A New Approach to the Mix Design of Bituminous Mixtures for Trench Sealing

Ezio Santagata
Politecnico di Torino, Torino, Italy

Emanuele Toraldo
Politecnico di Milano, Milano, Italy

Synopsis

Research in the area of bituminous mixtures for paving applications has lead to an improvement in the understanding of the mechanisms which control their performance in the field. The importance of aggregate structure, bitumen-filler mastic and of aggregate-bitumen interactions has been highlighted, spurring the development of function-specific mixtures for special applications.

In such a context the Authors have pursued the mix design of bituminous mixtures to be used for the sealing of narrow cuts in pavement surfaces. This specific need has arisen in a research project focused on the development of materials for the implementation of a new technology for the laying of underground telecommunication cables.

The aims of the mix design method described in this paper are the obtainment of mixtures characterized by an appropriate balance of workability, stiffness and shear resistance. In fact, a high level of workability is essential for the complete filling of the surface portion of the trench, while stiffness and shear resistance are needed to prevent post-compaction permanent deformation and lateral flow. Based on these requirements, the Authors decided to consider for design a hot-mixed bituminous material containing a single-sized aggregate (5/10 mm) and a filler-bitumen mastic obtained from the combination of a standard bitumen (70/100 pen) and cement filler.

The proposed design procedure was structured in five successive phases. In the first phase, the base materials (aggregate, binder and filler) were selected and characterized according to existing standards. These operations were followed by the experimental evaluation of the filler-bitumen ratio to adopt for the constitution of the bituminous mastic, performed in phase two. The third phase of design was dedicated to the definition of the aggregate-mastic ratios to use in the calculation of the mixture recipes. Finally, in the fourth and fifth phases of design the selected sealing mixtures were prepared in the laboratory and subjected to volumetric and mechanical tests.

Testing of the mastics, carried out on materials with a variable filler-bitumen ratio, was carried out by performing ductility tests at 25°C and direct tension tests in the low temperature range (0 and -6°C). Two filler-bitumen ratios, equal to 2.0 and 2.5, were subsequently selected for the preparation of the design sealing mixtures since they ensure a satisfactory balance in terms of strength and ductility.

The target mastic-aggregate ratio was established by modeling the structure of the mixture as a single-sized system saturated by bituminous mastic. The voids available in the aggregate structure for saturation were assessed by performing compaction tests on the aggregate by means of a gyratory shear compactor, for which a specific testing protocol was developed. The compaction properties of the corresponding design mixtures, the recipes of which were derived by means of volume-weight conversion, were thereafter studied for both the selected mastics. It was observed that the sealing mixtures have an acceptable residual void content (3.40-3.85%) which should ensure an adequate level of impermeability.

The mechanical characterization of the sealing mixtures was carried out in two stages in which the effects caused by variations of level of compaction, mastic composition and temperature were assessed. This was done by making use of standard test methods (elastic stiffness and indirect tensile strength) and of mechanistic-based characterization procedures (simple compression and direct tension) specifically developed by the Authors. The obtained results were coherent with expectations since stiffness and strength (in all the three modes considered) tend to increase as the mixture is compacted to a denser state and/or as the filling mastic is stiffened (either by increasing the filler-bitumen ratio or by reducing temperature). These same effects are generally accompanied by a certain degree of embrittlement which in extreme cases may limit mechanical performance.

The results obtained in the investigation support the conclusion that the mix design method proposed by the Authors is suited for the analysis of the specific kind of mixtures used for trench sealing. However, since stiffer mixtures exhibit brittle failure at lower temperatures, it is recommended that the choice of the design recipe to adopt in practice should also take into account the climatic conditions expected in service. Further improvements to the design method may also stem from the monitoring of actual field performance in order to develop acceptance criteria which may be included in technical specifications.

