

THE USE OF BITUMINOUS CONCRETE REINFORCED BY FIBRES FOR ROAD SURFACES

L. COURARD, J. M. RIGO

University of Liege, Belgium.

Streszczenie: Wyniki badań teoretycznych i doświadczalnych pozwoliły zaprojektować nawierzchnie drogowe z betonów bitumicznych nie ulegających głębokim wyżłobieniom. Parametry wytrzymałościowe betonu poprawiają krótkie stalowe lub syntetyczne włókna dodane do mieszaniny. Zaletami rozwiązania są, między innymi, przedłużony (minimum dwa razy) czas eksploatacji, mniejsza grubość nawierzchni oraz zmniejszone koszty napraw.

Summary: The results of theoretical and experimental investigations permitted designing road surfaces of bituminous concrete resistant to deep cracking. The resistance parameters of concrete are improved by addition, to the mixture, of short steel or synthetic fibres. The advantages of this solution, amongst others, are: increased exploitation time (minimum twice), decreased surface thickness and reduced costs of repairs.

Résumé: Les résultats donnés par les études théorétiques et expérimentales ont permis de définir une solution intéressante visant à lutter contre le craquellement des revêtements bitumineux le long des routes: l'incorporation dans le mélange de courtes fibres métalliques ou synthétiques. Les avantages de cette solution sont très clairs: par exemple augmentation (minimum deux fois) de la durée de vie des structures, possibilité de réduction de l'épaisseur du revêtement et réduction des frais de réparation.

Резюме: Результаты теоретических и экспериментальных исследований позволили спроектировать дорожные покрытия из битуминозных бетонов, не подвергающихся глубоким впадениям. Прочность бетона повышают короткие стальные или синтетические волокна, добавленные к смеси. Приметами решения являются м.др. продленное (минимум в два раза) время эксплуатации, меньшая толщина покрытий, а также уменьшение затрат на ремонты.

1. INTRODUCTION

The Belgian road network is one of the most dense in the world. A map shows it clearly. At present, the authorities are more and more often confronted with road repairs, and particularly with remove of the road overlays. Requirements of the users are increasing: safer roads, better visibility, mechanical comfort and decreased noise. So it is necessary to act with precision, rigour and discernment.

2. THE PROBLEM OF DEEP CRACKING

2.1. DEFINITION

Deep cracking is a permanent deformation parallel to the axis of the road; its length is equal to 4 times its width. This deformation can be more than 10 mm deep. It reduces

the safety of users of a road when the crack is from 15 to 17 mm deep, and the road must be repaired or the surface removed, when it is 25 mm deep.

2.2. CAUSES

2.2.1. External factors

2.2.1.1. Traffic. Experience shows that the more destroyed parts of the road are the ones characterized by:

heavy and canalized traffic (especially the overloads with regard to the admissible load of axle-trees);

slow speed of circulation (including the location stops of the vehicles);

tangential effects (slope, turning, crossroads).

2.2.1.2. Climatic effects. In addition to the traffic effects, we must consider some climatic effects such as the variation in water content of the soils, and the variation of temperature. The diagram presented below permits estimating the importance of these external factors. It is the result of investigations carried out in 13 countries.

	D	B	CDN	E	F	IRL	I	J	NL	GB	CH	TR	USA
	○	●	○	●	●	○	●	●	●	○	○	●	○
	○	●	●	●	●	○	●	●	●	●	○	●	○
	10	13	9	13	13	10	10	10	10	9	10	8	10
°C max	50	50	49	60	55	45	60	60	54	45	55	55	60

Importance: ● – great, ○ – small.

Fig. 1. External factors influencing roads

It concerns:

the importance of deep cracking,

the importance of overloads,

the maximum authorized weight by axle,

the maximum temperature of the overlayer.

We can immediately see the correlation between the importance of the overloads and deep cracking (Belgium, Spain, France, Italy, Japan, the Netherlands, Turkey). Only two countries (Great Britain and Canada) consider that the problem of deep cracking is not important, but there the maximum weight by axle is only 9 t and the maximum temperatures of the overlayer are less than 49 and 45 °C.

It appears that in the thirteen countries of the O.C.D.E., the most important factors having an effect on deep cracking can be classified as follows:

- a) overloads,
- b) maximum weight by axle,
- c) maximum temperature of overlayer.

2.2.2. Internal factors

Degradations of the transversal profile of a road with bituminous concrete can be also produced by irreversible deformations of some layers of the road structure. For motor traffic and climatic environmental conditions, the resistance of a road with bituminous concrete to deep cracking is a function of:

- the geometry of the structure (so, it is important to take the permanent deformation into account),
- the mechanical properties of the materials.

