PERFORMANCE OF A CONCRETE PAVEMENT CONSTRUCTED UNDER EXTREME WEATHER CONDITIONS

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ABSTRACT

During the summer of 1985, a concrete pavement was constructed under extreme weather conditions, in Aragón, in the NE of Spain and special measures were taken to avoid the possible negative effects.

Many checks were carried out during construction. The temperature of materials, grading of aggregates, slump and strength of concrete, evenness, etc. were frequently checked every day. In addition, special monitoring of cracking and opening of joints was carried out. By this study, the evolution of opening of joints with time, as well as their spacing were obtained. No correlation was observed between weather conditions and checking results, which means that the measures taken were adequate.

Apart from normal maintenance (so far practically unnecessary), specific studies of the pavement's performance were effected in 1986, 1987 and 1992. Concrete strength, evenness, texture, faulting and cracking were specially checked and, in general, satisfactory results have been obtained.

INTRODUCTION

During 1985 a by-pass for the N-123 road was constructed in Aragón in the north-east of Spain (Figure 1). This road is subject to relatively heavy traffic (total ADTT in excess of 1,000 in 1985 and over 2,000 now), since it is a direct link between two important cities, Zaragoza and Huesca. The fundamental objective of this project was to bring up to standard a 9.5 km stretch of the road in question, its characteristics being substantially worse than those of the rest of the route.

Firstly, there were two grade crossings of the railway track between the cities of Zaragoza and Barcelona. Moreover, the road's alignment was very uneven and, hence, the sight-distance for vehicles in certain parts of the section was very limited. Altogether, these factors combined to make this stretch of road very dangerous and an accident rate markedly higher than on the rest of the route had been observed.

With regard to the type of pavement, and considering the Standards in force at that time (1,2), options of both asphalting and concrete were considered. These Standards provided catalogues of structural sections to be selected on the basis of the number of 13 ton equivalent single axle loads, which is the maximum permitted in Spain, throughout the estimated lifetime of the pavement (20 years in the case of asphalt pavements and 30 years in the case of concrete), and of the subgrade category defined on the basis of its CBR. In accordance with the legal provisions then in force, a comparative study had to be carried out among solutions based on asphalt concrete and those based on cement concrete, in order to select the most economic one. This legislation laid down that, in the case of works of more than 70,000 square meters, as in this case, solutions with concrete could be up to 20% more expensive for the same project period. The purpose of this provision was to take into account the lesser need for maintenance which concrete pavements normally have, as well as to save asphalt materials at a time of energy crisis (3,4). According to the comparative estimates, the construction cost of concrete solutions was of the order of 2.7% more expensive, for which reason these were the ones finally applied.

The works were started at the beginning of 1985 and the pavement was constructed in high summer (from June to September). The weather conditions in summer on the job-site area are somewhat extreme, with temperatures frequently in excess of 40°C by day and about 10-15°C at night, very low humidity (< 40%) and wind velocity occasionally over 50 km/h. These are negative conditions for ensuring the adequate placing of concrete. Nevertheless, the need to have this stretch of road in service in the fall, made it necessary to construct the pavement under these adverse weather conditions. It was, therefore, essential to take the special measures which are described below. In addition, a thorough check of the pavement construction was carried out, as well as of the performance of the road once it was in service.

Furthermore, the Standards applied for the pavement project (1,2) were modified later and replaced by (5) and (6), by which the various structural sections were strengthened. Hence it was considered particularly important to carry out a subsequent follow-up of the behaviour of this job.

Some additional details about this job can be found in (7).

THE PAVEMENT PROJECT

The traffic envisioned on the pavement throughout the lifetime of the project was calculated on the basis of an ADTT at the time of construction of 1,000, with an annual increase of 4%. In view of the existing traffic in 1992 (ADTT in excess of 2,000), that projected annual increase was low. Up to now, the average annual increase has been of the order of 10%. The relationship between the number of commercial vehicles and the number of 13 ton equivalent single axle loads is established assuming a ratio of 0.5, a hypothesis included in the above-mentioned Standards (1,2). Using these data as a starting point, a traffic category "T1" was obtained in accordance with the Standards in question. This traffic category relates to a range of between 4,000,000 and 10,000,000 13 ton equivalent single axle loads. Considering the real ADTT in 1992, it should have been necessary to allow for the highest traffic category contemplated in the Standards relating to more than 10,000,000 13 ton equivalent single axle loads. Hence, using type traffic category "T1", it has become bordering on insecurity.

As far as the existing subgrade was concerned, the tests carried out produced the result of a somewhat variable CBR and, at all events, very low. For this reason, it was decided to place a capping layer 0.5 m thick, using selected material with a CBR over 20.

With these data as a starting point, a slab of HP-40 concrete (with characteristic flexural strength of 4.0 MPa at 28 days) was designed, with a constant thickness of 0.25 m, on a cement treated base of 15 cm. In accordance with the Standards applied, and taking into account the traffic envisioned and the fact that the rainfall in the area was low, it was decided to use short slabs without dowels. Sections similar to that referred to had previously been applied in other works in Spain (8,9), following the original Californian technique. In order to avoid any possible problems with pumping (8,9), a non-erodible lean concrete base was specified in this case and a geotextile was placed as a filter at the carriageway/shoulder interface.

Furthermore, the lean concrete base was extended 30 cm below the shoulder, as laid down in the Standards in force, also in accordance with the Californian technique (10) and with other international experiences and recommendations (11), to avoid pumping. The shoulders, also following previous experience, were designed with 4 cm of asphalt concrete on 40 cm of a granular base, as shown in the lay-out of Figure 2.

Since dowels had not been envisioned in the joints, these were designed obliquely 1/6 in respect of the roadway axis, to reduce the effect of vehicles passing on them. Moreover, the distance between the joints was specified in accordance with a variable sequence between 3.75 m and 4.50 m (3.75-4.50-4.00-4.25-4.00) to avoid the periodical irregularities produced in the case of faulting, with constant distances between the joints, which are more uncomfortable for driving. Due to the absence of dowels, it was decided to seal the joints.

With regard to texture, it was decided that this should be longitudinal, both in respect of the macro-texture and of the micro-texture. This type of texture provides good skid resistance and is less noisy than the transverse one (12), although its transverse draining efficiency in the event of rain is lower. However, due to the low rainfall of the area, this factor was not considered critical. This type of longitudinal textures has been largely applied in Spain (13,14) as well as in some other countries such as, for example, Austria (15), with excellent results.

CONSTRUCTION

Materials

Aggregates

Aggregates, of siliceous type, were obtained from an alluvial deposit close to the job site. Their Los Angeles abrasion loss was less than 15%.

