboratory tests

| | Splitting Tensile Strength (MPa) | | |
|---|---|---|---|
| Blended Cement 50/50 Content(%) | At 7 days | At 28 days | At 90 days |
| 10 | 1.1 | 1.8 | 2.2 |
| 11 | 1.3 | 2.4 | 3.0 |
| 12 | 1.9 | 2.9 | 3.5 |
| 13 | 2.3 | 3.5 | 4.6 |
| 14 | 2.6 | 3.6 | 4.9 |
| 15 | 2.7 | 3.6 | 5.2 |

Table 2. Splitting tensile strengths for RCC mixes

performed prior to carrying out an overlay stretch. The binder used was a cement obtained through joint milling of 47 % of Portland clinker, 2.5 % of gypsum, as a setting regulator, and 50 % of silica-alumina class F fly ash.

### 4.3. MOISTURE CONTENT AND COMPACTING ENERGY

The moisture content is determined in the same way as with cement treated bases (9,10). Both the modified Proctor test and the Kango vibrating hammer test are used. Tests are currently being run to obtain the density-moisture content curve using the Vebe consistometer complemented with a 9 kg (20 lb) weight, following a procedure similar to that employed in some RCC tests for dams. This test has the advantage of not altering the aggregate grading, as is sometimes the case with the above-mentioned procedures.

All these devices have also been used to make specimens for strength determinations. In this regard, it can be mentioned that in order to evaluate flexural strength directly, a device to cast prismatic specimens has been recently developed. It is composed of a vibrating table and a steel plate compressing the upper surface of the specimen during the compacting process.

In the works completed up to now the moisture content has fluctuated from 4.5 to 5.5 % of the total dry materials, or 105 to 130 kg/cu.m (175 to 220 lb/cu.yd).

One of the disavantages of RCC is their sensitivity to moisture variations affecting the degree of compaction obtained. An excess or shortage of water, plus any insufficient density, notably decrease their mechanical strength. On the other hand, any lack of moisture usually brings about risks of segregation and the appearence of setting faults in local areas, as well as compacting difficulties, while an excess of water produces faults in the surface evenness (fuffing of the material on being compacted). These faults may even show up with moisture variations of +/-0.5 % of the optimum degree of moisture. Official standards on this point stipulate that once the formula has been chosen its sensitivity to variations in moisture, relative to its immediate bearing capacity, must be checked.

Although the results depend on the mixes, it has been proven in some works that a 5% decrease in density can cause up to a 25% decrease in strength.

### 4.4. ADMIXTURES

One type of admixture that is usually essential (9,10), except when the temperature at the site is low, is the retarder which is used in order to increase the workability time of the mix, so that the compacting operations are not carried out once the setting process has already begun. And this is true in spite of the delays in the starting and ending of the setting process that inherently occur when binders with a high content of active additions are used. Table 3 shows some results obtained in this respect with these types of cement.

The official standards in force stipulate the minimum workability periods shown in Table 4, depending on the type of work involved. Although the workability period of a given mix may not coincide with the end of the setting time of the binder used, it can generally be deduced from a comparison of Tables 3 and 4 that it is necessary to add a retarder if such periods are to be achieved.

The amount of retarder usually fluctuates between 0.5 and 1 % by weight of binder. Since the workability period varies with the temperature, this has to be measured on site to evaluate the right dosage. The official standards stipulate that the temperature to be used to determine the workability period must be the average air temperature forecast for the period between 11:00 and 14:00 hours.

## 5. MIX MANUFACTURE

Both continuous plants (similar to those used in the mixing of cement-treated bases) and traditional batch plants have been used to produce the concrete (9,10).

For expressway construction it is complusory for the mixing plant to measure by weight the cement, as well as the fly ash content when used. Aggregates may be dosified by volume.

## 6. CONSTRUCTION

### 6.1. TRANSPORT AND SPREADING

Dump trucks have been used to transport the concrete from the mixing plant to the site, involving distances that on occasion have been over 40 km (25 ml).