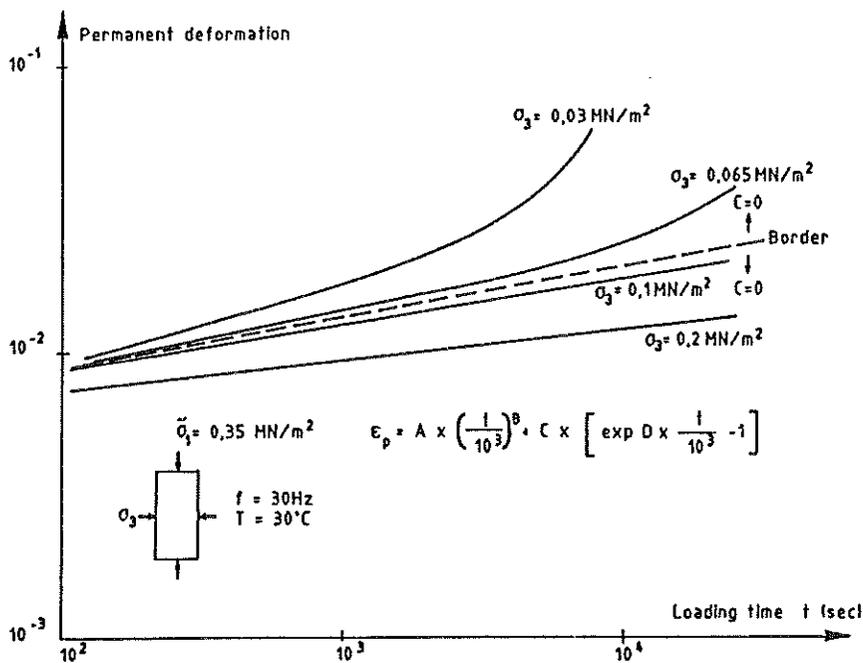


Fig. 2. Repeated loading test [7]

The mechanical behaviour of road materials is essentially characterized by:
 deformation modulus (or rigidity modulus),
 fatigue resistance,
 resistance to permanent deformations in dynamic compression.

Concerning this last point, research has been conducted by the Belgian Road Research Centre, showing that the resistance to permanent deformation under dynamic compression of such a material can be evaluated by means of curves of the dynamic creep, based on repeated loading tests (dynamic loading).

A general law giving the evolution of permanent deformation in the function of time for several sollicitation conditions (frequency, temperature, stress intensity) is given by

$$\varepsilon_p = A \left(\frac{t}{10^3} \right)^B + C \left(\exp D \frac{t}{10^3} - 1 \right).$$

We can see that we must try to choose layers with C equal to zero; experimental studies show that B is between 0.14 and 0.37. So, the increasing of permanent deformation is directly related to the parameter A . This parameter is inversely proportional to the bituminous concrete modulus of deformation E , which means to the composition, speed of loading and temperature.

As far as the determination of the modulus E is concerned, it has been shown that for a given temperature and frequency, the higher the voluminal ratio between the aggregates and binder, the higher the modulus of rigidity and the lower the thermal susceptibility. These theoretical considerations permit us to say that, if we want to design a bituminous concrete resistant to deep cracking, we have to choose a binder with high consistency and low thermal susceptibility, voluminal rates between aggregates and binder relatively high and, of course, a low percentage of binder.

3. EXPERIMENTAL APPROACH

A great number of fibres have been selected. Their basic parameters were as follows:
constitutive material,
physical characteristics,
shape and length.

The results which follow present the principal types of fibres that were considered. Glass fibres were rejected because of surface problems. Polypropylene and polyethylene fibres were also rejected because of temperature resistance problem.

3.1. MARSHALL TEST

The aim of this test is to determine the mechanical characteristics (stability and Marshall flow) of the bituminous concrete after a hot compaction under normalized conditions. In fact, the test consists in submitting the samples to a thermal ageing at 60 °C and thereafter they are subject to compression at a constant loading speed and with grips well defined. By means of the load-strain curve it is possible to determine the stability Pm and the flow Fm .

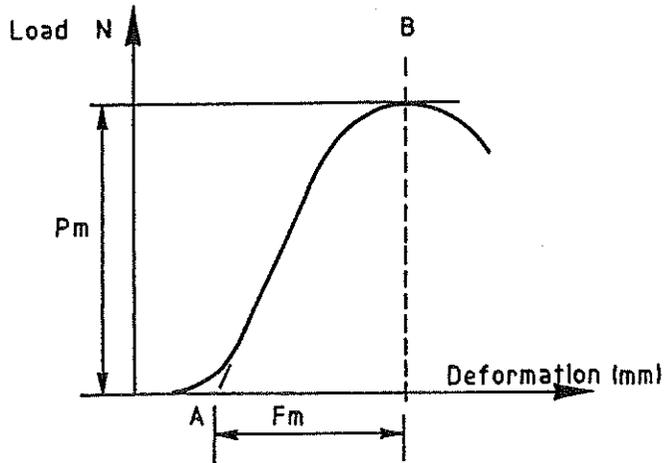


Fig. 3. Load-strain curve

The characteristics of the materials used for the making of the bituminous concrete of type I were as follows:

aggregates	10/20 - 8%,
(sandstone type)	7/10 - 29.4%,
	2/7 - 17%,
	0/2 - 37%,
filler	8.6%,
bitumen	50/60 - 6%.