Cement

Cement was selected taking into account the adverse atmospheric conditions under which concrete was to be placed. Attention was particularly paid to the fact that its hydration heat should not be high, in order to avoid problems during pavement construction. A blended cement of category 35 was chosen (compressive strength higher than 35 MPa at 28 days) with fly ash as active addition (69% clinker and 31% fly ash). Its hydration heat after 7 days was less than 225 J/g. Other characteristics of the selected cement are summarized in Table 1. In (16) the main characteristics of the cements normally used in Spain for the construction of concrete pavements are described.

Concrete

For the base concrete as well as for the top-layer concrete, continuous grading of aggregates was used. Cement content was equal to 160 Kg/m^3 for the base concrete and 305 Kg/m^3 for the top-layer concrete. Table 2 summarizes the results of slump of both types of concrete, compressive strength (cylindrical specimens 15 cm high x 30 cm diameter) of base concrete and flexural strength (prismatic specimens of 0.15 m x 0.15 m x 0.75 m) of top-layer concrete.

Concrete Mixing

Concrete was mixed in a discontinuous batching plant with four scales for the aggregates and one for the cement. Water and admixtures were dosed by volume. The batching plant had two mixers, with a combined output about 85 m^3/h. Mixing time and homogeneity of concrete were checked with two wattmeters.

Fresh concrete was controlled every hour. This check included slump measurement, concrete temperature, entrained air, as well as the making of two specimens to obtain the mechanical strengths. These specimens were cylindrical in the case of the lean concrete for the base, which were tested for compressive strength at 7 and 28 days, and prismatic in the case of the pavement concrete which were tested for flexural strength at 28 and 90 days.

Construction Process

Both the base and the top-layer were constructed by half widths, using a slip form paver. Each half width corresponded to one road lane. With a view to achieving suitable evenness at the top-layer, special precautions were also taken to obtain correct evenness in the base. Hence, the paver was supported on a more regular surface while laying the top-layer concrete, in order to improve the surface regularity of the latter, as was proved in practice.

The results of the evenness measurements carried out were as follows: viagraph coefficient of the lean concrete base, 15; viagraph coefficient of the top-layer, 12; roughness index measured with a BPR roughmeter applied to the top-layer, 107-163 cm/km.

Curing

Given the adverse conditions under which the placing of the concrete was to be carried out (high temperature, low humidity and strong wind), the choice of an adequate curing procedure was essential. According to previous experience on other jobs in Spain (9,17), some curing compounds are not effective when weather conditions are excessively extreme (high temperatures and low humidity). In these cases, the concrete dries out giving rise to a defective setting process. Therefore, a specific laboratory study was carried out to ensure that the curing compounds to be used on the job were sufficiently effective for the conditions under which the concrete was to be laid.

In the laboratory study, several curing compounds were applied to concrete specimens and these were subsequently exposed to conditions similar to those expected on the job. For the base concrete, an emulsified paraffin was chosen which, in addition to curing, should prevent adhesion to the top-layer concrete and, consequent possible reflective cracking. For the top-layer concrete, a rapid drying resin-based product was selected which would also powerfully reflect the sun's rays, to reduce their heating effect on the concrete.

While both selected compounds worked adequately for curing, that used on the base did not prevent adhesion to the top-layer. This was realized on the second day of laying the top-layer concrete, when reflection occurred with 22 of the base cracks (the widest open ones). This reflection took place entirely in the first 850 metres of the first half-width of top-layer placed. This problem has been described in several references (14,18) when the adhesion between the base and the top-layer is not completely prevented. In order to overcome this problem, from then on a polythene sheeting was placed on the base and this, physically separating the concretes of the two layers, prevented the reflection of cracks. The cracks already produced precluded the joints sawn nearby in the top-layer from opening, as could be confirmed by observing the vertical faces of the slabs.

The cracks in the top-layer were repaired with epoxy resin in a manner similar to that of an earlier Spanish job, where the top-layer had cracked as a result of the use of curing compounds unsuitable for the high temperatures prevailing during placing (17). This epoxy resin was placed using two different procedures, the first by injection of the resin under pressure and the second by gravity using a very fluid resin. In both cases, good results were obtained initially, as it was demonstrated by the opening, a few days later, of the nearby sawn joints in the top-layer, which had previously failed to open; but in 1992 about 60% of the treated cracks had reopened.

The precaution was taken of placing the resin at hours when temperatures were low, (beginning at six o'clock in the morning), and consequently the cracks were open. Thus, as the temperature rose during the day, the expansion of the slabs closed the cracks and aided their bonding, avoiding the occurrence of tensile stresses.

Joints

As mentioned in the foregoing paragraph, the joints were induced by sawing. The sawing produced a slot of 3 mm width and 60 mm depth which, in all cases, was adequate to create the related joint.

Given the prevailing weather conditions, special care was taken to saw the joints at the appropriate moment, so that a clean joint was obtained and the appearing of spontaneous cracks was avoided. Normally, they were sawn 12 hours after the laying of the concrete, although on the hottest days this was done after 8 or 9 hours. Sawing, therefore, mostly took place in the middle of the night.

Before the opening of the road to traffic, the joints were sealed with a two-component compound (resin and polysulphide).

SPECIAL PRECAUTIONS DURING CONSTRUCTION

As was mentioned above, the adverse atmospheric conditions prevailing during construction made it necessary to take special measures to ensure correct placing of the concrete. In (14) a comprehensive list is given of the precautions advisable in the case of construction of a concrete pavement under very warm weather conditions. The measures taken in the case described in this paper, some of which have been mentioned earlier, were those detailed below:

a) In order to reduce as far as possible the effect of the temperature on the setting of the cement, the concrete placing took place daily between 16.00 hours and 02.00 hours of the following day. Thus the warmest hours of the day (midday) were avoided at the moment when setting began.

b) Coarse aggregates (fractions of 5-20 mm and 20-40 mm) were continuously watered to keep their temperature down. Due to the low water retention capacity of these aggregate fractions, this addition of water did not pose any problem in the subsequent dosing of concrete.

c) As previously mentioned, the cement to be used was carefully selected, ensuring that its hydration heat was sufficiently low (see Table 1).

d) In order to avoid the direct action of the sun's rays on the batching plant, this was installed beneath an awning. In addition, a careful check of the temperature of the various materials was carried out and the following maximum temperature values were allowed: water, 25°C; cement, 50°C; fresh concrete, 30°C. In the event that these conditions were not met, appropriate measures were taken to correct them by protecting the materials from the sun's action and waiting, if possible, until they cooled down.

e) Ensuring adequate workability of the concrete when it reached the paver. To this end, a slump of 2 ± 0.5 cm was fixed for concrete immediately after mixing so that it would reach the paver with a slump always less than 2.

f) Ensuring correct curing of the concrete. For this, as previously mentioned, a prior study was carried out to ensure the effectiveness of the curing compounds to be used. Furthermore, an external cover was fixed to the curing compound spreading equipment to prevent the compound being dispersed by the wind, and so producing a non-homogeneous distribution on the surface of the layers. Despite this, concrete laying was stopped when wind speed exceeded 40 km/h. In addition, the surface was kept damp for three days following concrete laying, by means of a water spray.

