

CRACKING OF CONTINUOUSLY REINFORCED CONCRETE PAVEMENTS AT A YOUNG AGE

Jean-Louis NISSOUX, Laboratoire Central des Ponts et Chaussées (LCPC)
 Thierry LEMARIGNIER, Doctor ENPC
 Jacques MARZIN, Lafarge Ciments Company
 Paul ACKER, Laboratoire Central des Ponts et Chaussées (LCPC)

Cement concrete pavements have remained less common in France than in many other countries. This is primarily because of their relative lack of comfort, due to the presence, at regular intervals, of shrinkage joints intended to "localize" the transverse cracks caused by hydraulic and thermal shrinkage of the concrete, and to the evolution of these joints under traffic. These reasons have led to an interest in continuously reinforced concrete (CRC) in France, and, recently, pavements made of CRC have shown that this rigid pavement technique can be a very attractive alternative. It eliminates shrinkage joints and controls cracking (spacing and opening) by suitable longitudinal reinforcement.

How and to what extent is the transverse cracking of pavements effectively controlled on current sites? Can the cost of the longitudinal reinforcements and of their placement be reduced to make CRC more competitive? Such are a few of the questions that motivated the "Limited Cracking, Organization of Shrinkage" national project (FLORE) conducted from 1992 to 1996 under the aegis of the "Institut pour la recherche appliquée et l'expérimentation en génie civil" (IREX), with the participation of the professionals concerned by the subject [1]. This joint research programme has included, among other things, the following work, most of which has been described in a doctoral dissertation [2]:

- modelling the behaviour of CRCPs, treated as linear ribbons of homogeneous concrete subjected to a monotonic shrinkage that is restrained both by the presence of a continuous reinforcement and by friction with the base [2, 3].
- developing a new test to characterize the bond between the concrete and reinforcement and make it possible to apply a loading that is simpler, easier to analyze, and more realistic than in existing tests, especially when the cause of the cracks is shrinkage.
- developing an original half-scale test bench giving an experimental representation allowing comparison with a numerical model.
- a first parametric study on this bench, in which the slab thickness, the type of reinforcement (round or flat), and the type of substrate (lean concrete, geotextile, lubricated device) were varied; the influence of the percentage of reinforcements was also studied, using a numerical model fitted to the experimental results.

The article presents the main results of the last three parts of the work.

1 - CHARACTERIZATION OF STEEL-CONCRETE BOND: PULL OUT TEST OR TEST OF CONCRETE-REINFORCEMENT BOND?

This test is intended to validate a numerical model representative of the bond between a reinforcement and the concrete that surrounds it. In effect, in the tests of concrete-steel bond performed so far, the concrete block is simply placed on a fixed metallic slab. The mechanical loading applied, and in particular the distribution of stresses in the concrete, differ from that resulting from shrinkage, and the dispersion of the test results is large. The concrete-reinforcement bond test (*ABA in French Adhérence Béton Armature*) has been developed to alleviate these two drawbacks of the *pull out test*.

The test consists of subjecting a cylindrical specimen of concrete, through the axis of which passes the reinforcement of which it is desired to evaluate the bond, to a tensile force sufficient to attain a crack width in the central part of the specimen of up to 1.5 mm. The test is intended to characterize the interaction between

the reinforcement and the concrete. It specifically concerns the Concrete/Reinforcement pair. The mechanical strength of the concrete (in compression, in splitting, or in bending) and the yield strength of the steel must be determined at the same time.

The specimens were concrete cylinders 40 cm high (H) and 25 cm in diameter (D) in the first tests, 50 and 35 cm in the last tests [3] ; H and D are chosen according to the yield strength of the steel and the tensile strength of the concrete. The metallic reinforcement passes through the centre of the cylinder. The cylinder is divided in two in its midplane by a thin polyane washer (thickness 100 μm) that is perforated in the vicinity of the reinforcement.

The specimen is fitted with 16 anchors embedded in the concrete (8 at the top and 8 at the bottom) to transmit and distribute the tensile force.

The experimental device makes it possible to align the axis of the specimen on that of the press. This ensures the application of a pure tension to the steel and so avoids introducing spurious bending. This may be checked by the measurements from the three displacement sensors for the various values of applied force F. Tensioning is continuous and at a fixed rate of 0.03 mm/min, as specified by the draft standard [4].

The bond test is terminated:

- if the mean crack opening exceeds 1.5 mm,
- if the force applied is such that the steel is plasticized (yield strength exceeded),
- if the specimen exhibits generalized damage.