All the aggregates and sands have been washed, sieved and dried. The results are given in table 1.

Table 1

Parameters of aggregates and sands

Commercial name	Type	%	Marshall stability N	Marshall flow mm	Ratio $N \cdot mm^{-1}$
Without fibre	-	-	8500	3	2833
DRAMIX ZC 30/50	steel	1.5	10767	3.5	3076
HAREX SF 12-16	steel	1.5	11867	3	3956
DACRON D157-10mm	PES	0.3	10600	2.8	3786
DOLANIT 11 100/6	PAN	0.3	11400	2.9	3931
EXXON (G)	PP	0.3	13533	2.7	5012

3.2. BEHAVIOUR OF THE BITUMINOUS CONCRETE
AT ELEVATED TEMPERATURE

A new test has been developed to determine the behaviour of a bituminous concrete, loaded with a constant weight when the temperature regularly increases.

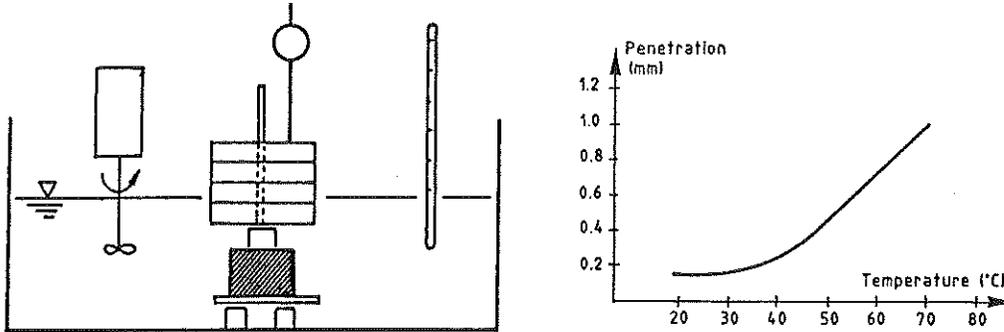


Fig. 4. Measurement of penetration depth vs. temperature

Samples of Marshall type (10 cm in diameter, 6.5 cm in height) are placed in a thermostat bath with glycerine. The increase in temperature is 1 °C per minute.

The load of the bituminous concrete samples is $5 \text{ kg} \cdot \text{cm}^{-2}$; a deformer allows us to follow the penetration depth of the sample as a function of the temperature (see the scheme and the curve in fig. 4). The results are also given in table 2 where penetration depths, depending on temperature, are presented.

Table 2

Penetration depths vs. temperature

Sample	Penetration depths at		
	40 °C	60 °C	80 °C
A8 without fibre	0.2	0.58	0.75
B8 DRAMIX ZC 30/50	0.08	0.47	0.72
C8 DOLANIT 11 100/6	0.03	0.33	0.46
H8 HAREX SF 12-16	0.13	0.58	0.72
I5 DOLANIT 10 30/6	0.19	0.35	0.53
O8 RP 17	0.05	0.3	0.5

The test, first of all, shows the positive effect of the incorporation of fibres into the bituminous concrete – from 40 °C we observe an excellent behaviour of some plastic and steel fibres – and secondly, the test shows that when the temperature increases, the

positive effect due to the incorporation of steel fibres becomes less significant and the one due to plastic fibres, such as DOLANIT and RP 17, remains important.

3.3. STUDY OF THE FIBRE SHAPE

We have to study the behaviour of the steel or plastic fibre in an unhomogeneous medium consisted of bitumen, sand and gravels. However, to simplify the approach, we shall consider that the bituminous concrete is homogeneous. Consequently, the bituminous concrete with fibres will be a composite system where the bituminous concrete and the fibres are homogeneous and dispersed phases, respectively.

We consider a part of a fibre of the length dx (figure 5). The forces acting on this element are in an equilibrium when a variation in the normal force is compensated by an opposed shear force:

$$\pi r^2 d\sigma_f = 2\pi r_f \tau dx,$$

$$\frac{r_f d\sigma_f}{2 dx} = \tau$$

where:

r_f – fibre radius,

σ_f – normal stress,

τ – shear stress at the interface.