Motor graders, pavers of the same type as those employed for cement-

| | Time of Setting | |
|---|---|---|
| Fly Ash Content (%) | Initial (hrs:min) | Final (hrs:min) |
| 0 | 1:30 | 2:15 |
| 20 | 2:10 | 3:10 |
| 30 | 2:35 | 3:35 |
| 50 | 3:20 | 4:15 |
| 60 | 4:25 | 5:20 |

Table 3. Influence of fly ash contents on time setting

| Type of work | | Minimum Workability Period (hrs) |
|---|---|---|
| Without Traffic | Total Width Construction | 5 |
| Without Traffic | Parcial Width Construction | 7 |
| Overlay under Traffic | | 9 |

Table 4. Workability periods

treated bases or for AC, and autogrades, have been used to lay the material.

In most urban road construction and that for secondary roads the spreading equipment used was the motor grader (4,5), more suitable for complex geometrical layouts which are very frequent in this type of works, where, in addition, the demands of surface evenness are not very high. Usually, RCC is constructed in one layer. In this regard, it should be pointed out, however, that even employing a paver, the thicknesses to be laid are very often beyond the limitations of the most common machines and for this reason it frequently happens that unevenness of the supporting layer is reflected onto the RCC finished surface. The best results have been obtained with equipment fitted with tampers (Fig. 8) which ensure a high degree of precompaction of the material (from 90 to 96 % of the maximum modified Proctor density), with the result that deformations caused by the subsequent passings of the rollers are less than when the equipment used is not fitted with tampers.

Although it is preferable, whenever possible, to spread the material across the full width of the roadway involved, most works have been carried out by half-widths. This is either because of the characteristics


Fig. 8. Spreading of RCC with paver-finisher equipped with double tamping screed

of the equipment available or because of the work progress required, as in the case of the Cadi Tunnel (Fig. 9), where it was indispensable to keep the pavement open to work traffic. To avoid a longitudinal joint's forming, a 40 to 50 cm (16" to 20") strip of the first half width is left uncompacted and this serves as a lateral contention for that half. This central strip is later compacted together with the second half-width of the pavement. In any case, and as official standards prescribe, the full width must be laid within the workability period of the first material laid, in order to prevent a cold joint from appearing.

## 6.2. COMPACTION

It is essential to obtain an adequate density to achieve correct behaviour in RCC. Spanish specifications require in this respect that the average density achieved be no lower than 97 % of the maximum modified Proctor density, while at the bottom of the layer this density must

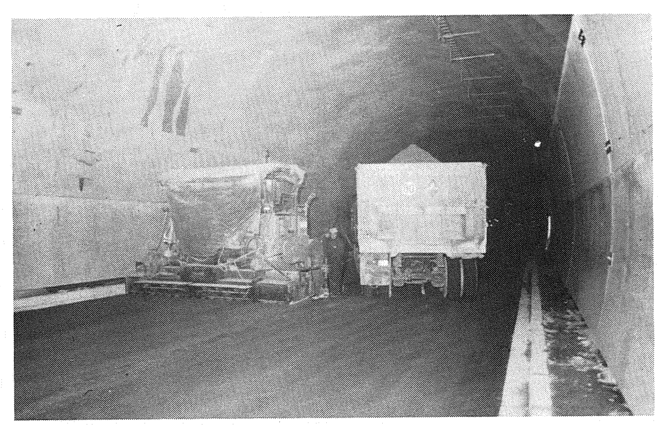

Fig. 9. Construction of the Cadí Tunnel RCC pavement

not be less than 95 %. To this end it is advisable to build a test stretch previously, in order to check how many passes the compacting equipment needs to make.

Normally the equipment used consists of one heavy smooth drum vibratory roller (Fig. 10) and one heavy rubber-tyred roller (Fig. 11) to seal the surface (3,9,10). According to the standards in force, the first must have a static weight per linear centimeter of width of the drive roll of no less than 30 kp (175 lb/in), while in the second the load per wheel must be 3 t (6.75 kips) or higher and the contact pressure not less than 0.8 Mpa (115 psi). In one particular work, good results were obtained with a mixed roller (smooth drum on the front axle and tyres at the rear).

The rubber-tyred rollers have not been used in construction work on low traffic roads (4,5), nor in some more important works. It must not be forgotten, however, that the first type of works is usually finished by mechanical trowelling after water or grout has been spread over them; and this process also seals the surface at the same time.

