The influence of cellulosic fibres on the performances of draining bituminous mixtures

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Synopsis

The following research provides the results of the experiment carried out on draining bituminous mixtures, to which stabilizing micro-fibres of pure cellulose in compressed granules have been added.
Several samples of draining mixtures with and without the addition of fibres have been subjected to the Marshall Test and to the Indirect Tension Strength Test.
The coefficient of permeability K has been determined for all the tests.
The experimental results have proven that in an open mixture the fibres act as a support for the binder, improving the mechanical characteristics and increasing the ductility of the material.
Moreover, the increase in the coefficient of permeability K improves the draining function of the mixtures with added fibres.

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INTRODUCTION

Across time the concept of paving has considerably evolved; a paving must be able to assure an adequate carrying capability for satisfying the users needs, considering contingent conditions such as climatic and environmental conditions, and must guarantee users comfort and safety conditions at the same time.

Generally, the principal function of a paving is to:

- assure that the traffic can move on its surface in the best safety conditions;
- absorb the tangential stresses which are a consequence of the accelerations and brakings of the vehicles;
- distribute the vertical loads applied to the surface by transferring them onto the road foundation, compatibly with its carrying capability;
- protect the road from infiltrations of water;

This means that a paving must accomplish structural and functional tasks. From a structural point of view, a paving must be able to transfer the loads to the ground, resisting the development of cracks due to the fatigue of the materials and resisting the permanent deformations that the paving tends to accumulate.

From a functional point of view, a paving must provide top characteristics of draining macro-roughness and of acoustic insulation.

For this reason draining friction layers are very important. In spite of several advantages such as reducing or eliminating the water stagnation from the rolling plane, eliminating the phenomenon known as aquaplaning and reducing the nebulization of water raised from the wheels of moving vehicles, draining friction layers present several inconveniences due to their composition.

Infact, draining friction layers have a high percentage of air voids due to the granulometric composition of the aggregates, which reduces the contact points between the aggregates consequently increasing the number of concentrated stresses. In the mixture it's easy to find cracks and breaks on the bituminous membrane which wraps up the aggregates due to the high level of stresses and to the presence of air voids which cause the oxidation of the binder.

For this reason it would be advisable to use polymerized bitumens and to add to the mixture particular additives such as fibres, which have basically the function to control the diffusion and propagation of micro-breaks [1, 2].

Fibres, in fact, have the capability to bind themselves mechanically to the bitumen, holding the bitumen and avoiding it to move from the aggregates, which happens in draining mixtures especially during the phases of transportation and spreading.

The following experiment shows the contribution that fibres of pure cellulose in compressed granules have given to the draining capability, to the resistance and to the deforming capability of the support layers of an open bituminous mixture.

PRELIMINARY STUDY

The aim of this experimental research is to study the influence of fibres on the mechanical properties of draining bituminous mixtures [3, 4].

Moreover, it appears very interesting to study the behaviour of an open mixture while it removes the water by filtering it from the surface.

Therefore, the tests have been carried out to make the mechanical and deformation responses as well as the permeability coefficients of the draining bituminous mixtures comparable to those of the mixtures with an identical composition plus the addition of fibres.

Particular attention has been placed on the design of the bituminous mixtures [5,6], which must be in accordance with the requirements provided by particular technical rules *(Norme Tecniche dei Capitolati Speciali d'Appalto)*.

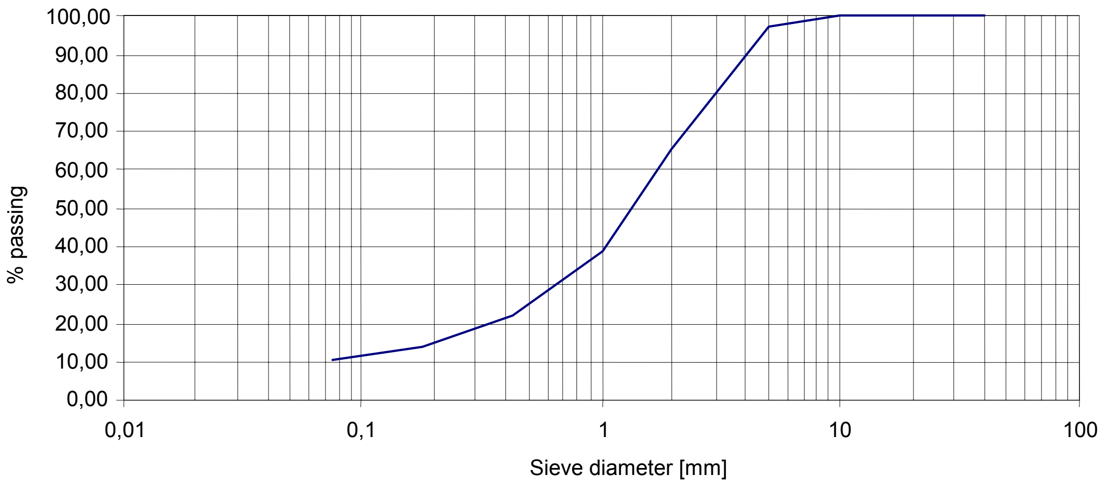
TRADITIONAL DRAINING BITUMINOUS MIXTURE

Materials
Aggregates
The preparation of a traditional bituminous mixture has been made by selecting aggregates with a different granulometric composition.
The thin particles (D < 5 mm) are made of calcareous sand, while the big aggregates are made of basaltic grit (6 < D < 12 mm) and basaltic fine crushed aggregate (10 < D < 18 mm).
The characteristics of the aggregates used for the experiment are the following:

CALCAREOUS SAND

Aggregate type		Aggregate1 SIPA	
Sample weight		598,46	g
Notes:			
sieve diameter (mm)	cumulative not passing	% not passing	% passing
40	0,00	0,00	100,00
30	0,00	0,00	100,00
25	0,00	0,00	100,00
20	0,00	0,00	100,00
15	0,00	0,00	100,00
10	0,00	0,00	100,00
5	15,41	2,60	97,40
2	206,86	34,60	65,40
1	366,92	61,30	38,70
0,425	466,40	77,90	22,10
0,18	516,68	86,30	13,70
0,075	536,03	89,60	10,40

Granulometric analysis

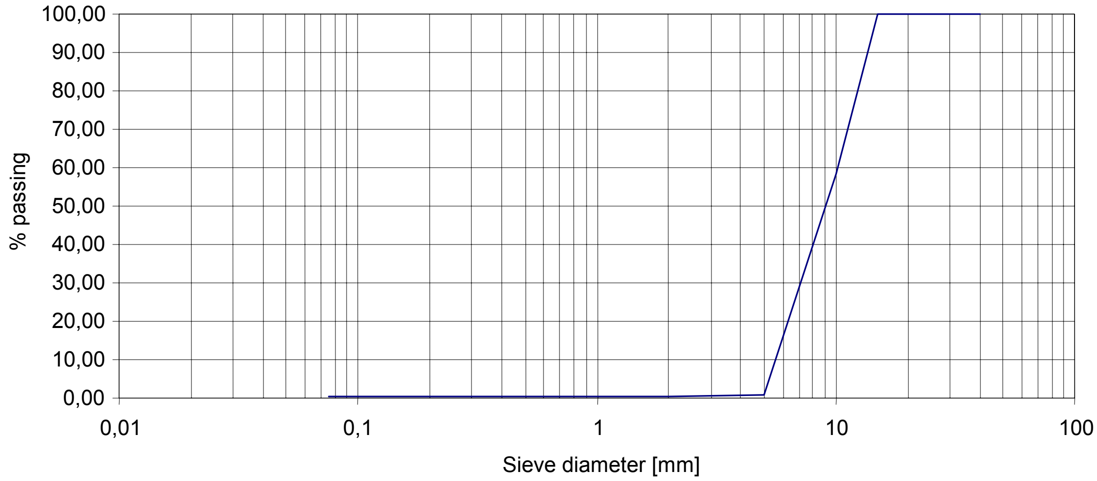


Tests carried out	Values found
Granules apparent volumic mass (Kg/cm^3)	2.69
Aggregate apparent volumic mass (Kg/cm^3)	1.57
Air void index	0.71
Sieve passing 0.075 (%)	9.64
Sand equivalent	63.41

BASALTIC GRIT

Aggregate type		Aggregate2 SIPA	
Sample weight		1857,00	g
notes:			
sieve diameter (mm)	cumulative not passing	% not passing	% passing
40	0,00	0,00	100,00
30	0,00	0,00	100,00
25	0,00	0,00	100,00
20	0,00	0,00	100,00
15	3,04	0,20	99,80
10	777,04	41,80	58,20
5	1843,04	99,20	0,80
2	1849,15	99,60	0,40
1	1849,49	99,60	0,40
0,425	1849,66	99,60	0,40
0,18	1849,83	99,60	0,40
0,075	1850,39	99,60	0,40