The absence of correlations between weather conditions during the construction period (from June to September) and the results of the checks carried out (concrete workability, mechanical strengths, etc.) shows that the precautions taken were sufficient to avoid negative climatic effects during the works.

STUDY OF JOINT OPENING

The prevailing atmospheric conditions (specifically the severe thermal gradients) and the use of siliceous aggregates made it advisable to carry out a follow-up of the opening of cracks in the lean concrete base and of the sawn joints in the top-layer. In so doing, it would be possible to carry out, in parallel, a check on the behaviour of the concretes concerned, shortly after placing. Cracks excessively near to or notably divergent from the perpendicular to the axis of the roadway would have been an indication of some problem in the pavement. In such a case, it would have been necessary to analyze the causes of such problems (e.g. insufficient precautions in respect of the prevailing weather conditions) and to seek and apply the appropriate corrective measures.

This follow-up could be only partial in the case of the base concrete since, once the top-layer concrete had been laid, it was impossible to see the cracks. In the case of the top-layer concrete, the check was carried out by observation of the vertical side of the slab where a crack had been noted in the vicinity of the opened joint. All these checks were carried out daily.

Practically all the cracks in the lean concrete base appeared perpendicular to the road axis, with a maximum deviation of the order of 10°. Furthermore, over 98% of the cracks which appeared in the first half-roadway were reflected in the same section of the second roadway due to the effect of the thermal gradients and to friction between the slabs at the contact edges.

The relationship between the spacing between cracks in the lean concrete base and the number of them observed after 36 hours following placing, is shown in Figures 3 and 4. Figure 3 shows the cumulative curve of the number of cracks, while Figure 4 shows the distribution curve, taking an interval of 1 m in abscissas, which is that which makes an easily interpretable graph. In Figures 5 and 6 these same relations have been shown after a longer term (up to the placing of the top-layer concrete several days later which, as has been mentioned, was the maximum period in which the study on the base could be carried out). The results included in these graphs (Figures 3 to 6) relate to a length of 8,329 m of half the roadway. After 36 hours (Figures 3 and 4), a total of 984 cracks was counted which gives an average distance between cracks of 8.5 m. After several days (Figures 5 and 6), the total number of cracks counted was 1,210, producing an average distance of 6.9 m. Logically, with the passing of time, the number of cracks went on increasing and the average distance between them decreasing until the final situation was reached.

It is interesting to note in these Figures, especially in numbers 4 and 6, that the distances between cracks exhibit some clearly marked maxima. These maxima coincide with distances between cracks of 4 m and multiples of this distance (8 m, 12 m, 16 m). This fact indicates that the concrete cracking process tends to be produced at distance intervals of 4 m (i.e. about 25 times the thickness of the layer), which corresponds to the final situation and that, in the initial stages following the laying of the concrete, the cracks occur at multiples of this distance (of the order of 16 m), creating slabs which are subsequently sub-divided (16 m -> 8 m -> 4 m). This process can be observed more clearly in Figure 7 (superposition of Figures 3 and 5) and in Figure 8 (superposition of Figures 4 and 6). In Figure 8 a certain degree of deviation towards the left of the graph can be seen with the passing of time, maintaining the distances in which the maxima are produced.

With regard to the top-layer concrete, information was obtained about the interval between opening of joints and spreading of concrete. The evolution of the opening of joints followed a pattern similar to that described for the base, although in this case, logically, the spacing was pre-established by the sawn cuts. Consequently, the first joints which opened were 12 or 16 m apart. Later, the rest of them opened. Only at the beginning of the job, as mentioned earlier, did spontaneous cracks appear due to the reflection of the cracks in the base as a result of the insufficient separation created between the two layers by the curing compound applied to the base.

In Figures 9 and 10, the results are shown in this case relating to the joints opened depending on the time elapsed from the laying of the concrete, this one divided into intervals of 24 hours. Figure 9 corresponds to the distribution curve and Figure 10 to the cumulative curve. In both Figures, two cases are differentiated. The first relates to the major portion of the work, when the temperature was usually over 35°C and the second relates to the last week of the job, when climatic conditions were milder and the temperature usually under 25°C. These curves demonstrate the importance which temperature, particularly thermal gradients, has on the speed of joint opening. In this respect, for example, almost two thirds of the joints were open at 36 hours from the concrete placing when temperatures were in excess of 35°C, while only a quarter of them were open when temperatures were under 25°C. Clearly, in the long term in both cases, 100% of joints opened. Consequently, joints must be sawn in time to avoid spontaneous cracking, and this depends on the weather conditions during construction (temperature and thermal gradients). In the case described in this paper, joints had to be sawn before, and certainly not later than, 12 hours after concrete placing.

PERFORMANCE OF THE PAVEMENT

As previously mentioned, the extreme weather conditions prevailing when the pavement was constructed, as well as the modification of the official Standards for the project subsequent to its construction, made it advisable to carry out a special follow-up of its performance. Therefore, in 1986, 1987 and 1992 successive inspection campaigns were carried out, in which studies were made of pavement evenness, its texture and the strength of concrete (inspection campaigns of 1986 and 1987) and the existence of pumping and faulting in the pavement and its state of cracking (inspection campaigns of 1986, 1987 and 1992).

Only in the case of the state of cracking of the slabs was some evolution observed over the years, as will be described in more detail below. At all events, this cracking is still at present only somewhat incipient. Both in regard to the evenness of the pavement and to its texture or to concrete strength, no significant variations have been observed, compared with the initial post-construction situation. Nor have any indications of pumping or faulting been observed. In view of the foregoing, and despite the state of cracking to be described below, it can be stated that both the project specifications (e.g. the non-erodible lean concrete base to prevent pumping or the use of siliceous aggregates to ensure durability of texture), and the precautions taken during construction have so far been effective, even with the traffic density which has been greater than that initially envisioned.