1.1 - Acoustic Transmission and Cracking of Concrete

Acoustic transmission techniques have been used at the Laboratoire Central des Ponts et Chaussées (LCPC) for several years to monitor the cracking of concrete specimens subjected to a loading. They detect and locate microcracks created inside the specimen, making it possible to ascertain the dimensions of the damaged zone at any stage of loading [5]. This technique has been used to monitor some ABA tests, for the purpose of determining the length of concrete damaged in the vicinity of the reinforcement, in other words to determine the length over which the bond between the reinforcement and the concrete that surrounds it is broken. The acoustic signal recorded is produced either when a microcrack is created by loss of cohesion of the grains of sand or when existing microcracks coalesce. These microcracks are detected by sensors bonded to the surface of the specimen.

Two localization modes have been used:

- linear localization: two sensors are bonded to the ends of the reinforcement. They make it possible to calculate the locations of sources in the immediate vicinity of the reinforcement,
- plane localization: four sensors are placed on the surface of the specimen, in a square 175 mm on a side, and determine a plane located 3 cm above the plane of the crack.

1.2 - Numerical Modelling of Bond Tests

Finite-element numerical modelling of the ABA test is performed by the César-Lcpc software package, using special interface elements. It was based on the tests described above.

In this study, the meshes that reproduce the geometry of the loaded specimens are defined. For each diameter ($\varnothing 6$, $\varnothing 8$, $\varnothing 10$, $\varnothing 12$) of round steel reinforcement, the structure is discretized. The cylindrical geometry of the parts makes it possible to do two-dimensional calculations having symmetry of revolution and model only a quarter of the structure (X = 125 mm, Y = 200 mm). The finite elements are triangular elements having 6 nodes and contact elements also having 6 nodes (figure 1).

1.3 - Conclusions

This new test led to the following conclusions, some of which are illustrated in figure 2:

- In a concrete road, under the conditions of the study, with notched round reinforcements of FeE 500 more than 10 mm in diameter, the anchoring of the reinforcement is such that for a crack opening of 0.02 mm, the steel is loaded nearly to its yield strength.
- Under the same conditions, the Flexarm (steel notched ribbon) is loaded to only 60 % of its yield strength; the notching had to be changed to reach 100 %. This change has given birth to the Flexarm + TM.
- There is a linear relation between the reinforcement diameter and the crack opening that corresponds to a stress of 500 MPa, the guaranteed yield strength of the reinforcements commonly used in France.
- There is a short zone, approximately 40 mm long, where the reinforcement is completely unbonded from the concrete and only frictional contact persists in this zone. The size of this zone can be determined by the penetration of a fluid dye (Organol Red) in the edges of the centre crack in the ABA test and confirmed by ABA tests coupled with damage location by acoustic emission.
- For notched round reinforcements of FeE 500 10 mm or more in diameter, the dimensions of the ABA test specimen should be increased; this was done in the tests following the above-mentioned series.
- The two-dimensional model correctly represents the ABA test and can be used both to analyze the stresses that develop round the reinforcement and to determine the parameters of the steel/concrete contact. The quality of the simulation appears to be rather insensitive to the fineness of mesh (from 340 to 2500 nodes).

2 - RESTRAINED DISPLACEMENT TEST OF REINFORCED CONCRETE

2.1 - Choice of Test Object

The smallest element representative of the structure can be determined from the planes of symmetry of the structure, which are:

- the vertical plane midway between two cracks
- the central plane midway between two reinforcements
- the vertical plane midway between the edges of a crack.

In fact, the length L between two cracks is not known. One is therefore led to design a longer test object, ideally three to four times greater than L , in order to induce the formation of at least two cracks, so that the behaviour between these two cracks will be independent of the boundary conditions of the experimental device and therefore actually representative of a CRC.

We use a device designed so that the fixing of the ends of the specimen imposes zero horizontal displacement in the steel and in the concrete. In this case, the probability of appearance of the first crack is uniform, since the strains of the concrete specimen are zero at both ends. Thus, the stresses induced by the shrinkage will increase uniformly in the concrete and the crack can appear at a small distance from one of the ends. But if this distance is less than the anchoring length, (L_a), the crack will not behave like a real crack (asymmetry of anchoring and of friction).

To avoid this, we must favour the appearance of the crack in the central zone of the specimen. This leads us to use a specimen with widened ends ("dovetail").