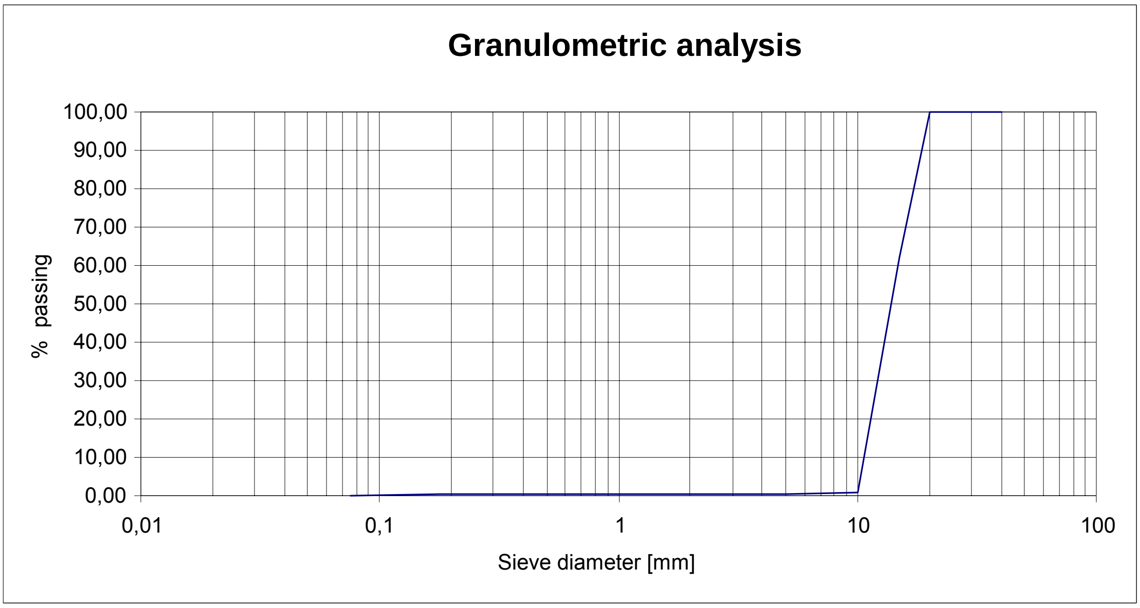
Granulometric analysis



Tests carried out	Values found
Granules apparent volumic mass (Kg/cm^3)	2.76
Aggregate apparent volumic mass (Kg/cm^3)	1.50
Air void index	0.85
Sieve passing 0.075 (%)	0.81
Mean coefficient of imbibition	0.012
Coefficient of abrasion Los Angeles	14
Coefficient of crushing	97

BASALTIC FINE CRUSHED AGGREGATE

Aggregate type		Aggregate3 SIPA	
Sample weight		2298,0	g
notes:			
sieve diameter (mm)	cumulative not passing	% not passing	% passing
40	0,00	0,00	100,00
30	0,00	0,00	100,00
25	0,00	0,00	100,00
20	0,00	0,00	100,00
15	874,00	38,00	62,00
10	2281,00	99,30	0,70
5	2290,36	99,70	0,30
2	2290,50	99,70	0,30
1	2290,56	99,70	0,30
0,425	2290,64	99,70	0,30
0,18	2290,79	99,70	0,30
0,075	2293,32	99,80	0,20



Tests carried out	Values found
Granules apparent volumic mass (Kg/cm^3)	2.78
Aggregate apparent volumic mass (Kg/cm^3)	1.47
Air void index	0.88
Sieve passing 0.075 (%)	0.51
Mean coefficient of imbibition	0.012
Coefficient of abrasion Los Angeles	14.2
Coefficient of crushing	96
C.L.A.	0.47 ÷ 0.48

Bitumen

Bitumen 50/70 modified with 5.3% of thermoplastic elastomeric polymers, percentage which is included in the range provided by the *Capitolato della Società Autostrade*, has been used as a binder for the mixture's composition.

The mixing and compacting temperatures are those indicated in the provisions for the "determination of the stability and of the flowability of bituminous mixtures and stony aggregates using Marshall apparatus". [7]

Bituminous mixture

To prepare the mixture, the granulometric composition must be included in the *Fuso "A"* of the *Norme Tecniche della Società Autostrade* established for draining carpets.

The results of the granulometric test and of the analysis of the granulometric composition, determined by the experiment, are the following:

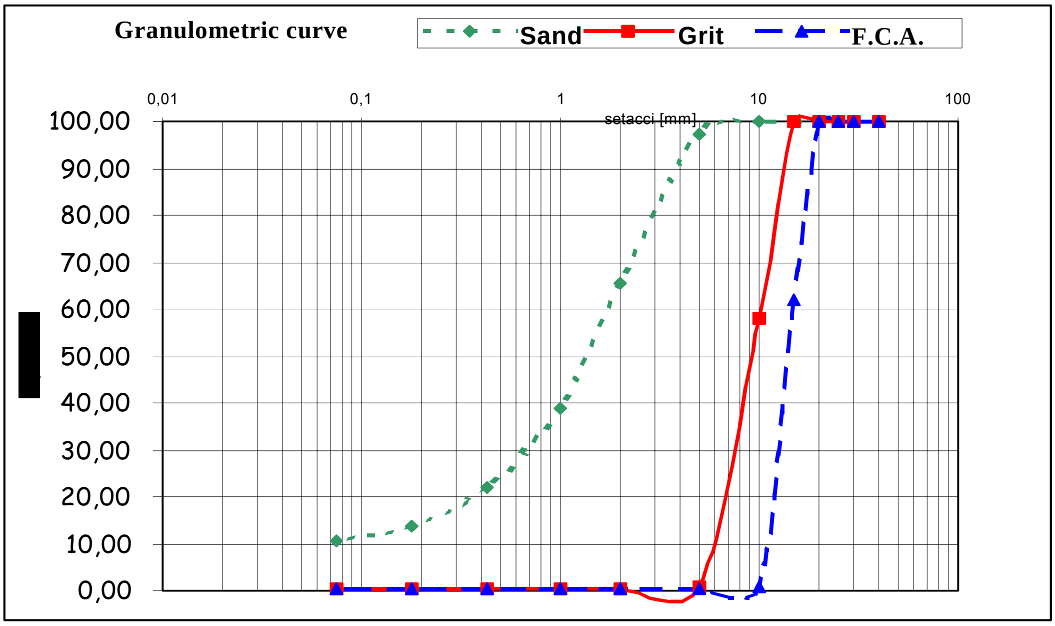
GRANULOMETRIC ANALYSIS

GRANULOMETRIC ANALYSIS

Aggregate type	SAND	GRIT	FINE CRUSHED AGGREGATE
Aggregate weight	598,46 g	1857 g	2298 g

Sieve diameter (mm)	Cumulative not passing	% Not passing	% Passing	% 16	Cumulative not passing	% Not passing	% Passing	% 32	Cumulative not passing	% Not passing	% Passing	% 52	TOTAL PASSING
40	0,00	0,0	**100,0**	16,0	0,00	0,0	**100,0**	32,0	0,00	0,0	**100,0**	52,0	100,0
30	0,00	0,0	**100,0**	16,0	0,00	0,0	**100,0**	32,0	0,00	0,0	**100,0**	52,0	100,0
25	0,00	0,0	**100,0**	16,0	0,00	0,0	**100,0**	32,0	0,00	0,0	**100,0**	52,0	100,0
20	0,00	0,0	**100,0**	16,0	0,00	0,0	**100,0**	32,0	0,00	0,0	**100,0**	52,0	100,0
15	0,00	0,0	**100,0**	16,0	3,04	0,2	**99,8**	31,9	874,00	38,0	**62,0**	32,2	80,2
10	0,00	0,0	**100,0**	16,0	777,04	41,8	**58,2**	18,6	2281,00	99,3	**0,7**	0,4	35,0
5	15,41	2,6	**97,4**	15,6	1843,04	99,2	**0,8**	0,2	2290,36	99,7	**0,3**	0,2	16,0
2	206,86	34,6	**65,4**	10,5	1849,15	99,6	**0,4**	0,1	2290,50	99,7	**0,3**	0,2	10,8
1	366,92	61,3	**38,7**	6,2	1849,49	99,6	**0,4**	0,1	2290,56	99,7	**0,3**	0,2	6,5
0,425	466,40	77,9	**22,1**	3,5	1849,66	99,6	**0,4**	0,1	2290,64	99,7	**0,3**	0,2	3,8
0,18	516,68	86,3	**13,7**	2,2	1849,83	99,6	**0,4**	0,1	2290,79	99,7	**0,3**	0,2	2,5
0,075	536,03	89,6	**10,4**	1,7	1850,39	99,6	**0,4**	0,1	2293,32	99,8	**0,2**	0,1	1,9