With regard to the cracking observed, Figure 11 shows the 8 different types of cracks which were taken into consideration when carrying out the count of the number of slabs affected in each case and which have been identified successively by the letters A to H. These types of cracks were selected in an effort to include the majority of foreseeable possibilities and so that each of them corresponded to a specific case of interest. Thus, types A and B correspond to cracks which divide the slabs in half, either (approximately) transversally (A) or parallel (B) to the roadway axis; types C and D to corner cracks which form a triangle, either acute (C) or obtuse (D); type E to localized edge defects; type F to small surface cracks, usually at 45° to the roadway axis, which do not reach the edges, and types G and H to cracks parallel (G) or transversal (H) to the roadway axis which start from one edge but which do not reach the other. Evidently, some other additional types could have been considered. Nevertheless, the types indicated could cover all the cases observed. The cause of the appearance of each of these types of cracks could be assigned to a specific phenomenon. However, with the exception of the cracks appearing in the short term which could have been due to shrinkage, the rest are indications of concrete fatigue. The count of the slabs affected was carried out distinguishing between the two lanes of the roadway.

Table 3 includes the results obtained from the counting of the affected slabs, both in terms of absolute value and percentage. In total, in each campaign, 4,150 slabs were checked, 2,075 in each traffic direction. As can be seen in this table, very few slabs presented cracks in the investigations of 1986 and 1987. In that of 1992 a clear increase in the slabs affected by some of the types of cracks can be observed, although in terms of relative value they continue to be few. The types which increased in the most significant manner were those corresponding to acute angle cracks at the corners of the slabs, forming a triangle (type C in Figure 11) and the cracks in the middle of the slab from the shoulder to the longitudinal joint, (type B in Figure 11). As previously mentioned, this increase in cracking is an indication of the progression of concrete fatigue, although it is still of little importance.

With regard to the results shown in Table 3, the following comments can be made:

- corner cracks have developed basically in the acute angles, while the obtuse angles have hardly presented any problems. This fact can be explained by taking into account the fact that, in acute angles, the breaking section is less and so, consequently, is the structural capacity. In spite of this, it is worth pointing out that the difference between some angles and others is very small (the 1/6 bias of the joint means only some 19° of difference). On the other hand, there could also have been an influence of the different effect of the traffic on consecutive slabs on passing from one to another;
- cracks have particularly developed from edge to edge, parallel to the roadway axis and not perpendicular to it. In this case, there could have been an influence from the specific stress state caused by traffic loads and thermal gradients;
- apart from the cracks mentioned in the foregoing points, the rest are few in number and hence it is difficult to extract any conclusions in respect of them;
- a clear distinction is observed between the number of slabs affected in relation to the traffic direction, in that the number is much higher for the northward direction. In view of these results, a specific traffic study was carried out in 1992 from which it was seen that there was no significant difference between the number of vehicles, light or heavy, travelling in each direction. Nevertheless, it was deduced taking into account the economic activity of the region that the commercial vehicles normally travelled loaded towards the north and normally returned empty towards the south, which explained the different incidence of the affected slabs in each of the two lanes.

In view of the results of these campaigns and of the good behaviour observed, no maintenance works have so far been carried out. Finally, it should be pointed out that part of the initial cracks produced in the top-layer by reflection from the base (of the order of 60%) have opened up again, according to the investigation carried out in 1992.

CONCLUSIONS

The main conclusions obtained from this job and from the studies carried out may be summarized in the following points:

a) By adopting suitable preventive measures it is possible to construct concrete pavements under relatively extreme weather conditions. In the case described in this paper, the temperatures were frequently in excess of 40°C and, on occasions, the wind speed exceeded 50 km/h. The measures adopted in this case included the use of a cement with low hydration heat, the control of the temperature of the various materials and of the concrete batching plant (watering of the aggregates and covering of the batching plant), the construction of the pavement during the coolest hours of the day (16.00 to 02.00 hrs), the laying of the concrete with very low variation in its workability or the use of an effective curing compound for the conditions in which it was to be used and its correct application on the concrete surface. The good results obtained have confirmed that the measures taken were sufficient.

b) The good performance of the pavement for 7 years following its construction indicates that the project specifications were suitable, even though the sections used in accordance with the traffic and the type of subgrade existing (short slabs without dowels, on a non-erodible lean concrete base) were subsequently eliminated from the Standard and replaced by others with a thicker structural section and dowels. It should also be stressed that the traffic has been substantially heavier than envisioned. The factors which are considered especially important in this respect are, on the one hand, careful construction and, on the other hand, the use of a non-erodible base to avoid pumping and consequent faulting.

c) If a complete lack of adherence between the base and the top-layer is not guaranteed, it is very likely that cracks in the base will be reflected in the top-layer. The curing compound used in this case, initially selected to prevent adhesion, did not function satisfactorily and it was necessary to use polythene sheeting to separate physically the base concrete from that of the top-layer.

d) Resin injections used to repair the reflective cracks from the base in the top-layer caused by the adhesion between the two layers turned out not to be completely effective in the long run. Both the opening of the joints neighbouring the cracks and the tests carried out on cores extracted from cracked zones shortly after their injection suggested a good behaviour of these repairs. Despite this, in 1992 about 60% of the treated cracks had reopened.

e) The study carried out on the appearance of cracks and the opening of joints in the pavement layers indicates that, in this case, cracking has developed predominantly on the basis of initial distances of multiples of 4 m (8 m, 12 m, 16 m, 24 m) which, with time, are subdivided until the final situation is reached with, in most cases, slabs 4 m long.

f) The temperature and specifically the thermal gradients have a very important influence on the opening of the pavement joints. The lower temperature during the last week of the placing of the pavement discussed in this paper produced the proof of this difference. As a significant fact it may be pointed out that, in this case, after 36 hours following the laying, a temperature in excess of 35°C had already brought about the opening of almost two thirds of the sawn joints, whereas with a temperature of under 25°C, the opening of only a quarter of the joints had occurred. This fact also indicates that it is essential to saw the slabs in time (even only 12 hours after placing) in order to avoid spontaneous cracks, if the temperature is very high.

g) From the follow-up campaigns carried out in 1986, 1987 and 1992, it has been seen that the pavement is performing well. In particular, from the study of cracked slabs carried out in each of these years, it was observed that relatively few slabs have begun to show fatigue symptoms.

