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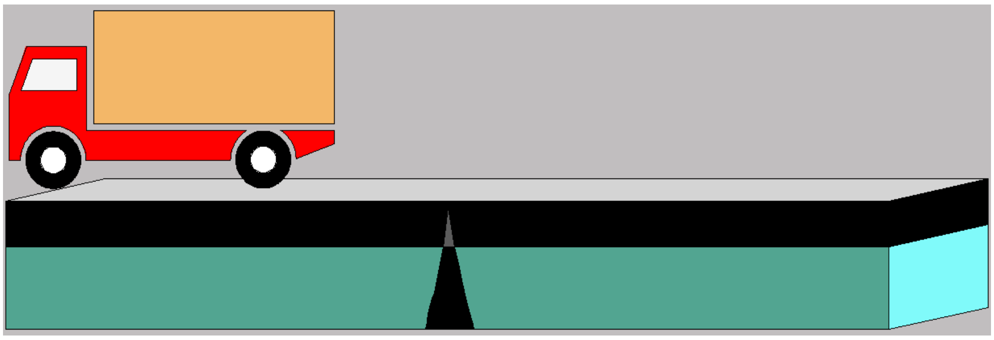
TECHNICAL UNIVERSITY OF CIVIL ENGINEERING BUCHAREST

DOCTORAL SCHOOL

PHD THESIS SUMMARY

CONTRIBUTIONS REGARDING THE ANALYSIS BY MODELING THE REHABILITATED ROAD STRUCTURES AT LOADS ASSIMILATED TO ROAD TRAFFIC



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CONTRIBUTIONS REGARDING THE ANALYSIS BY MODELING THE REHABILITATED ROAD STRUCTURES AT LOADS ASSIMILATED TO ROAD TRAFFIC

CONTENTS

CHAPTER 1. INTRODUCTION

In the last 20 years, the strategy of the national road infrastructure administration has focused on modernization and rehabilitation of the road network, activities that involved improving road traffic conditions on an old road network, including improving road surface conditions. This option has led to the adoption of quality upgrade solutions at the level of the road structure, in order to meet the requirements of increased traffic.

The development of efficient design / execution methods, which guarantee a long life cycle of the road structure, without unnecessary consumption of resources or the destruction of the environment, is a mandatory condition in our times.

1.1 The purpose of the doctoral thesis

Through the approached topic, the doctoral thesis entitled **Contributions regarding the analysis by modeling the rehabilitated road structures at loads assimilated to road traffic**, studies by experimental modeling of road structure, requirements equivalent to an assimilated road traffic at the scale of the model. Through these atypical tests of regulated laboratory tests, it is desired to obtain new information, used for the protection of old cracked pavements (pre-cracked mixed road structures, protective layer of asphalt laid over cracked concrete), in various cases.

The main objective of the thesis is to reduce the research costs intended to anticipate the behavior of asphalt road materials, used as protective layers in the rehabilitation activity of cracked road structures. Thus, through accelerated attempts to simulate road traffic, the aim is to obtain the performance of optimal recipe solutions as well as traditional tests.

The results of the thesis can be materialized by obtaining a new way, other than the classic tests, faster and cheaper, to anticipate the normal operation of the protective asphalt layer, placed over an old road pavement, to anticipate the appearance and propagation of the crack at surface.

Processing the results by identifying the parameters that influence the cracking of asphalt layers placed over a pre-cracked concrete is another necessary step of the doctoral thesis, as well as establishing calculation relationships between these parameters, taking into account the applicability of previous research in the literature.

1.2 Doctoral thesis research program

The three research reports related to the doctoral thesis had as final goal the establishment of a test methodology for the specimens with the help of the Cracking Device of Temperature Control [1], by simulating the effects of traffic on them.

- Research by structural modeling in the laboratory of the effects of traffic on rehabilitated road structures [2]
- Analysis by statistical interpretation of the solutions obtained in accelerated regime in the laboratory at loads equivalent to road traffic [3]
- Identification of the parameters of influence of crack propagation through protective asphalt layers for degraded pavements [4]

1.3 The structure of the doctoral thesis

The doctoral thesis is structured in two distinct parts on 9 chapters, bibliography and annexes, as follows:

Chapter I - INTRODUCTION describes the purpose and research program of the doctoral thesis to show the timeliness and necessity of the topic developed in the paper, but also the initial stages proposed for final conclusion. Also, in this chapter, the structure of the thesis was presented by briefly describing each chapter.

PART 1 DOCUMENTARY SYNTHESIS with the research of the phenomenon of reflective cracking in asphalt layers, used to maintain degraded roads by cracking the road surface.

In **Chapter II - THE EFFECTS OF ROAD TRAFFIC ON ROAD STRUCTURES**, two approaches are described in order to establish the effects of road traffic loads on road structures and more precisely the study AASHTO and Aggression.

Chapter III - MIXED ROAD STRUCTURES (COMPOSITE - ASPHALT ON CONCRETE), briefly presents the characteristics of mixed road structures, the difference in behavior between the materials of which they are composed (concrete and asphalt mixtures).

Chapter IV - THE TENDENCY OF CRACKING OF ASPHALT LAYERS ON CONCRETE SUPPORT PAVEMENT, addresses the cracking in terms of the causes from which it occurs, namely the shearing of asphalt due to the clinking of concrete slabs, seasonal thermal variations which is an important element the difference in stiffness of the 2 layers. In the last part of the chapter, the phenomenon of fatigue of the asphalt layers due to the traffic demands was also analyzed.

Chapter V – FRACTURE MECHANICS IN ASPHALT LAYERS, reviews the theories that formed the basis of studies of cracking asphalt mixtures, an approach that involves the introduction of a stress intensity factor (Paris's law) that expresses the speed of crack propagation.

Chapter VI - THEORETICAL AND EXPERIMENTAL MODELING OF THE CRACKING OF COMPOSITE ROAD STRUCTURES, presents the calculation scheme of the composite structure required by traffic and temperature loads. This chapter exemplifies how the theories of fracture mechanics can be applied in the case of mixed road structures, but also how the thickness of the protection layer influences the crack. At the same time, there are some experimental methods for testing the cracking of road structures in the laboratory.

PART 2 EXPERIMENTAL STUDY OF REFLECTIVE CRACKING, by small-scale modeling in the laboratory

Chapter VII - CONTRIBUTIONS TO THE EXPERIMENTAL RESEARCH THROUGH LABORATORY MODELING OF THE REFLECTIVE CRACKING IN ASPHALT LAYERS ON ROADS. The basic principles of the experimental methods described in Chapter VI can also be applied to the mixed ones, under certain conditions, the equipment needing some modifications in this respect. One of these equipments is the Cracking Device with Temperature Control described from the point of view of the operation scheme, both mechanically and data acquisition.

Chapter VIII - CONTRIBUTIONS AND INTERPRETATIONS OF REFLECTIVE CRACKING PARAMETERS THROUGH OBSERVATIONS AND PROCESSING OF RESULTS IN EXPERIMENTAL MODELING, introduces in experimental studies the new parameters needed to be determined to characterize the reflective crack in to make some observations related to these parameters. The capacity to transfer the crack from concrete to asphalt is developed in a subchapter. Another novelty element of the thesis is the multicriteria interpretation, through parametric indices. The last subchapter is reserved for the parallelism between the measurements performed on site and those in the laboratory.

Chapter IX - FINAL CONCLUSIONS, PERSONAL CONTRIBUTIONS AND FUTURE RESEARCH DIRECTIONS, summarizes the conclusions and experimental observations, pointing out the important elements, new in the study of cracking, highlight the personal contributions offered by the doctoral thesis, but at the same time the steps which must be followed after its completion as future directions of research.

The **ANNEXES** present the results of the experimental tests performed in the thesis, as well as their processing.

CHAPTER 2. THE EFFECTS OF ROAD TRAFFIC ON ROAD STRUCTURES

Knowing the effects of traffic loads on road structures is very important from several points of view [5]:

- technical (design of road structures, recipes for the component materials of each layer in the composition of the road structure),
- administrative (limitation of axle load and total vehicle load),
- economical (efficient, economical transport and setting fees for the use of communication routes).

The traffic load is transmitted to the road structure by means of wheels. The axles can be simple, in tandem or tridem, the distribution of the load on them is not always the optimal one.

Vehicles not only induce vertical loads in the road structure, but also horizontal loads resulting from the acceleration-braking actions of vehicles.

2.1 The AASTHO study (LEF, ESALs)

A first study on the effects of traffic loads on road structures was presented by the experimental program AASHTO (American Association of State Transportation Officials) in the 1950s. Analyzing the test data, empirical expressions were developed representing relationships between traffic load, road system performance, and their design variables. These expressions were used to introduce the so-called load equivalency factors (LEF), used to quantify the effects of various axle configurations and loads, by an equivalent number of passes of a particular axle configuration and load.

$$LEF = \frac{The\ number\ of\ loads\ of\ the\ standard\ axle\ that\ causes\ a\ certain\ loss\ of\ service\ level}{The\ number\ of\ loads\ of\ an\ X-axis\ that\ causes\ a\ certain\ loss\ of\ service\ level} \text{ [6]}$$

There are 3 general methods in determining LEF [6]:

- Empirical
- Theoretical
- Mechanical (or mechanical-empirical).

Analyzing in detail the data of the AASHTO tests, a new concept was developed, ESALs (equivalent single-axle load). It was created to turn the various loads and configurations encountered in traffic into an equivalent number of simple 80kN axles. This concept was based on two hypotheses:

- the destructive effect of a number of stresses of a group of axes (defined by the size and configuration of the load) can be expressed by a different number of stresses of a standard load.
- the damage to the structure or the change of the service level has a linear evolution [7].

Due to the changes in configuration and loading of vehicles since the AASHTO studies, new calculation models must be developed that can be applied to the current loading conditions, but also to the materials that are part of the road structure layers.

In this sense, the development direction of the doctoral thesis was conceived, respectively an experimental modeling, which would highlight the cumulated effects assimilated from traffic demands and seasonal temperature variations as a factor of the variation of environmental conditions.

2.2 Traffic aggression

As concluded by Mr. Dicu Mihai [8] [9] (ideas taken from one of my elective disciplines [10], but also in my dissertation [11]), traffic through its composition acts differently at the level of the road structure. Thus, on extra-urban roads the road traffic is characterized by the presence of heavy goods vehicles and traffic speed, while in the locality the road traffic consists mainly of light vehicles (cars and vans) at which the traffic speed is reduced, and the frequency of starts-stops is higher than on extra-urban roads, mainly due to the presence of intersections.

In this situation, the influence of the repetition of heavy vehicle loads on the load-bearing capacity of the road structure is taken into account on extra-urban roads, while in the case of urban roads the effects of tire-road contact are analyzed, rather than the influence on tangential wear demands.

The justification of the appearance and propagation of cracking of road pavements is generally characterized by the effect of loading-unloading cycles given by heavy vehicles.

Calculate the number of breaking loads (Nt and Nz) and the injuries, respectively, defined by:

$$D_t = \frac{1}{N_t} \qquad D_z = \frac{1}{N_z}$$

When one axle has to be compared with another axle, the notion of relative injury is used in the literature. For this, a reference axis is chosen whose aggressiveness is equal to 1. This reference axis is associated with the values dt and dz of the injuries. In this way, a certain axle is characterized by the two values Dt and Dz; enter the reports:

$y_t = \frac{D_t}{d_t}$ $\quad\quad y_z = \frac{D_z}{d_z}$

The two sizes yz and yt are representative of the relative damage suffered by the road support and the concrete layer and translate the aggressiveness of an axle or a group of axles. In order to be able to make comparisons between tasks, it is convenient to reduce them to a single parameter y = F (yz, yt).

The aggressiveness of a heavy vehicle is determined by summing the aggressions yi of the different axles or groups of axles Σyi and dividing the result obtained by the sum of the aggressions of the axles of the reference vehicle (yt + yz).

$A = \frac{\Sigma y_i}{y_t + y_z}$

Aggressiveness on a type of road structure can be calculated with the relationship:

$$A = n_1 Y_1 + n_4 Y_4 + n_{5,6} Y_{5,6}$$

where: n_1 = the number of registered simple axles;
n_4 = the number of registered tandem axles;
$n_{5,6}$ = the number of registered tridem axles;
A = traffic aggression.

A traditional flexible structure cannot withstand heavy traffic, except when the terrain is excellent and the asphalt is very deformable, but then „waves" will appear.

Rigid road structures, with concrete pavement, under the action of external loads and temperature variations, work on bending and are presented in the form of slabs, being fragmented by joints arranged transversely and longitudinally.

Replacing the semi-rigid layer with a base layer of road concrete in mixed (composite) structures has a number of advantages in terms of taking over traffic loads.

CHAPTER 3. MIXED ROAD STRUCTURES (COMPOSITE - ASPHALT ON CONCRETE)

3.1 Mixed road structures

The study of reflective cracking is suggestive to research in the case of mixed road structures, made by combining rigid with flexible layers within the same road system, despite radical differences in behavior under the action of traffic and natural agents, allow a more economical solution to problems put in road constructions, in that the properties of concrete and asphalt complement each other.

The main problem of this type of composition in the case of asphalt on an old concrete pavement cracked during operation, is the transmission of concrete joints and cracks in the bituminous pavement (reflective cracking of concrete in asphalt).

The appearance of cracks in the asphalt road pavement is favored by two factors: temperature variations and traffic loads.

3.2 Transfer of the load to the cracked concrete layer

3.2.1 Transfer to the interface by friction, to the concrete layer

In order for the cement concrete layers to behave properly to the action of the given traffic loads, the crack opening must be kept below a certain limit so that the load is transmitted from one slab to another, near the joint, respectively in the crack area in the case of the rehabilitated (cracked) road structure, only by the contribution of friction.

In order to illustrate the mechanism of load transfer to the crack appeared in a concrete layer working in a first stage as road pavement, the mineral aggregate reduced to a granule of diameter (d) is considered; in this way the vertical displacement (Δz) of the end of a fragment driven by the load (P) given by the wheel can be highlighted, in relation to the end of the adjacent slab fragment.

The load transfer is ensured by the contact of the two faces of the slab fragments.