Generally speaking, the smooth drum roller is first passed over them once or twice without vibration so as not to cause dragging of the dry material, and after this, it is passed over them at least four to six times vibrating. Similarly, the rubber-tyred roller is usually passed at least six times. In the most recent works a continuous control of the compacting process has been carried out by means of nuclear density gauges, and in this way the rollers continued to pass over until the required densities were achieved. In some works where the rubber-tyred rollers were not available, several final passes with the smooth drum roller, without vibration, were made to seal the surface.

The compacting of side edges and construction joints is a very delicate matter. The best results have been obtained when a lateral contention has previously been installed, as is the case with urban streets with

Fig. 11. Compaction with heavy rubber-tyred roller

curbs. When a concrete layer has been laid without any side contention, subsequent checks have sometimes shown a rather important lack of compaction. In some cases light equipment (such as vibrating-plate compactors or manually driven rollers) have been used near the edges (Fig. 12).

## 6.3. PROBLEMS ASSOCIATED WITH THE CONSTRUCTION PROCESS

It has been mentioned that RCC strengths depend to a great extent on the density obtained through compaction. Surface evenness is also closely related to the precompaction obtained by means of the spreading equipment. In this regard, we can mention the following points (3):

1. The thicknesses normally used, between 20 and 23 cm (8" and 9") of compacted material, generally imply 4 or 5 additional centimeters

Fig. 10. Compaction with heavy smooth drum vibratory roller

Fig. 12. Edge compaction with vibrating-plate

(1.6" or 2") of non compacted concrete. These figures are beyond the maximum working thickness of the pavers used on most sites. The outcome of this is some defects in the surface evenness of the concrete behind the pavers, reproducing the irregularities of the supporting layer beneath.

2. It has been noted in some works that the densities obtained do not meet specifications because the compacting equipment has not passed enough times over the layer concerned. This had led to a reduction of in situ strengths. In some works the splitting tensile strengths found are in the order of 2.35 MPa (335 psi) at 90 days and 2.8 MPa (400 psi) after one year, while in laboratory tests the value of 3.3 MPa (470 psi) at 90 days required by the standards was easily obtained. On the contrary, in the construction of one expressway pavement built in the summer of 1986, where a strict compaction control was carried out using a nuclear gage, and the rollers were made to pass as many times as necessary to reach the required values, the strength obtained after 28 days measured with cores was close to 2.6 MPa (370 psi). With this it is to be expected that the 3.3 MPa (470 psi) value can be reached at 90 days in view of the fact that the cement used contained about 50 % of active additions.

3. When, as is the case with low traffic roads, the compacted concrete has been laid in smaller thicknesses, not exceeding 20 cm (8"), the strengths obtained have been remarkable, a sign of right compaction. Good proof of this is the results of a core extraction program carried out in 1985 (5) across 20 different works completed between 1969 and 1984 with compacted concrete thicknesses of 15 and 20 cm (6" y 8"). Four samples were taken from each site. Two of them were tested for compression and two for splitting. Although there was a considerable dispersion of results, as expected in view of the few controls that took place during construction, the strengths attained notable values. For example, the average tensile splitting strength result was 3.4 MPa (485 psi), with 80 % of the samples exceeding 2.8 MPa (400 psi) and this with binder content in the order of 260 kg/cu.m (440 lb/cu.yd), of which one third was fly ash. A good correlation was also proved between core densities and core strengths. All the foregoing shows that, through experience, a fully adequate technology has been developed for low traffic roads.

4. Likewise, large dispersions have been noted in the strengths obtained in cores extracted from pavements for heavy traffic. This may be attributed to the use of mixing plants with dosification of the binder content by volume.

5. Except in the case of urban road construction where curbs are usually installed before the RCC is laid, this operation has generally been carried out without a lateral contention. This has resulted in a great decrease of density near the edges, in the order of 5 to 10 points relative to the average values measured in the centre of the road.

### 6.4. JOINTS

Whether or not joints are needed in RCC pavements was some years ago a highly controversial subject, but in the last works joints have been systematically disposed. This trend, also reflected in the revisions of the official specifications, is based on two reasons:

-if a joint becomes reflected on the surface of the AC wearing course it is likely to last longer than a spontaneous crack with jagged edges.

-if on the contrary, cracks reflected on the surface are not wanted, since their location is known, it is possible to make use of some of the methods (such as geotextiles, grids, etc.) used in semi-rigid pavements to try to avoid this appearance's taking place. One of these procedures based on high modulus polyester grid treated with polymer modified asphalt (Fig. 13) was applied in the construction of the first stretch of expressway built of RCC during the summer-autumm of 1987.