A New Approach to the Mix Design of Bituminous Mixtures for Trench Sealing

Research in the area of bituminous mixtures for paving applications has lead to an improvement in the understanding of the mechanisms which control their performance in the field. The approach adopted by researchers has gradually shifted from empirical observation to theoretical modeling and simulation, with a great amount of work devoted to the use of fundamental principles for the evaluation of the properties of materials and of the performance of pavements. The importance of aggregate structure, binder rheology and of aggregate-bitumen interactions has been highlighted, spurring the development of function-specific mixtures – porous, antiskid, sound-absorbing, self-compacting, etc. – which can be employed for special applications. For these materials it is now possible to define mix design procedures and technical specifications which are based on a solid scientific background and may be tailored to suit specific needs.
In this paper the Authors give a good example of this kind of task, by illustrating the results they obtained in the development and use of a mix design procedure defined for bituminous mixtures to be used for the sealing of narrow cuts in pavement surfaces. This specific need has arisen in a research project focused on the implementation of a new technique for the laying of underground telecommunication cables in urban streets.
The technique involves the excavation of a mini-trench (approximately 30 cm deep and 7-8 cm wide), the placement of the telecommunication cables or pipes and the backfilling of the trench, by employing only one piece of equipment which works in a single pass [1]. Surface sealing of the backfilled trench is then carried out by placing a proper bituminous mixture in the top 3-5 cm of the trench. The advantages which derive from this new technique are mainly related to its speed, to the limited extension of the working area and to the reduction of disturbances to traffic and residents.
In a preliminary phase of the project, the requisites of the materials used for the backfilling of the trench and for its surface sealing were defined [2]. It was shown that backfilling should preferably be carried out by employing a cementitious Controlled Low-Strength Material (CLSM), characterized by self-compacting and self-leveling properties. For surface sealing various options were considered: fine-grained wearing course mixtures, pourable mixtures of the Gussasphalt type, storable open-graded cold mixtures and field-mixed cold mixtures. However, further research was recommended in order to define specific mix design procedures for both the CLSM [3] and the top finishing bituminous material.

EXPERIMENTAL INVESTIGATION

Design approach

The sealing mixture needs to be designed in order to obtain a material characterized by an appropriate balance of workability, stiffness and shear resistance. In fact, a high level of workability is essential for the complete filling of the surface portion of the trench, where the effects of rollers may be counterbalanced by the supporting action of the adjacent pavement. Moreover, stiffness and shear resistance, which are frequently antithetic to workability, are needed to prevent post-compaction, permanent deformation and lateral flow. In order to prevent ravelling and spalling phenomena it was also considered necessary for the mixture to be totally impermeable to water and to develop a good adhesion with the adjacent bituminous pavement. Finally, since the sealing technique should be easily implementable in practice and possibly included in the single-pass equipment by means of proper modifications, it was decided to design the mixture by employing standard, readily available materials, thus avoiding selected, more expensive aggregates or binders.
Based on these observations and on previous experience carried out in the performance-related evaluation of bituminous mixtures used for the construction of asphaltic plug joints [4], the Authors decided to consider for design a hot-mixed bituminous material containing a single-sized aggregate skeleton saturated by a filler-bitumen mastic of adequate stiffness. In order to obtain a material which ensures adequate load spreading and can follow the deformation of the existing pavement without fracturing, it is essential to guarantee a homogeneously distributed point-to-point contact of the aggregate particles and a uniform distribution of the bituminous mastic. Once these conditions are reached, the mixture should behave satisfactorily with the containment contribution of the surrounding pavement.
Following this design approach, the mix design procedure was structured in five successive phases. In the first phase, the base materials (aggregate, binder and filler) were selected and characterized according to existing standards. These operations were followed by the experimental evaluation of the filler-bitumen ratio to adopt for the constitution of the bituminous mastic, performed in phase two. The third phase of design was dedicated to the definition of the aggregate-mastic ratios to use in the calculation of the mixture recipes. Finally, in the fourth and fifth phases of design the selected sealing mixtures were prepared in the laboratory and subjected to volumetric and mechanical tests.