2.2 - The Equipment

The restrained shrinkage bench includes a very rigid frame, an anchoring device at each end, means of measurement of the displacements and of the force, and a mould in which to make the specimens. This machine can keep the length of a specimen practically constant once it is poured in the mould. It restrains the expansion or shrinkage of the material as it ages (figure 3).

The rigidity of the mechanical subassembly and the anchoring system at both ends of the frame are intended to limit the variations of length of the specimen.

The depth of the mould with slipping internal faces, allows the pouring of a test slab 15 cm wide in the running section. The length of the concrete specimen is 2.62 m. It is extended at both ends by a 0.365 m anchoring zone. The height is variable, making it possible to test thick slabs or reinforced concrete on various substrates.

The specific rigidity of the frame can not be infinite; we decided, a priori, that it should be such that the strains of the frame are less than 5 % of the strains caused by shrinkage in the concrete structure studied. This corresponds, for a total moisture shrinkage of approximately 300 $\mu\text{m/m}$, and a bench 4 m long, to a variation of 0.06 mm. There is then in the specimen a tensile force of the order of 150 kN.

The design of the bench is based on a frame with longitudinal members consisting of high-performance concrete blocks (HPC - 140 MPa) post-tensioned by Dividag bars and, at each end, a rigid steel cross-member.

The end slab is joined to the cross-member by eight ϕ 30-mm ties (cross-sectional area 707 mm^2 each). The mean tensile force in a tie does not exceed 18 kN. Note that the forces transmitted are measured by bolts having necks cut on a lathe, to which gauges are bonded. The total elongation of the anchoring system is less than 0.07 mm.

To measure restrained shrinkage in different environments (variable temperature, etc.), a device that can simulate a thermal shock on the test object has been imagined. An insulating caisson is built round the HPC blocks constituting the bench. To reproduce the effect of lowering the temperature on the concrete bar, the bench is expanded by resistors on each prestressing bar.

Since HPC and steel have similar thermal expansion coefficients (between 10 and $12 \cdot 10^{-6}$ per degree), this test is performed practically without modifying the prestressing of the bench.

The variations of length of the bench are monitored using longitudinal invar steel rod and electronic sensors. Intermediate supports (rollers placed on an upright of the bench) bear the weight of the rod without introducing friction.

2.3 - Principle and Operation

The bench also includes a device to measure the forces developed by the restrained strains up to the time of cracking of the specimen. The force sensors incorporated in the anchoring bars at the ends of the specimen, and their calibration device, were designed at the LCPC. The forces exerted on the anchorings are centered, whatever the height (20 cm or 35 cm).

During the phase of swelling of the concrete, these force sensors are subjected to a compressive force and, during the phase of shrinkage, they are subjected, up to failure of the concrete, to a tensile force. This test makes it possible to observe the behaviour of a concrete as soon as it is placed, in other words as soon as it is bonded to the anchoring heads.

Gauges embedded in the concrete are used to measure the strains of the specimen. They are placed along the length of the specimen. Each test includes 10 gauges that are placed as close as possible to the top and bottom surfaces of the slab at the time of pouring, in the midplane of the specimen. Five pairs of gauges are placed at regular intervals of one sixth the length of the beam.

The temperature of the concrete is recorded at the same time at both heights.

To study the strains of the concrete simply, complementary moulds are arranged to measure the free shrinkage of the concrete as soon as it is placed. In this case, the dimensional variations of swelling and free shrinkage are recorded. A 2.7-metre measurement base is used to determine the global strain of the specimen, measured using an specific gauge described above.

2.4 - Study of Controlled Strains in the Bench

The evolution of the measured internal stresses and of the cracking in the bench in controlled shrinkage has been analyzed in the following cases:

- a thick slab test - specimen 35 cm high without reinforcement,
- a reinforced concrete test - specimen 20 cm high, on a slippery substrate, with a deformed round reinforcement 16 cm in diameter,
- a reinforced concrete test - specimen 20 cm high on a slippery substrate, with a Flexarm,
- a reinforced concrete test - specimen 16.4 cm high on a slippery substrate, with a Flexarm,
- a test - specimen 19.3 cm high on a composite geotextile,
- a test - specimen 20 cm high on a lean concrete.

The tests are performed in accordance with the procedure. The evolution of stresses due to the controlled shrinkage is rapid during the 48 first hours; the phenomenon then stabilizes.

As an illustration, the second test will be described below.