However, in the first RCC jobs, the most common practice was not to saw any joint, allowing RCC to crack spontaneously (Fig. 7). In these cases, average distance between cracks has been found to vary widely between 10 m (33') and 25 m (83'). Weather conditions prevailing during pouring and spreading of RCC have a great influence on these variations. In more recent works a tendency has been noted to dispose sawed joints (Fig. 14, 5 and 6). Usually, it is posible to let some days elapse before cutting the joints; and at very low relative humidity

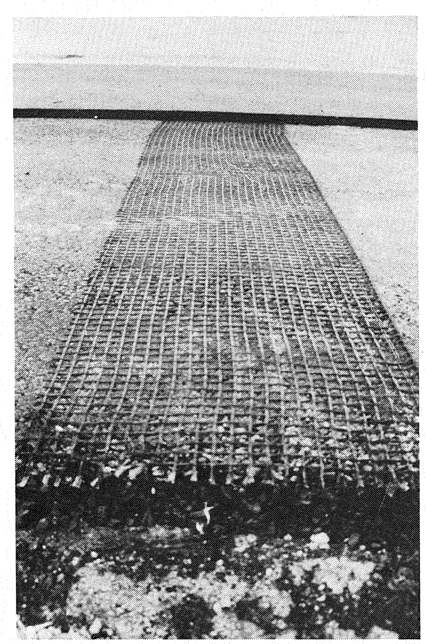

Fig. 13. Polyester grid placed above a sawed joint to prevent its transmission to the asphalt surface

Fig. 14. Sawing of joints

levels, time span for sawing joints is almost as critical as with vibrated concrete, since they must be cut only a few hours (6 to 8) after laying RCC.

It must be pointed out that in the case of low volume roads, joints have been customarily sawed every 10 or 15 m (33' or 50').

An effort is made to create perfectly vertical edges for the transverse construction joints made at the end of each work day. In a work where such a precaution was not taken the result was that the ends of slabs overlapped and, in addition, large expansions of the RCC occured as a result of having used an ash with a high free lime content (class C type according to ASTM 618 standard).

Regarding longitudinal joints, they have not been disposed in any of the road stretches built using RCC, although a number of precautions have been taken during construction to avoid the formation of cold joints during laying. Such mesures have proved succesful even when pavements were built up to 14 m (47') wide (constructed in successive partial widths with several passes of the spreading equipment), or under very high atmospheric temperatures, a condition provoking cracks as a result of shrinkage.

### 6.5. CURING AND SURFACE PROTECTION

The surface of RCC must be protected against dessication in order to ensure a good adherence for the wearing course, particularly when this consists of a surface treatment. The protection for this purpose consists of a curing seal, and before this the surface must be kept continuously wet by means of a fine spray of water, avoiding the formation of pools which may cause compacting problems. This has generally been done with tank trucks occasionally aided by hand watering.

Except in the construction of secondary roads, where curing is carried out with one or two days watering since the concrete is left exposed (4,5), in most cases RCC has been protected by a curing seal of a bituminous emulsion (9,10). Special polymer-based products, which react with the cement in the upper millimeters producing a harder and stronger surface mortar, have only occasionally been used, because they do not allow immediate opening of the finished stretch to traffic.

Before laying the wearing course it is advisable to allow a certain time to permit an important part of the fissuration to develop. In order to allow the running of traffic, the bituminous emulsion is protected with sand, which must be laid within a maximum period of 5 minutes after the emulsion application, and the roller compacted. The RCC layer treated in this way may be opened to traffic once the emulsion has set, generally about 2 hours after the sand was laid. In some exceptional cases that period was reduced to 1 hour.

### 6.6. CONSTRUCTION LIMITATIONS. RAIN. FREEZING TEMPERATURES

The process of compacting concrete by rollers is very sensitive indeed to water (9,10). The excess of water produced by rain may cause fluffing of the material, apart from washing it down. It has been shown in some cases that in a stretch of RCC recently opened to traffic a heavy fall of rain can be damaging. For this reason, RCC should not be laid in the rain.

It must also be taken into account that because, normally, binders used for RCC have a high content of active additions and consequently develop their strength slower than other cements without any additions or with a lower proportion of them, the material is more sensitive to freezing temperatures during the hardening period. For this reason, RCC works have to be suspended if freezing conditions might occur.