Phase 1 – Selection and characterization of materials

Based on the analysis of its required properties, the sealing mixture was designed by making use of a single-sized aggregate (5/10 mm) and of a mastic obtained from the combination of a standard non-modified bitumen (70/100 pen) and Portland cement filler (32.5 type). The size of the aggregate particles is compatible with the dimensions of the volume to lay in the trench (70-80 mm in width, 30-50 mm in depth) and the 5/10 fraction is usually commercially available in quarries or mixing plants. The 70/100 pen bitumen is also easily available and may be mixed with aggregates and mineral filler at relatively low temperatures, certainly lower than those necessary for modified binders, obtaining a uniform coating of the particles. In combination with the appropriate dosage of filler it can also yield mastics which may exhibit a satisfactory behaviour in terms of stiffness and strength (i.e. not too stiff and brittle, not excessively deformable and prone to viscous flow).

The base materials were subjected to standard characterization tests, the results of which are given in Tables 1 and 2. The 5/10 aggregate was preliminarly sieved and washed in order to control its gradation and eliminate dust or impurities. Similarly, the fraction retained on the n. 200 sieve was eliminated from the filler.

Table 1: Characterization of the 5/10 aggregate

Apparent density of the particles (g/cm^3)	2.775
Bulk density, vibrating table (g/cm^3)	1.545
Percent voids, vibrating table (%)	44.3
Shape coefficient	0.21
Flatness coefficient	13.1

Table 2: Characterization of the 70/100 pen bitumen

Penetration at 25°C (dmm)	77.2
Softening point, R&B (°C)	47.1
Ductility (cm)	> 100

Phase 2 – Evaluation of the design filler-bitumen ratio

The filler-bitumen mastic not only contributes to the mechanical behaviour of the sealing mixture, but has also the specific function, especially in the medium and low temperature range, of withstanding local tensile stresses that may cause loss of aggregates. Moreover, at very low temperatures it should be sufficiently ductile in order to prevent the formation of thermal cracks.

As a result of these observations, the optimum composition of the mastic was defined by performing ductility tests at 25°C and direct tension tests, carried out according to the SHRP protocol B-004, in the low temperature range (0 and -6°C). The four candidate mastics considered in the investigation were prepared with a filler-bitumen ratio comprised between 1.5 and 3.0 (with increments of 0.5).

As expected, ductility decreases when the filler-bitumen ratio is increased. This is clearly shown in Figure 1, where it can be observed that the decrease is certainly non-linear. The mastic abruptly changes its behaviour at a filler-bitumen ratio equal to 2.0 (where the ductility is equal to 7.9 cm); for ratios above this threshold value, ductility changes very slightly.

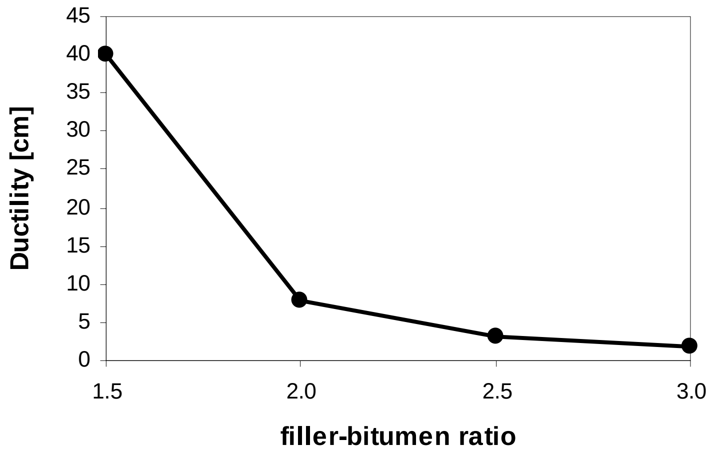

Figure 1: Ductility test results

In the case of direct tension tests, the mastics exhibited a completely different behaviour at 0 and -6°C. At the upper temperature they reached viscous flow conditions and the corresponding stress-strain data were consequently recorded until a maximum deformation of 6%; at -6°C brittle failure was observed. The average data at failure (or at 6% strain) and the total dissipated energy, calculated from 4 nominally identical samples, are given in Table 3.