The conclusion reached was that, in order to contribute to the transfer of the load, the concrete aggregate granule must comply with the condition:

$d \geq 2(\Delta x)$

3.2.2 The influence of asphalt pavement on transfer

In the situation of consolidating with an asphalt layer an old concrete cladding that has cracked, an improvement of the transfer to the crack is reached and therefore, a removal of the moment of fragmentation of the slab.

The problem is that sooner or later the crack propagates through the asphalt layer, due to the phenomenon of fatigue from the repetition of traffic loads. Therefore, it is important to know the parameters that are mitigating factors of this cracking process and that help delay its appearance on the road surface.

As the fatigue process of the asphalt structure advances, so of its behavior in the plastic stage, the value of wear at the level of the concrete crack increases, at which point the process of crack propagation through asphalt begins.

3.3 The collaboration between the protective asphalt layer and the cracked concrete pavement

The distribution diagram of the bending tensile stress varies in the asphalt layer and in the one of the concrete foundation, depending on the adhesion between them.

If the two layers work separately (without adhesion to the interface), the bending stress diagram develops in each of them. Yielding occurs in the layer where the permissible tensile strength of the bend is exceeded. In the case of asphalt-concrete adhesion, a tensile stress diagram appears in the opposite direction on the thickness of the adhesive layer that is created in the asphalt pavement, in the adhesion area.

Cracking of asphalt pavement occurs when the asphalt elongation limit capacity is exceeded.

CHAPTER 4. THE TENDENCY OF CRACKING OF ASPHALT LAYERS ON CONCRETE SUPPORT PAVEMENT

4.1 Mixed road structures cracking

The appearance of cracks in the asphalt, near the concrete joints, is caused by the shear forces that appear in the joints, by the differential thermal expansion and by the fatigue of the material.

4.2 Shearing the asphalt due to the clamping effect of the tiles

Incomplete support, especially at the corners, due to the phenomenon of pumping the fine part of the support environment caused by the shocks transmitted by mobile loads, can eventually lead to the clinking of the tiles. The independent vertical displacements of the edge of the tiles generate cutting forces in the joints that appear instantly. Bituminous layers has a low resistance to shear stresses and cracks.

4.3 Seasonal thermal variations in mixed road structures

At seasonal temperature variations, concrete slabs have significant variations in volume. The co-operation between concrete and asphalt mixture at temperature variations is difficult due to the nature of the binder and the different coefficients of expansion. The coefficient of expansion of asphalt is much higher than that of concrete and is not constant, having a pronounced variation with temperature.

Expansion and contraction of the concrete slab lead to a narrowing or enlargement of the joint opening. Asphalt pavement must take on these demands only on the length corresponding to the opening of the joint, on which it can move freely.

4.4 The phenomenon of fatigue in asphalt layers due to the effect of repeated shocks under traffic on the rigid support

Pavements shocks occur whenever the tires, at full speed, suddenly encounter unevenness or the vehicle is not driving or is not running smoothly [12].

Fatigue of the material by repeated impacting can seriously affect the treads, made of asphalt mixtures, placed on a rigid support, if they are too small. When using a plastic asphalt that can follow the axial movements of the slabs without cracking, there is a danger of creep (with hard bitumen and crushing aggregates) but by decreasing plasticity cracks can appear above the joints of concrete slabs.

CHAPTER 5. FRACTURE MECHANICS IN ASPHALT LAYERS

Cracking is considered to be one of the main causes of damage to road structures, which involves the allocation of large financial resources to repair and maintain them in optimal operating parameters.

”Reflective cracking” is the process of transmitting to the surface of the roadway the cracks of hydraulic or thermal contraction in the layers made of natural aggregates stabilized with hydraulic or puzzolanic binders. In the case of reinforcements of existing roads, this process may relate to the transmission to the surface of the new bituminous pavement of cracks and / or cracks existing in the old road pavement." [13]

In conclusion, reflective cracking occurs due to the stresses given by traffic loads, but also by temperature variations that induce contraction and stretching efforts in the structure.

We can consider that there are 2 stages of the cracking process [14], without taking into account the last stage of failure, in which the crack propagation speed increases rapidly:

- Crack initiation, characterized by microcracks that transform into macrocracks and can be defined as the number of cycles in which the stress is applied to which the crack is visible in the protective layer.
- Crack propagation, represents the stage in which the crack propagates to the surface of the layer, on its entire thickness. The propagation of the crack in the case of flexible clothing can be expressed by the law of Paris and Erdogan (relation 1) [15].

$$\frac{da}{dN} = C \cdot (\Delta K)^n \tag{1}$$

5.1 The energy criterion

The energy release rate G is defined as the variation of the potential energy with the cracked surface of an elastic linear material. [16]

$$G = \frac{\pi \cdot \sigma^2 \cdot a}{E} \tag{2}$$

Relation 2 is valid in the case of a plate of infinite dimensions (the width of plate B is much larger than 2a) subjected to a stretching force, having a crack length equal to 2a.

5.2 Stress intensity factor K

The stress intensity factor characterizes the state of stresses and deformations at the top of the crack and has as equation:

$$K_I = \sigma \cdot \sqrt{\pi \cdot a} \tag{3}$$

The relationship between the energy release rate and the stress intensity factor is obtained from the equations 2 şi 3:

$$G = \frac{K_I^2}{E} \tag{4}$$

5.3 Propagation of the crack over time due to fatigue

To determine how a crack propagates through the material, we can use the law of Paris (equation 1) which expresses the speed of propagation of the crack (da / dN) as a function of the stress intensity factor K. We can thus find in any moment which is the length of the crack, therefore, in the case of asphalt protection layers, which is the optimal moment at which the responsible authorities must intervene, with minimum costs.

5.4 Cracking of materials with elastic behavior

A material has a linearly elastic behavior when the relationship between stress and strain is linear, and the strain returns to 0 when the applied load is removed. The law that governs these materials is Hooke's law. The stress intensity factor was determined taking into account the size of the plasticized area r, which appears at the top of the crack. The Irwin model assumes the plasticized area in the form of a circle.

The Dugdale-Barenblatt model is another approach to finding the plasticized area, which is no longer in the shape of a circle, but has an elongated shape.

Plasticity corrections can extend the conclusions in the elastic linear domain and beyond, but when the behavior of the material becomes nonlinear, as in the case of asphalt mixture, the stress intensity factor no longer characterizes the crack (calculated with the relationships in the crack mechanics in the linear stage elastic). Therefore, two other ways of calculating its behavior at the crack tip were introduced, CTOD (crack type opening displacement) - the displacement of the opening from the crack tip and the integral on the J contour. [6]

5.5 Cracking of materials with elastic-plastic behavior

In a material with elasto-plastic behavior, the relationship between stresses and deformations is no longer linear, and the deformation does not return to 0 when the applied load is removed.

At the beginning of the load the material behaves elastically, the relationship between stress and deformations being linear, and after the stress exceeds a certain value, the material becomes plastic, the relationship becoming nonlinear, the discharge being linear with a slope equal to the modulus of elasticity elastic zone).

5.5.1 CTOD

The need for the CTOD parameter arose when Wells [17] observed that before the crack propagated (the stresses in the plasticized area reach and exceed the crack resistance of the material), the crack tip no longer has a sharp shape, but has a bluntness. It can be said that the tip of the crack has a certain opening marked with δ.

The CTOD parameter ([6]) was determined, starting from the Irwin model, with the plasticized area of radius r_y [18], considering the opening $\delta = 2 \cdot u_y$. $u_y$is the displacement on the y direction of the crack determined in the hypothesis of linear elastic behavior. Relationship 5 is valid when the flow area of the material is very small.

$$\delta = \frac{4}{\pi} \cdot \frac{K_I^2}{\sigma_{YS} \cdot E} = \frac{4}{\pi} \cdot \frac{G}{\sigma_{YS}} \tag{5}$$

Another method of calculation is based on the Dugdale-Barenblatt model. The hypotheses of this model are a flat state of effort and material that retains its elasticity (does not stiffen).

$$\delta = \frac{K_I^2}{\sigma_{YS} \cdot E} = \frac{G}{\sigma_{YS}} \tag{6}$$

5.5.2 J-integral

J-integral was introduced by Rice [19] in 1968 and it represents the energy available per unit area of the crack (taking into account the plasticized area) [20]. Its applicability to nonlinear-elastic and elasto-plastic materials has several restrictions, the most important being that the unloading must not take place. In other words, it is not valid for cyclic uploads (these involve upload-download).

CHAPTER 6. THEORETICAL AND EXPERIMENTAL MODELING OF THE CRACKING OF COMPOSITE ROAD STRUCTURES

6.1 Theoretical modeling

6.1.1 Schematic of calculation of a road structure at combined traffic stresses and temperature variations of the material.

Analytical methods for sizing a road structure are based on an analytical scheme. Based on them, the road structure is phenomenologically modeled to determine the calculation parameters.

The given traffic demand represented by 13 ton axles is modeled by a vertical force placed on a transverse strip located at a distance x from the position of the crack in the concrete foundation. Figure 6.1 shows the loading scheme on a three-dimensional model representing a traffic lane.

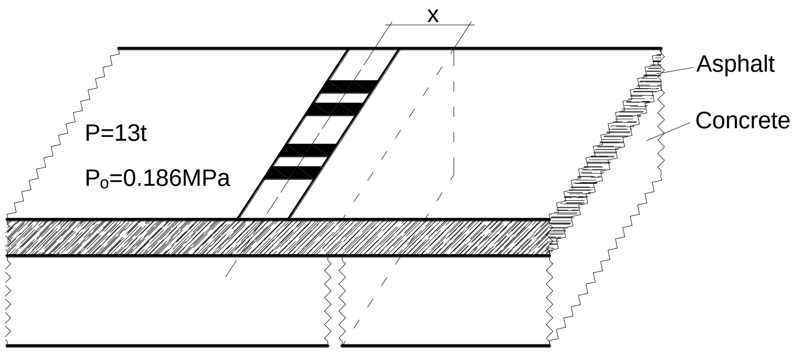


Figure 6.1 Three-dimensional calculation model

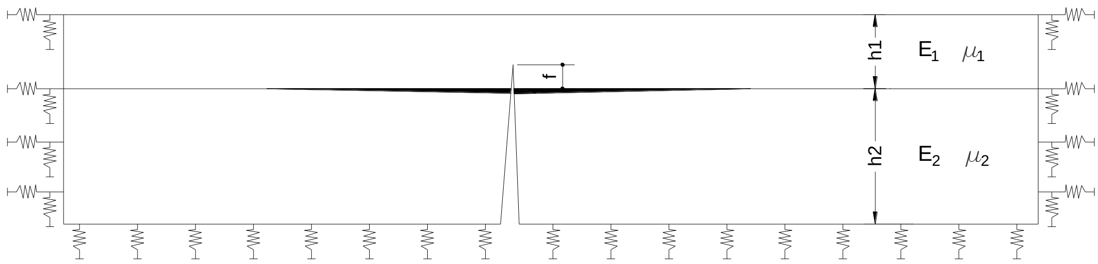


Figure 6.2 Two-dimensional calculation model

Regarding the two-dimensional calculation model (Figure 6.2), it has the following characteristics:

- The tread (wear) of thickness h_1 has the modulus of Young E_1,
- The foundation of the road system consists of a single layer of thickness h_2 and the module E_2,
- The earth foundation is represented by a Winkler environment,
- The top layer is cracked to a depth f.

The general schemes for modeling the traffic stress and the temperature variation stress can be found below:

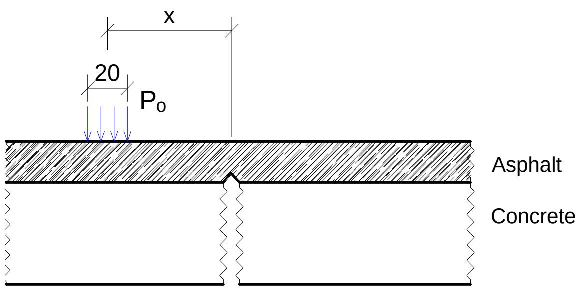


Figure 6.3 Traffic load model

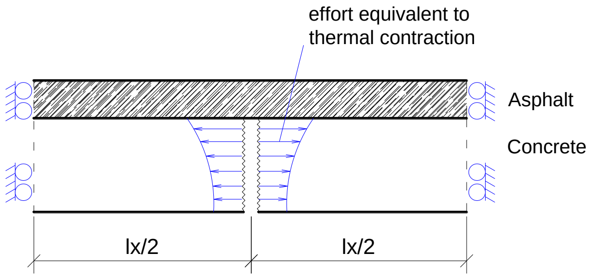


Figure 6.4 Temperature load model

6.1.2 The phenomenon of road materials fatigue at load cycles

K. Majidzadeh şi D.V.Ramsamooj [18] They showed that the term structural fatigue is associated with the disturbance or damage to repeated loading cycles of the connections between the road layer components.

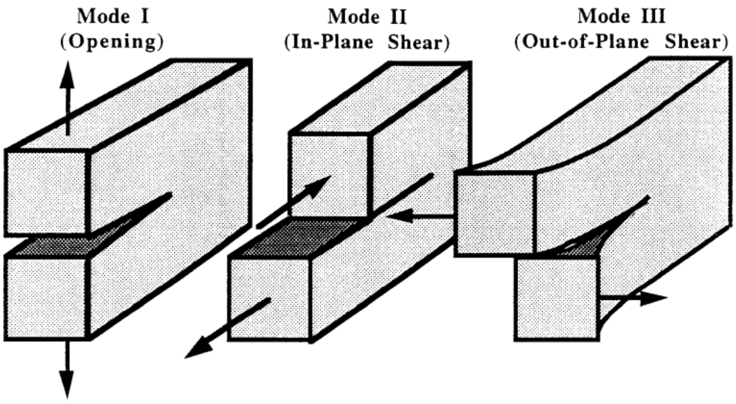
The process of initiating cracking and ending by the appearance of rupture differs from material to material. The development of the crack on the layer thickness is associated with the appearance of structural discontinuities and energetic variations in this area.

The structural discontinuity is equivalent to the plasticization of the material in the crack head which, by exceeding a certain limit, allows its development on the thickness of the road layer.