GRANULOMETRIC CURVES

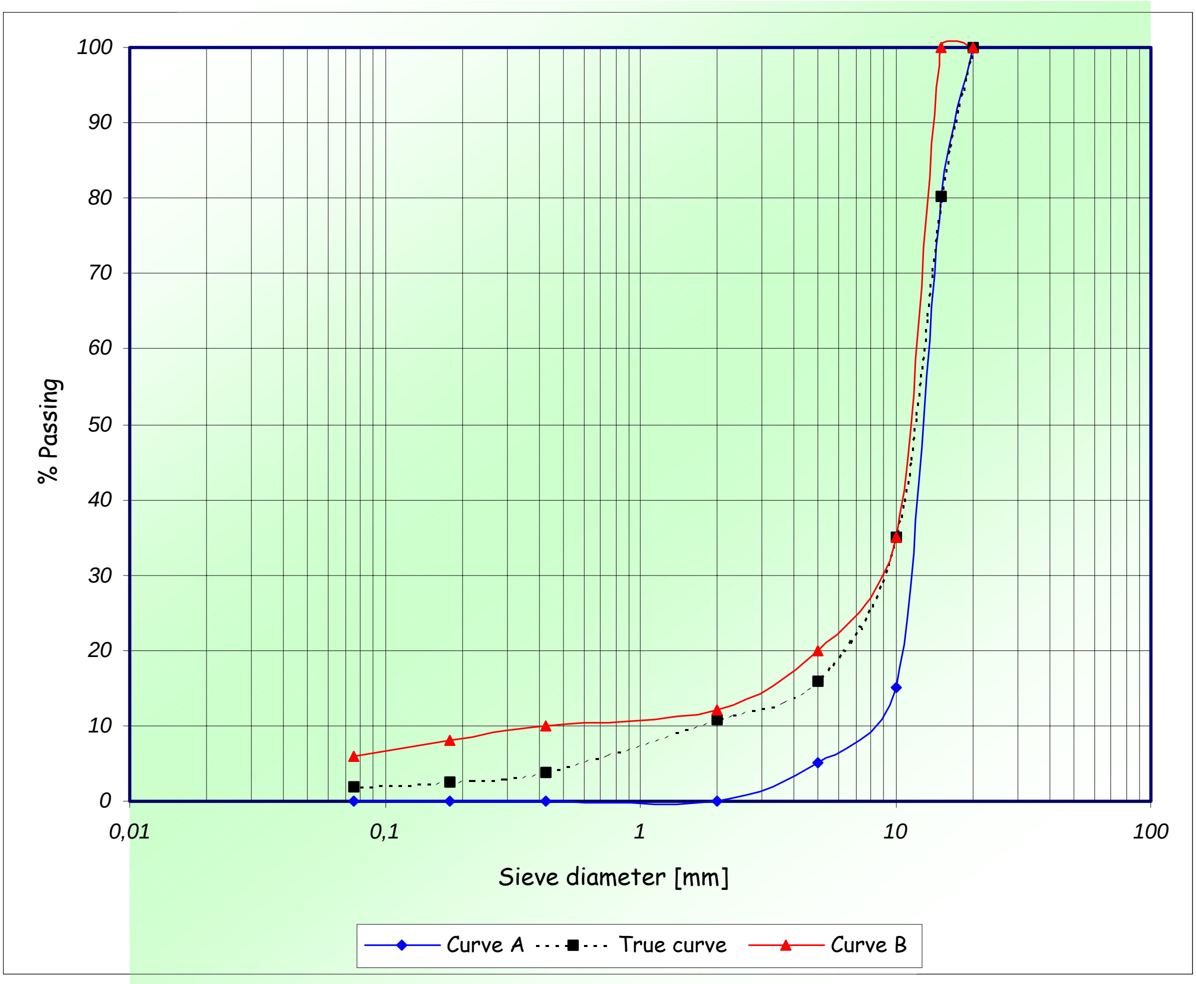


MIXTURE COMPOSITION

diameter	curve A	curve B	True
20	100	100	100,0
15	80	100	80,2
10	15	35	35,0
5	5	20	16,0
2	0	12	10,8
0,425	0	10	3,8
0,18	0	8	2,5
0,075	0	6	1,9

Sand	**16**
Grit	**32**
Fine crushed aggregate	**52**

GRANULOMETRIC SIZE DISTRIBUTION



The experiment

Physical characteristics of a draining mixture

Moreover, in order to determine the percentage of air voids v, dealing with a mixture which has an amount of air voids above 10-12%, it's important to remember that the CNR rules n° 40 "Determination of the volume weight in mixtures of stony aggregates with bitumen or tar" [8] and n° 39 "Determination of the porosity or percentage of air voids in mixtures of stony aggregates with bitumen or tar" [9] do not apply to these cases.

In case of open conglomerates, infact, using liquid paraffin wouldn't be correct because it would cause the filling of the superficial air voids, consequently determining a miscalculation of the sample's volume weight and also of the percentage of air voids [10].

The geometrical method, as defined by the rule ASTM D 3549 [11], is used to determine the conglomerate's weight or volumic mass.

The determination of the volumic mass and, therefore, of the porosity has been made on twenty samples.

DETERMINATION OF APPARENT VOLUMIC MASS OF THE DRAINING MIXTURE													
Sample n°	**Diaameters (cm)**				**Mean diameter (cm)**	**Heights (cm)**				**Mean heigh (cm)**	**Volume (cm^3)**	**Weight (g)**	**Volumic mass (g/cm^3)**
	1	2	3	4		1	2	3	4				
1	10,17	10,16	10,07	10,13	10,13	6,56	6,60	6,59	6,53	6,57	529,77	1053,00	1,99
2	10,13	10,16	10,09	10,16	10,14	5,50	5,57	5,51	5,47	5,51	444,72	889,00	2,00
3	10,16	10,15	10,15	10,13	10,15	5,50	5,51	5,47	5,50	5,50	444,40	894,00	2,01
4	10,14	10,13	10,11	10,17	10,14	6,01	6,00	6,02	6,08	6,03	486,51	988,00	2,03
5	10,10	10,14	10,15	10,14	10,13	6,61	6,61	6,56	6,64	6,61	532,59	1079,00	2,03
6	10,14	10,13	10,15	10,16	10,15	6,14	6,17	6,22	6,14	6,17	498,54	1000,00	2,01
7	10,16	10,15	10,12	10,17	10,15	6,58	6,60	6,59	6,57	6,59	532,82	986,00	1,85
8	10,12	10,15	10,15	10,15	10,14	6,14	6,16	6,23	6,17	6,18	498,90	1013,00	2,03
9	10,11	10,03	10,13	10,14	10,10	6,11	6,13	6,12	6,11	6,12	490,37	987,00	2,01
10	10,12	10,12	10,12	10,01	10,09	6,03	6,03	6,03	6,02	6,03	482,20	972,00	2,02
11	10,13	10,12	10,20	10,11	10,14	6,80	6,70	6,70	6,71	6,73	543,27	1064,00	1,96
12	10,13	10,13	10,13	10,13	10,13	6,34	6,51	6,51	6,41	6,44	519,23	1064,00	2,05
13	10,13	10,17	10,13	10,12	10,14	6,39	6,42	6,36	6,33	6,38	514,56	1033,00	2,01
14	10,18	10,15	10,13	10,17	10,16	6,35	6,32	6,26	6,28	6,30	510,71	1021,00	2,00
15	10,06	10,09	10,11	10,09	10,09	6,21	6,23	6,23	6,17	6,21	496,30	997,00	2,01
16	10,12	10,24	10,17	10,18	10,18	6,08	6,03	5,97	6,00	6,02	489,74	1000,00	2,04
17	10,13	10,13	10,10	10,13	10,12	5,81	5,8	5,8	5,82	5,81	467,36	973,00	2,08
18	10,12	10,03	10,10	10,13	10,10	5,92	5,92	5,91	5,92	5,92	473,63	972,00	2,05
19	10,11	10,10	10,10	9,91	10,06	6,12	6,12	6,13	6,13	6,13	486,36	1009,00	2,07
20	10,12	10,13	10,13	10,12	10,13	6,30	6,40	6,31	6,30	6,33	509,46	1027,00	2,02
										Apparent mean volumic mass			**2,01**
										Sample mean volume			**497,57**

considering that:

γ = 2.01 g/cm^3 is the mean apparent volumic mass of the mixture;
b_c = 5.3% the percentage of bitumen;
γ_b = 1.03 g/cm^3 the specific weight of the binder;
γ_a = 2.74 g/cm^3 the apparent volumic mass of the granules, calculated as a function of granulometric composition of the mixture, the porosity of the mixture can be determined as the arithmetic average of the porosity of the twenty tests, in accordance with the ASTM D3203 rule [12].

DETERMINATION OF THE PERCENTAGE OF POROSITY OF A DRAINING MIXTURE GEOMETRICAL METHOD – Rule ASTM D3203								
Mean apparent volumic mass of aggregates					2,74			
Bitumen percentage 0,053			Bitumen specific weight 1,03					
Notes:	Draining misture with basaltic aggregates							
Sample N°	Total weight	Total volume	Bitumen weight	Aggregate weight	Bitumen volume	Aggregate volume	Airvoid volume	Porosity %
1	1050,00	529,77	55,65	994,35	54,03	362,90	112,84	21,3
2	886,00	444,72	46,96	839,04	45,59	306,22	92,91	20,9
3	890,00	444,40	47,17	842,83	45,80	307,60	91,00	20,5
4	988,00	486,51	52,36	935,64	50,84	341,47	94,20	19,4
5	1079,00	532,59	57,19	1021,81	55,52	372,92	104,14	19,6
6	1000,00	498,54	53,00	947,00	51,46	345,62	101,46	20,4
7	986,00	532,82	52,26	933,74	50,74	340,78	141,30	26,5
8	1013,00	498,90	53,69	959,31	52,13	350,11	96,66	19,4
9	987,00	490,37	52,31	934,69	50,79	341,13	98,46	20,1
10	972,00	482,20	51,52	920,48	50,02	335,94	96,24	20,0
11	1064,00	543,27	56,39	1007,61	54,75	367,74	120,78	22,2
12	1064,00	519,23	56,39	1007,61	54,75	367,74	96,74	18,6
13	1033,00	514,56	54,75	978,25	53,15	357,03	104,38	20,3
14	1021,00	510,71	54,11	966,89	52,54	352,88	105,29	20,6
15	997,00	496,30	52,84	944,16	51,30	344,58	100,41	20,2
16	1000,00	489,74	53,00	947,00	51,46	345,62	92,66	18,9
17	973,00	467,36	51,57	921,43	50,07	336,29	81,00	17,3
18	972,00	473,63	51,52	920,48	50,02	335,94	87,67	18,5
19	1009,00	486,36	53,48	955,52	51,92	348,73	85,71	17,6
20	1027,00	509,46	54,43	972,57	52,85	354,95	101,66	20,0
				Mean percentage porosity of the mixture				**20**

Marshall Test – Experimental results

During the experiment the Marshall [7] test has been made on the four samples of traditional draining bituminous mixtures indicated by number 17 to number 20.
This procedure will also be applied to a bituminous mixture with addition of fibres only to compare the results found: it's common knowledge, infact, that in case of open mixtures the Marshall test does not permit a correct evaluation of the effect induced by the fibres on the mixture [1].
The results of the experiment on these four samples are the following:

MARSHALL TEST – DRAINING MIXTURE					
N° Sample	**Height (cm)**	**Flowing (mm)**	**Kg**	**Correction coefficient**	**Corrected stability (Kg)**
17	5,81	2,50	550,00	1,1587	637,29
18	5,92	3,20	642,86	1,1241	722,64
19	6,13	4,00	578,57	1,0586	612,47
20	6,33	3,40	700,00	1,0050	703,50
Average		**3,28**			**669**

Stiffness: (Kg/mm)	**204**

Therefore, the values obtained considering a draining mixture are the following:

Stability	669 Kg
Flowing	3.28 mm
Stiffness	204 Kg/mm

The values of stability and stiffness found respect the limits imposed by the *Capitolato della Società Autostrade* for the mixtures included in size distribution"A", which are:

Stabilità : > 500 Kg
Rigidezza : > 200 Kg/mm.