Table 3: Direct tension test results

	T = 0°C			T = -6°C		
f/b	σ_f [N/mm^2]	ε_f [%]	W [J]	σ_f [N/mm^2]	ε_f [%]	W [J]
1.5	0.85	6.00	0.061	3.07	4.24	0.099
2.0	1.49	6.00	0.105	3.99	2.79	0.083
2.5	1.96	6.00	0.131	4.19	2.96	0.106
3.0	2.62	6.00	0.169	4.56	1.74	0.058

At 0°C the tensile behaviour of the mastic proved to be extremely sensible to variations of the filler-bitumen ratio, with an almost constant rate of increase of the stress measured in stable flow conditions (equal to 1.2 N/mm^2). At -6°C this type of susceptibility was slightly reduced and for filler-bitumen ratios greater than 2.0 small increases of tensile strength were observed (σ_f comprised between 4.0 and 4.5 N/mm^2 in the 2.0-3.0 filler-bitumen ratio range). As expected, as the dosage of filler is increased the strain at failure decreases, with a central range, corresponding to filler-bitumen ratios comprised between 2.0 and 2.5, in which ε_f is almost constant. At a ratio of 3.0 an abrupt increase in brittleness is observed, with a corresponding significant decrease of the dissipated energy. The results obtained at -6°C are synthesized in Figure 2.

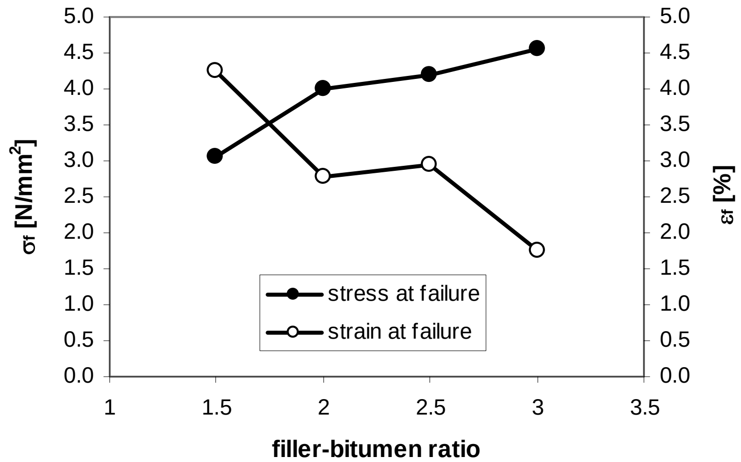

Figure 2: Direct tension test results obtained at -6°C

By considering the results obtained in this phase of mix design, two values of the filler-bitumen ratio, equal to 2.0 and 2.5, were selected as appropriate for use in the successive experimental activities. This is due to the fact that the corresponding mastics exhibit a similar behaviour with a satisfactory balance in terms of strength and ductility.

Phase 3 – Evaluation of the design mastic-aggregate ratio

In the third phase of design the target mastic-aggregate ratio was established by modeling the structure of the mixture as a single-sized system saturated by bituminous mastic. This required an estimate of the voids available for saturation in the aggregate structure, which was carried out by performing compaction tests on the aggregate by means of a gyratory shear compactor. The recipe of the corresponding target sealing mixture was thus calculated by interpreting such a void content as the available VMA and by making use of simple volume-weight conversion relationships.

The testing protocol adopted for the compaction of the clean dry aggregate is based on the use of standard cylindrical moulds (100 mm in diameter) in which 1525.6 g of loose material are poured with no additional manual tamping required. Careful control of the mass of each specimen, which may be ensured by operating on a simple laboratory balance, is considered essential in order to obtain repeatable results during compaction which is carried out in standard conditions as defined by SUPERPAVE for bituminous mixtures (gyration angle 1.25°, vertical pressure 600 kPa).

Compaction curves represented in the N-C (number of gyrations - compaction) plane may be derived from the data recorded by the gyratory equipment by calculating the ratio between progressive bulk density (calculated geometrically) and apparent density of the aggregate particles. Results may also be expressed by referring to progressive void content (also geometrically calculated) and by plotting data points in the N-%v plane.

As expected, due to its single-size nature, the aggregate exhibited most of its densification in the initial part of the compaction tests in which the system rapidly tended, under the combined effects of normal and shear contact stresses which cause displacements and reorientation, towards a stable structure characterized by well distributed aggregate-to-aggregate contact points. Further densification effects, observed after these conditions have been reached, can be mainly attributed to local fracture and pulverization phenomena, and to a limited extent to the displacements and reorientations which are caused by these alterations of the original particles. These observations are supported by the test results shown in Figure 3, which contains the N-%v curves obtained by imposing a total of 10, 20 and 30 gyrations to the aggregate samples. It can be observed that the curves overlap almost perfectly and that in all cases the slope of the curve changes quite rapidly as the number of gyrations increases.