From this point of view, the existing theories accept the following stages of crack evolution [21]:

- Energy accumulation in the elastic field
- Energy storage in the plastic field
- Energy storage at break

The mechanics of cracking were demonstrated by Irwin by introducing the stress intensity factor. Thus, he observed that three stages of the state of tension can be distinguished in the opening of the crack as a measure of the propagation of this phenomenon. (Figure 6.5).



Mode I (Normal stress)

Mode II (Shearing stress)

Mode III (Tearing stress)

Figure 6.5 Ways of developing the state of tension

6.1.3 Experimental characterization of cracking road structures

In research conducted at the Technical University of Ohio, USA, the applicability of the theory of cracking through asphalt layers was examined by two concepts as calculation hypotheses:

- the material must be considered homogeneous, isotropic and with elasto - plastic behavior;
- the crack in the plastic area must be small by reporting the opening of the base crack.

6.1.3.1 The mechanism of cracking in the elasto - plastic stage

The concentration of the effort at the top of the crack leads to the plasticization of the area around it. Since the plasticized area is limited around the crack tip, the overall behavior of the layer structure is linearly elastic.

The concept of limited plastic flow can be evaluated qualitatively by comparing the ratio between the size of the plasticized area at the top of the crack and the other dimensions of the structure related to its depth (f) and its gap (d). Quantitatively this ratio was established by A.S.T.M. (American Society for Testing and Materials) 1/50.

6.1.3.2 Propagation of the cracking process from the foundation to the clothing

There are several variants of crack propagation in asphalt pavement:

- Vertical propagation with or without adhesion

- Horizontal propagation with, without or partial loss of adhesion

The propagation of the crack is done under the effect of two distinct stresses: thermal and traffic stresses.

6.1.3.3 Calculation of the stress intensity factor from the temperature

At slow loads resulting from cycles of daily temperature variations, the asphalt pavement suffers a decrease in stiffness. Consequently, the deformations of the cracked base layer are little influenced by the change in the rigidity of the asphalt pavement.

The calculation of the stress intensity factor from the temperature is made in the hypothesis that the propagation of the crack in the asphalt layer takes place while its gap at the base of the layer remains constant.

6.1.3.4 Integrating the law of Paris

The integration of the Paris law leads to the expression of the number of days when the crack appears on the road surface:

$$n = \frac{e^{m\gamma h} h^{(1+m/2)}}{(1+m/2)C_1}$$

6.1.3.5 Influence of asphalt protection layer thickness (h)

The crack propagation time is proportional to two terms that depend on the thickness (h) of the asphalt pavement:

- an exponential term $ee^{m\gamma h}$ which represents the influence of the thermal protection of the cement concrete layer;
- a monomer $h^{(1+m/2)}$, which shows that at an identical stress, an increase in the thickness of the asphalt pavement by 20% - 30% doubles the time of propagation of the crack at the road surface.

6.1.3.6 Fatigue life cycle

The integration of the Paris law led to the obtaining of a curve of different shape from the one corresponding to the temperature demand.

Considering separately the number of stress cycles compared to the total number of cycles, when the crack propagated to the road surface, the following observations could be made: the crack propagation speed is slower at traffic demand than in temperature in the initial phase and in the final phase this situation is reversed.

6.2 Experimental modeling

6.2.1 Empirical modeling of reflective cracking in the CFDP-UTCB laboratory

In the doctoral thesis of Mihai DICU [22], a series of devices were used, in order to highlight separately a series of parameters related to the asphalt-concrete cooperation within a model of mixed road structure (composite). The operating principles of the devices and the results obtained are presented below.

6.2.1.1 Characteristics of the laboratory test stand

The element of the road structure modeled in the laboratory, subjected to investigation tests by simulating the traffic loads, consists of three layers, namely: a concrete slab with surface dimensions of 51x14 cm and thickness of 10 cm, which rests on a layer of sand 14 cm thick. A bituminous mixture 3 cm thick is applied over the concrete.

The plate is fixed at one end to the support A, and the other end is pulled with a horizontal force H. A vertical cyclic force P̃ simulates the traffic load, which requires repeated bending of the slab. The load is applied to the surface of the system, having the pressure equal to 5 daN / cm2 and the diameter of the circular trace of 5 cm. The charging cycle is 5 s.

This loading stand simultaneously simulates on the one hand, the bending request given by the traffic and on the other hand, the thermal contraction of the concrete foundation. The intensity of the effort, the number of load cycles and the appearance of the crack in the clothing are measured.

6.2.1.2 Repeated bending tests on concrete slabs

This determination performed in the laboratory allows a separate analysis of the behavior of the compacted concrete layer at alternating cycles of a vertical stress. The realization of the repeated bending stress at the level of the concrete slab was achieved by superimposing the effect of the cyclic vertical load with a tension H = 200 daN.

6.2.1.3 Asphalt stretching tests for concrete shrinkage

The behavior of the mixed road structure model at negative temperatures is analyzed. These conditions simulate the behavior of the mixed road structure in winter, when the contraction of the foundation concrete appears at the negative temperature simulated by the increase of the horizontal force H, which leads to the reduction of the elongation capacity of the asphalt in these conditions.

6.2.2 Measurements by experimental modeling in the laboratory

6.2.2.1 Simulation of crack propagation through road structures

In order to develop a pertinent theory of the phenomenon of cracking in road layers, we start with the analysis of this phenomenology on beams.

Thus, the reinforcement layer testing equipment from TTI (Texas A&M Transportation Institute) laboratory allows the analysis on road materials by small-scale modeling of cracks on the beams. The equipment has the possibility to measure cracks at a certain number of loading cycles, for which the following parameters can be determined:

- • crack development speed (df / dN) depending on the pseudo-member J;
- • crack development speed (df / dN) depending on the reinforcement factor;
- • the load measured according to the reference displacement, used to calculate the pseudo-energy.

6.2.3 The concept of reflective cracking published in the dedicated literature

Reflective cracking is the process of transmitting to the surface of the roadway the thermal shrinkage cracks in the layers made of natural aggregates stabilized with hydraulic or puzzolanic binders, or from the dynamic stresses generated by intense and heavy road traffic. In the case of reinforcing existing roads, this process may refer to the transmission to the surface of the new bituminous pavement of cracks and / or cracks existing in the old road pavement [13]. So, the reflective cracking occurs due to the traffic loads, but also to the temperature variations that induce in the structure contraction and stretching efforts.

From the processing of this information extracted from the literature (Jorge C. Pais and Paulo AA Pereira [23], F. Zhou și L. Sun [24], Montreal School of Advanced Technology (QC, Canada) [25]), can draw the following defining conclusions for reflective cracking and characterization of generation parameters, as follows:

- The potential of reflective cracking is generated by a function characteristic of the properties of materials, mainly the thickness of the coating and its rigidity
- Reflective cracking is the result of vertical and horizontal differential movements above the crack in the existing structure. These movements, also called crack activity, are caused by temperature stresses, traffic loads, or a combination of the two.
- To take into account the effects of temperature that affect the horizontal component, it must reach at least 50% of the vertical component after laying. Since the maximum horizontal value is 50% of the vertical value, the effects of temperature are negligible in reflective cracking.
- In this overlapping effect of road traffic stresses with seasonal temperature variations in the composite road structure (asphalt on concrete), there are shearing stress in the asphalt layer over the existing crack / fracture in the concrete support layer, which by the development of the local fatigue phenomenon, leads to the initiation and development during the exploitation of the road of the cracking and its transmission through the asphalt layer
- The notion of equivalent shear appears in the area of the existing crack / fracture in the asphalt support layer, which can be defined by the fatigue life

- Reflective cracking occurs in 3 stages:
    - Detachment of the asphalt layer from the existing structure.
    - As the number of loading cycles increases, this detachment area increases. Studies show that part of this detachment is beneficial for preventing the process of reflective cracking, but up to a width of 10cm.
    - Vertical development of the crack towards the upper face of the protective layer.

CHAPTER 7. CONTRIBUTIONS TO THE EXPERIMENTAL RESEARCH THROUGH LABORATORY MODELING OF THE REFLECTIVE CRACKING IN ASPHALT LAYERS ON ROADS

7.1 Small-scale laboratory simulation method of crack propagation through road structures

To simulate a phenomenon, it is first necessary to describe it in reality.

Fatigue of the road structure associated with cracking when shearing and bending moments given by heavy traffic create a state of local tension, which leads to the propagation of the crack in the protective asphalt layer. Usually this phenomenon develops in road structures with pavements degraded by cracking and which have been protected by laying asphalt layers.

Seasonal temperature variations lead to horizontal displacements at the level of the old layer degraded by cracking (especially to layers connected with hydraulic binders).

This effect has a more aggressive character in winter when the crack opens, by the contraction of the layer bound with hydraulic binder and the stiffening of the asphalt protection mat.

7.2 Procedure for laboratory scaling the heavy vehicle load test on a road structure

Modeling an object involves applying a reduction in geometric dimensions [1].

The simulation of the vehicle load in reality at the scale of the model in the laboratory, implies the reduction of the constructive dimensions at the scale of the model, by analyzing the constructive elements of contact between the vehicle and the track.

The main scheme of the test stand, from the point of view of the constructive disposition is presented in Figure 7.1.

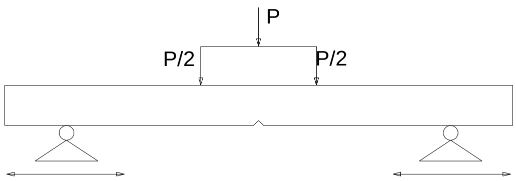


Figure 7.1 Construction scheme of the test stand

For the simulation of the calculation axis, the loading with the force P will be done by means of a component with variable magnitude depending on the needs of the loading.

The request will be made at a controlled frequency imposed by the values recommended by the literature, respectively 4Hz.

7.3 Procedure for laboratory scale evaluation of road materials

The hypotheses of scaling down and the types of tests of behavioral similarity according to the current standards in the field of road transport infrastructure, are the following:

- a reduction in the scale of the mineral skeleton in the material structure of the road layer
- a scaling down of the amount of binder required.

7.4 Stages of development of experimental equipment in the laboratory, able to simulate the loads from temperature and traffic

The realization of the laboratory equipment for the testing of the reflective crack, supposes:

- identification of the main behavioral parameters of the crack propagation phenomenon
- elaboration of an analytical scheme for simulating the phenomenon, which would define the cracking parameters
- the conception of a small-scale model that can simulate the phenomenon of cracking in reality on various road materials.
- obtaining equipment assisted by a high-performance acquisition system, which allows the evaluation of the behavior of a road material in relation to the phenomenon of crack propagation at dynamic test cycles and temperature variations
- elaboration of a procedure for interpreting the obtained data and a method for evaluating the performances of the road material in relation to the cracking phenomenon.

7.5 Cracking Device with Temperature Control

The equipment for studying the cracking phenomenon of composite road structures is a complex system that simulates the stress of traffic and climatic factors on test pieces in the form of a plate.

7.5.1 Mechanical operating scheme of the Cracking Device with Temperature Control

The scheme of operation of the specimen [26] is similar to the bending tensile test on beams, regulated in the laboratory test rules. The difference is the "inverted" test mode (Figure 7.2), to allow the placement of video cameras, in order to acquire data on the initiation and propagation of the crack through the test specimen.

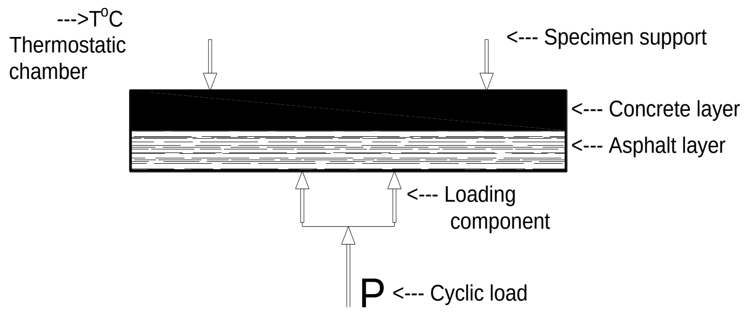


Figure 7.2 Mechanical operating scheme of the Cracking Device with Temperature Control

7.5.2 Specimen loading scheme

In order to speed up the occurrence of the cracking phenomenon and the propagation of the crack under cyclic loads, it is possible to resort to loading stages, following the evolution of the deformation of the specimen in extreme stress conditions. Using constant loading cycles and equivalent stress steps, the optimal recipe can be determined by behavioral reporting in terms of the evolution of the cracking phenomenon.

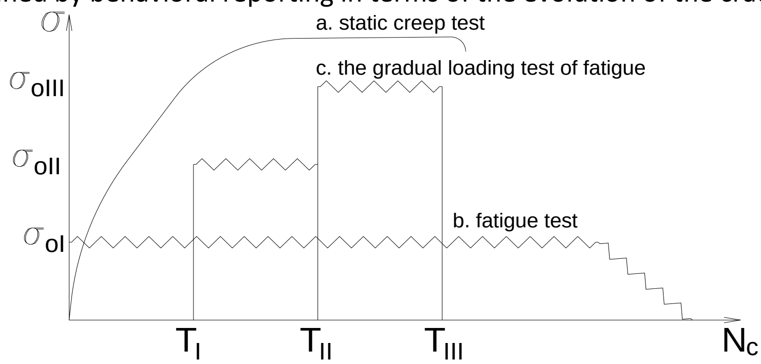


Figure 7.3 Types of crack tests.

As mentioned previously, the test mode is reversed, so the application of the load is done from the bottom up (Figure 7.4). This allows the placement of the 2 video cameras (at the top of the concrete slab and on the side of the specimen), with the help of which you can see and even measure the propagation of the crack through the asphalt layer.