2.5 - Controlled Shrinkage, 20 cm slab with Round Reinforcement

This test uses a concrete bar 20 cm high on a slippery substrate; through it passes a round reinforcement 16 mm in diameter. The percentage of reinforcement is thus 0.67 %. The reinforcement used is taken from the same batch as the reinforcements tested in the ABA tests.

As in all of the tests, the side walls were disconnected from the end slabs before the swelling of the concrete, 10 hours after the production of the concrete.

The temperature rise in the concrete starts approximately 10 hours and 30 minutes after the addition of the mixing water. Starting from this time, a compression of the slab is observed. The maximum temperature is reached at 25 hours and is 25.5°C. At this time, the swelling of the concrete is maximum. A compressive force of 10,800 N or compressive stress of 0.34 MPa is measured. As the concrete cools, tensile stresses appear.

At 7 days, a thermal shock on a recently built pavement is simulated on the slab by heating and expansion of the frame.

In this test, three cracks were observed in the slab. The first crack formed at a force of 56,170 N, corresponding to a tensile stress of 1.78 MPa. The expansion of the frame is very small at this time because the difference between the temperatures recorded in the uprights of the HPC frame never exceed 1.5 °C. At the time of each cracking, the reinforcement takes out part of the forces released by the concrete. The tensile stress in the slab drops to 1.1 MPa. We continued the test to three failures to obtain an estimate of a critical cooling (figure 4).

Figure 5 shows the evolution of the strains measured by the gauges embedded in the concrete.

2.6 - Numerical Modelling of Tests on the Bench

The finite-element numerical modelling is done by the CESAR-LCPC software package, using special interface elements. It has been done with two-dimensional (2D) and three-dimensional (3D) models, on the basis of the restrained shrinkage tests reported in table 1.

As an example, the case of the concrete slab 20 cm thick with Flexarm reinforcement is presented here. For numerical reasons, we used a mesh corresponding to a concrete slab 1,200 mm long. This made it possible to model the slab between the two planes of symmetry constituted by the planes of two successive cracks, therefore flanking a crack.

Several loadings were simulated, with a maximum stress of 2.5 MPa. Failure occurred at an applied stress of 1.9 MPa. The opening indicated by the numerical calculation is of the order of 0.5 mm for this stress.

The cracking model used here is not a constitutive law, and so can not model the drop in stress that occurs following a failure in the concrete.

Figure 5 shows the longitudinal stresses in the steel and in the concrete at different distances from the crack.

Plotting the forces in the concrete and in the steel versus distance from the crack on the same graph produces a graphic representation of the profile of the force, a profile that appears to be bilinear.

2.7 - Conclusion of the numerical calculations

The numerical model used here yields a satisfactory description of the problems of steel-concrete contact. For example, in the case of the concrete slab 20 cm thick with a deformed Ø16 mm reinforcement, the test produced three cracks. From this is deduced an equivalent loading that corresponds to a lowering of the temperature by 4°C, 3.5°C and 3.5°C, for a total of 11°C for the 3 cracks. The order of magnitude of the crack openings is:

- 0.07 mm for the first when it appears,
- 0.13 mm for the first two when the second appears
- 0.32 for the first two and 0.19 mm for the third when the third appears.

Globally, the 2-D numerical calculation indicated a cracking pattern with openings of:

- 0.26 mm for the first when it appears
- 0.30 mm for the first and 0.28 mm for the second when the second appears
- 0.35 mm for the first and 0.30 mm for the second and third when the third appears.

The lengths over which there is loss of cohesion round the cracks are of the order of 500 mm.

In 2-D, the opening values are overestimated at the start of loading. At the end of loading, the order of magnitude of the openings is correct.

The numerical results from the 3-D calculation lead to a crack opening of the order of 0.22 mm for an applied stress of 1.85 MPa. The length over which there is loss of cohesion is then approximately 480 mm on either side of the crack.

3 - CONCLUSION

Calculation of steel-concrete structures calls for understanding the bonding mechanisms, then, to reproduce them, formulating models of behaviour representative of the interface between the two materials in contact.

In view of the researches already performed in this domain, we thought it essential to make use of a new test that would simulate the behaviour of a concrete adhering to a reinforcement and be capable of leading to a constitutive law for the interface. Analysis of these bond tests served to characterize, for a given reinforcement, the relation expressing the crack opening versus the applied tensile force. In addition, a linear relation was found between the reinforcement diameter and the crack opening that corresponds to it at an applied stress of 500 MPa, the guaranteed yield strength of the reinforcements commonly used in France. Steel-concrete contact phenomena influence in particular the functioning of pavements made of continuously reinforced concrete. The interpretation of laboratory bond tests leads to selection a simple linear elastic law with Coulomb friction criterion as the steel-concrete contact law.