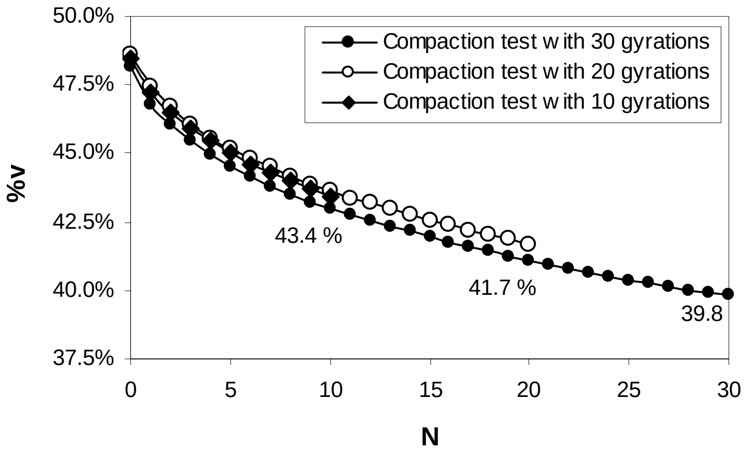

Figure 3 – Compaction curves of the single-sized aggregate

The level of compaction of the aggregate structure which was considered as a target in the mix design procedure was that which corresponds to the initial densification which leads to a stable structure. This is due to the fact that the final goal of the procedure was to identify mixtures which can be easily compacted in the field, possibly by means of light rollers and/or manual tamping the use of which is compatible with the limited width of the pavement cuts. Moreover, fracture and pulverization phenomena are certainly to be prevented since they may yield, under the effects of traffic, loss of aggregate particles and other undesired distresses of the sealing mixture.
At the end of each test the aggregates were carefully inspected, before and after demoulding. In the case of samples compacted at 10 and 20 gyrations only a limited number of fractured aggregates was reported, mainly located on the upper and lower surface, and to a more limited extent on the lateral surface. By increasing the number of gyrations to 30 such phenomena appeared to be more severe and distributed within the mass of the specimen.
Based on these observations the compaction level corresponding to 20 gyrations, at which the average void content is equal to 41.7%, was selected as the design condition to consider in the proportioning of the sealing mixtures. This corresponds, by assuming total saturation of the voids by means of mastic, to a theoretical mastic-aggregate volume ratio equal to 71.5%. Calculations were therefore carried out in order to derive, for each of the two previously selected candidate mastics, the design mastic-aggregate weight ratios.
The volume-to-weight conversion was performed by considering the values of the apparent density of the aggregate particles, already evaluated in phase 1 (Table 1), and of the density of the mastics, which needed to be evaluated by means of an appropriate experimental procedure.
Batches of the two mastics were conditioned at a temperature of 152°C and then poured in a metallic mould of the same type used in phase 5 for the advanced testing of the bituminous mixtures in the direct tensile mode. The specimen, approximately 150 mm in height and with a circular transverse section variable between 55 and 70 mm, was allowed to cool to room temperature and thereafter subjected to testing for the determination of density (in saturated surface-dry conditions) as indicated in the ASTM standard D 2726. The mean values obtained for the two mastic, calculated from two independent repetitions, were equal to 1.825 g/cm^3 (for a filler-bitumen ratio equal to 2.0) and to 1.933 g/cm^3 (for a filler-bitumen ratio equal to 2.5).
It is important to stress the fact that in the volume-to-weight conversions the Authors decided to make use of the density values measured as described above instead of those derived from application of ASTM standard D 70 (based on the use a pycnometer). This choice was due to the fact that in the design mixtures overfilling of the aggregate skeleton by means of mastic had to be absolutely prevented. Thus, since there was no guarantee that in the mixture the micro-voids which are distributed in the mastic could be efficiently eliminated, in the design calculations the most conservative choice, which corresponds to considering mastics compacted only by their own weight, was made.