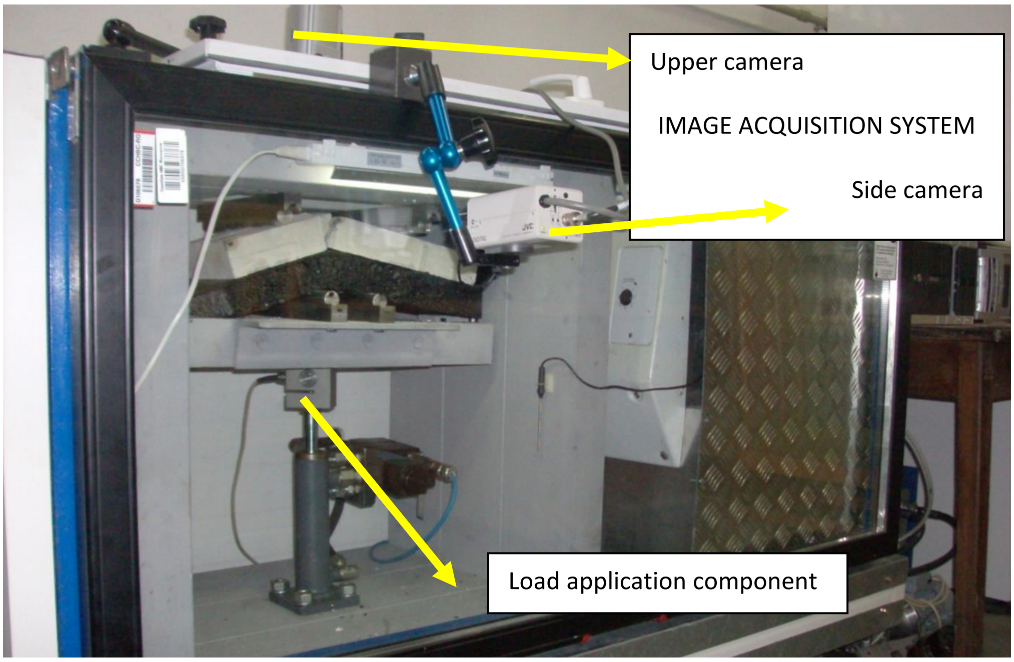


Figure 7.4 Positioning of video cameras to monitor the fracture phenomenon

CHAPTER 8. CONTRIBUTIONS AND INTERPRETATIONS OF REFLECTIVE CRACKING PARAMETERS THROUGH OBSERVATIONS AND PROCESSING OF RESULTS IN EXPERIMENTAL MODELING

8.1 Experimental measurements on composite structures using the Cracking Device with Temperature Control

With the help of this device, the following parameters can be measured via the video acquisition system (Figure 8.1):

- w =the vertical deformation of the asphalt-concrete specimen,
- db = the opening of the existing crack in the old pre-cracked concrete layer,
- e = detachment at the asphalt-concrete interface in the crack area,
- f = crack length in the asphalt protective layer,
- d = crack opening in the asphalt protective layer.

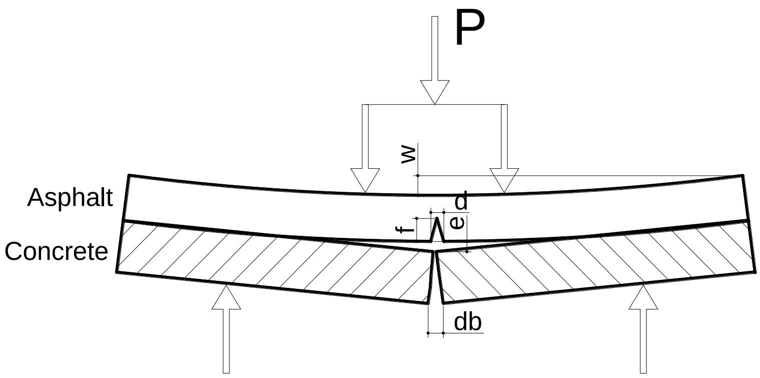


Figure 8.1 Reflective cracking parameters

The measurable parameters, at the appearance of the fatigue phenomenon on site, by the propagation of the crack at the road surface are the registered deformations (w), after a certain number of stress cycles possible to be quantifiable (nc). db, d, e, f can be purchased imagistically (video cameras with data processing software) in the recordings during the crack test on the Cracking Device with Temperature Control.

8.1.1 Asphalt-concrete specimen deformation (w)

The initial performance studies performed by comparative analyzes on the Cracking Device with Temperature Control, highlighted the contribution brought by a geomembrane anti-crack system [27], at the delay of the propagation of the reflective cracks through the protective asphalt layer (Figure 8.2). These performance studies were performed using the variation of the vertical deformation *w* over time (number of cycles, n_c).

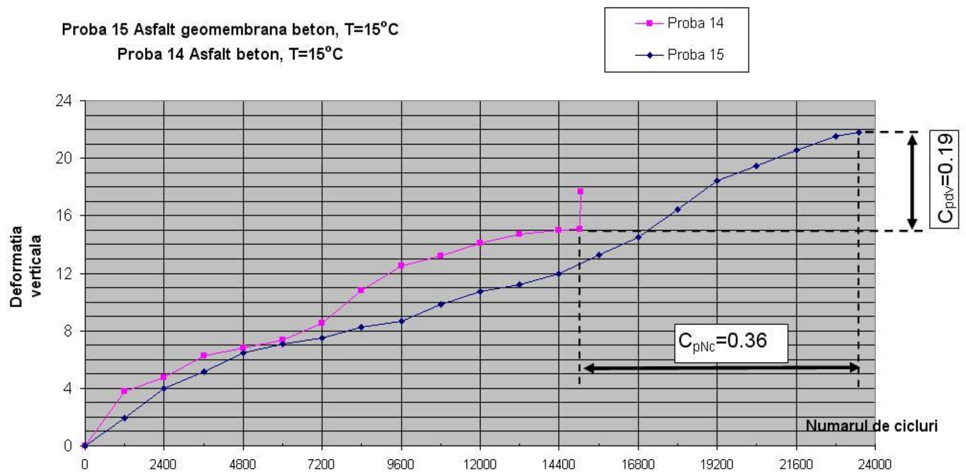


Figure 8.2 The contribution of the anti-crack system to the delay of the propagation of the reflective crack

The following notations were made in Figure 8.2:

- C_{pdv}= coefficient of performance at vertical deformations (***w***),
- C_{pNc}= coefficient of performance related to the number of cycles supported by crack propagation on the thickness of the protective asphalt layer.

Performance coefficients [28] of the anti-crack solution with geocomposite were highlighted by reporting the homologous elements measured on the Cracking Device with Temperature Control.

- with the performance coefficient at vertical deformations Cpdv = 0.19, a 19% reduction of the deformation related to the propagation of the reflective crack in the degraded cement concrete layer can be appreciated, due to the geocomposite taking over the tensile stresses from bending;
- with the coefficient of performance at the number of loading cycles CpNc = 0.36, it is possible to appreciate an increase of the life assimilated to the solution with anti-crack geotextile of 36%.

The tested specimens were required in steps, starting from a force of 40daN and an amplitude of 40daN. Each charging stage changes every 1200 cycles, meaning every 5 minutes [29] (Figure 8.3).

Number of cycles	Amplitude *daN*	Load *daN*
0	40	40
1200	40	80
2400	40	120
3600	40	160
4800	40	200
6000	40	240
7200	40	280
8400	40	320

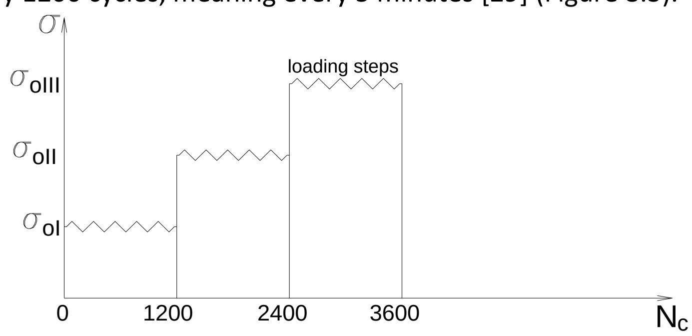


Figure 8.3 Loading steps

8.1.2 Regression relations between the reflective fracture parameters

With the help of nonlinear regression, relations were obtained between these parameters taken two by two (vertical deformation w, length f and opening d of the crack, depending on the number of load-unload cycles, nc).

I. between vertical deformation and number of cycles
$w = a_0 \cdot e^{b_0 \cdot nc}$

II. between the opening of the crack in the asphalt and the number of cycles
$d = a_0 \cdot e^{b_0 \cdot nc}$

III. between the length of the crack in the asphalt and the number of cycles
$f = a_0 \cdot ln(n_c) - b_0$

IV. between the opening and the length of the crack in the asphalt
$d = a_0 \cdot e^{b_0 \cdot f}$

8.1.3 Observations on the experiments performed

Below are some observations on the experiments performed on a number of 10 specimens (4b, 5a, 5b, 6a, 7a, 7b, 8a, 8b, 9a, 9b).

I mention that the experimental model had the same precast concrete slab, but also the same asphalt mixture as MAS16 protection layer [30], as we presented in the research report number 2.

The notation of the specimens with a and b were made for mixing plates (15x30cm) cut from the same plate 30x30cm, as detailed in the presentation of the reflective cracking test equipment, Cracking Device with Temperature Control. Example: a plate called 5 having the dimension 30cm wide, 30cm long was made [31]; from this, by cutting in half, resulted 2 plates 5a and 5b, which correspond to a small-scale slab model, depending on which the level of load assimilated to a road traffic was established for the laboratory test equipment.

These asphalt slabs, which retain the thickness of an asphalt layer, were glued to the pre-cracked concrete support with a bitumen primer and then tested one after another. In this scenario, the successive test leads to the modification of the transfer to the predetermined crack of the concrete support.

The experimental observations are related to the different conditions for priming the asphalt slab on the pre-cracked concrete support, to the initial opening of the existing crack in the concrete support and of course to the structural conditions obtained when making the asphalt slabs.

8.2 Observations and interpretations of the results of the test calibration specimen 4b

The force at which the crack of the precast concrete was transmitted in the protection layer and the specimen yielding occurred is 80daN, the number of cycles at which the cracking occurred is n_{ci4b} = 1000 (crack initiation in the asphalt layer), respectively n_{cCR4b} = 1553 fracture (the propagation of the crack over the entire thickness of the asphalt layer). The total test time is 388 seconds, provided that the frequency of load is constant.

Figure 8.4 shows the evolution of the vertical deformation (determined by imaging processing and recorded by the software of the equipment), depending on the number of cycles. The number of cycles at which the experiment was stopped was noted with Failure 4b, and with Fracture 4b the moment when the crack propagated through the entire thickness of the protective asphalt mixture. Thus, we can consider the reflective crack resistance capacity for 4b a number of cycles of 1259 and as the lifetime (315 seconds). The calibration of these data obtained by experimental modeling can be achieved by comparative analysis with an experimental sector, when the situation of defects by cracking a rigid road pavement is known, before applying a protective asphalt layer.

For the time being, the analysis by experimental modeling in the laboratory will be done only up to this research point, respectively until the reflective crack appears on the surface of the asphalt layer and is "visible" over 80% of the thickness of this layer.

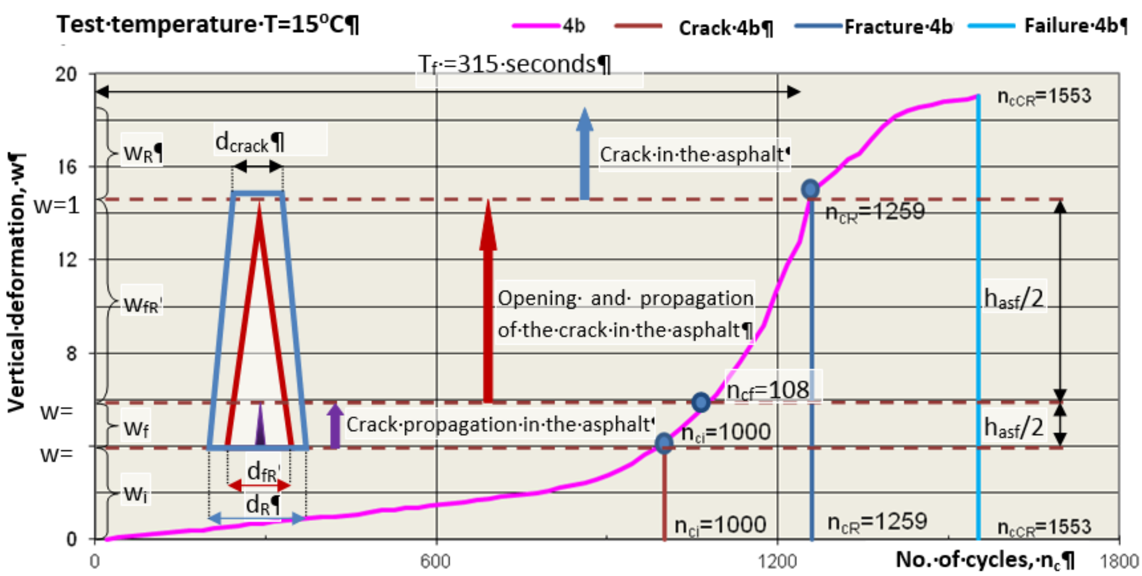


Figure 8.4. Increase of the vertical deformation according to the number of cycles for 4b

In order to have a enough period for the capability of the device for progressive recording of the reflective crack through the asphalt layer of the specimen, the test temperature is set at 15°C, corresponding to a controlled rigidity of the asphalt layer.

Specimen 4b was used to calibrate the experimental program, in order to identify the parameters of the reflective crack test for the simulation of the asphalt protection layer for crack-degraded concrete pavements.

Thus, Figure 8.4 highlights the main terms of cracking in the accelerated test by experimental modeling in the laboratory.

A Therefore, the following analysis parameters can be identified:

- Accelerated cracking service life (T_f)
- crack opening in the asphalt protective layer (d)
- detachment at the asphalt-concrete interface in the crack area (e)
- Number of cycles at crack initiation and propagation $\mathbf{n_{ci}}$, at the opening and propagation of the crack on the thickness of the asphalt layer $\mathbf{n_{cf}}$ and at fracture $\mathbf{n_{cR}=n_{ctot}}$.
- Vertical deformation (deflection) at the initiation and propagation of the crack $\mathbf{w_i}$, at the opening and propagation of the crack on the thickness of the asphalt layer $\mathbf{w_f}$, at fracture $\mathbf{w_{fR}}$ and at failure $\mathbf{w_R}$.
- the opening of the existing crack in the old pre-cracked concrete layer (db)

In the case of flexible or semi-rigid road structures, the vertical deformation (deflection) at the beginning of the crack w_i can highlight the maximum deflection in the ground (d_{adm}), and when the crack appears on the surface of the asphalt protection layer in the ground (d> dadm). In the case of rigid road structures, where the wear layer is asphalt (the case developed in the doctoral thesis), the vertical deformation (w), is due to the reduction of the transfer to the existing crack on the entire thickness of the cement concrete support layer.