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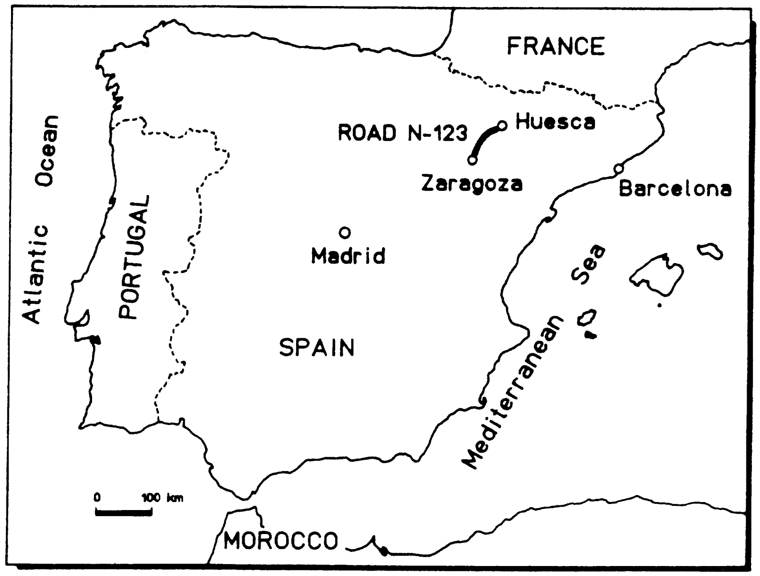

Figure 1. Location of the road.

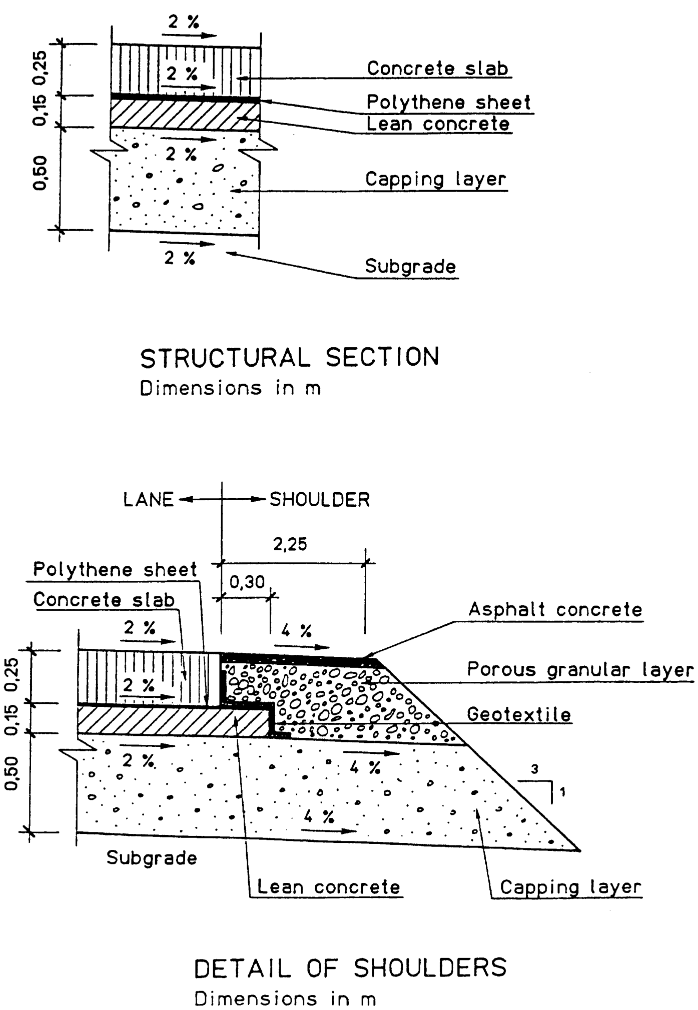

Figure 2. Structural section and detail of pavement shoulders.

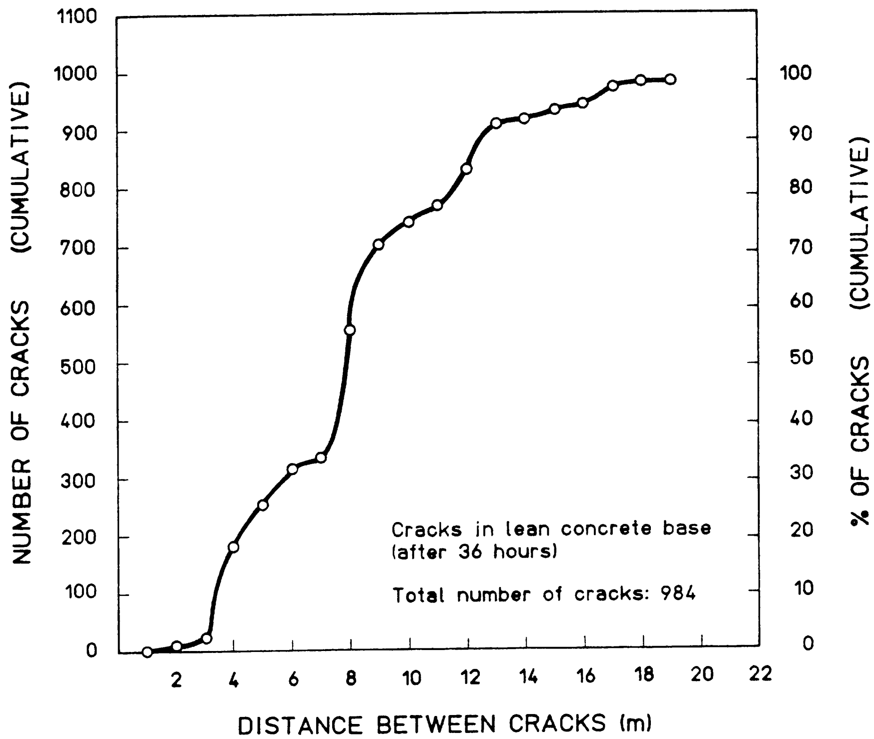

Figure 3. Cumulative relationship between number of cracks and crack distance for the lean concrete base (after 36 hours).