Based upon these measurements, hypotheses and calculations, the design mastic-aggregate ratio was obtained for the two sealing mixtures which differ in the filler-bitumen ratio of their binding mastic. These design values, considered in all the successive phases of design, are shown in Table 4.

Table 4: Design mastic-aggregate ratios

f/b	m/a
2.0	47.0
2.5	49.8

Phase 4 – Preliminary evaluation of the design mixtures

A preliminary evaluation of the design mixtures (Table 4) was carried out by considering their volumetric and mechanical properties as a function of the selected filler-bitumen ratio (equal to 2.0 or to 2.5) and of the imposed level of compaction (corresponding to 10, 20 or 30 gyrations).

Based upon initial trials it was observed that in order to obtain homogeneous mixtures it is necessary to prepare the mastic first, and to add to it the aggregate only in a second time, followed by thorough mixing. In both phases of the preparation an operating temperature of 152 ± 5°C was selected as suggested by the Italian CNR standard for mixtures containing 80/100 pen bitumen.

Mixing batches were prepared by using the material necessary to form, in the gyratory compactor, a zero void content sample with a target height of 70 mm and a diameter of 100 mm (standard mould). Special care was taken in ensuring that each sample contained the exact quantity of mastic and aggregate defined by design: thus, in the preparation of the batches a slight excess of mastic was used in order to counterbalance the material which adheres to the various mixing instruments. It was visually checked that all aggregate particles were transferred to the mould and by operating on a weighting scale the total weight of the sample was always controlled. After compaction, which was carried out at 152 ± 5°C, the specimens were allowed to cool for a while, until they reached a temperature of approximately 70°C, and then demoulded by employing a hydraulic pump extruder.

The volumetrics of the specimens was assessed by performing density tests (in saturated surface-dry conditions) and by calculating void content as a function of the maximum theoretical density (TMD). The average values of TMD, calculated by considering two independent test repetitions for each mixture performed according to ASTM standard D 2041, were equal to 2.461 g/cm^3 for a filler-bitumen ratio equal to 2.0 and to 2.487 g/cm^3 for a filler-bitumen ratio equal to 2.5.

The average values of density and void content are given in Table 5. It can be observed that in no case actual saturation conditions were reached: this is due to the fact that a great part of the micro-voids comprised in the un-compacted mastic were eliminated during compaction of the mixtures. At the design level of compaction, which corresponds to 20 gyrations, the void content (equal 3.85 or 3.40% depending upon mastic type) should be sufficient to allow volume changes due to thermal effects and should also guarantee a satisfactory impermeability to water.

The data shown in Table 5 are affected by uncertainties which depend upon the fact that in most cases it was observed that part of the pre-weighted mastic was lost either because it was squeezed out of the mould during compaction or because it adhered to the mould and to the upper and bottom plate. Nevertheless, as expected, for each mixture a decrease of void content was observed as a result of an increase of the number of gyrations; it was also observed that for any given number of gyrations a stiffening of the mastic, caused by an increase of the filler-bitumen ratio, leads to a reduction of the void content. The results obtained at 30 gyrations do not respect this trend, probably as a result of the above mentioned biasing effects originated during compaction and demoulding.

Table 5: Results of volumetric tests (phase 4)

Gyrations	f/b	n. specimens	D [g/cm^3]	%v [%]
10	2.0	3	2.350	4.52
	2.5	3	2.392	3.82
20	2.0	5	2.367	3.85
	2.5	5	2.403	3.40
30	2.0	3	2.390	2.91
	2.5	3	2.413	3.00

A closer look to the actual compaction mechanics of the sealing mixtures can be given by analyzing the data recorded by the gyratory equipment represented in the VMA-N (voids in the mineral aggregate – number of gyrations) plane. As shown in Figure 4, the average curves obtained on the samples subjected to 30 gyrations with both filler-bitumen ratios can be compared to the curve derived from tests carried out on the clean dry aggregate. In this case the progressive value of VMA is equal to the void content %v previously plotted in Figure 3.