On the experimental sector, by means of deflectometric measurements, N_{ci} corresponding to the achievement of the admissible deflection (d_{adm}) and N_{cf} corresponding to the compaction related to the appearance of the crack at the surface of the asphalt layer can be determined. In the case of the rigid road structure with a layer of wear from the asphalt mixture, the interpretation of the reflective crack is indirect, respectively, when the crack appears on the road surface, ie in the asphalt layer, so the crack propagation process has ended. use of the procedure described in this thesis.

The interpretation is indirect, because in addition to field investigations, classic laboratory tests must be used to determine the residual characteristics of road clothing materials. Thus, it is possible to evaluate the capacity to take over the reflective crack at the moment of the analysis, as well as the evolution of the afferent parameters through the study on the experimental model that can be researched on a specimen extracted from the road. In this way, the reserve can be anticipated from the operation duration of the rigid road pavement, through a coefficient of performance resulting from the reflective cracking behavior of the specimen to the result of the same process performed on a similar test tube.

For the asphalt material used, the time (t_i) and the number of cycles at which the cracking initiates the cracking at the asphalt- concrete interface (n_{ci}) is determined experimentally, as well as the final time (t_f) and the number of cycles recorded when the crack appears on the asphalt layer (N_{CF}). Thus, for other works with the same recipe, times related to the normal operating time can be anticipated, respectively $D_t = t_f - t_i$.

A simple calculation indicates that approximately 80% of the life of the mixture is consumed until the crack appears and 20% of the time is represented by the propagation of the crack through the asphalt plate. (Table 8.1).

This observation is consistent with the reality, which is known that the role of resistance to fatigue cracking, in the case of a composite road structure, such as asphalt wear layer on concrete support, has this last layer, respectively the base road layer.

Table 8.1 Reflecting cracking index, specimen 4b

Specimen	**Reflecting cracking index, specimen, *I_{fr}***	**Number of cycles at reflective crack propagation**
4b	$I_{fr} = \frac{n_{ci}}{n_{cR}} = \frac{1000}{1259} = 79.43\%$	$n_{cR} - n_{ci} = 1259 - 1000 = 259$

Two of the parameters measured in the experiment, which indirectly influence the propagation of the crack through the asphalt protection layer, are: the initial opening of the cement concrete crack (d_{bi}, friction work between aggregates and / or between cement stone, between crack walls), and the initial detachment of the asphalt layer from the concrete slab (they, the bitumen primer, at the interface between the concrete and the mixture).

These are highlighted on the experimental model afferent to the laboratory equipment in Figure 8.5, and the values for sample 4b, used in the calibration study of the experimental program, are presented by the imaging processing generated by the equipment software in Table 8.2.

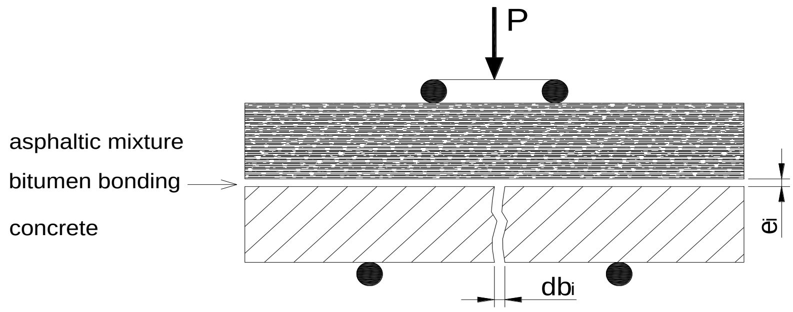


Figure 8.5 Initial parameters of the crack study

Table 8.2 Initial opening values db_i and the initial detachment (bitumen bonding) e_i

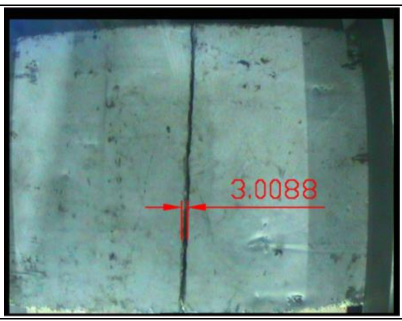
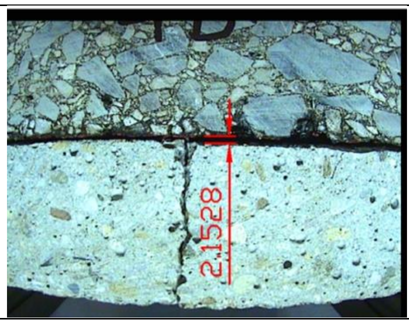
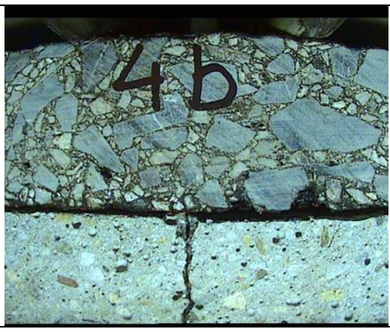
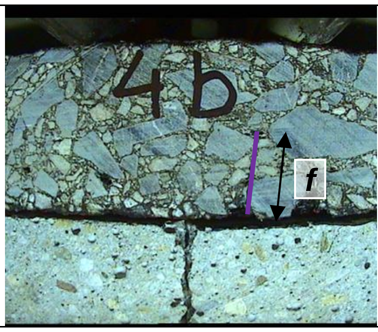
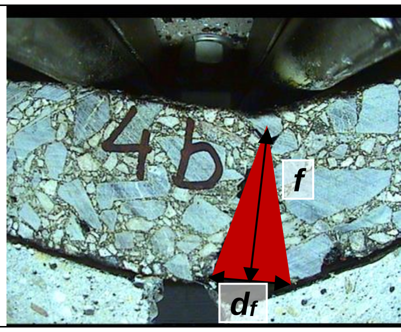
Specimen	Upper view **db_i**= the initial concrete opening (*mm*)	Side view **e_i**= the initial detachment of the asphalt from the concrete (*mm*)
4b		
	db_i=3.0088	**e_i=2.1528**

Table 8.3 Stages of reflective cracking in the case of laying the protective asphalt layer over a pre-cracked concrete pavement

Specimen	*Stage 1.* The stress is taken up by the friction between the pre-cracked concrete slabs	*Stage 2.* The concrete crack was transmitted to the protective asphalt (propagation)	*Stage 3.* The crack reached the surface of the protective asphalt (opening and propagation of the crack through the asphalt)
4b			
	Number of cycles: 0-n_{ci} Vertical deformation: 0-w_i Crack length: f=0 Crack opening: d_f=0	Number of cycles: n_{ci} -n_{cf} Vertical deformation: w_i -w_f Crack length: f=0-h_{asf}/2 Crack opening: d_f=0	Number of cycles: n_{cf} -n_{cR} Vertical deformation: w_f -w_{fR} Crack length: f=h_{asf}/2- h_{asf} Crack opening: d_f

For the calibration of the mathematical model with the results obtained by experimental modeling on the Cracking Device with Temperature Control, it is used, following the research of the reflective crack from the pre-cracked concrete support layer in the asphalt upper layer with the role of wear and protection at the same time. cracked in operation, the following notations:

- $n = \frac{n_c - n_{ci}}{n_{cR} - n_{ci}}$ -pentru $n_c \geq n_{ci}$
- **d exp** – asphalt crack opening measured on an experimental model
- **d calc** – asphalt crack opening measured on an mathematical model
- **f exp** – asphalt crack length measured on an experimental model
- **f calc** – asphalt crack length measured on an mathematical model
- **db exp** – concrete crack opening measured on an experimental model
- **db calc** – concrete crack opening measured on an mathematical model

The results of the research in this direction, highlighted the following principles of evaluation of the parameters of reflective cracking, as follows:

➢ The measurements and processing of these parameters, the length and opening of the crack for specimen 4b, indicate:

- The variation of the crack opening **d**, but also of the length **f** in the asphalt layer, in relation to the increase of the number of cycles **n**, is nonlinear (Figure 8.6). The regression model that best describes this relationship is:

$$y = \frac{a_0 \cdot n}{1 + a_1 \cdot n + a_2 \cdot n^2} \qquad (7)$$

➢ We can thus determine the number of cycles the crack propagation reaches half the thickness of the protective asphalt plate (h = 50mm): n_{cf} = 1080 cycles (n = 0.3, or we can say that the crack length has reached h / 2, at 30 % of its total propagation duration). This finding is extremely important in relation to other experimental models used in the evaluation of the fatigue phenomenon in asphalt layers, which establish that the strength of the layer is consumed if half of the deformation accumulated during the stress cycles has been consumed.

In Figure 8.6, it can be observed that the initial resistance to cracking of the asphalt layer is higher, by the accentuated increase of the crack opening value (d) and the slower evolution of the crack propagation (f). It is also noted that the diagram of experimental phenomenological evolution is accurately presented by the related mathematical law.

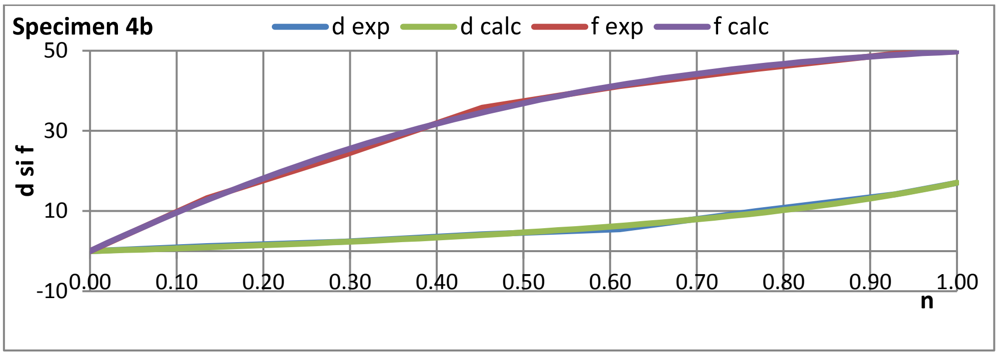


Figure 8.6 Variation of crack opening d and length f as a function of n, specimen 4b

- The regression model found for the evolution of the concrete opening db in relation to n is the MMF model (Morgan-Morgan-Finney), Figure 8.7:

$$db = \frac{a_0 \cdot a_1 + a_2 \cdot n^{a_3}}{a_1 + n^{a_3}} \tag{8}$$

To find out the actual opening of the concrete at a point, the value of the initial opening will be added to the value resulting from the MMF model db_i (Table 8.2)

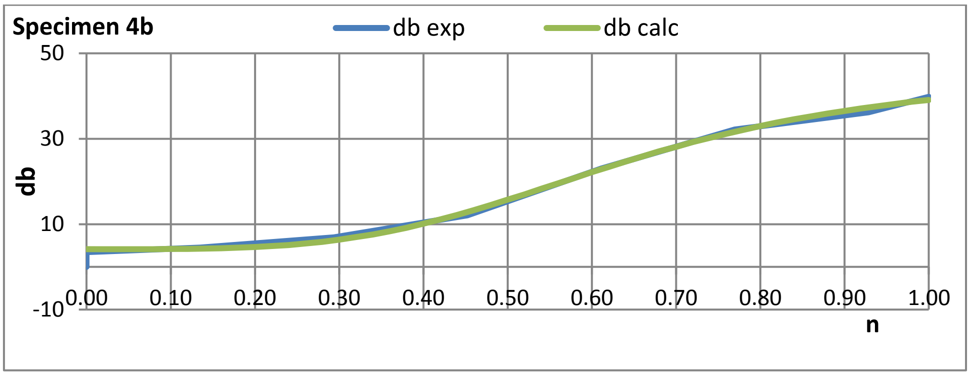


Figure 8.7 The variation of the concrete opening db depending on n, specimen 4b

Considering the regression models found between these 4 parameters (2 by 2), we can observe their evolution in a representation:

- Crack opening **d**, length **f** and number of cycles **n$_c$,** in asphaltic layer (Figure 8.8),
- opening **d**, length **f** of the crack in the asphalt and concrete opening **db** (Figure 8.9)

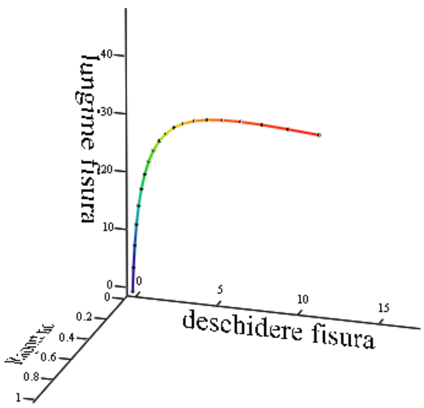


Figure 8.8 Tridimensional representation d, f, n, specimen 4b.

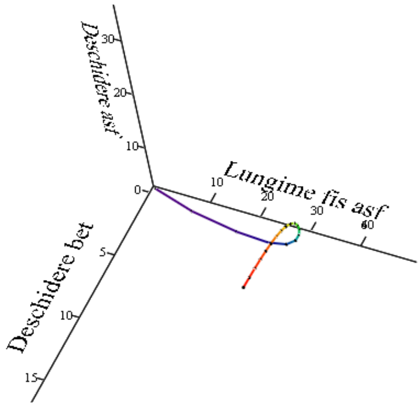


Figure 8.9 Tridimensional representation d, f, db, specimen 4b.

In Figure 8.8, the graphic representation highlights the length of the crack and its opening at the base of the asphalt layer in the three working phases of the asphalt, respectively in the elastic stage (blue color), plastic elasto (green color) and plastic (red color), when the fracture process begins from reflective cracking.