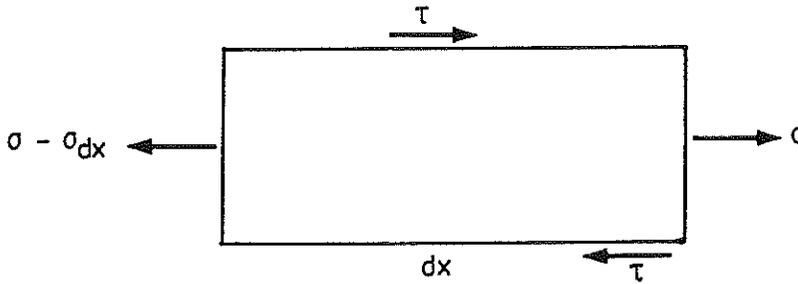


Fig. 5. The forces acting on a fibre of the length dx

The shear force comes from the shearing γ of the matrix around the fibre and this effect is proportional to the displacement u due to the presence of the fibre in the matrix. We can write:

$$\tau = G_m \gamma = CG_m \frac{U}{r_f}$$

where C is a constant, and G_m the shear modulus of the matrix.

$$d\sigma_f = \frac{2}{r_f} CG_m \frac{U}{r_f} dx,$$

$$\frac{d\sigma_f}{dx} = \frac{2}{r_f^2} CG_m U,$$

$$\frac{d^2\sigma}{dx^2} = \frac{2}{r_f^2} CG_m \frac{dU}{dx}.$$

Hooke's law gives:

$$\sigma_f = E_f \varepsilon_f = E_f \frac{dU}{dx},$$

so

$$\frac{d^2\sigma}{dx^2} = \frac{2}{r_f^2} CG_m \frac{1}{E_f} \sigma_f.$$

We note:

$$\frac{1}{x^2} = \frac{2}{r_f^2} CG_m \frac{1}{E_f},$$

and

$$x_0 = r_f \sqrt{\frac{E_f}{2CG_m}}.$$

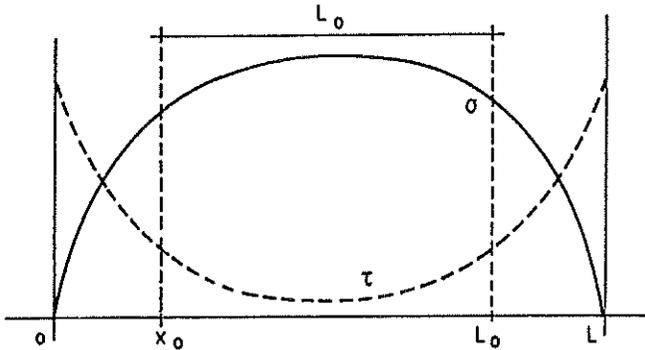


Fig. 6. Variation in the normal stress σ and the tangential stress τ along the fibre

Only the length l_0 of the fibre is influenced by the matrix and is strained, which means that the deformation of the fibre increases progressively from the extremities and is equal to the one of the composite at a distance proportional to $r_f \sqrt{E/G_m}$. So it is as if only a small quantity of fibres x_0/l had the same deformation as the composite, and the rest was almost not deformed.

Consequently, the fibres must be relatively long to have any influence on the modulus; there is a critical length for the fibre. As to the shape of the fibre, its influence will be important at the extremities of the fibre, where the shear stresses are maximum.

The shear modulus G_m can be written:

$$G_m = \frac{E}{2(1 + \text{Poisson's coefficient})} \approx \frac{E}{2(1+0.3)} \approx \frac{E}{2.6},$$

as Poisson's coefficient is supposed to be 0.3 for the bituminous concrete.

The values of the viscoelastic modulus E of the bituminous concrete (for a speed of $60 \text{ km} \cdot \text{h}^{-1}$) are presented in table 3.

Table 3

Values of viscoelastic modulus E (in MPa) of bituminous concrete at different temperatures

Bituminous concrete	-20 °C	0 °C	+20 °C	+40 °C	+60 °C
types I and IV	30,000	22,000	9,000	900	90
type II	25,000	20,000	7,000	700	60
type III	30,000	22,000	10,000	1,300	100

We can calculate $r_f \sqrt{E_f/G_m} = Z$ for a bituminous concrete of type I at different temperatures (table 4).

Table 4

Various parameters of bituminous concrete

Fibre type	R_f mm	E_f $\text{N} \cdot \text{mm}^{-2}$	T °C	Bituminous concrete		Z mm
				E $\text{N} \cdot \text{mm}^{-2}$	G $\text{N} \cdot \text{mm}^{-2}$	
Steel	0.25	206,000	-20	30,000	11,538	1.056
Steel	0.25	206,000	0	22,000	8,462	1.233
Steel	0.25	206,000	+20	9,000	3,462	1.928
Steel	0.25	206,000	+40	900	346	6.100
Steel	0.25	206,000	+60	90	35	19.180
Acrylo-nitrile	0.009	18,000	-20	30,000	11,538	0.011
Idem	0.009	18,000	0	22,000	8,462	0.013
Idem	0.009	18,000	+20	9,000	3,462	0.021
Idem	0.009	18,000	+40	900	346	0.065
Idem	0.009	18,000	+60	90	35	0.204

The conclusion is: to play an efficient role, the steel fibres must be relatively longer than the synthetic fibres.

3.3.1. Steel fibres

A test was carried out to quantify the influence of the steel fibres shape on the adherence to bitumen. The pull-out resistance of the fibres from bitumen of 50/60 type has been measured. The immersion depth was 1 cm, and the temperature 20 °C.