Indirect Tension – Experimental results

The indirect tension strength test (Brazilian) is very important within this experimental research.
This kind of test proves that when the sample is subjected to breaking along the vertical plane, the same conditions described by the fracture mechanics occur. Moreover, this test shows the contribution provided by the fibres in open bituminous mixtures, as the theories developed by Santagata also have shown [2].
A number of sixteen samples have been subjected to breaking under diametral compression; the test has been carried out at the temperature of 25 °C in accordance with the formalities established by the rules of mixtures of aggregates and hydrocarbonic binders [13-14].
The temperatures of the samples subjected to the indirect tension strength test have been checked with a laser thermometer.
The experimental results are the following:
The experimental values of resistance to indirect tension shown in the table have been checked by applying the fidelity criterion (see Appendix) in accordance with the rules.

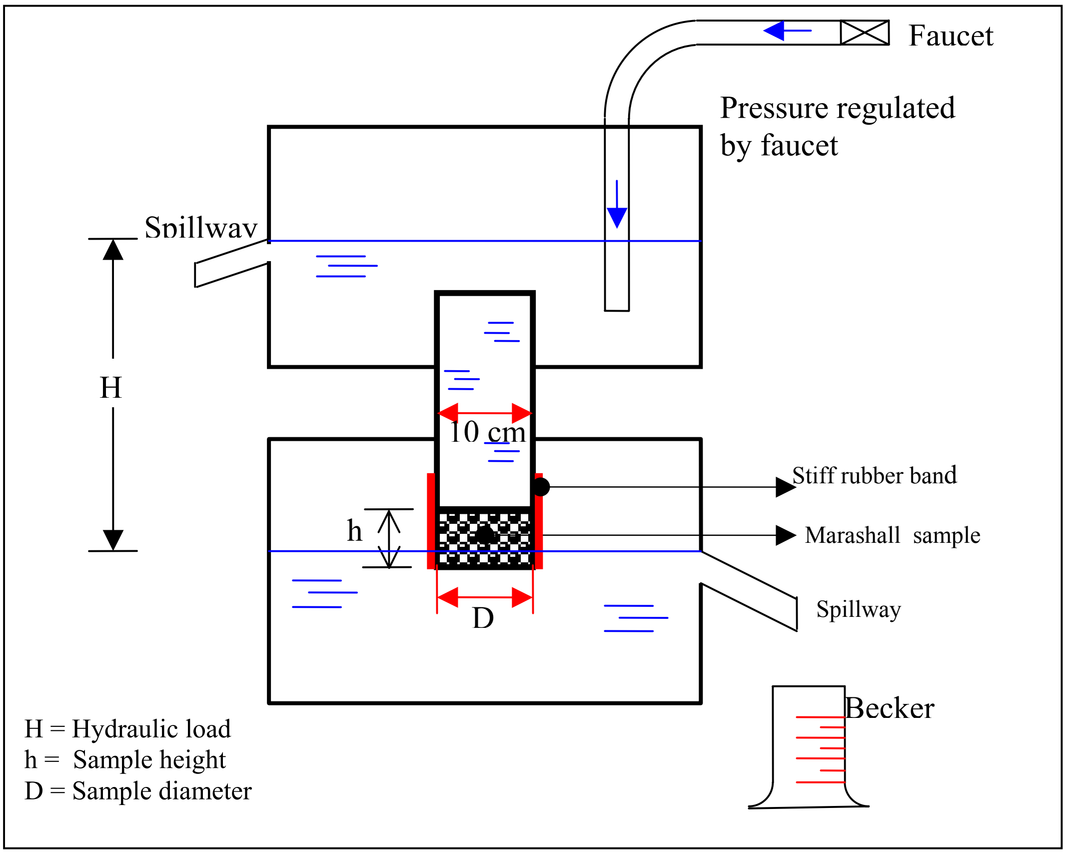
DETERMINATION OF THE RESISTANCE OF THE DRAINING MIXTURE TO INDIRECT TENSION Rule CNR 134/91											
TEMPERATURE TEST:			**25°C**								
Sample n°	Effective temperature	Mean diameter	Mean height	Ultimate tensil strength	Resistance to indirect tension	Diameter deformation under breaking					
						Under diametral compression			Under indirect tension		
	(°C)	(cm)	(cm)	(daN)	(daN/cm²)	(cm)	(cm)		(cm)	(cm)	
		D	H	P	Rt	ΔDc	Dv	ΔDc/D	ΔDt	Do	ΔDt/D
1	25	10,13	6,57	672,5	**6,44**	0,115	10,02	**0,01135**	0,33	10,46	**0,03258**
2	25	10,14	5,51	610,0	**6,95**	0,07	10,07	**0,00690**	0,25	10,39	**0,02465**
3	25	10,15	5,50	522,5	**5,96**	0,042	10,11	**0,00414**	0,25	10,40	**0,02463**
4	25	10,14	6,03	662,9	**6,91**	0,056	10,08	**0,00552**	0,29	10,43	**0,02860**
5	25	10,13	6,61	596,2	**5,67**	0,11	10,02	**0,01086**	0,34	10,47	**0,03356**
6	25	10,15	6,17	524,4	**5,33**	0,21	9,94	**0,02069**	0,24	10,39	**0,02365**
7	25	10,15	6,59	429,4	**4,09**	0,14	10,01	**0,01379**	0.25	10,17	**0,00171**
8	25	10,14	6,18	485,3	**4,93**	0,06	10,08	**0,00592**	0,34	10,48	**0,03353**
9	25	10,10	6,12	545,3	**5,62**	0.04	10,10	**0,00028**	0.35	10,12	**0,00241**
10	25	10,09	6,03	289,3	**3,03**	0,005	10,09	**0,00050**	0.26	10,11	**0,00179**
11	25	10,14	6,73	665,2	**6,21**	0.07	10,14	**0,00048**	0.32	10,16	**0,00219**
12	25	10,13	6,44	863,2	**8,43**	0.05	10,13	**0,00034**	0.23	10,15	**0,00158**
13	25	10,14	6,36	858,3	**8,48**	0.05	10,14	**0,00034**	0.28	10,16	**0,00192**
14	25	10,16	6,30	718,2	**7,15**	0,06	10,10	**0,00591**	0,34	10,50	**0,03346**
15	25	10,09	6,21	686,3	**6,98**	0,11	9,98	**0,01090**	0,34	10,43	**0,03370**
16	25	10,18	6,02	656,0	**6,82**	0,07	10,11	**0,00688**	0,26	10,44	**0,02554**
MEAN RESISTANCE TO INDIRECT TENSION					**6,19**						

The value of resistance to indirect tension, corrected by the fidelity criterion will be assumed equal to : **σ_{Tm} = 6.09 (daN/cm^2).**
Moreover, the values of vertical and horizontal diametral deformation have been surveyed.

Permeability – Experimental results

Permeability is the property of a material to allow a liquid to pass through its pores. Moreover, permeability depends on the permeability coefficient K, determined from Darcy's Law.
Permeability is the most important property of a draining bituminous mixture. The value of K can be determined with the Darcy formula, supposing a laminar flow of water.
In the Material Test Laboratory of the Department of *"Vie e Trasporti" (Politecnico di Bari)* a permeameter able to carry out permeability tests applying the Darcy Theory on the samples has been manufactured to evaluate the draining capabilities of the bituminous mixture.
This equipment consists of (see figure) two superimposed water tanks, a measurement cell constrained by the higher tank which contains the sample and a hose connected to a faucet.
The higher and the lower tank are both equipped with spillways; the higher tank keeps the water level constant, while the lower tank picks up the water filtered through the sample.
The hydraulic load H is constant and equivalent to the difference expressed in centimetres between the water levels of the two tanks.
In conditions of laminar flow, the coefficient of permeability K of the sample's water, can be calculated, vertically, as a function of the quantity of water that has gone through the sample in a set time interval and as a function of the area of the sample's section.
Therefore, the value K is multiplied by a correction coefficient η which considers the variation of the water's viscosity according to the variations of temperature

Permeameter Diagram



The experiment has been carried out on three samples of draining bituminous mixtures with a permeability which has been determined multiplying the value of the coefficient of permeability K by the correction coefficient which considers the variation of the water's viscosity as a function of a temperature of 16 °C.
The size of the samples and the results of the experiment are written in the following tables.