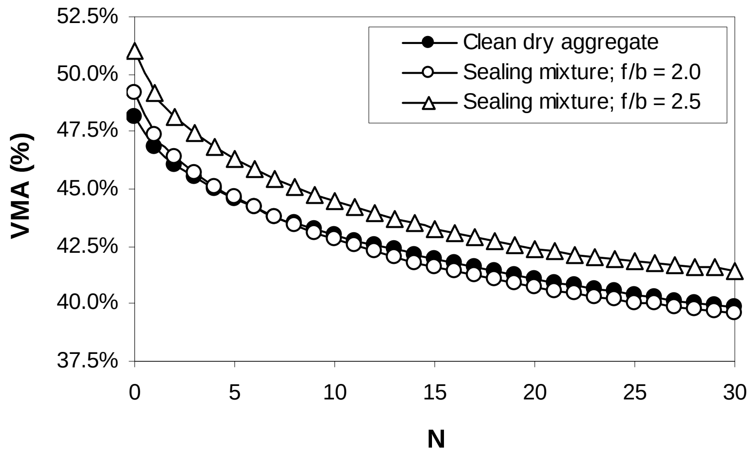

Figure 4 - Compaction curves of the aggregate and of the design mixtures

The three curves represented in Figure 4 are characterized by a close similarity in terms of shape. Furthermore, the curve which represents the progressive packing of the particles of clean dry aggregate is almost overlapping with the curve derived from the compaction of the design mixture which contains the mastic with the lower dosage of filler. In this case it can concluded that aggregate interactions seem to be affected only to a limited extent by the presence of the mastic. However, the curve obtained for the design mixture containing the stiffer mastic (i.e. with a higher filler content) is clearly shifted upwards: for any given number of gyrations a decrease in aggregate packing is obtained as a result of the mastic which, through its viscosity and its volume, certainly modifies the mechanics of compaction of the aggregates.
Similar comparisons between compaction curves were carried out for the specimens subjected to 10 and 20 gyrations. The corresponding results were coherent with those recorded on the specimens compacted at 30 gyrations.
In the preliminary phase of evaluation the mechanical properties of the sealing mixtures were assessed in the indirect tensile configuration by measuring the elastic stiffness (from impulsive loading at 20°C, with a rise time of 120 ms and a target horizontal deformation of 5 μm) and the indirect tensile strength (by means of quasi-static loading with a rate of vertical deformation equal to 50.8 mm/min). The corresponding average results, calculated from 4 repetitions, are shown in Table 6.

Table 6: Results of mechanical tests (phase 4)

Gyrations	f/b	E [MPa]	σ_f [N/mm^2]	ε_f [%]
10	2.0	767	0.37	3.05
	2.5	1050	0.43	0.75
20	2.0	956	0.42	1.04
	2.5	1337	0.50	0.77
30	2.0	1011	0.48	0.52
	2.5	1225	0.55	0.46

Elastic stiffness results were characterized by a high degree of variability both when comparing measurements performed along different directions on the same specimen and when considering different, nominally identical, specimens. Nevertheless, the dependency of the mean values from mixture volumetrics and mastic composition is coherent with expectations. At all levels of compaction a stiffening of the mastic produces a stiffening of the mixture; moreover, by increasing the compaction effort a denser mixture is obtained and an increase in modulus is also recorded. As in the case of volumetric results, the only exception to these trends was represented by the specimens of the stiffer mixture prepared with 30 gyrations.
Similar observations can be made when analyzing the results obtained from indirect tensile strength tests. As the void content decreases, an increase in strength is obtained for each mixture; moreover, the stress at failure also increases as a result of the stiffening of the binding mastic (i.e. by passing from a filler-bitumen ratio equal to 2.0 to a value of 2.5). In all cases strength increases are accompanied by a reduction of the strain at failure.
It should be noted that the reported values of both the elastic stiffness and the indirect tensile strength are quite low when compared with those of standard bituminous mixtures employed for paving applications. This is not at all surprising since these peculiar sealing mixtures, due to the single-size of their aggregate particles, cannot rely on aggregate interlock but only on a distributed point-to-point contact. Moreover, their

mechanical response is strongly affected by binder content, which is quite high when compared with values generally adopted in the design of standard bituminous mixtures. Nevertheless, the field performance of such mixtures may be satisfactory since they are not intended to form a layer subjected to repeated bending, but should work as in a longitudinal joint comprised within a very narrow and shallow trench.