Fibre type	Load (g)
Right fibre \varnothing 500 μm	1020
	800
	1060
	average 960
Fibre with hooks \varnothing 500 μm	1470
	1640
	1480
	average 1530
Gulf fibre \varnothing 500 μm	2050
	2600
	2300
	average 2317

Fibres with waves or hooks exhibit a higher bitumen adherence. This is normal and due to mechanical interlocking, so that a higher cohesion may be expected from bituminous concrete where fibres with waves or hooks are incorporated.

3.3.2. Synthetic fibres

Now it was necessary to determine how the fibre-bitumen adherence was influenced by the fibre cross-section type. For the same quantity of incorporated fibres in weight, some cross-section types were analysed (figure 7).

Bituminous concrete cohesion and fibre-bitumen adherence are in close relation: the larger the external fibre surface, the higher the adherence force (of course if the substrate surface energy is higher than the binder one). Taking account of this statement, the following conclusions can be drawn:

The worst is the circular section (I).

The best could be the band (VI) or the circular one with rugosity (II). But it would be necessary to increase the quantity of bitumen to ensure a good wetting. This is against the considerations of chapter 2.2.2.

The solutions III, IV and V are good:

solution III: it can produce a reduction of the tensile resistance and some problems of dispersion;

solution IV: the sections are added to a good surface development, there is a mechanical effect at the level of the "a" zones;

solution V: it seems to be better because the dispersion of the fibres will be easier. Indeed, in order to produce an agglomeration with this type of fibres, we would have such a structure which is statistically not probable.

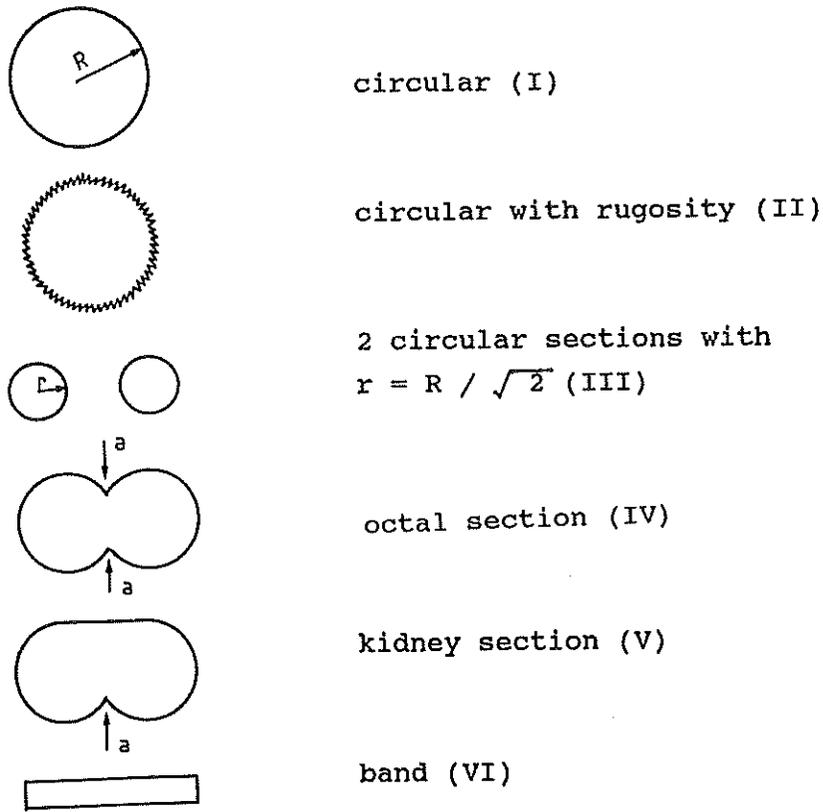


Fig. 7. Cross-sections of fibre types

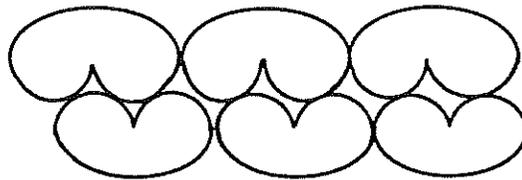


Fig. 8. Agglomeration of easily dispersible fibres

3.4. INFLUENCE OF THE SURFACE TREATMENT

3.4.1. Steel fibre

We considered three types of fibres made from steel, solder and galvanized steel, 0.5 mm in diameter each. The samples of such fibres were immersed in a 50/60 bitumen

with an anchorage length of 3 cm. We determined the pull-out force of the wire at the temperature of 20 °C . The results are as follows:

	Load (g)
Steel	3500
	3270
	average 3385
Solder	2850
	3350
	average 3100
Galvanized steel	3150
	3500
	average 3325

The treatment of the fibre, which can eventually be of interest due to its resistance to corrosion, has no influence on the behaviour or adhesion of the bitumen.