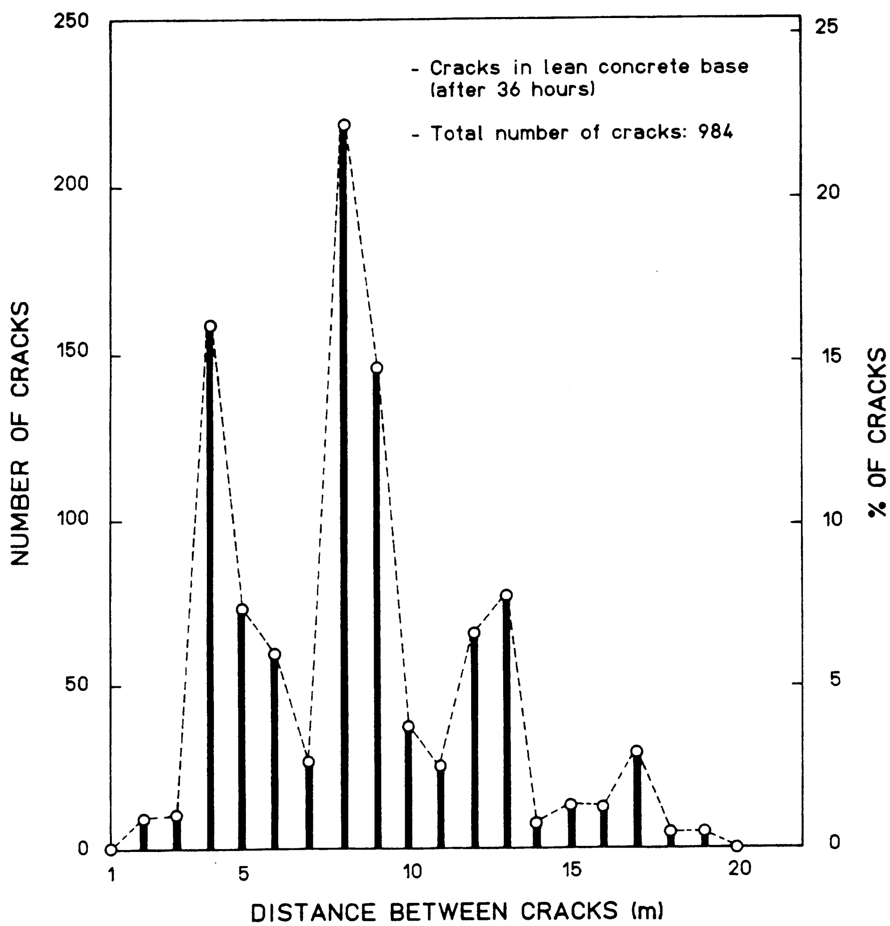

Figure 4. Number of cracks – crack distance relationship for the lean concrete base (after 36 hours).

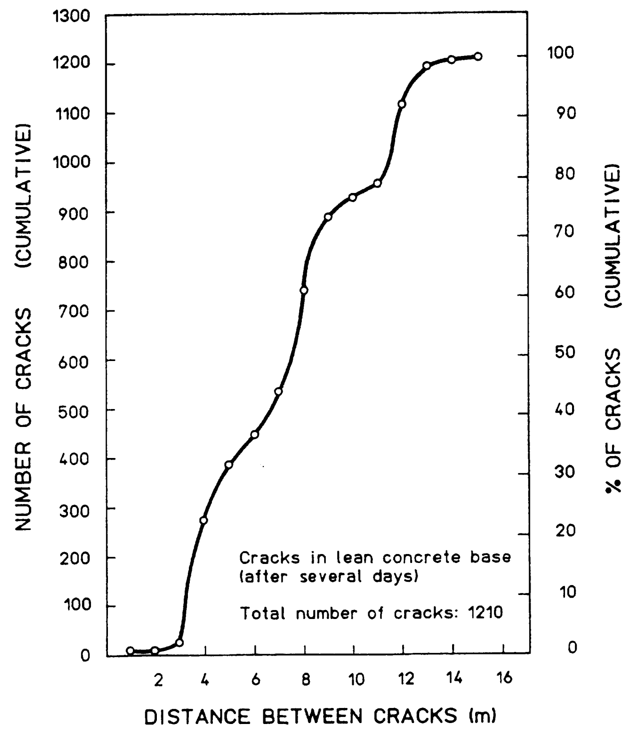

Figure 5. Cumulative relationship between number of cracks and crack distance for the lean concrete base (after several days).

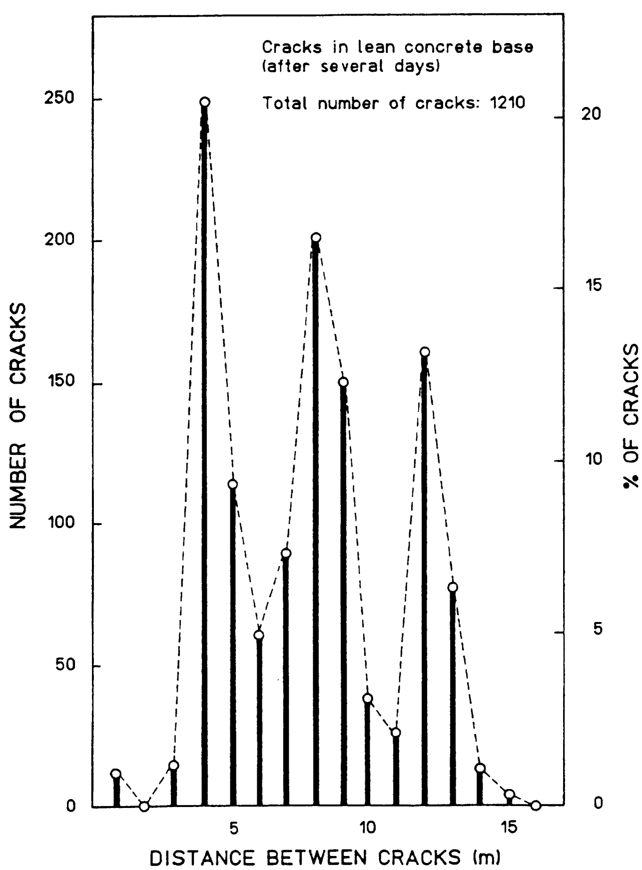

Figure 6. Number of cracks – crack distance relationship for the lean concrete base (after several days).

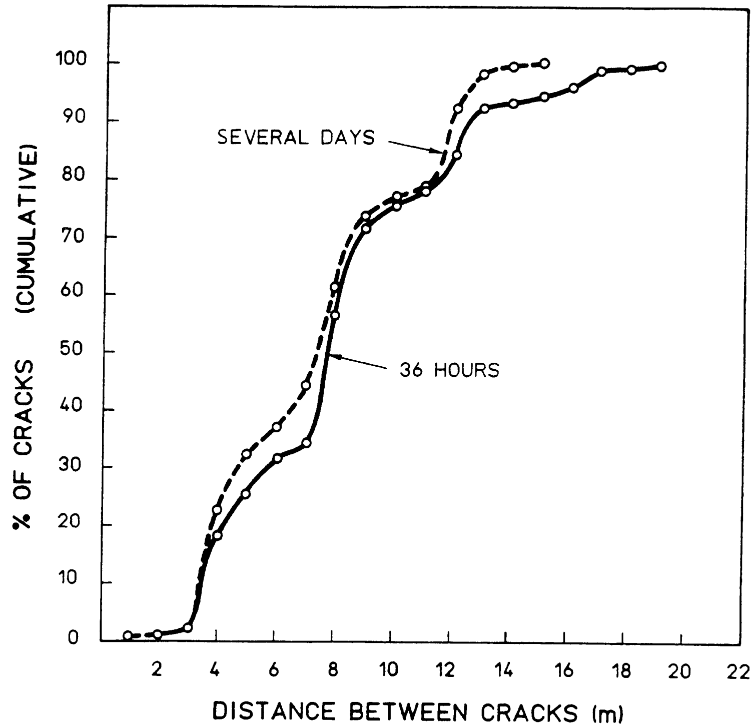

Figure 7. Cumulative relationship between number of cracks and crack distance for the lean concrete base (after 36 hours and after several days).