Sample N°	Diameter (D) cm	Height (H) cm	Base Area (A) cm^2
1	10.12	6.50	80.40
2	10.09	5.63	79.92
3	10.12	6.86	80.40

Determination of the coefficient of permeability K

DETERMINATION OF THE COEFFICIENT OF PERMEABILITY K OF THE DRAINING MIXTURE
Darcy'law

Sample: Draining mixture
Water specific weight (g/cm^3) = 1.003; Temperature test T = 16C°
Water viscosity correction coefficient η = 1.1056

Sample N°	Water quantity weight (g)			Water volume (cm^3)			Time (s)	Hydraulic load H (cm)	Coefficient of permeability. K			K mean	K mean corrected
	P_1	P_2	P_3	V_1	V_2	V_3			K_1	K_2	K_3		
1	2754.4	2694.3	2652.3	2746.16	2686.24	2644.37	30	23	0.32	0.31	0.32	0.32	0.35
2	2604.7	2617.2	2598.5	2596.91	2609.37	2590.73	30	23	0.27	0.28	0.27	0.27	0.29
3	2760.2	2711.3	2708.9	2751.94	2703.19	2700.80	30	23	0.31	0.31	0.31	0.31	0.34
								Mean permeability: 0.30(cm/s)					
								Mean corrected permeability (cm/s)					**0.33**

considering that:

$$k = \frac{V \cdot h}{A \cdot t \cdot H} \eta$$

The value of the the coefficient of permeability determined is included in the limits provided by the *Capitolati* K ≥ 0.15 cm/s.

DRAINING BITUMINOUS MIXTURE WITH ADDITION OF FIBRES.

Fibres of pure cellulose in compressed granules have been added to the same mixtures used to manufacture the draining mixture. (see following picture)

These samples have been subjected to the same experimental program followed for the draining mixtures. It's a common knowledge, infact, that the main limitation of open conglomerates is their short durability caused either by their own structural characteristics or by the phenomena of oxidation and dripping of bitumen from the aggregates, both due to the mixture's high porosity.
The purpose of the experiment, therefore, is to check if the addition of fibres in draining mixtures is able to "stabilize" and to create a "support" for the bituminous binder which, while spreading itself more uniformly throughout the mixture, will improve the mecchanical and deforming characteristics of the mixture.

The fibres

The type of fibre used for the experiment is manufactured by Iterfibra/C and appears in compressed granules; the physical and performance characteristics are written in the following table.

ITERFIBRA/C Microfibretta Naturale Compressa		
Proportion of ingredient (on aggregate weight)		0.30 ÷ 0.45
Composition		Pure cellulose compressed in granules
Proprietà fisiche:	Appearance	Microfibre
	Mean length	200 μ ÷ 300 μ
	Density	400 ÷ 500 gr/litro
	Colour	Brown - grey

The samples with addition of fibres have been prepared with particular attention.
This kind of fibre, infact, is introduced directly into the mixer after the introduction of the aggregates from the sieves and before the introduction of the bitumen.
This procedure has been reproduced in laboratory during the preparation of the samples.
The fibres, dosed at 0.4% of the aggregates weight, have been previously crashed (see following picture) and carefully mixed to the aggregate; subsequently, the bitumen has been added to the mixture.

The experiment

Phsical characteristics of the draining mixture with addition of fibres

The apparent volumic mass of the mixture with addition of fibres has been determined by applying the geometrical method, in accordance with the ASTM D3549 rule, as we have seen in the case of a normal draining mixture. [11]
The volumic mass and, therefore, the porosity, of twenty samples have been determined as follows.

DETERMINATION OF THE APPARENT VOLUMIC MASS OF THE DRAINING MIXTURE WITH ADDITION OF FIBRES													
Sample	**Diameters (cm)**				**Mean diameter (cm)**	**Height (cm)**				**Mean height (cm)**	**Volume (cm^3)**	**Weight (g)**	**Volumic Mass (gr/cm^3)**
	1	2	3	4		1	2	3	4				
1	10,20	10,19	10,17	10,16	10,18	6,82	6,77	6,75	6,82	6,79	552,66	1053,1	1,91
2	10,15	10,13	10,15	10,16	10,15	6,04	6,13	6,16	6,08	6,1	493,53	956,6	1,94
3	10,21	10,19	10,23	10,21	10,21	6,29	6,25	6,30	6,33	6,29	515,19	992,1	1,93
4	10,19	10,19	10,21	10,23	10,21	6,13	6,11	6,08	6,14	6,12	500,16	952,0	1,90
5	10,20	10,20	10,17	10,20	10,19	6,21	6,24	6,18	6,19	6,21	506,28	1003,5	1,98
6	10,18	10,22	10,18	10,18	10,19	5,90	6,03	5,99	5,90	5,96	485,65	944,2	1,94
7	10,22	10,23	10,27	10,24	10,24	6,03	6,10	6,11	6,00	6,06	499,07	974,0	1,95
8	10,14	10,14	10,23	10,19	10,18	6,25	6,28	6,35	6,34	6,31	512,68	981,0	1,91
9	10,13	10,07	10,18	10,13	10,13	6,13	6,04	6,11	6,21	6,12	493,20	949,0	1,92
10	10,23	10,28	10,34	10,17	10,26	6,20	6,26	6,16	6,13	6,19	511,07	962,1	1,88
11	10,13	10,15	10,14	10,13	10,14	6,11	6,09	6,09	6,15	6,11	493,17	939,6	1,91
12	10,11	10,22	10,22	10,23	10,20	6,25	6,13	6,18	6,30	6,22	507,35	975,5	1,92
13	10,10	10,12	10,10	10,23	10,14	5,70	5,73	5,73	5,69	5,71	461,08	907,6	1,97
14	10,15	10,16	10,18	10,19	10,17	6,09	6,11	6,12	6,11	6,11	496,13	958,7	1,93
15	10,17	10,16	10,16	10,16	10,16	5,93	5,85	5,84	5,90	5,88	476,95	932,0	1,95
16	10,24	10,20	10,20	10,20	10,21	6,11	6,14	6,10	6,11	6,12	500,65	968,2	1,93
17	10,15	10,17	10,15	10,17	10,16	5,84	5,79	5,84	5,83	5,83	472,25	922,5	1,95
18	10,16	10,17	10,17	10,17	10,17	5,99	6,00	5,93	5,99	5,98	485,33	966,4	1,99
19	10,21	10,21	10,19	10,21	10,21	6,03	6,13	6,11	6,03	6,08	496,89	967,8	1,95
20	10,19	10,21	10,19	10,20	10,20	5,72	5,91	5,87	5,77	5,82	475,13	941,7	1,98
										Mean apparent volumic mass			**1,94**
										Sample mean volume			**496,72**

Considering that:

γ = 1.94 g/cm^3 is the average apparent volumic mass of the mixture;
b_c = 5.3 % the percentage of bitumen;
γ_b = 1.03 g/cm^3 the specific weight of bitumen;
γ_a = 2.74 g/cm^3 the apparent volumic mass of the granules, calculated as a function of the granulometric composition of the mixture, the porosity of the mixture can be determined as the arithmetic average porosity of the twenty samples, by applying the geometrical method in accordance with ASTM D3203 [12].

DETERMINATION OF THE PERCENTAGE POROSITY OF THE DRAINING MIXTURE WITH ADDITION OF FIBRES GEOMETRICAL METHOD - Rule ASTM D3203								
Mean apparent volumic mass of aggregates					**2,74**			
Bitumen percentage		**0,053**	Bitumen specific weight		**1,03**			
Notes:	Draining mixture with basaltic aggregates and fibres							
Sample N°	Total weight	Total Volume	Bitumen weight	Aggregate weight	Bitumen Volume	Aggregate Volume	Air void Volume	Porosity %
1	1144,35	575,01	60,65	1083,70	58,88	395,51	120,62	21,0
2	1104,51	559,04	58,54	1045,97	56,83	381,74	120,46	21,5
3	1122,26	572,98	59,48	1062,78	57,75	387,88	127,36	22,2
4	1053,83	548,66	55,85	997,98	54,23	364,23	130,21	23,7
5	1087,28	568,38	57,63	1029,65	55,95	375,79	136,65	24,0
6	1061,51	554,08	56,26	1005,25	54,62	366,88	132,58	23,9
7	1085,05	572,53	57,51	1027,54	55,83	375,02	141,68	24,7
8	1105,70	563,05	58,60	1047,10	56,90	382,15	124,00	22,0
9	1033,22	524,89	54,76	978,46	53,17	357,10	114,62	21,8
10	969,95	506,69	51,41	918,54	49,91	335,23	121,55	24,0
11	1013,56	525,70	53,72	959,84	52,15	350,31	123,24	23,4
12	1034,06	535,81	54,81	979,25	53,21	357,39	125,21	23,4
13	1001,00	515,93	53,05	947,95	51,51	345,97	118,46	23,0
14	1045,44	545,53	55,41	990,03	53,79	361,33	130,41	23,9
15	976,26	503,89	51,74	924,52	50,23	337,42	116,24	23,1
16	954,72	489,85	50,60	904,12	49,13	329,97	110,75	22,6
17	932,20	491,51	49,41	882,79	47,97	322,19	121,36	24,7
18	956,60	501,45	50,70	905,90	49,22	330,62	121,61	24,3
19	937,60	483,03	49,69	887,91	48,25	324,05	110,73	22,9
20	924,80	480,66	49,01	875,79	47,59	319,63	113,44	23,6
				Mean porosity of mixture				**23**

Marshall Test – Experimental results

Samples of draining bituminous with added fibres indicated by number 1 to 4, as well as the normal draining mixture, have been subjected to the Marshall Test [7], although the limitation seen before.
The results of the experiment on the four samples are the following:

MARSHALL TEST– DRAINING MIXTURE WITH ADDITION OF FIBRES					
Sample N°	**Height (cm)**	**Flowing (mm)**	**Kg**	**Correction coefficient**	**Corrected stability (Kg)**
1	6,79	3,81	735,71	0,9000	662,14
2	6,10	3,45	628,57	1,0679	671,25
3	6,29	3,60	757,14	1,0150	768,50
4	6,11	3,63	778,57	1,0617	826,61
Average		**3,62**			**732**
				Stiffness: (Kg/mm)	**202**

Therefore, considering the draining mixture the following values are obtained:

Stability	732 Kg
Flowing	3.62 mm
Stiffness	202 Kg/mm

The values of stability and stiffness found respect the limits imposed by the *Capitolato della Società Autostrade* for the mixtures included in Fuso “A”, which are:

Stabilità : > 500 Kg
Rigidezza : > 200 Kg/mm.