Figure 8.9 represents the evolution of the reflective crack in the asphalt, respectively the increase of the length and the opening of the crack, but in relation to the opening of the crack in the concrete support plate. It can be seen that the development of the red line of behavior in the plastic stage of the asphalt layer in Figure 8.8 appears, consecutive with the opening of the crack in the concrete. When the load transfer to the crack in the concrete support is consumed and the entire load of the vertical load assimilated to road traffic is taken over by the asphalt layer, the reflective crack appears on the road surface.

This experimental analysis leads to the conclusion that in the case of asphalt layer over an old concrete road pavement, the appearance of reflective cracking on the road surface, involves consuming the load-bearing capacity of the asphalt layer and milling the asphalt to lay a new flexible layer, is an inefficient solution.

In this case, it is recommended to apply complementary studies to evaluate the load-bearing capacity of the entire road complex in order to apply a possible solution to strengthen the road structure.

- in the same plan for all the 4 parameters (Figure 8.10). To make the drawing more suggestive, the value of the parameter was reported at one point to the total value (example: $f/_{f_{tot}}$, where f –the length of the crack at the point considered, f_{tot} - the length from the moment the crack propagates over the entire thickness of the asphalt layer)

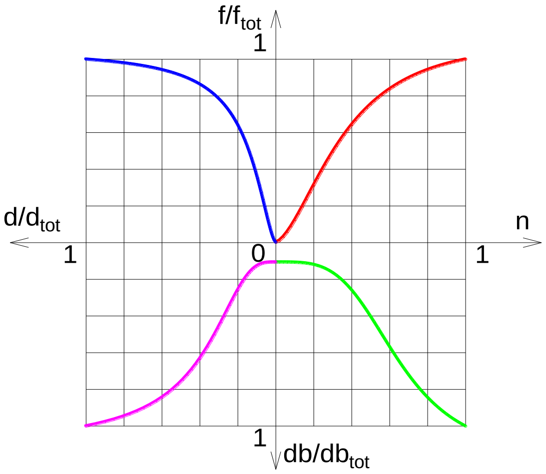


Figure 8.10 The 4 parameters graph, specimen 4b.

This multicriteria analysis diagram allows the identification of the less visible parameter in the imaging processing of the data obtained with the software related to the Cracking Device with Temperature Control.

- Variation rates of crack opening (Figure 8.11), of the propagation (length) of the crack (Figure 8.12) through asphalt, respectively of the opening of the concrete (Figure 8.13), is calculated by deriving the function

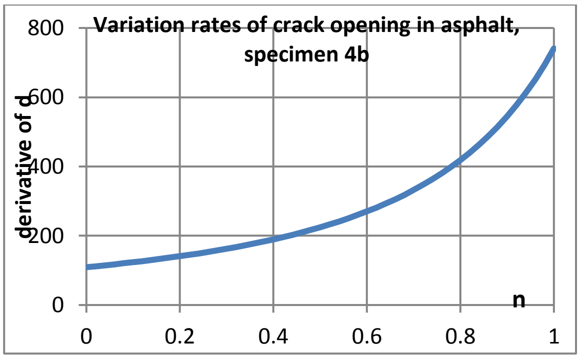


Figure 8.11 Variation rate of crack opening d, specimen 4b

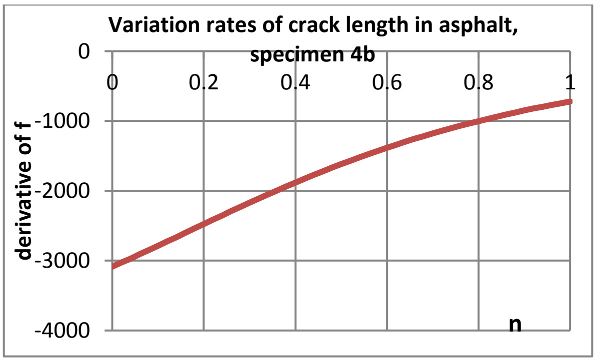


Figure 8.12 Variation rate of crack length f, specimen 4b

Depending on the curvature of the diagrams, the connection between the parameters of the reflective crack can be ascertained, thus, if the variation speed at the opening of the crack in the asphalt is lower, following that at the end of the test the reflective propagation will increase sharply at the beginning of the test, fading towards the end. This different behavior between the crack opening speed and its length by propagation on the thickness of the asphalt layer, is explained by the rheological behavior of this road material and by the transition from elastic to plastic behavior during the development of local deformation in the "crack tip", according to Irwin's theory.

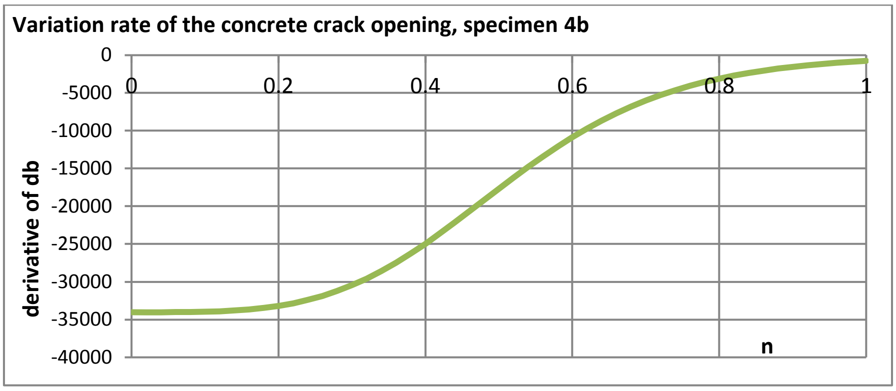


Figure 8.13 Variation rate of the concrete crack opening, specimen 4b

Figure 8.13, which shows the speed of variation of the crack opening in the concrete substrate, highlights the phenomenon created by the effect of transfer to the crack by the initial friction of the parts of this substrate, attenuated by the damping of the transfer process by the presence of the asphalt layer at the upper fiber of the concrete layer, which works together with it by applying the technological bonding operation. Thus, initially, when working the transfer from the crack of the concrete layer together with the damping of the asphalt layer present at its surface, the capacity to take over the vertical deformation (deflection under load) is higher and therefore the opening speed of the existing crack in the concrete it is smaller.

In the intermediate stage, when the transfer to the crack of the concrete support layer is consumed and mobilizes the capacity to take over the transmission of the crack through the asphalt layer, the curvature of the diagram changes, so that in the final phase of reflective propagation the crack opening speed of concrete to grow at a lower deflection.

All these experimental findings, transposed for phenomenological explanation in mathematical modeling, can find their practical utility by using the working procedure proposed in the doctoral thesis, in case of applying an extensive research program, on several types of asphalt road materials used as variants. execution at the asphalt protection layer of a concrete coating degraded during the exploitation period.

8.3 The transfer capacity of the crack from the concrete to the protection layer

The reflective crack appeared at the road surface, without being accompanied by the appearance of local compaction, presupposes that the propagation phenomenon occurs without the opening at the level of transfer loss at the level of concrete layer and then, the detachment parameter at the asphalt-concrete interface is practically zero, while when there are also compaction, it is assumed that the transfer to the crack in the concrete support layer has been consumed and there are also interface detachments, respectively it appears the parameter (e).

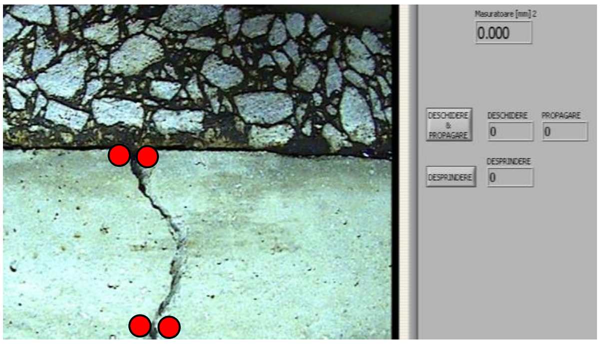


Figure 8.14 Slab with fracture collaboration (db=3mm), cracking in slab

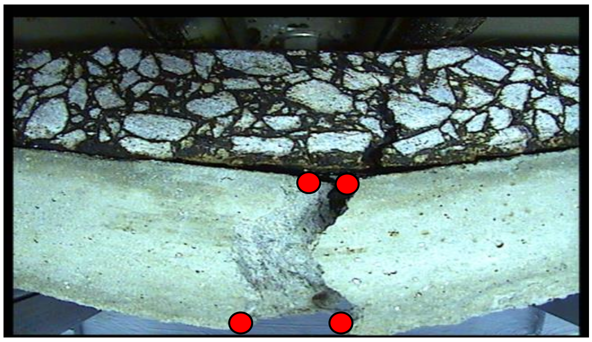


Figure 8.15 Slab without fracture collaboration (db=7mm), cracking in slab

In order to be able to interpret the way of crack propagation through an asphalt layer of protection of a concrete coating degraded by cracking, cracks that can be of various degrees of severity depending on their opening, an experimental study was conducted on 8 specimens [27], which differ from each other by the predetermined opening of the crack in the concrete.

The propagation time of the crack through the protective asphalt layer is determined indirectly by the number of cycles related to the cracking process and by the resulting vertical deformation (arrow w).

For the precast concrete support with the predetermined opening of 3mm (Figure 8.14), it is observed that initially there was transfer capacity in the support, the arrow for cracking in the asphalt protection layer is 4mm (sample 3a), and for the following asphalt specimens glued on the same support already tested in sample 3a, the arrow increases to 13 mm due to the reduction of the crack transfer from the concrete.

In sample 2a it is found that at a 13mm arrow, the number of cycles related to the propagation of the crack through the asphalt layer drops to 9000, which means that the support layer has a lower capacity to take the stress of bending by transfer to the crack, this being taken over by the asphalt layer.

The same mechanism of propagation of the crack through the asphalt protection layer is found in the case of the analysis of this process depending on the opening of the crack in the asphalt specimen.

Sample 2b broke instantly from the first stress cycles because there was no more crack transfer in the concrete layer.

Regarding the analysis of the process of reflective propagation of the crack in the pre-cracked layer of concrete in the asphalt protection layer, the results obtained in the laboratory highlight the same development mechanism presented in previous analyzes, respectively a shorter propagation time when opening the crack in the concrete support is larger. The expression in shorter propagation time is indirect, through the number of stress cycles, which is lower in the case of cracks in the concrete layer (example db = 7mm).

For the asphalt specimens glued on the pre-cracked concrete support with a 7mm opening, the finding made is obvious by the fact that the number of cycles in which the crack propagates through them is much reduced (sample 2b cracks at 300 cycles compared to sample 2a at 9000 cycles).

There was a shorter propagation time when the crack opening in the concrete support is larger. The expression in shorter propagation time is indirect, through the number of stress cycles, which is lower in the case of cracks in the cement concrete layer (example db = 7mm).

It should be noted that the length of the crack propagated in the asphalt test tube propagates on the layer thickness (5cm) at a number of 12900 cycles when there is also transfer to the existing crack in the concrete support (db = 3mm), but practically propagates to the thickness of the asphalt layer of 5cm at only 3600 cycles when there is no more transfer cooperation in the support layer (crack, db = 7mm).

8.4 Multicriteria interpretation of the reflective cracking process

The multicriteria interpretation of the reflective cracking process at rigid road structures rehabilitated by overlaying a protective asphalt, involves a combined analysis between the factors influencing the process of transmission and propagation of the crack in the cracked concrete pavement in the protective asphalt layer.

These influencing factors are described in the form of parametric indices:

- load cycle parameter index $\mathbf{I_{nc}}$,
- the index of the variation parameter of the opening in time of the existing crack in the cement concrete support $\mathbf{I_{db}}$,
- the index of opening of the reflective crack in the asphalt layer $\mathbf{I_d}$,
- the index of reflective crack length in the asphalt layer $\mathbf{I_f}$.

The diagrams of multicriteria interpretation of the process of reflective propagation of the crack through the asphalt layer of the experimental model are presented in the Annex of the doctoral thesis, for each test piece.

4b is the test calibration specimen, since the imaging also showed that all those analysis parameters (n_c, d_b, d, f) evolved through interdependence, and their variation is proportional. (Figure 8.6 şi Figure 8.7).

An increase can be observed on the right side of the bisector in the quadrant of the variation of the opening of the concrete crack (I_{db}) with the crack opening index in the asphalt layer (I_d) of the experimental model (Figure 8.10).

An explanation of this behavior at the reflective cracking of the asphalt layer has a reduced transfer effect in the crack in the concrete, at which the initial opening db_i=3.01mm (Table 8.2).

Comparing this cracking behavior of the experimental model of asphalt-concrete road structure with model 7a, a different evolution can be seen in the I_{nc}/I_f quadrant, due to the crack transfer from the pre-cracked concrete layer where db_i = 1.25mm.

- The increase of the crack transfer from the concrete layer, approximately 2 times, in sample 7a compared to 4b, leads to a development by the propagation of the crack at the test tube 7a in the I_{nc}/I_f quadrant in the direction of the first bisector, which means that this phenomenon represents the bearing capacity. when fatigue cracking of the asphalt layer.
- In the case of sample 4b, due to the reduced transfer in the prestressed concrete layer, the main stress underlying the evolution of the reflective crack in the asphalt layer is that of bending tension, and the evolution curve in the I_{nc}/I_f quadrant is above the first bisector (Figure 8.10).

8.5 On site measurements for calibration of laboratory tests

In order to follow the evolution in time of the degradations of the road structure, we need information related to the type and thickness of the layers in the structure, the degradations that appear over time at the level of the road (visible part of the road system), their dimensions, but and information on traffic on that road sector (vehicle categories, number, weight distribution by axle type) and daily and seasonal temperature differences.

Once known, decisions can be made on how and when to intervene on the road (either by surface treatments, or by replacing the upper layers of protection, or by the complete restoration of the road system).

One of the most efficient methods today, to centralize the information collected from the field, is the GIS (Geographical Information System). They allow a better organization of data, store, process and view the information entered.

For the collection and up-to-date maintenance of interesting information from the point of view of the road infrastructure, a combined video / GPS system has been designed (it can consist of a laptop to which a GPS receiver and video cameras are connected), mounted on a machine that runs on the respective road and measures through the technology assimilated to the scan the degradations appeared on the surface of the road system, positioning them as a location on the road side with the help of GPS receivers.

After the measurements made in the field with the help of this vehicle, the data is processed.