3.4.2. Synthetic fibre

To ensure a good substrate wettability (and so to wet fibre with hot bitumen), it is necessary for the substrate surface energy to be greater than that of the liquid one. The surface energy of the bitumen is $\pm 25 \text{ mJ} \cdot \text{mm}^{-2}$. For the synthetic fibres, we have:

PP: $\pm 32 \text{ mJ} \cdot \text{m}^{-2}$,

PA: $\pm 41 \text{ mJ} \cdot \text{m}^{-2}$,

PAN: $\pm 40 \text{ mJ} \cdot \text{m}^{-2}$.

So there is no problem with PA or PAN types and shall have a good adhesion between these types of products and the hot bitumen.

3.5. SIMULATION OF TRAFFIC TEST

The most important test to be realized was the deep cracking test by simulation of traffic. Indeed, it was essential to study directly the influence of the fibre on the appearance of deep cracking in a bituminous concrete. The results of the tests described above allowed the selection of a certain number of fibres: it was then necessary to point out some of their parameters which are as follows:

the constitutive material of the fibre,

the fibre shape,

the fibre diameter,

the fibre length,

the percentage of fibres.

1. *Principle of the test.* The aim of the test is to estimate, for certain experimental conditions, the susceptibility of a compacted bituminous concrete to deep cracking and

to evaluate the effect of the fibres on this phenomenon. The surface of the samples is loaded by means of two loaded wheels.

2. *Description and characteristics of the test.* A sample of 63 cm in diameter and 5 cm thick is placed in a fixed mould on the rotative part of a traffic simulation testing machine. Two wheels rotate in a fixed vertical plane, around horizontal axle (figure 9).

Characteristics:

maximum circumferential speed: $1 \text{ m} \cdot \text{s}^{-1}$,

load applied on each wheel: 40 kG,

type of wheel: VREDESTEIN $260 \times 85-4 \text{ P/R}$,

air pressure of the wheels: 6 bars (this corresponds to the load of $35 \text{ to } 40 \text{ kg} \cdot \text{cm}^{-2}$ on the bituminous concrete),

temperature of the test: $40 \text{ }^\circ\text{C}$.

3. *Test procedure.* A recorder allows determining the number of rotations, and the measurement of the deep cracking is realized on two perpendicular diameters (4 measurements) by means of a dial gauge.

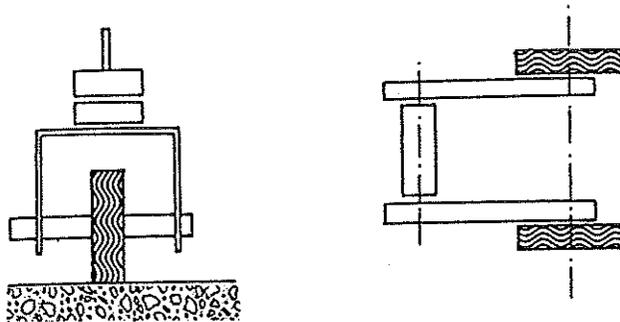


Fig. 9. Wheels loaded with series of 20 kg weights

4. *Test results.* In table 5 the results for different types of fibres and the percentages are presented.

It is also possible to present the results in the form of graphs where the values of the deep cracking measurements versus the number of cycles of loading are presented. These graphs are drawn in order to compare the results obtained with different types of fibres and different percentages in relation to a reference sample (fig. 10).

Basing on the data presented we can draw the following conclusions:

1. From figure 11 it is evident that, in comparison with bituminous concrete not reinforced with fibres, the incorporation of steel fibres under the optimum conditions (percentage, length, etc.) produces a reduction of the deep cracking equal to about 50%; the use of synthetic fibres, such as acrylonitrile fibres, allows the reduction of deep cracking to 60%.

Table 5

Test results

Maximum depth of deep cracking (mm)					
Sample	Commercial mark	%	Type	Results	Voids %
1	DRAMIX ZL 30/50	0.5	A	5.8	6.9
2	idem	1	A	4.6	6.4
3	idem	1.5	A	7.2	7.5
4	reference	—	—	9.6	5.2
5	HOECHST 11 100/6	0.3	AN	3.6	5.3
6	HAREX SF 12-16	1.5	A	5.2	5.3
7	HOECHST 10 30/6	0.3	AN	3.6	5.4
8	DRAMIX ZC 40/50	0.5	A	6.0	6.5
9	idem	1	A	6.0	6.0
10	idem	1.5	A	6.2	5.3
11	DRAMIX ZC 30/50	0.5	A	6.2	5.3
12	idem	1	A	4.6	4.5
13	idem	1.5	A	5.4	4.3
14	DACRON D 157-10 mm	0.3	PES	3.8	11.5
15	DRAMIX 30/50 golf 1.2 mm	0.5	A	4.6	7.3
16	idem	1	A	7.2	10.6
17	idem	1.5	A	6.0	4.2
18	idem, golf 1 mm	0.5	A	4	4.5
19	idem	1	A	3.8	7.0
20	idem	1.5	A	4.8	6.4
21	bicouche 1% DRAMIX +0.3%				
	HOECHST			4.4	7.2
22	bicouche 0.5% DRAMIX +0.3%				
	HOECHST			3.8	8.5

A – steel, AN – acrylonitrile, PES – polyester.