For several types of reinforcements (round steels of different diameters and notched flat steels), numerical values for the coefficients C and ϕ of the contact law were obtained following a simulation of the tests by the CESAR-LCPC program. Under the test conditions and in the context of French sites, the values found for the contact parameters are: cohesion C close to 7.5 MPa for notched round Fe E500 steels 16 mm in diameter, and 4.5 MPa for Flexarm. The value of the angle of friction ϕ has little effect on the response to shrinkage loading, and the value $\phi = 5^\circ$ is proposed.

Based on this numerical modelling, it is found that shear is highly localized along the central reinforcement. It is noted that the length over which there is loss of cohesion, which corresponds to plastification of the interface, varies with the reinforcement diameter. It is also observed that the normal stresses that develop

along the interface are highly localized in its vicinity. The mechanical phenomena remain concentrated in the vicinity of the reinforcement over the anchoring length.

It is found that the bulk of the forces developed in the test bench are of thermal origin. The setting of the concrete is accompanied by an exothermal reaction that dilates the structure. Concrete hardens in a dilated condition, and the return to ambient temperature generates tensile stresses.

These tests have also made it possible to study the behaviour of three types of substrates on the bench. One is smooth, the second is a composite geotextile, and the third is a lean concrete. The results show that absorption of the mixing water by the composite geotextile leads to a loss of the mechanical strength values of the concrete.

The experimental apparatus used revealed a frictional behaviour of the CRC-lean concrete interface. This friction is due to the surface roughness of the lean concrete. The crack appeared at a high tensile stress. Analysis of the results leads to the conclusion that part of the tensile force measured when the crack appeared is due to the presence of the lean concrete. A bond breaker must therefore be placed between the CRC course and the the substrate.

In addition, this device was used to study, with the same concrete, applications with a deformed $\varnothing 16$ FeE 500 reinforcement and with a flat steel having a 40 mm x 2.44 mm cross-section. It was found that 0.4 % reinforcements in the slab with Flexarm and 0.67 % in the slab with a round steel lead in our bench to similar test cracking patterns. Two cracks were found in the test with Flexarm and three cracks in the test with the round steel, with an active slab length of 2.7 metres.

These tests were modelled in two, then three dimensions. The observed behaviour is globally consistent with the various experimental findings, in particular with the lengths over which there is loss of cohesion. The influence of cohesion, which acts in the law of friction, was also analyzed, as was that of the E-modulus. The modulus has no significant influence either on the length of loss of cohesion or on the crack opening. The 2D model seems to be less representative than the 3D model of the actual working of such a structure.

The various tests performed under this programme have shown that shear is highly localized along the central reinforcement and that the length of loss of cohesion varies with the reinforcement diameter. The percentage of reinforcements turns out to be an important parameter, because too low a percentage can cause plastification of the steel in the crack plane. The other important finding concerns the effects due to thermal shrinkage, which here seems to be the preponderant factor in the cracking mechanism. The logical consequence is to recommend, wherever possible, the use of calcareous aggregates, whose coefficient of expansion is substantially smaller than that of siliceous aggregates.

TABLES

TABLE 1 - Tests used to adjust the model of cracking by restrained shrinkage

TABLE 1 - Tests used to adjust the model of cracking by restrained shrinkage			
Slab thickness (cm)	Reinforcement		Type of substrate
	Type	Percentage (%)	
20	Ø 16 mm deformed bar	0.67	slippery
16.2	Flexarm	0.4	slippery
20	Flexarm	0.33	slippery

FIGURES

- Figure 1 - Mesh used for the finite-elements model of the ABA test.
- Figure 2 - Crack opening versus stress in steel for different reinforcements.
- Figure 3 - Evolution of controlled-shrinkage stress versus time in a slab reinforced with a $\varnothing 16$ mm deformed bar and having no friction with its substrate.
- Figure 4 - Evolution of strains measured by gauges embedded in concrete. The time origin is 12 h 30 min. This is the when the rigidity of the concrete becomes greater than that of the gauge. Plotting the measured strains produces a curve that corresponds to an extension of the gauges during the swelling of the concrete. Since the swelling is restrained, the extension is less than $10 \mu\text{m/m}$. The curves then show a contraction of the gauges during the thermal shrinkage.
- Figure 5 - Longitudinal stress in the steel and concrete. On either side of a crack, it is successively observed a substantial loss of cohesion zone (about 130 mm length), a zone of diffusion corresponding to deterioration of the steel-concrete bond (about 200 mm length) and after the stress and strain fields are uniform.