In the case of reflective cracking when analyzing the fatigue phenomenon for composite road structures (asphalt pavement on concrete support), the longitudinally cracked one is chosen from the scanned surface. This type of cracking is dedicated to the phenomenon of structural fatigue, resulting as a reflective cracking from the failure of the lower road layers. Longitudinal fatigue cracks appear on the road surface, which are generally accompanied by permanent deformations assigned to the local track or settlements, so to the vertical deformations (w), studied in the case of experimental modeling with the Cracking Device with Temperature Control.

It is possible to visualize the asphalt-concrete interface cooperation, through tests with Georadarul, in order to ascertain the changes of adhesion, respectively, the appearance of the detachment parameter and by measurements in the way.

If traffic measurements are also available [32], which involves knowing the number of loading cycles related to the Nc traffic volume [30] [31] [32], it means that a second equivalent search parameter is available (n_c). With the two parameters evaluated on an experimental sector in reality, the analysis procedure established by the experimental program of this doctoral thesis can be used, dedicated to determining the performance of the composite road structure, by reporting the behavior of the small-scale model tested in the laboratory with the Cracking Device.

What this way of acquiring and processing data does not offer us, at least in terms of cracking road structures, is what happens until the crack appears on the surface, more precisely the time when it propagates from the foundation, through the upper layers. . Also, another inconvenience is the long follow-up time necessary to evaluate the behavior of the adopted solutions.

In order to remove these inconveniences, experimental modeling is performed that simulates as accurately as possible the evolution of degradations due to traffic and temperature variations at the design stage of the asphalt mixture recipe in the laboratory, anticipating the research procedure proposed by the doctoral thesis. , an extremely important factor for the elaboration of the intervention strategies on the way, namely, the normed duration of operation of the designed road structure.

Thus, road test specimens were extracted from the field on the occasion of a quality technical expertise, specimens that were subsequently processed to obtain the dimensions provided for testing by experimental modeling in the laboratory.

For this part of the Experimental Program of the Doctoral Thesis, two locations were used as follows:

From the first location, located on DNCB (Bucharest ring road), samples were taken from the road clothing with wear layer from MAS 16, with an operating duration of 7 years, which aimed to determine the characteristics of reflective cracking in the case of a mixture asphalt with a high degree of severity.

From the second location, other specimens were taken from the road, on the occasion of another road expertise in the area of the Arad-Nădlac Highway, which was under construction in 2014.

The asphalt layer was cut from the road surface, either together with the concrete support, or by the effective detachment of the asphalt wear layer at the level of the primer with the concrete base layer.

In this case there are two options for researching reflective cracking:

1. On the specimen that has adhesion to the concrete support, a cut is made to the lower fiber of the concrete layer, in order to obtain the weakening of the section of the rigid layer, in order to anticipate the reflective cracking at demands with the cracking device;
2. For the specimen where it was succeeded in core drilling, detachment from the concrete layer, the method described in the case study applied in the thesis is applied, namely, cutting the asphalt slab in the laboratory to the size of the pre-cracked concrete slab and gluing the asphalt on the precast concrete. In this case, the quality of the primer at the asphalt-concrete interface is highlighted.

The samples taken from the road (MAS 16 layer with thickness H = 5 cm) and prepared at the scale of the experimental model, were laid on the same pre-cracked concrete support, by priming the interface (case 2), as was done in the case of the program experimentally performed on asphalt specimens made in the laboratory.

It is mentioned that the transfer to the crack in the concrete was partially consumed, due to the tests from the first experimental program. In this case, the decrease of the transfer in the crack in the concrete support is taken into account by reporting the results compared to the last sample tried in the first experimental program.

The percentage calculation shows that 95.5% (9a), respectively 80% (9b) of the life of the mixture is consumed until the crack appears and 4.5% (9a), respectively 20% (9b) of the time is the propagation of the crack through the asphalt (Table 8.4). There is a considerable increase in the behavior of the protective state after the appearance of the crack in it in specimen 9b.

Table 8.4 Index of reflective crack length in the asphalt layer, 9a and 9b

Specimen	The index of reflective cracking length, $I_f = \frac{n_{ci}}{n_{cR}}$ (%)	Number of cycles
9a	95.50%	564
9b	79.80%	2940

The results of the laboratory tests performed on this set of specimens extracted from the field were as follows:

1. On the specimens extracted at DNCB, when the opening of the initial crack at the concrete support is db = 5mm (considered a crack)

It can be concluded, as in the case of the large opening in the concrete support, so in the case of lack of transfer to the crack when mobilizing only the tensile strength of bending in the asphalt layer, which also has a share of structural fatigue strength during of operation already carried out until the moment of sampling from the track, the reserve of capacities to take over the reflective crack is 6342/11972 = 0.53, respectively 53%.

It can be seen that following the reflective cracking test after the end of the first experimental program, respectively after the test 9b, to open the initial crack considered db = 3mm, the asphalt specimen initially cracks at the lower fiber at 2864 cycles with w = 3.98mm, and over the entire thickness at a number of cycles of nc = 9838 cycles with w = 14.15mm. In this case it can be found that the reflective crack reserve is 9838/11972 = 0.82 in the case of the existence of the transfer to the crack of the supporting concrete, 82%;

2. On the specimens extracted from the section of highway under construction at the time of taking the specimens from the asphalt pavement, and where the occurrence of a cracking process with a low severity in the concrete support was observed, when making the reflective cracking model be tested on the cracking device, db = 0mm was taken into account, so a perfect closing of the crack in the concrete support was followed.

It can be seen that the number of cycles obtained on the experimental model that uses the field-processed specimen related to an asphalt layer immediately after laying in the road and therefore not yet circulated, corresponds to the values obtained on the specimen in which the asphalt layer was made in the laboratory. This fact demonstrates that the research of the initial performance of the reflective cracking behavior of an asphalt mixture proposed for execution in the field, can be analyzed from the design phase of the asphalt mixture recipe in the laboratory, when analyzing the optimal recipe for paving the road.

CHAPTER 9. FINAL CONCLUSIONS, PERSONAL CONTRIBUTIONS AND FUTURE RESEARCH DIRECTIONS

9.1 Final conclusions

The doctoral thesis entitled "*CONTRIBUTIONS REGARDING THE ANALYSIS BY MODELING THE REHABILITATED ROAD STRUCTURES AT LOADS ASSIMILATED TO ROAD TRAFFIC*", had as main purpose the identification of a procedure of parametric analysis of the results of reflective cracking tests obtained in the laboratory. CFDP-UTCB. To achieve this goal we organized the content of the doctoral thesis in two distinct parts, respectively PART 1 DOCUMENTARY SYNTHESIS, with the main studies and research analyzed in the literature, which published the results obtained in testing asphalt mixtures for reflective cracking and PART 2 PERSONAL CONTRIBUTIONS TO THE STUDY OF REFLECTIVE CRACKING using Cracking Device with Temperature Control.

In PART 1 I have synthesized a series of theories and publications from the literature, which highlighted the main characteristics of the development of reflective cracking from used road layers in operation in new asphalt layers, with the role of protection and wear at such road structures.

In PART 2 I identified and interpreted through the tests performed on the cracking device, the following parameters of the reflective cracking through the asphalt protection layer of a rigid road pavement degraded by cracking:

- Accelerated cracking service life (T_f)

- Crack opening in the asphalt protective layer (d)
- Detachment at the asphalt-concrete interface in the crack area (e)
- Number of cycles at crack initiation and propagation $\mathbf{n_{ci}}$, at the opening and propagation of the crack on the thickness of the asphalt layer $\mathbf{n_{cf}}$ and at fracture $\mathbf{n_{cR}=n_{ctot}}$.
- Vertical deformation (deflection) at the initiation and propagation of the crack $\mathbf{w_i}$, at the opening and propagation of the crack on the thickness of the asphalt layer $\mathbf{w_f}$, at fracture $\mathbf{w_{fR}}$ and at failure $\mathbf{w_R}$.
- The opening of the existing crack in the old pre-cracked concrete layer (db)

Figure 8.4, resulting as a graphical representation obtained during the tests, shows the recorded variation of the vertical deformation (w) of the specimen in relation to the increase in the number of loads (n_c). It is possible to determine the increase of the elasto-plastic deformation of the asphalt layer on the pre-cracked concrete support until the moment of occurrence of the reflective crack at the lower fiber subjected to the bending stress cycles (when it can be determined n_{ci} - the number of cycles , followed by phase 2, the propagation of the crack on the thickness of the asphalt layer, when n_{cf} is determined, and the last phase (phase 3), when the surface crack turns into a crack over 0.5 mm and the rupture of the specimen occurs. These stages are also found in reality, when the visual investigation of the evolution of the crack on an experimental road sector is made and consequently, the reflective crack can be interpreted at the moment of appearance at the road surface depending on its opening, depending on the thickness of the asphalt layer. (h_{asf}) and traffic evaluations (N_c-real traffic, transformed into computational traffic, comparable to the number of cycles determined on the test tube extracted from the road, n_c).

Also, if there were measurements performed with the georadar on the experimental sector, it can be determined by non-destructive measurements and the eccentricity of the reflective crack, depending on the detachment parameter at the asphalt-concrete interface (e). Of course, an important parameter that can be measured in the field is the settlement (w) next to the analyzed crack.

Tests performed on test specimens extracted from the road on an uncracked area, prepared at the scale of the test model on the Cracking Device, can establish the parameters of the reflective crack at the time of analyzing the road structure on the experimental sector, considered as effective values in the field. By reference to values obtained on similar specimens, but made in laboratory conditions, dimensionless performance coefficients can be determined, in the form of crack indices, which can qualitatively present information on the resistance to reflective cracking of existing asphalt pavement.

Through this analysis, it can be established until the scheduled time on this qualitative research path, the perspective period of the asphalt layer restoration intervention, respectively the milling of the existing one and its restoration with a new asphalt layer, whose normal operation duration can be anticipated by testing with the Cracking Device.

The results obtained within the Experimental Program and in the stage of Interpretation of the results obtained by Mathematical Modeling, can be summarized as follows:

I. RESEARCH STAGE 1 "**Experimental measurements on composite structures using the Cracking Device with Temperature Control**"

At the time of establishing the Experimental Program of the doctoral thesis, the equipment was in the prototype phase of the device intended for the study of reflective cracking through asphalt specimens such as rectangular plates, used for experimental modeling.

In this study stage, I went through a stage of calibration of the experimental model, in order to record the parameters by imaging acquisition, during the test for crack propagation through the asphalt layer, in case of testing the experimental model in accelerated cycles (in steps successive and predetermined load-bearing forces) of the demand equivalent to road traffic.

Using this reflective crack test scheme from the pre-cracked concrete support in the protective asphalt layer, various behavioral interpretations of the asphalt concrete composite road structure can be obtained.

II. RESEARCH STAGE 2 "**Analysis of the parameters defining the phenomenon of crack propagation in degraded concrete pavements through the protective asphalt layer**"

In the case of the evolution of the crack propagation in asphalt specimens on concrete, the parameters presented in stage 1 can be analyzed. (Figure 9.1).

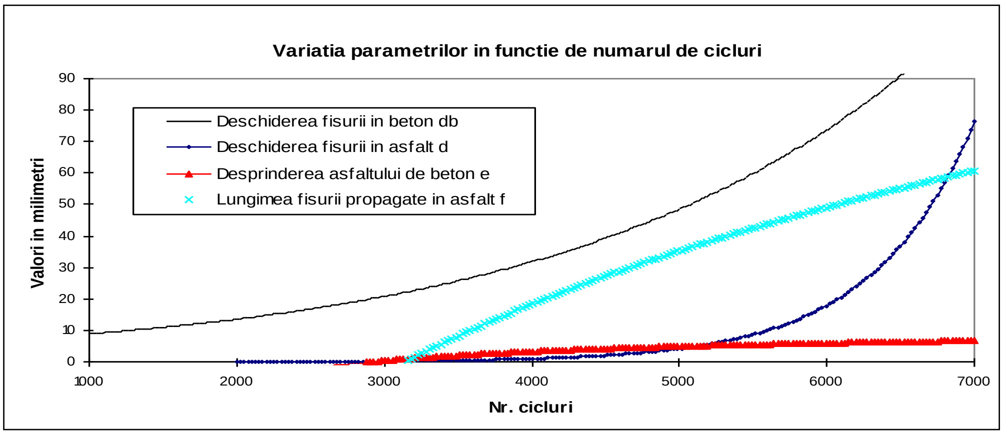


Figure 9.1 Variation of crack parameters according to the number of cycles

As can be seen from the graphical representation of the evolution of the mentioned parameters, the appearance of each parameter occurs in stages, as seen in the image processing (Figure 8.14 și Figure 8.15), respectively first occurs the opening of the concrete crack (db), due to reduction the ability to take on the tensile stresses from repeated bending, then the crack at the base of the protective asphalt layer (d) is primed, while, practically, the detachment at the asphalt-concrete interface (e) develops during the crack propagation on the thickness of the asphalt layer protection (increases the length of the crack on the thickness of the asphalt layer).

III. RESEARCH STAGE 3 "**Interpretation of laboratory results**"

The laboratory research on the Cracking Device with Temperature Control, highlights two types of analyzes at the procedure for evaluating the performance in operation of the solution for the protection of concrete coatings degraded by the appearance of cracks and fissures during the operation period, namely:

- the performance of the asphalt protection layers provided with an anti-crack system of the geocomposites type;
- crack propagation performance from the degraded concrete layer to the asphalt protection layer, depending on the degree of severity at cracking (crack with db = 3mm, crack with db = 7mm).
- It was found that in the case of a crack with small opening (db = 3mm) in the concrete support layer, when there is transfer of tensile stress from bending to cyclic stresses assimilated to road traffic, the number of cycles (n_c) is greater (example Sample 3a, db = 3mm, w = 4mm, n_c = 12700), and when the degradation occurred is a crack in the support (db = 7mm), so there is no perfect cooperation between the crack walls, the number of N_c cycles related to crack propagation through the asphalt layer is much smaller (example Sample 4b, db = 7mm, w = 24mm, n_c = 3600).
- It must also be taken into account that the asphalt specimens were glued by priming to the same pre-cracked support, which means that as the number of cycles applied increases, the adhesion of the joint to the crack in the concrete slab is consumed, thus decreasing the transfer capacity at the crack of the support layer, the speed of its propagation through the protective asphalt layer increases.