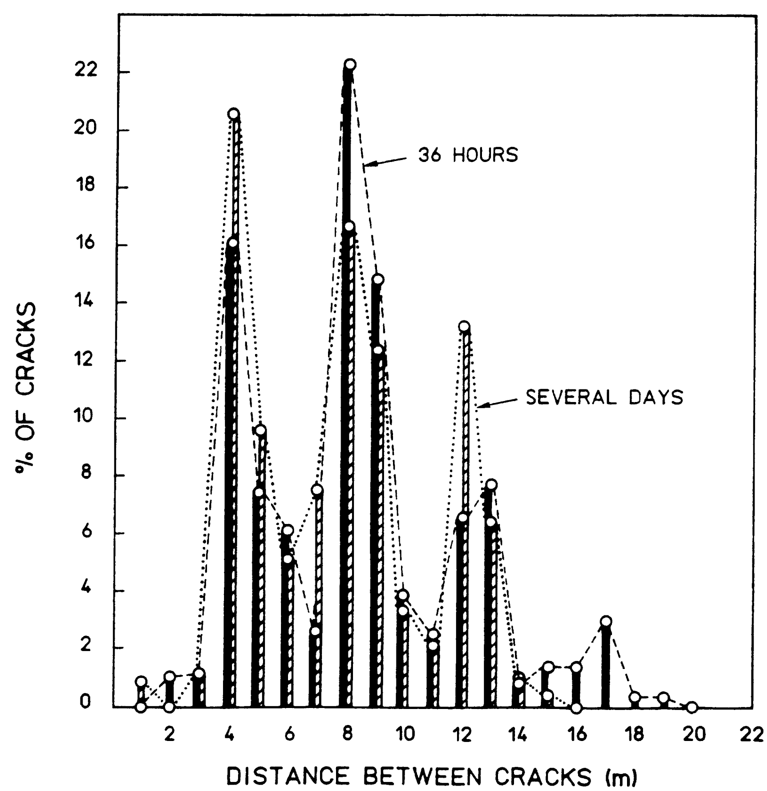

Figure 8. Number of cracks – crack distance relationship for the lean concrete base (after 36 hours and after several days).

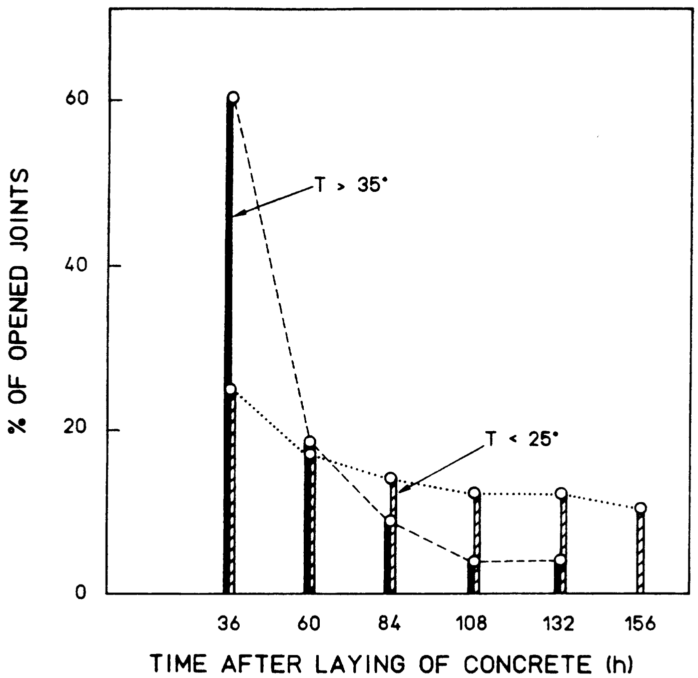

Figure 9. Evolution of opened joint percentage of the top layer with time after concrete laying when temperature is higher than 35°C or lower than 25°C.

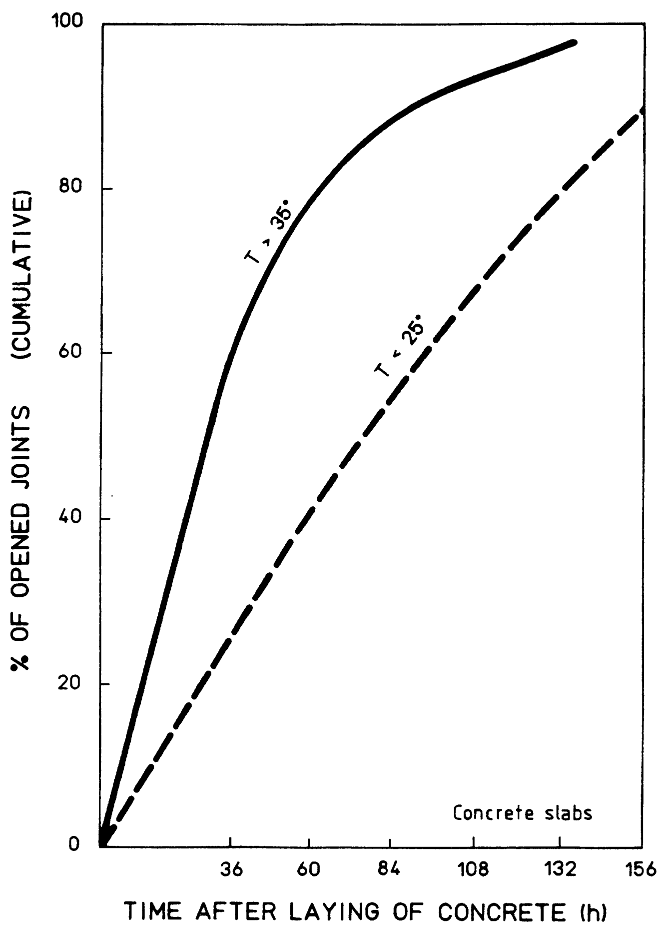

Figure 10. Evolution of cumulative opened joint percentage of the top layer with time after concrete laying when temperature is higher than 35°C or lower than 25°C.