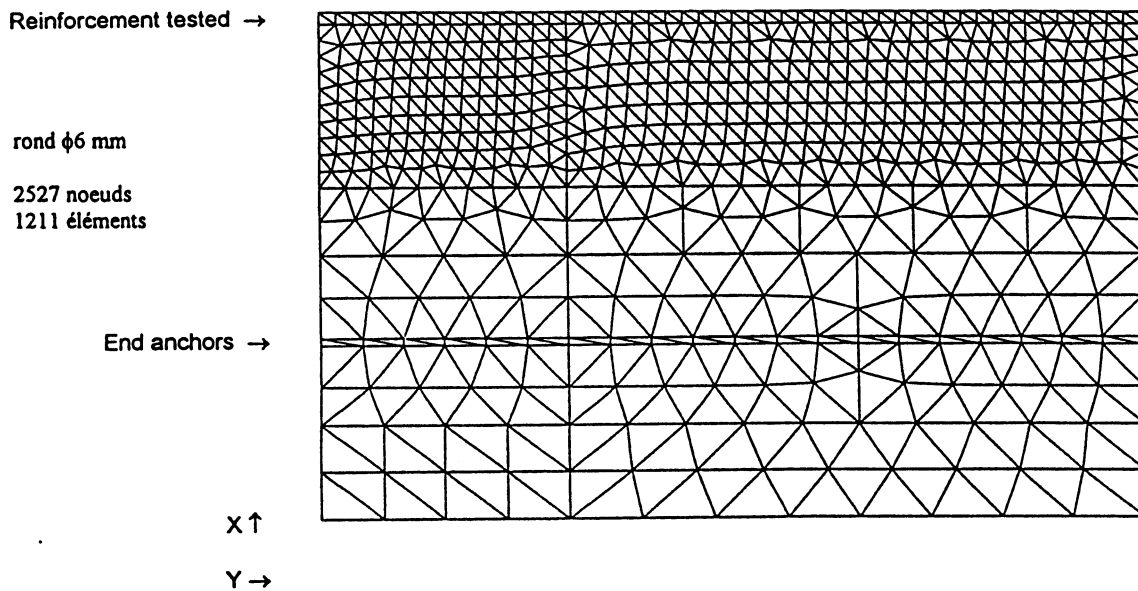


Figure 1 - Mesh used for the finite-elements model of the ABA test.

Crack opening versus stress in steel for different diameters and type of reinforcement

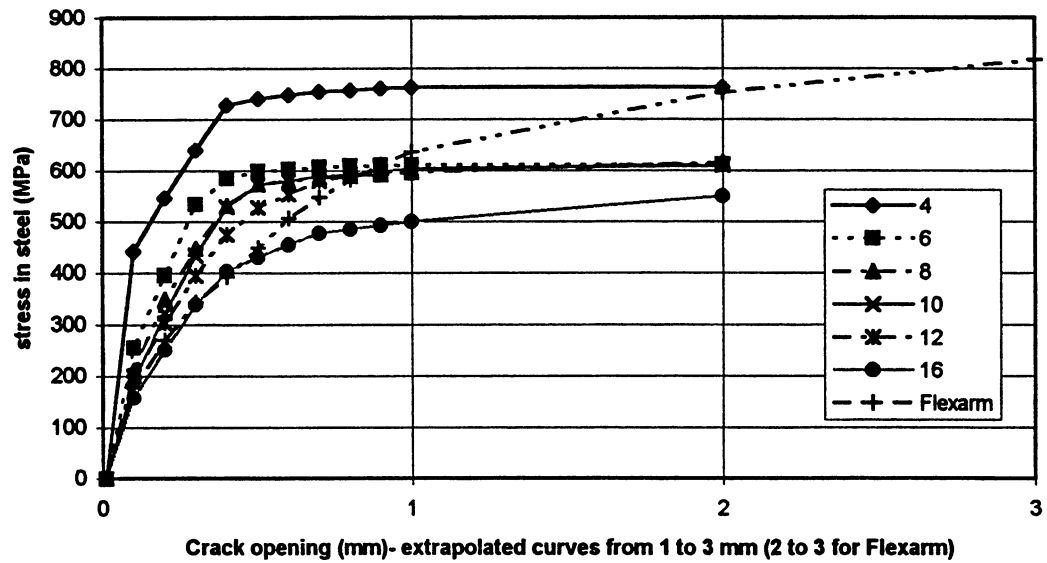


Figure 2 - Crack opening versus stress in steel for different reinforcements.