IV. RESEARCH STAGE 4 "**Interpretation of results obtained by experimental modeling, using mathematical modeling**"

Following the laboratory tests obtained by experimental modeling for research by phenomenological simulation of the reflective crack from the pre-cracked concrete support in the asphalt overlayer during the exploitation period, we move to the stage of mathematical modeling of these results for the evaluation of laws of evolution of the reflective crack.

V. RESEARCH STAGE 5 "**Parametric interpretation of the process of reflective cracking**"

The following are some observations on the experiments performed on a number of 10 specimens (4b, 5a, 5b, 6a, 7a, 7b, 8a, 8b, 9a, 9b), in terms of the consecutive variation of the parameters of the reflective crack, obtained with the cracking device.

These asphalt slabs, which retain the thickness of an asphalt layer, were glued to the pre-cracked concrete support with a bitumen primer and then tested one after another. In this scenario, the successive test leads to the modification of the transfer to the predetermined crack of the concrete support.

The experimental observations are related to the different bonding conditions of the asphalt slab on the pre-cracked concrete support, to the initial opening of the existing crack in the concrete and of course to the structural conditions obtained when making the asphalt slabs.

In order to have a sufficient period for the capability of the device to record the progressive reflection of the reflective crack through the asphalt layer of the specimen, the test temperature is set at 15°C, corresponding to a controlled rigidity of the asphalt layer.

In the following summary table, such an analysis of the parameters of the reflective crack is presented.

Table 9.1 Crack parameters db_i, e_i, e_f and the number of cycles (crack and fracture)

Specimen	db_i	e_i	e_f	n_{cR}	n_{cf}	n_{cR}- n_{cf}
6a	1.1480	2.9161		10520	9974	546
7a	1.2487	2.5909	0	7790	7496	294
8a	1.3547	3.7808	-30.312	11338	11100	238
8b	1.4843	3.7651	-5.2985	12081	11550	531
9a	1.5641	3.9895	-5.3206	12536	11972	564
5b	1.7432	2.5419	18.0604	12429	12116	313
7b	1.7652	3.7385	5.2845	4283	4183	100
9b	1.8062	3.1721	0	14552	11612	2940
5a	2.1008	1.6753	27.4216	12556	12200	356
4b	3.0088	2.1528	17.4627	1259	1000	259

a. Two of the parameters measured in the experiment, which indirectly influence the propagation of the crack through the asphalt protection layer, are: the initial opening of the concrete crack (db_i, friction cooperation between aggregates and/or between cement stone, between crack walls) , and the initial detachment of the asphalt layer from the concrete slab (e_i, the bitumen primer, at the interface between the concrete and the mixture).
b. It is identified by a crack index (Table 9.2), determined by reporting the number of cycles determined at the end of the reflective crack to the number of cycles determined at the initiation of the crack at the lower fiber of the asphalt layer, life and duration of operation of the asphalt layer during the crack propagation process in the degraded lower layer during the exploitation period:

Table 9.2 Crack/fracture life cycle of the specimens.

Specimen	The index of reflective cracking length I_f	Ratio $(n_{cR}-n_{ci})/n_{cR}$
6a	94.81%	5.19%
7a	96.23%	3.77%
8a	97.90%	2.10%
8b	95.60%	4.40%
9a	95.50%	4.50%
5b	97.48%	2.52%
7b	97.67%	2.33%
9b	**79.80%**	**20.20%**
5a	97.16%	2.84%

In Table 9.2, it can be seen that if the ratio between the number of cycles at the initial crack and the number of cycles at the final crack has a higher value, so the crack propagates in a longer time, the index is lower, respectively the normal operating time relative to the crack propagation period is longer (for example, in sample 9b, at a crack index of 79.8%, the normal operating time may increase by 20.2%);

c. The results of the experimental modeling on the cracking device can be expressed using a mathematical model, more precisely regression functions that describe the variations of the cracking parameters, depending on what is wanted:
   - The length of the crack depending on the number of cycles - we can determine how long the crack propagates on half the thickness of the protection layer. This finding is extremely important in relation to other experimental models used in the evaluation of the fatigue phenomenon in asphalt layers, which establish that the strength of the layer is consumed if half of the deformation accumulated during the stress cycles has been consumed;
   - Calculating the speed of variation of the crack opening existing in the concrete support, highlights the phenomenon created by the transfer effect to the crack by the initial friction of the walls of this support layer, attenuated by damping the transfer process by the presence of asphalt to fiber of the concrete layer, which works together with it by applying the technological operation of priming. Thus, initially, when working the transfer from the crack of the concrete layer together with the damping of the asphalt layer present at its surface, the capacity to take over the vertical deformation (deflection under load) is higher and therefore the opening speed of the existing crack in the concrete it is smaller;
   - In the intermediate stage, when the transfer to the crack of the concrete support layer is consumed and the capacity to take over the crack transmission through the asphalt layer is mobilized, the curvature of the diagram changes, so that in the final phase of reflective propagation the crack opening speed from the concrete layer to grow at a lower deflection.

VI. RESEARCH STAGE 6 **"Multicriteria interpretation of the reflective cracking process"**

The multicriteria interpretation of the reflective cracking process at rigid road structures rehabilitated by laying a protective asphalt layer, involves a combined analysis between the influencing factors of the process of transmission and propagation of the crack in the cracked concrete pavement in the asphalt layer.

These influencing factors are described in the form of parametric indices:

- load cycle parameter index $\mathbf{I_{nc}}$,
- the index of the variation parameter of the opening in time of the existing crack in the cement concrete support $\mathbf{I_{db}}$,
- the index of opening of the reflective crack in the asphalt layer $\mathbf{I_{d}}$,
- the index of reflective crack length in the asphalt layer $\mathbf{I_{f}}$.

a. The increase of the crack transfer from the concrete layer, approximately 2 times, in sample 7a compared to 4b, leads to a development by the propagation of the crack at the test tube 7a in the I_{nc}/I_f quadrant in the direction of the first bisector, which means that this phenomenon represents the bearing capacity. when fatigue cracking of the asphalt layer.

b. In the case of sample 4b, due to the reduced transfer in the prestressed concrete layer, the main stress underlying the evolution of the reflective crack in the asphalt layer is that of bending tension, and the evolution curve in the I_{nc}/I_f quadrant is above the first bisector (Figure 8.10).

c. Approximately 95% of the life of the mixture is consumed until the crack appears and 5% of the time is the propagation of the crack through the asphalt plate.

VII. RESEARCH STAGE 7 **"On site measurements for calibration of laboratory tests"**

Thus, road test specimens were extracted from the field on the occasion of a quality technical expertise, specimens that were subsequently processed to obtain the dimensions provided for testing by experimental modeling in the laboratory.

It can be concluded that in case of large opening in the concrete support, so in case of lack of transfer to the crack when mobilizing only the tensile strength of bending in the asphalt layer, which also has a share of structural fatigue strength during of operation already carried out until the moment of sampling from the track, the reserve of capacity to take over the reflective crack is 53%. If there is a transfer to the crack of the supporting concrete, it can be found that the reflective crack reserve is 82%. These conclusions are valid in the case of samples taken from the Bucharest ring road.

On the specimens extracted from the section of highway under construction at the time of taking the specimens from the asphalt pavement, and where the occurrence of a cracking process with a low severity in the concrete support was observed, when making the reflective cracking model be tested on the cracking device, db = 0mm was taken into account, so a perfect closing of the crack in the concrete support was followed.

It can be seen that the number of cycles obtained on the experimental model that uses the field processed specimen related to an asphalt layer immediately after laying in the road and therefore not yet circulated, corresponds to the values obtained on the specimen in which the asphalt layer was made in the laboratory. This fact demonstrates that the research of the initial performance of the reflective cracking behavior of an asphalt mixture proposed for execution in the field, can be analyzed from the design phase of the asphalt mixture recipe in the laboratory, when analyzing the optimal recipe for paving the road.

I emphasize at this moment that the laboratory testing on the Cracking Device equipment is done in accelerated mode, using its conceptual characteristics, while the reflective cracking in reality, determined on the test specimen, occurs during operation under the effects of actual traffic during analyzed.

This situation presupposes an in-depth research, which will have as finality the obtaining of coefficients of equivalence of the traffic assimilated to the loads in accelerated regime with the Cracking Device (number of cycles at which the reflective cracking begins ncf) with the real traffic (N_{cef}) obtained by processing the data related to the experimental sector, from which the specimen is extracted for testing on the laboratory model.

In this research scenario of reflective cracking, the coefficient of performance related to supported traffic is $C_{pnc.f} = n_{c.f} / N_{cef}$, a qualitative and informative coefficient. This, together with the other parameters of the reflective crack obtained in the laboratory, can facilitate an interpretation of the characteristics of the tested asphalt layer on the crack propagation behavior of the support layer, which was cracked when applying the maintenance work with the protective asphalt layer.

In the second scenario presented in the case of the construction stage exemplified by extracting the specimen from the highway section, the performance coefficient for reflective cracking, related to perspective traffic, is determined by reporting the number of cycles (n_{c1}), tested on the specimen. asphalt layer designed and made in the laboratory, compared to the number of cycles (n_{c2}), also obtained by testing on the cracking device, but with experimentally modeled asphalt layer from the specimen extracted from the path.

The result is $C_{pnc.f} = n_{c1} / n_{c2}$, which is a qualitative and informative coefficient. This, together with the other parameters of the reflective crack obtained in the laboratory, can facilitate an interpretation of the characteristics of the tested asphalt layer regarding the crack propagation behavior in the support layer, immediately after completion of a composite road structure, such as concrete layer. provided with asphalt wear layer.

9.2 Personal contributions

The main contribution of this doctoral thesis is the creation of a methodology for working with the prototype device, namely the Cracking Device with Temperature Control.

This device was conceived and created within a CEEX project entitled “Method of complex testing of composite road structures and component materials in order to evaluate and certify according to European norms”, under the guidance of Professor Dr. Mihai DICU. From the team that participated in this project, I took care of the experimental part.

In the thesis we detailed the way in which the test is done, starting from the preparation of the cracked concrete specimens over which the protective layer was glued (either with a mixture prepared in the laboratory or plates taken from the field). Particular attention must be paid to the way in which the gluing is done: the amount of bitumen, the way of pouring it, but also to the initial opening of the concrete crack (to be as close as possible to 0) in order to observe the transfer to the crack, precisely the contribution of the friction of the two parts of the cracked concrete.

The next step is the actual test. This is done at requests equivalent to accelerated road traffic. We established the loading steps during the experiments performed for the present thesis, starting from the conclusions drawn from the tests made before the start of the research program. The basic idea is to shorten the time required for the test, both due to the construction of the device, but also to track the propagation of the crack, transmitted from the concrete, through the protective layer. I consider that the force steps and amplitude chosen at this moment are optimal for the tests on the device.

In order to best describe the reflective crack, we introduced a series of parameters, measured using the video system and recorded by the data acquisition system, such as crack opening in concrete db, vertical deformation **w**, crack length **f** and opening **d** of the protective asphalt, the detachment of the aphalt from the concrete **e**, but also the number of cycles until which the fracture appears, $\mathbf{n_c}$.

We found that using the existing software of the automatic video acquisition system can lead to considerable measurement errors, given the quality and zoom of the image on which the parameters are manually determined and the fact that their values are of the order of millimeters to four decimal places. At the same time, the measurement is made in real time, there is the possibility of rapid propagation of the crack, the data recorded so far to be insufficient for a statistical quality processing. For this, after the crack started, we reduced the saving time of the images during the test, depending on the speed of its propagation, even up to 5 seconds difference, and then the correspondence between the measurements made with the device software and the image processing after completion of the test, thus increasing the available data set.

A third stage is the processing of experimental data through a mathematical modeling, using nonlinear regression functions. It can be seen that i was able to find certain functions that describe the relationships between the parameters followed.

A final step is to interpret the data provided by the equipment. For this I introduced in the thesis the performance coefficients (noted with C_p), necessary both for the comparison of two give several recipes of mixture prepared in the laboratory, either between the plates extracted from the path and those prepared in the laboratory, but also between specimens , in this way it is possible to appreciate how it affects the distribution of the traffic on different road sectors.

Another element that helps us to interpret the results of the experiments is the determination of parametric indices such as:

- load cycle parameter index $\mathbf{I_{nc}}$,
- the index of the variation parameter of the opening in time of the existing crack in the cement concrete support $\mathbf{I_{db}}$,
- the index of opening of the reflective crack in the asphalt layer $\mathbf{I_d}$,
- the index of reflective crack length in the asphalt layer $\mathbf{I_f}$.

Their processing gives us a three-dimensional image of the reflective crack, thus linking the parameters mentioned above (db, f, d, w, nc). After calibrating the mathematical model, any parameter can be found if two others are known.

Subsidiary to this element of novelty, as a contribution, is the bibliographic synthesis of the literature, the concerns in the reflective fracture being current and constantly changing. The use of the finite element thus becomes mandatory in simulating the effects of traffic demands on the road structure, at the same time calibrating the results of the mathematical modeling of the experimental results, but also of the real situation in the field.

9.3 Future directions of research

From the content of the doctoral thesis and from the completion of the Experimental Program, which led to the drafting of the FINAL CONCLUSIONS and PERSONAL CONTRIBUTIONS, it results the need to continue the research, in order to solve the following future topics:

1. Application of the research procedure of the phenomenon of reflective cracking from pre-cracked layers, assimilated to degraded road coverings, in asphalt protective layers, by extending the range of road materials used as wear layers. In this way, performance coefficients for reflective cracking on various materials used in the execution of road pavements will be obtained.
2. Carrying out the equivalence of the road traffic from predetermined experimental sectors, with the number of cycles afferent to the dynamic regime request on the Cracking Device with Temperature Control. In this way, a correlation is made between the system for supporting the road layers in reality with the one offered by the equipment, which is based on the scheme of requesting the stretched beams from the bend.

3. Upgrading the prototype equipment with a device capable of inducing horizontal loads, in order to highlight the cumulation of equivalent traffic and temperature loads, specific to road layers agglomerated with hydraulic binders, used in both semi-rigid road structures and and the rigid ones.

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