### 6.7. CONTROLS

Controls during construction basically concentrate on checking the thicknesses and densities on the newly laid concrete. The careful control of this last parameter (density) is very important because the strengths of RCC depend largely on it. The Expressway Instruction (1) stipulates that the following controls must be carried out to this end at the plant:

-moisture content of the mix at least 5 times a day
-mix grading, especially fines and binder contents, twice a day
-the average consumption of binder

In addition weight control of the cement and the fly ash being used is compulsory, while the water added is to be controlled by a flow meter and a totalizer.

The official standards specify that thickness should be checked every 10 m (33') in uncompacted material, by driving a calibrated stake into the material, bearing in mind the reduction the material will undergo on compaction. If for greater accuracy these checks are made on compacted material, then leveling methods must be used.

For density control the most advisable method is to use nuclear gauges, much more operational than the sand method which has also been employed on occasions. The testing must be carried out at random with a minimum rate of one test for every 100 sq.m (120 sq.yd) of pavement. Likewise, a moisture content test must be made on the paving site, at random locations corresponding to the tests carried out during plant controls. Generally speaking, the moisture content should fall within the optimum and two percentage points below this. Any area where a substantial deviation in the moisture content is found, must be corrected immediately.

The concrete strength is checked by means of specimens prepared for the purpose of determining the splitting tensile strength value.

## 7. SURFACE FINISHING

Except for low speed pavements, where it has already been said that the usual finish is mechanical trowelling to provide them with some degree of roughness, the usual practice is to lay a wearing course.

The most economical solution for this purpose is to apply a surface treatment, although, as has already been stated, this may present some drawbacks.

In the most recent works the solution adopted has been to spread an AC layer. An 8 cm (3") AC wearing course has also been used on the structural sections of expressways with RCC layers. For medium traffic roads thickness of the wearing courses fluctuates between 4 and 6 cm (1.6" and 2.4").

The best results in the behaviour of the wearing course are obtained when this is laid several weeks after the traffic has been running over the RCC surface, and most of the potential shrinkage cracks have already appeared. Spanish specifications require that 7 days must have elapsed before such a course is laid, but it is recommended that this period be extended to one or two months, particularly during cold weather.

As happens with semi-rigid pavements with cement treated bases, one source of concern is the subsequent progress of the shrinkage cracks that become reflected in the wearing course. The 10 centimeters (4") thick wearing course stipulated by the legal standards is a means of delaying as much as possible the appearance of such cracks on the surface within limits that might make RCC structural sections feasible from an economic angle, in comparison with other alternative solutions.

## 8. ECONOMIC ASPECTS

Use of RCC in the construction of medium-to-heavy traffic roads is relatively recent. This is why it is not yet possible to forecast with a certain degree of accuracy what their maintenance costs will be over a design life of 20 to 30 years; nor is it possible, either, to establish comparisons between its total cost as against other methods over the same period. If we only take into consideration the initial costs involved, then it is possible to say that under present conditions in Spain, savings of 10 to 20 % can be obtained in the cost of RCC as against traditional vibrated concrete. Owing to this difference, it is possible to put a thick AC layer on top of RCC, the total cost of the structural section remaining still similar to those of the solutions with vibrated concrete or with cement-treated or bituminous bases. The following figures, based on an exchange rate of US $ 1 = pts 120, can be considered as representative of average bid prices:

- cement for vibrated concrete pavements and vibrated lean concrete bases ( having an active addition content about 35 %): 62.5 $/t

- cement for RCC and cement-trated bases (having an active addition content about 50 %): 58.3 $/t

(It must be pointed out that the above-mentioned cement prices apply only to road works, prices for other uses being about 30 % higher)

- asphalt: 183.3 $/t

- construction cost of 1 cu.m of compacted concrete (300 kg/cu.m or 500 lb/cu.yd of cement; construction rate: 150 cu.m/hr or 200 cu.yd/hr):

| | |
|---|---|
| . labour | 1.44 $ |
| . materials | 35.13 $ |
| . machinery | 3.58 $ |
| . total | 40.15 $ |
| . total cost of 1 cu.yd | 30.70 $ |