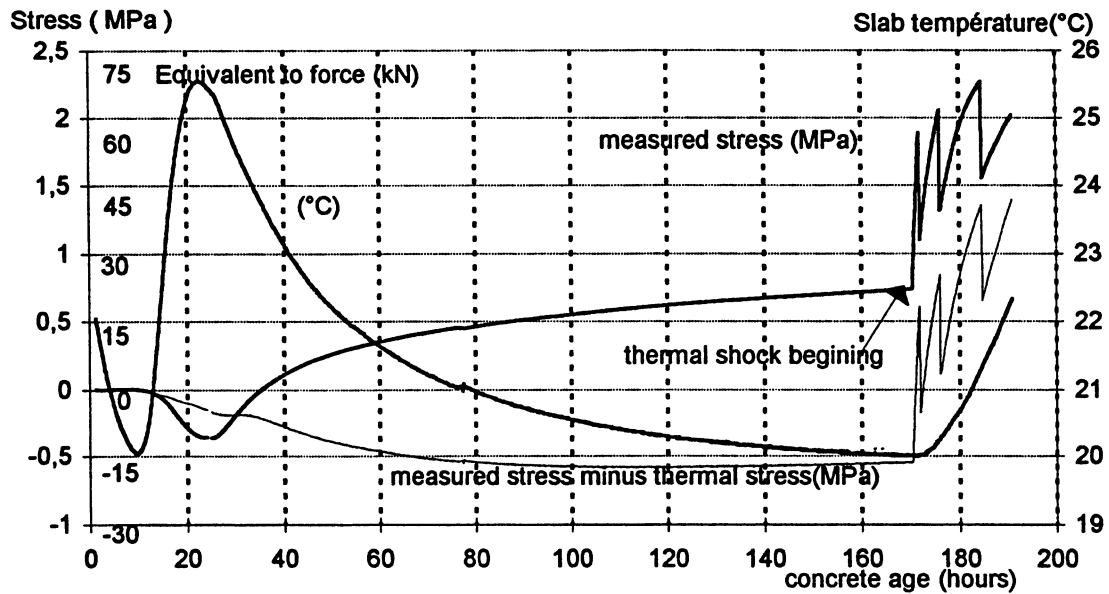


Figure 3 - Evolution of controlled-shrinkage stress versus time in a slab reinforced with a Ø16 mm deformed bar and having no friction with its substrate.

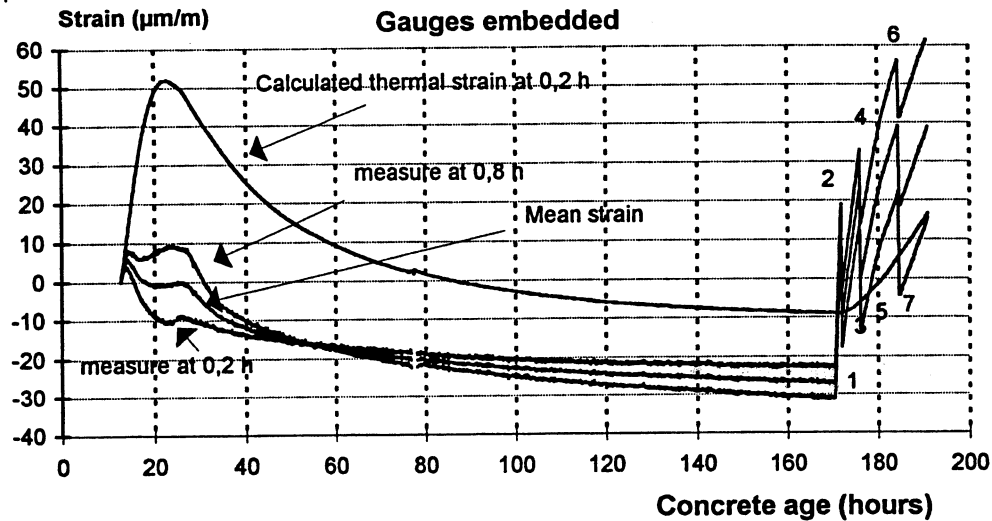


Figure 4 - Evolution of strains measured by gauges embedded in concrete. The time origin is 12 h 30 min. This is the when the rigidity of the concrete becomes greater than that of the gauge. Plotting the measured strains produces a curve that corresponds to an extension of the gauges during the swelling of the concrete. Since the swelling is restrained, the extension is less than $10 \mu\text{m/m}$. The curves then show a contraction of the gauges during the thermal shrinkage.