Indirect tension – Experimental results

As described before, sixteen samples of mixtures with added fibres have been subjected to the indirect tension strength test [13-14].
The experimental results are the following:

DETERMINATION OF THE RESISTANCE TO INDIRECT TENSION OF THE DRAINING MIXTURE WITH ADDITION OF FIBRES **Rule CNR 134/91**											
TEMPERATURE TEST::			**25°C**								
Sample n°	Effective temperature	Mean diamet	Mean height	Ultimate tensil strength	Resistance to indirect tension	Diameter deformation under breaking					
						Under diametral compression			Under indirect tension		
	(°C)	(cm)	(cm)	(daN)	(daN/cm^2)	(cm)	(cm)		(cm)	(cm)	
		D	H	P	Rt	ΔDc	Dv	ΔDc/D	ΔDt	Do	ΔDt/D
5	25	10,18	6,99	661,7	**5,92**	0,09	10,09	**0,00884**	0,38	10,56	**0,03733**
6	25	10,18	6,81	668,6	**6,14**	0,10	10,08	**0,00982**	0,4	10,58	**0,03929**
7	25	10,17	7,06	759,1	**6,73**	0,05	10,12	**0,00492**	0,26	10,43	**0,02557**
8	25	10,16	6,95	775,2	**6,99**	0,10	10,06	**0,00984**	0,35	10,51	**0,03445**
9	25	10,16	6,48	726,1	**7,02**	0,06	10,10	**0,00591**	0,25	10,41	**0,02461**
10	25	10,17	6,24	712,8	**7,15**	0,10	10,07	**0,00983**	0,4	10,57	**0,03933**
11	25	10,19	6,45	613,3	**5,94**	0,06	10,13	**0,00589**	0,31	10,50	**0,03042**
12	25	10,17	6,60	500,5	**4,75**	0,05	10,12	**0,00492**	0,2	10,37	**0,01967**
13	25	10,17	6,36	565,0	**5,56**	0,12	10,05	**0,01180**	0,48	10,65	**0,04720**
14	25	10,18	6,70	738,4	**6,90**	0,20	9,98	**0,01965**	0,47	10,65	**0,04617**
15	25	10,15	6,23	636,3	**6,41**	0,04	10,11	**0,00394**	0,26	10,41	**0,02562**
16	25	10,16	6,05	624,8	**6,47**	0,10	10,06	**0,00984**	0,40	10,56	**0,03937**
17	25	10,16	6,06	619,2	**6,41**	0,04	10,12	**0,00394**	0,18	10,34	**0,01772**
18	25	10,17	6,17	696,2	**7,07**	0,13	10,04	**0,01278**	0,40	10,57	**0,03933**
19	25	10,16	5,96	693,9	**7,30**	0,06	10,10	**0,00591**	0,21	10,37	**0,02067**
20	25	10,17	5,92	653,7	**6,92**	0,06	10,11	**0,00590**	0,23	10,40	**0,02262**
MEAN RESISTANCE TO INDIRECT TENSION					**6,48**						

The value of the resistance to indirect tension, corrected by the fidelity criterion (see Appendix), corresponds to the mean value and will be assumed equal to: **σ_{Tm} = 6.48 (daN/cm^2).**
Moreover, the values of vertical and horizontal diametral deformations have been surveyed.

Permeability – Experimental results

As described before, three samples of draining bituminous mixtures with addition of fibres have been subjected to the experimentation.
During the test, the water temperature has resulted equal to 14°C, therefore the coefficient of correction η which considers the variation of water viscosity as a function of the temperature has been assumed equal to 1.651.
The size of the samples and the experiment results are written in the following tables.

Sample N°	Diameter (D) cm	Height (H) cm	Base Area (A) cm^2
1	10.18	6.79	81.35
2	10.15	6.10	80.87
3	10.21	6.29	81.83

Determination of the coefficient of permeability K

DETERMINATION OF THE COEFFICIENT OF PERMEABILITY K OF THE DRAINING MIXTURE WITH ADDITION OF FIBRES
Darcy'law

Sample: Draining mixture with addition of fibres
Water specific weight (g/cm$^{3)}$ = 1.003; Temperature test T = 14C°
Water viscosity correction coefficient η = 1.1651

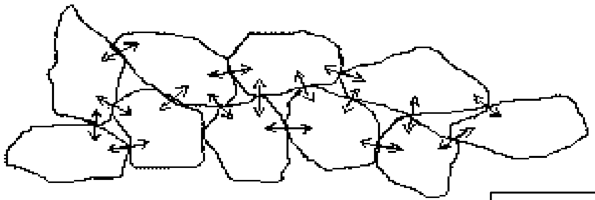
Sample N°	Water quantity weight (g)			Water volume (cm^3)			Time (s)	Hydraulic load H (cm)	Coefficient of permeability. K			K mean	K mean corrected
	P_1	P_2	P_3	V_1	V_2	V_3			K_1	K_2	K_3		
1	2721.20	2700.60	2737.10	2713.06	2692.52	2728.91	30	22.5	0.34	0.33	0.34	0.34	0.39
2	2859.60	2870.50	2866.80	2851.05	2861.91	2858.23	30	23	0.31	0.31	0.31	0.31	0.36
3	2647.60	2634.50	2633.10	2639.68	2626.62	2625.22	30	23.5	0.29	0.29	0.29	0.29	0.33
								Mean permeability: 0.31(cm/s)					
								Mean corrected permeability (cm/s)					**0.36**

considering that: $k = \frac{V \cdot h}{A \cdot t \cdot H}\eta$

Also this value of the coefficient of permeability is included in the limits provided by the *Capitolati* K ≥ 0.15 cm/s.

ANALYSIS OF THE RESULTS

The comparison of the experimental results show the contribution that the fibres give to the performances of the draining mixture, improving the mechanical, deforming and ductility characteristics.
The structural pattern of an open bituminous mixture (see figure) shows how the high percentage of air voids due to the typical granulometric discontinuity of these mixtures reduce the number of points of contact between the aggregates more than in a compacted dense mixture [2, 15].



Structural pattern of the open bituminous mixture

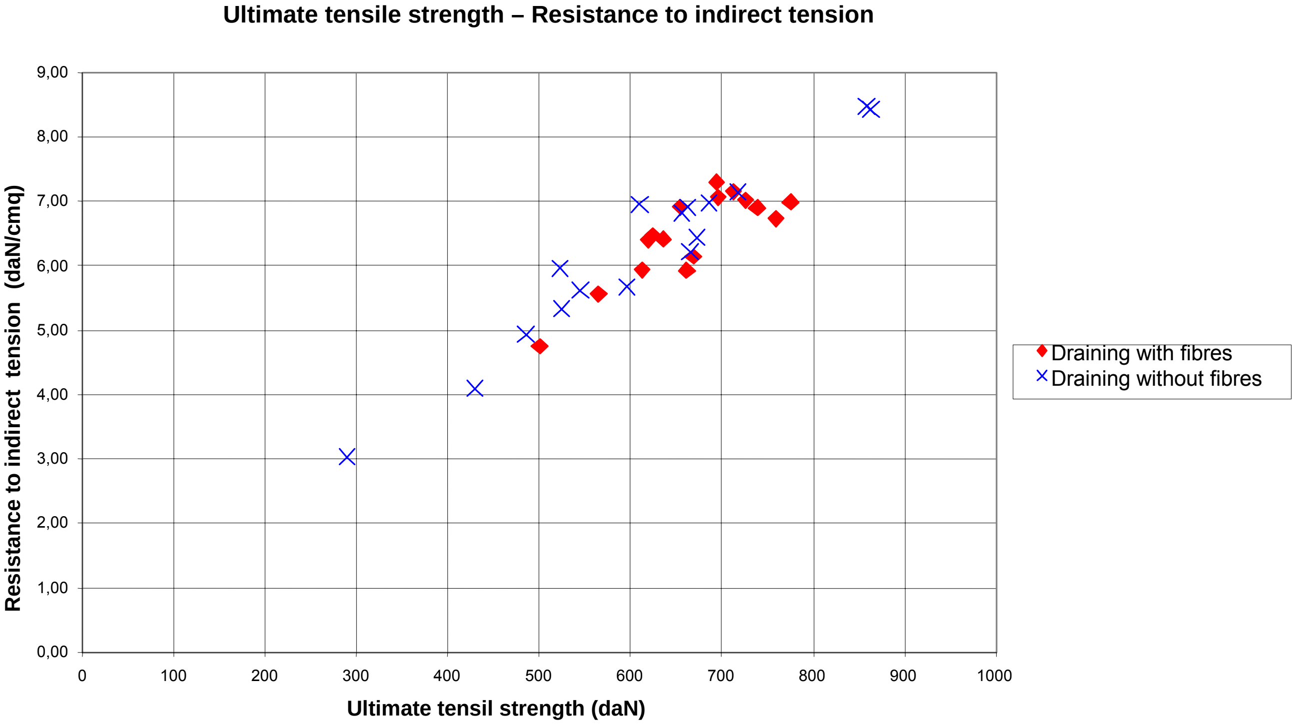
The high percentage of air voids, although being the main characteristic of a draining mixture which has a high porosity that allows the mixture to perform its functions, causes a high concentration of tensions located in a few points penalizing the resistance of the mixture and reducing the mechanical characteristics.
The presence of fibres, as the experimental results prove, has increased the mean porosity from 20 % to 23%, consequently increasing the coefficient of permeability K from 0.33 cm/sec to 0.36 cm/sec and the Marshall stability (although the limitations of this test on mixtures with added fibres) from 669 to 732 Kg.
The flowing value has resulted equal to 3.28 mm for the draining mixture and has increased to 3.62 mm after the addition of fibres.
The mean value of resistance to indirect tension, corrected by the fidelity criterion, has increased from 6.09 daN/cm^2 to 6.48 daN/cm^2 in the case of a mixture with added fibres.
The experimental results of the two types of mixture can be compared as follows:

MARHALL TEST	NORMAL DRAINING MIXTURE	DRAINING MIXTURE WITH FIBRES
Stability (Kg)	669	732
Flowing (mm)	3.28	3.62
Stiffness (Kg/mm)	204	202

PERMEABILITY	NORMAL DRAINING MIXTURE	DRAINING MIXTURE WITH FIBRES
(cm/sec)	0.33	0.36

INDIRECT TENSION	NORMAL DRAINING MIXTURE	DRAINING MIXTURE WITH FIBRES
(daN/cm^2)	6.09	6.48

The physical explanation of this phenomenon is in the capability of the fibres to thicken the bitumen, much more than the traditional filler, holding it in the points of contact of the aggregates, which result less subjected to wearing and more covered by the binder’s membrane.
The influence of the fibres on the mechanical characteristics is confirmed by the indirect tension strength test data.
In addition, fibres do not allow dripping of binder by reducing dispersion in the mixture.
The comparison between the values of resistance to indirect tension of draining mixtures with and without fibres is shown in the following diagram.

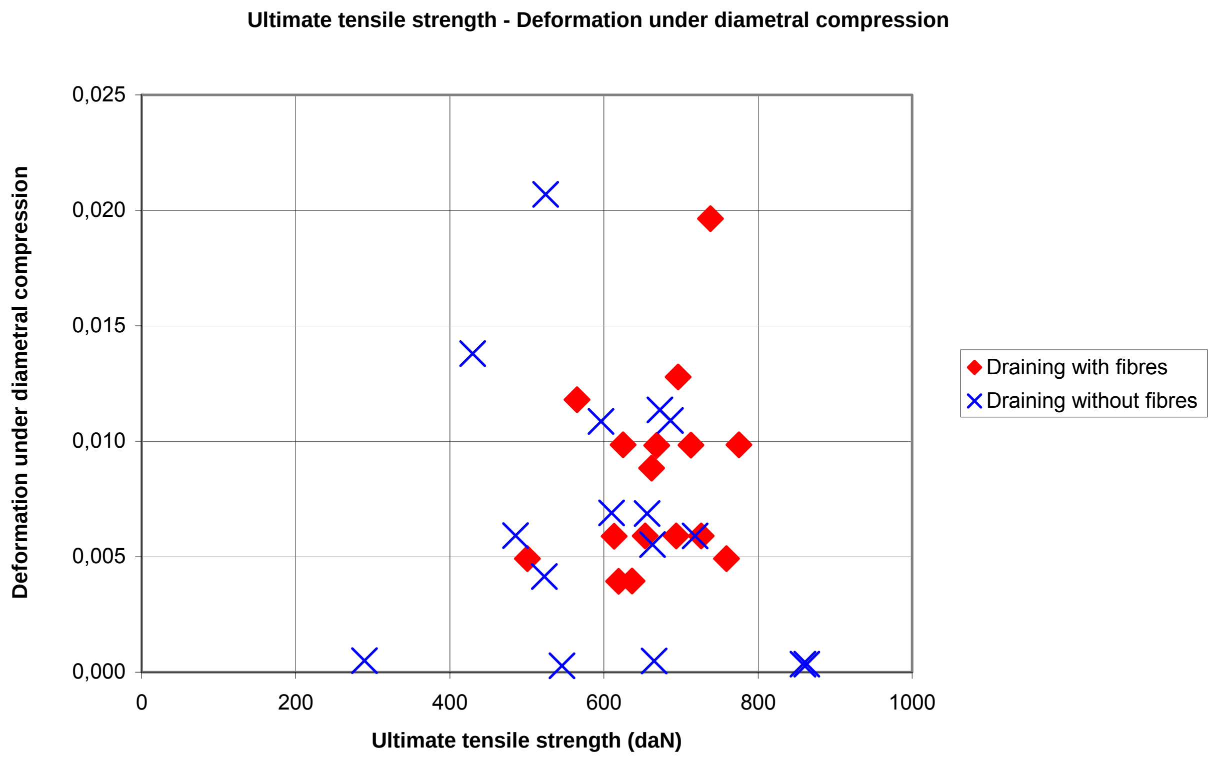


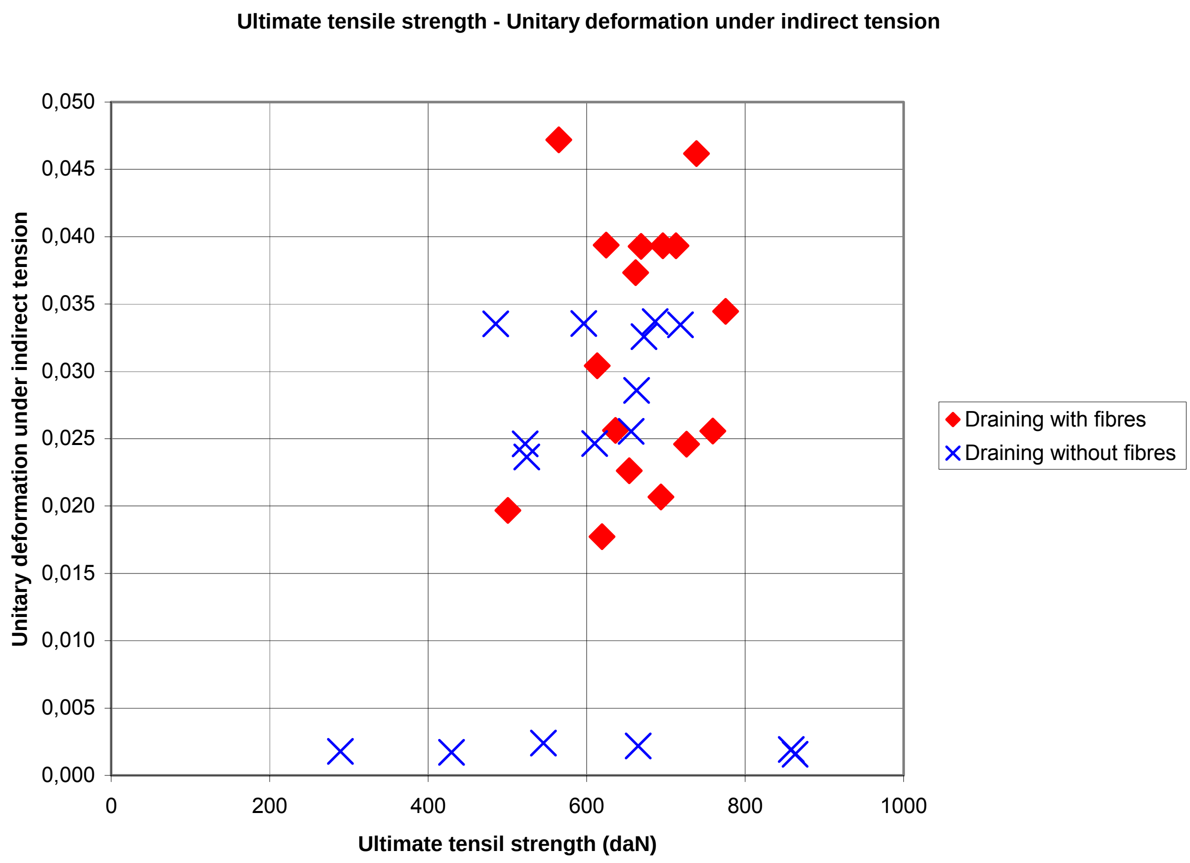
Concerning the values σ_{Tm} of the resistance to indirect tension of the mixture with added fibres, there has been an increase in the mean value from 6.19 to 6.48 daN/cm^2; moreover, the samples subjected to the experiment tended to increase.

Concerning the samples with fibres, the diagram shows a general migration to higher values of resistance to indirect tension as the ultimate tensile strength increases.