- construction cost of 1 cu.m of vibrated concrete (330 kg/cu.m or 555 lb/cu.yd of cement; construction rate: 150 cu.m/hr or 200 cu.yd/hr):

| | |
|---|---|
| . labour | 1.81 $ |
| . materials | 41.66 $ |
| . machinery | 4.45 $ |
| . total | 47.92 $ |
| . total cost of 1 cu.yd | 36.64 $ |

- construction cost of 1 sq.m of structural section consisting of : 10 cm (4") af AC, 25 cm (10") of RCC and 20 cm (8") of soil-cement, on subgrade with a CBR of over 20 (capable of supporting a commercial traffic of over 2,000 trucks/day on the design lane during a design period of 30 years):

| | |
|---|---|
| . 10 cm (4") AC | (0.10x67.26 $/cu.m) 6.73 $ |
| . tack coat | 0.20 $ |
| . 25 cm (10") RCC | (0.25x40.36 $/cu.m) 10.09 $ |
| . 20 cm (8") soil-cement | (0.20x17.05 $/cu.m) 3.41 $ |
| . joint sawing | 0.21 $ |
| . total | 20.64 $ |
| . total cost of 1 sq.yd | 17.26 $ |

- construction cost of 1 sq.m of structural section consisting of: 28 cm (11") of vibrated concrete and 15 cm (6") of vibrated lean concrete with transverse joints every 5 m (17'), sealed and doweled and longitudinal joints tied and sealed (for the same subgrade and traffic conditions as the above solution):

| | |
|---|---|
| . 28 cm (11") vibrated concrete | (0.28x47.92 $/cu.m) 13.42 $ |
| . 15 cm (6") vibrated lean concrete | (0.15x30.66 $/cu.m) 4.60 $ |
| . joint sawing and sealing | 1.63 $ |
| . dowels | 0.94 $ |
| . total | 20.59 $ |
| . total cost of 1 sq.yd | 17.22 $ |

In the example given above, both solutions are almost identical in price. It should be mentioned that the cost of the vibrated concrete section could have been increased by approximately 1.5 $/sq.m (1.25 $/sq.yd) if the subgrade had a CBR of 10 to 20, since then it would have been necessary to lay 20 cm (8") aggregate subbase under the vibrated lean concrete layer. Conversely, even under these new subgrade conditions, the above section using RCC would still be valid.

In the case of pavements for low traffic roads, RCC solutions equally show a great competitivity, as they allow the use of mechanized construction methods that are not always feasible with alternative solutions, e.g., vibrated concrete pavements, since small slip-form pavers are not very available in Spain. It must not be forgotten, either, as mentioned earlier, that in view of the low speeds usual on this type of roads, they can be finished with mechanical trowelling without adding a wearing course of any kind. Good proof of this is provided by more than 4 million sq.m (near 5 million sq.yd) of pavement built with this method by local contractors who have developed this technique over a period of 15 years within an area no greater than 10,000 sq.km (3,800 sq.ml).

## 9. FINAL OUTCOME OF COMPLETED WORKS AND CONCLUSIONS

Mention has already been made of the fact that the first applications of RCC pavements on major roads with medium or heavy traffic in Spain did not take place until 1984 although work began in the early 70's on low traffic roads. As a result, we do not yet have sufficient experience with this type of roads to be able to judge accurately enough the success of the methods employed. Nevertheless it can be said that they have behaved correctly to date and this is the case both for major highways and for secondary roads.

By way of summary of all the foregoing, it can be pointed out that the RCC technique offers great advantages over other alternative methods as regards the savings that can be achieved and as regards the availability of construction equipment. Nevertheless, from the works completed, it can be deduced that at least for heavy traffic, it is necessary to take care over the following points:

1. Guaranteeing the maximum uniformity of the material by using mixing plants installed at least with weight control systems for binder content, and avoiding both the excess and the shortage of moisture.

2. Adapting the thicknesses to be built to the capacity of the spreading and compacting equipment available, or viceversa. In this respect construction in two layers may make it easier to obtain the densities required and also improve surface evenness.

3. Applying strict controls during the compaction process, checking densities by rapid response nuclear gauges and having the rollers make as many passes as necessary.

4. Compacting edges either with suitable lateral contentions, e.g. building the road shoulders previously, or building the RCC layer with an extra width or, as an extreme case of this last measure, building the road shoulders with the same structure as the main roadway.

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