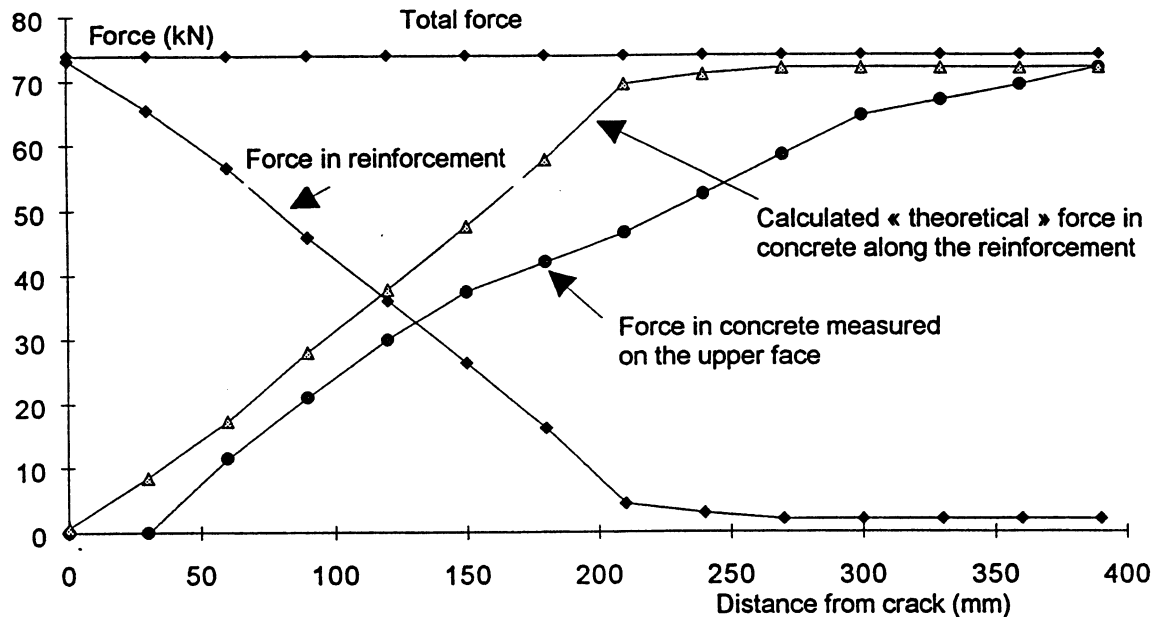


Figure 5 - Longitudinal stress in the steel and concrete. On either side of a crack, it is successively observed a substantial loss of cohesion zone (about 130 mm length), a zone of diffusion corresponding to deterioration of the steel-concrete bond (about 200 mm length) and after the stress and strain fields are uniform.

REFERENCES

1. P. ACKER, G. GUERIN, Chaussées en béton armé continu : réflexions sur le comportement mécanique et l'origine de la fissuration, Bull. des labo. des P. et Ch. n° 191, p 3-14, mai 1994.
2. T. LEMARIGNIER, Fissuration des chaussées en béton armé continu au jeune âge. Thèse de doctorat de l'ENPC, Paris juillet 1996.
3. A. BENNANI, Modélisation des chaussées rigides par la méthode aux éléments finis : application au béton armé continu. Thèse de doctorat de l'Université Pierre et Marie Curie, Paris 1994.
4. NF P 98-17x, Projet de Norme Essais d'adhérence béton - armature (ABA). AFNOR Paris.
5. P. ROSSI, J.-L. ROBERT, J.-P. GERVAIS et D. BRUHAT, The use of acoustic emission in fracture mechanics applied to concrete, Engineering Fracture Mechanics, vol. 35, n° 4/5, p 751-763, 1990.

ACKNOWLEDGMENTS

The authors thank the following companies and organizations, partners in the FLORE national project, in the context of which this work was done: Chryso, Cofiroute, Lafarge Ciments, LCPC, SAM, Scétauroute, Service Technique des Routes et Autoroutes (SETRA), Sollac, and Techniques Spéciales de Sécurité (TSS).