2. As regards the percentage of fibres, the incorporation of steel fibres into the bituminous concrete equals to 0.5, 1 and 1.5% by weight. Figure 12 clearly shows that the optimum percentage of fibres is established at the fibre content equal to 1% by weight.

The reasons are probably as follows:

for percentages lower than 1%, the number of fibres incorporated into the bituminous concrete is insufficient to influence the rigidity and the behaviour of concrete in the case of deep cracking;

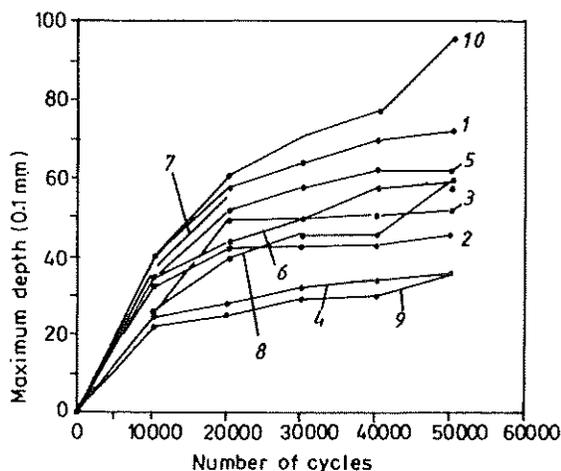


Fig. 10. Depth of cracking vs. number of cycles

1 - 0.5 ZL 30/50, 2 - 1.0 ZL30/50, 3 - 1.5 ZL 30/50, 4 - VF 11 100/6, 5 - VF 10 30/6,
6 - SF 12-16, 7 - 0.5 ZC 40/50, 8 - 1.0 ZC 40/50, 9 - 0.5 ZC 30/50, 10 - reference

for percentages greater than 1%, the mixing and the homogenization are not so good and the cohesion of the concrete can decrease.

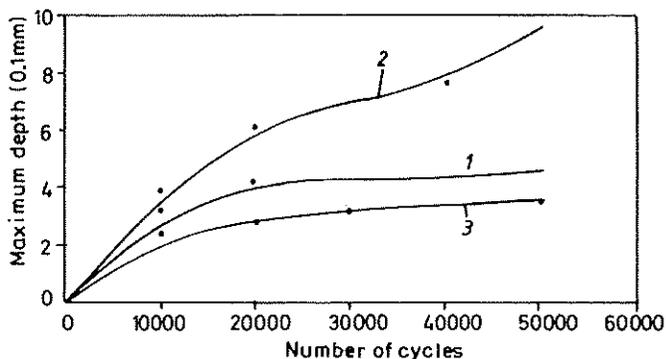


Fig. 11. Number of cycles vs. depth of cracking; 1 - reference, 2 - steel, 3 - synthetic fibre

3. The results of the tests do not show clearly any influence of fibre length; from the theoretical point of view, it is necessary to impose a minimum length to ensure noticeable effect (see point 3.4.1), and, from the technological point of view, it is necessary not to exceed a certain value to avoid problems during on-site placement.

4. Comparison of fibre shape is possible when the steel fibres are taken into account (table 6).

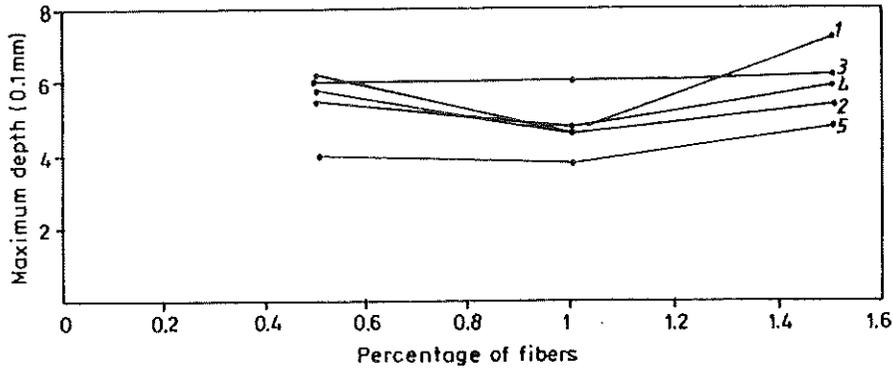


Fig. 12. Percentage of fibres vs. maximum depth of cracking
 1 – ZL 30/50, 2 – GOLF 1.0 30/50, 3 – ZC 40/50, 4 – TOTAL, 5 – ZC 30/50

Table 6

Comparison of different types of DRAMIX fibres
 (for 1% by weight)

Type of DRAMIX	Maximum deep of cracking (mm)	Percentage of voids
ZL 30/50	4.6	6.4
ZC 30/50	4.6	4.5
GOLF 1 mm	3.8	7
GOLF 1.2 mm	7.2	10.6
ZL 40/50	6	6

In spite of a high void volume, the best results were obtained with a golf fibre (30 mm long, 400 μ m in diameter and 1 mm golf amplitude).