A similar comparison can be made on the diametral deformations.

In the following diagrams the y coordinates represent respectively the ratios between the deformations under diametral compression (shortening) ΔDc and under indirect tension (extension) ΔDt of the samples, and their diameters D.


Ultimate tensile strength - Deformation under diametral compression
0,025
0,020
0,015
0,010
0,005
0,000
0
200
400
600
800
1000
Deformation under diametral compression
Ultimate tensile strength (daN)
Draining with fibres
Draining without fibres


Ultimate tensile strength - Unitary deformation under indirect tension
0,050
0,045
0,040
0,035
0,030
0,025
0,020
0,015
0,010
0,005
0,000
0
200
400
600
800
1000
Unitary deformation under indirect tension
Ultimate tensil strength (daN)
Draining with fibres
Draining without fibres

The analysis of the results of the samples with added fibres shows a substantial migration to higher values of diametral deformations than in the case of normal draining samples, also due to higher ultimate tensile strength.
The fibres determine an increase in the ductility of the material, because in the matrix binder they form a kind of grating that acts as a support for the mixture itself.

CONCLUSIONS

The analysis of the results show the positive contribution that fibres in pure cellulose provide when they are used as an additive in traditional draining bituminous mixtures.
Infact, these fibres increase the values of mechanical resistance, the ductility of the material, and the permeability of the mixture, consequently improving the draining function of the paving.
This happens because the fibres thicken the mixture, holding the bitumen in the points of contact of the aggregates, where there are most of the concentrated loads.
Moreover, the fibres reduce the phenomenon of isolation, avoid the bitumen from dripping inside the mixture and increase the porosity of the material.
Therefore, the experimental results prove that the fibres in pure cellulose, increasing the ductility of the material, exert a general control over phenomena of micro-fractures and of fracture propagation, as shown also by Santagata [2].

APPENDIX

Criterion of fidelity for the indirect tension test of the draining mixture.

Series 1

N° Sample	Resistance to indirect tension (daN/cm^2)
1	6.44
2	6.95
3	5.96
4	6.91
Average **(m)**	6.57
Root mean square deviation **(S)**	0.47

The values of the resistances will be increasing:

$(X_1 \leq X_2 \leq X_3 \leq X_4) \Rightarrow 5.96 < 6.44 < 6.91 < 6.95$

The differences will be calculated as follows: $S_1 = (X_1 - m)$ e $S_4 = (X_4 - m)$:

$$S_1 = 5.96 - 6.57 = -0.61$$

$$S_4 = 6.95 - 6.57 = 0.38$$

and it will be verified whether the grater between the two values S_1 e S_4 in absolute value, is less than or equal to: 1.46 S = 0.68.

$$|S_1| < 1.46 \cdot S \Rightarrow |0.61| < 0.68$$

Verified.

Series 2

N° Sample	Resistance to indirect tension (daN/cm^2)
5	5.67
6	5.33
7	4.09
8	4.93
Average **(m)**	5.00
Root mean square deviation **(S)**	0.68

The values of the resistances will be increasing:

$(X_1 \leq X_2 \leq X_3 \leq X_4) \Rightarrow 4.09 < 4.93 < 5.33 < 5.67$

The differences will be calculated as follows: $S_1 = (X_1 - m)$ e $S_4 = (X_4 - m)$:

$$S_1 = 4.09 - 5.00 = -0.91$$

$$S_4 = 5.67 - 5.00 = 0.67$$

and it will be verified whether the grater between the two values *S_1* e *S_4* in absolute value, is less than or equal to: 1.46 S = 0.99.

$$. \ |S_1| < 1.46 \cdot S \Rightarrow |0.91| < 0.99$$

Verified.

Series 3

N° Sample	Resistance to indirect tension (daN/cm^2)
9	5.62
10	3.03
11	6.21
12	8.43
Average **(m)**	5.82
Root mean square deviation **(S)**	2.74

The values of the resistances will be increasing:

$$(X_1 \leq X_2 \leq X_3 \leq X_4) \Rightarrow 3.03 < 5.62 < 6.21 < 8.43$$

The differences will be calculated as follows: $S_1 = (X_1 - m)$ e $S_4 = (X_4 - m)$:

$$S_1 = 3.03 - 5.82 = -2.79$$
$$S_4 = 8.43 - 5.82 = 2.61$$

and it will be verified whether the grater between the two values *S_1* e *S_4* in absolute value, is less than or equal to: $1.46 \cdot S = 4.00$.

$$|S_1| < 1.46 \cdot S \Rightarrow |2.79| < 4.00$$

Verified.

Series 4

N° Sample	Resistance to indirect tension (daN/cm^2)
13	8.48
14	7.15
15	6.98
16	6.82
Average **(m)**	7.36
Root mean square deviation **(S)**	0.25

The values of the resistances will be increasing:

$$(X_1 \leq X_2 \leq X_3 \leq X_4) \Rightarrow 6.82 < 6.98 < 7.15 < 8.48$$

The differences will be calculated as follows: $S_1 = (X_1 - m)$ e $S_4 = (X_4 - m)$:

$$S_1 = 6.82 - 7.36 = -0.54$$
$$S_4 = 8.48 - 7.36 = 1.12$$

and it will be verified whether the grater between the two values S_1 e S_4 in absolute value, is less than or equal to: 1.46 S = 0.37.

$$|S_4| > 1.46 \cdot S \Rightarrow |1.12| > 0.37$$

Not verified**.**

The rules provide in this case the deviation of one of the two extreme values of the series in which the criterion of fidelity is not verified; in the series 4 the deviation is: 8.48 daN/cm^2.
The mean value of the resistance to indirect tension of the series 4 is given by the remaining three values:

Average (m^*) = 6.98 (daN/cm^2)

The mean value of the resistance to indirect tension of the draining mixture will be equal to:

$$\sigma_{Tm} = \frac{m^{serie1} + m^{serie2} + m^{serie3} + m^*}{4} = 6.09 \text{ (daN/cm}^2\text{)}$$

Criterion of fidelity for the indirect tension test of the draining mixture with addition of fibres.

Series 1

N° Sample	Resistance to indirect tension (daN/cm^2)
5	5.92
6	6.14
7	6.73
8	6.99
Average **(m)**	6.44
Root mean square deviation **(S)**	0.49

The values of the resistances will be increasing:

$(X_1 \leq X_2 \leq X_3 \leq X_4) \Rightarrow 5.92 < 6.14 < 6.73 < 6.99$

The differences will be calculated as follows : $S_1 = (X_1 - m)$ e $S_4 = (X_4 - m)$:

$$S_1 = 5.92 - 6.44 = -0.52$$

$$S_4 = 6.99 - 6.44 = 0.55$$

and it will be verified whether the grater between the two values S_1 e S_4 in absolute value, is less than or equal to: 1.46 S = 0.71.

$$|S4| < 1.46 \cdot S \Rightarrow |0.55| < 0.71$$

Verified.

Series 2

N° Sample	Resistance to indirect tension (daN/cm^2)
9	7.02
10	7.15
11	5.94
12	4.75
Average **(m)**	6.21
Root mean square deviation **(S)**	1.11

The values of the resistances will be increasing:

$(X_1 \leq X_2 \leq X_3 \leq X_4) \Rightarrow 4.75 < 5.94 < 7.02 < 7.15$

The differences will be calculated as follows: $S_1 = (X_1 - m)$ e $S_4 = (X_4 - m)$:

$$S_1 = 4.75 - 6.21 = -1.46$$

$$S_4 = 7.15 - 6.21 = 0.94$$

and it will be verified whether the grater between the two values S_1 e S_4 in absolute value, is less than or equal to: 1.46 S = 1.60.

$$|S_1| < 1.46 \cdot S \Rightarrow |1.46| < 1.60$$

Verified.

Series 3

N° Sample	Resistance to indirect tension (daN/cm^2)
13	5.56
14	6.09
15	6.41
16	6.47
Average **(m)**	6.33
Root mean square deviation **(S)**	0.56

The values of the resistances will be increasing:

$$(X_1 \leq X_2 \leq X_3 \leq X_4) \Rightarrow 5.56 < 6.41 < 6.47 < 6.90$$

The differences will be calculated as follows: $S_1 = (X_1 - m)$ e $S_4 = (X_4 - m)$:

$$S_1 = 5.56 - 6.33 = -0.77$$

$$S_4 = 6.90 - 6.33 = 0.57$$

and it will be verified whether the grater between the two values S_1 e S_4 in absolute value, is less than or equal to: $1.46 \cdot S = 0.81$.

$$|S_1| < 1.46 \cdot S \Rightarrow |0.77| < 0.81$$

Verified.

Series 4

N° Sample	Resistance to indirect tension (daN/cm^2)
17	6.41
18	7.07
19	7.30
20	6.92
Average **(m)**	6.92
Root mean square deviation **(S)**	0.37

The values of the resistances will be increasing:

$$(X_1 \leq X_2 \leq X_3 \leq X_4) \Rightarrow 6.41 < 6.92 < 7.07 < 7.30$$

The differences will be calculated as follows: $S_1 = (X_1 - m)$ e $S_4 = (X_4 - m)$:

$$S_1 = 6.41 - 6.92 = -0.51$$
$$S_4 = 7.30 - 6.92 = 0.38$$

and it will be verified whether the grater between the two values S_1 e S_4 in absolute value, is less than or equal to: 1.46 S = 0.54.

$$|S1| > 1.46 \cdot S \Rightarrow |0.51| > 0.54$$

Verified.

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