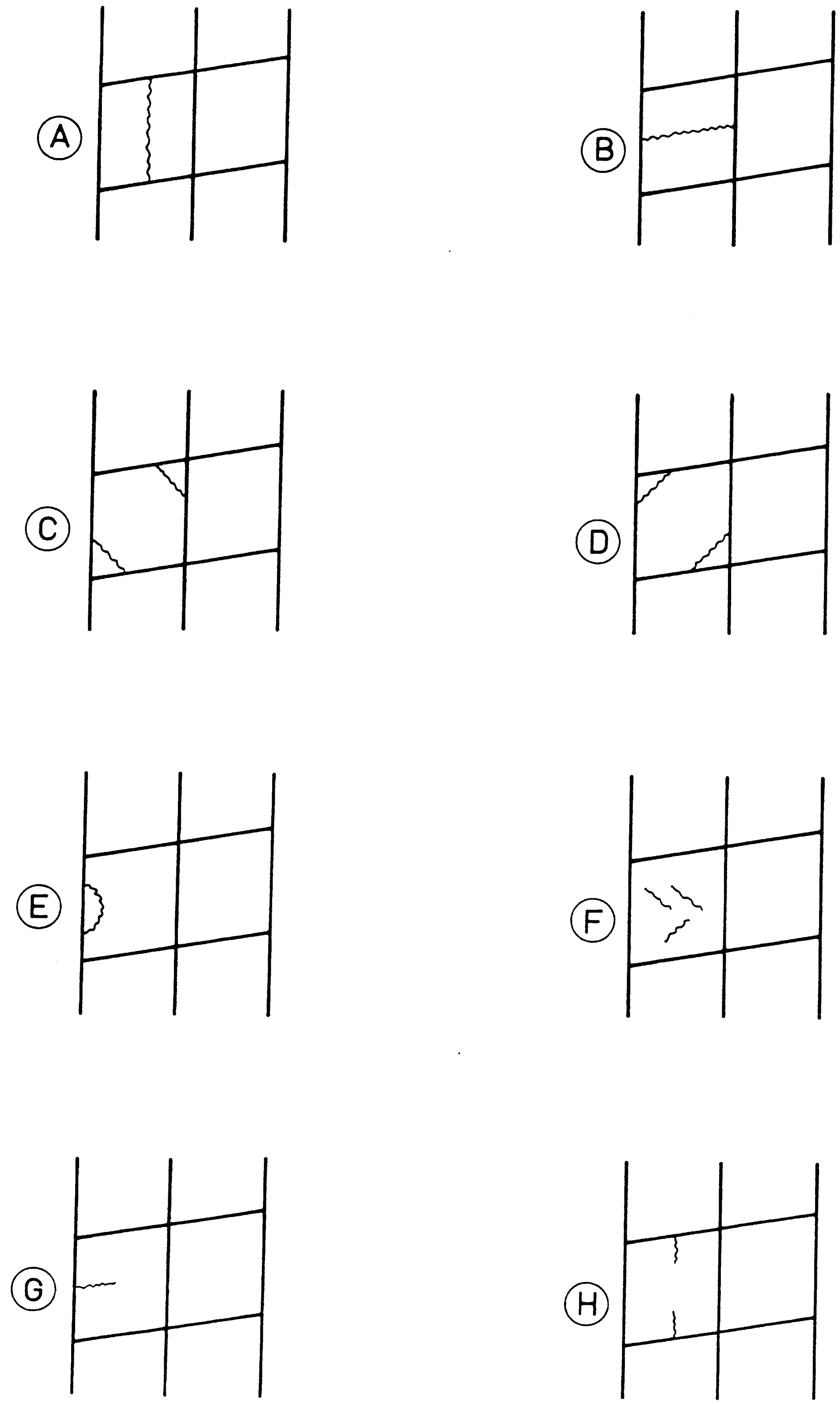

Figure 11. Crack types considered in the 1986, 1987 and 1992 inspection campaigns.

TABLE 1

CHARACTERISTICS OF CEMENT

<table>
<tr><td colspan="2">% passing 90 μm sieve</td><td colspan="3">97.45</td></tr>
<tr><td colspan="2" rowspan="2">Setting time</td><td colspan="2">Initial</td><td colspan="2">Final</td></tr>
<tr><td colspan="2">2h 45min</td><td colspan="2">3h 50min</td></tr>
<tr><td>Strength</td><td>3 days</td><td>7 days</td><td>28 days</td><td>90 days</td></tr>
<tr><td>Flexural (MPa)</td><td>4.3</td><td>5.5</td><td>7.4</td><td>8.5</td></tr>
<tr><td>Compressive (MPa)</td><td>21.5</td><td>28.5</td><td>42.0</td><td>51.5</td></tr>
</table>

TABLE 2

RESULTS OF SLUMP, COMPRESSIVE AND FLEXURAL STRENGTH OF CONCRETES

<table>
<tr><td>Test</td><td colspan="2">Base Concrete</td><td colspan="2">Top-layer Concrete</td></tr>
<tr><td>Slump</td><td colspan="2">x=1.89 cm
n=385
σ=0.68 cm</td><td colspan="2">x=2.12 cm
n=612
σ=0.54 cm</td></tr>
<tr><td rowspan="2">Compressive Strength</td><td>7 days</td><td>28 days</td><td colspan="2" rowspan="2"></td></tr>
<tr><td>x=9.62 MPa
n=169
σ=2.04 MPa</td><td>x=14.51 MPa
n=147
σ=1.91 MPa</td></tr>
<tr><td rowspan="2">Flexural Strength</td><td colspan="2" rowspan="2"></td><td>28 days</td><td>90 days</td></tr>
<tr><td>x=5.86 MPa
n=415
σ=0.92 MPa</td><td>x=6.52 MPa
n=195
σ=0.83 MPa</td></tr>
</table>

x = mean
n = number of specimens
σ = standard deviation

TABLE 3

NUMBER AND PERCENTAGE OF CRACKED SLABS OBSERVED IN 1986, 1987 AND 1992

Type of crack	1986		1987		1992	
	NL	SL	NL	SL	NL	SL
A	-	-	-	-	2 (0.10%)	-
B	1 (0.05%)	-	11 (0.53%)	-	37 (1.78%)	4 (0.20%)
C	2 (0.10%)	4 (0.20%)	15 (0.75%)	5 (0.25%)	123 (5.93%)	37 (1.78%)
D	1 (0.05%)	-	1 (0.05%)	2 (0.10%)	6 (0.29%)	2 (0.10%)
E	-	1 (0.05%)	-	1 (0.05%)	4 (0.20%)	6 (0.30%)
F	-	2 (0.10%)	-	-	14 (0.67%)	15 (0.75%)
G	-	-	-	-	14 (0.67%)	-
H	-	-	-	-	8 (0.40%)	1 (0.05%)

NL = Northward lane
SL = Southward lane