3.6. BENDING TEST

The sample is placed on two bearing supports and a load is applied at its centre. This test permits us to determine the value of the bituminous concrete rigidity modulus. The conclusions are as follows:

the most important growth of the modulus E is observed for PES synthetic fibres;

the PAN fibres also induce growth of the modulus E in each condition;

for steel fibres, the most important growth is observed for 0.5 or 1% of fibres by weight;

a 1.5% addition of steel fibres generally produces a reduction of the value of the modulus E .

3.7. DESCRIPTION OF ON-SITE WORKS

Several on-site works have been realized in order to check the products quality and the laying down procedure. Observations have been made before and after the works. The principal characteristics of the on-site works are given below:

1. Works of DUMONT-WAUTHIER I

- Surface: $\pm 1000 \text{ m}^2$.
- Foundation: 30 cm gravels.
- Underlays: 6 cm type III.
- Overlay: 5 cm type Ia (with steel fibres).

2. Works of DUMONT-WAUTHIER II

- Surface: 738 m^2 .
- Foundation: concrete with 100 kg of cement.
- Underlays: 5 cm Ia (with steel fibres and acrylonitrile).

3. Works of MALLES-TERRES

- Surface: 4000 m^2 .
- Foundation: gravels.
- Underlays: 5 cm type III (with steel fibres).
- Overlay: 5 cm type Ia (with acrylonitrile fibres).

The reference sections (no fibres) deteriorate undoubtedly faster than the treated zones. These sections were loaded by heavy traffic (40 ton dumpers). As far as the manufacturing of the bituminous concrete is concerned, the incorporation of fibre only needed few material adaptation. The mixing time was longer. For the on-site placement, no adaptations or modifications of the finishing machines were needed if the fibre percentage was smaller or equal to 1% for steel fibres and 0.3% for synthetic fibres. For higher values some problems occurred.

On the other hand, for the same reasons the fibre length was limited to the size of maximum aggregates.

4. CONCLUSIONS

The results obtained due to the theoretical and experimental approaches permitted defining an interesting solution for avoiding bituminous concrete deep cracking along the roads: the incorporation of short steel or synthetic fibres to the mixture.

The optimum parameters for steel fibres of a bituminous concrete of the Belgian type I are:

- Fibre length (L): 1 or 2 times the maximum dimension of the aggregate.
- Fibre percentage: 0.4 to 1.5% by weight.
- Ratio of fibre length to fibre diameter: $40 < L/D < 100$.
- Fibre shape: generalized waves with specific anchorage.
- Surface treatment: against corrosion.

The optimum parameters for synthetic fibres of a bituminous concrete of the Belgian type I are:

Fibre length: 0.5 to 1 times the maximum dimension of the aggregate.

Fibre percentage: 0.1 to 0.7% by weight.

Fibre shape: kidney.

Fibre raw material: must be resistant to temperatures higher than 190 °C, without any deterioration.

The advantages of these solutions are very clear:

1. Increase of the road structure service life (minimum two times).
2. Reduction in the repair costs.
3. No recycling problems.
4. Possibility of reduction of the road structure thickness (because of increasing of the rigidity modulus).
5. Almost no adaptation of the fabrication techniques or laying down machines.

Finally, the solution adopted by the LEGROS S.A., public works society in Anthisnes (Belgium), with the aim to avoid psychological problems due to the possible presence of corroded fibres at the overlay surface, was to use steel fibres in the underlays and synthetic fibres for the overlay. This system is protected by an international patent.

REFERENCES

- [1] WAGNER P., Rouler sûr, rouler bien! Touring info.
- [2] FAGNOUL A., Université de Liège, Faculté des Sciences Appliquées. Cours de Routes, Fascicule VII.
- [3] RIGO J.M., Université de Liège, Faculté des Sciences Appliquées. Science des Matériaux de Construction non métalliques, Tome I.
- [4] Centre de Recherches Routières. Code de bonne pratique pour le renforcement des chaussées souples à l'aide de matériaux bitumeux. Recommandations CRR – R56/85.
- [5] Centre de Recherches Routières. Code de bonne pratique pour le dimensionnement des chaussées à revêtement hydrocarboné. Recommandations CRR – R49/83.
- [6] Centre de Recherches Routières. Code de bonne pratique pour la formulation des enrobés bitumeux denses. Recommandations CRR – R61/87.
- [7] GOTTSCHALL A., HOLLSTEINER S., *Steel fibre reinforced asphalt*, 3rd Eurobitume Symposium, La Haye, 1985.
- [8] Fibre Pave, Hercules, incorporated. Wilmington, Delaware and Norcross, Georgia (U.S.A.).