Phase 5 – Advanced mechanical characterization of the design mixtures

Given the peculiar structure of the design mixtures and their expected functions in the field, it was considered necessary to complete the mechanical characterization with a rational evaluation of their failure properties at 0 and 20°C. This goal was pursued by adapting laboratory equipment and testing protocols previously developed by the Authors for the analysis of the behaviour in direct tension and simple compression of fine-grained wearing course mixtures [5-6] and of bituminous materials employed for the construction of asphaltic plug joints [4]. Moreover, further elastic stiffness and strength tests were carried out in the indirect tensile configuration at both temperatures.
This part of the experimental investigation was limited to the assessment of the behaviour of the sealing mixtures considered only at their design compaction level. In the case of indirect tensile tests, the specimen preparation procedure adopted in phase 4 was followed and 20 gyrations were imposed during compaction, thus obtaining specimens 100 mm in diameter and approximately 70 mm in height.
In the case of direct tension and simple compression tests, the quantity of material to use for the preparation of each specimen was derived from the geometric final volume of the specimens and by assuming a target void content equal to that measured on the corresponding specimens subjected in phase 4 to indirect tensile testing (Table 6). Specimens were considered representative of the material in its design conditions when the obtained void content was within ± 0.5% of the target values (3.85% for f/b equal to 2.0; 3.40% for f/b equal to 2.5%). Trial specimens were prepared in order to verify that this requirement was met and when necessary the employed quantities were adjusted by means of an iterative process. Mixing of the components and transfer of the mixture to the moulds was carried out by following protocols similar to those adopted for the preparation of 100 mm diameter specimens. A slight change was only necessary for the calculation of the quantity of mastic in excess to include in each batch to take into account the loss of material which results from mixing and handling operations.

Simple compression tests

Simple compression tests were performed on slender cylindrical specimens, 70 mm in diameter and with a height of 150 mm, which ensure an almost uniform stress distribution (height to diameter ratio greater than 2) and are compatible with the particle size of the aggregates. This required the construction of a proper gyratory mould and some modifications of the compactor's loading piston [6]. Compaction was carried out by imposing the final height of the specimen (150 mm).
Demoulding of the specimens was performed when they reached a temperature of 40°C. The specimens were then allowed to cool down to room temperature and before being subjected to testing they were then conditioned for at least 12 hours in a climatic chamber set at test temperature.
The equipment used for simple compression tests is constituted by a two-plate test jig which is mounted on a standard mechanical testing machine. The system is instrumented with a load cell and with an LVDT mounted in the vertical direction, the signals of which are recorded during testing by a multi-channel data acquisition system (with a sampling frequency of 100 Hz). Tests are carried out by moving the lower loading plate in the upward direction at a speed of 4 mm/min, thereby subjecting the test specimen to quasi-static loading conditions. Figure 5 contains a picture of the test equipment and examples of the stress-strain curves obtained after data processing.
Simple compression tests were carried out in 4 repetitions for each combination of filler-bitumen ratio and temperature. The corresponding mean values of stress and strain at failure are given in Table 7.

Table 7: Simple compression test results (phase 5)

	T = 20°C		T = 0°C	
f/b	σ_f [N/mm^2]	ε_f [%]	σ_f [N/mm^2]	ε_f [%]
2.0	0.74	3.69	5.00	2.17
2.5	0.98	3.47	6.30	2.12

As expected, both mixtures proved to be extremely sensitive to temperature changes: by decreasing temperature from 20 to 0°C a notable increase of compression strength and a non-negligible reduction of strain at failure were recorded. It was also observed that for both mixtures the ratios between the stress or strain at failure evaluated at the two temperature is almost constant ($\sigma_{f,0°C}/\sigma_{f,20°C}$ equal to 6.4-6.8; $\varepsilon_{f,0°C}/\varepsilon_{f,20°C}$ equal to 0.6). This clearly indicates that in simple compression the temperature susceptibility of the failure properties does not depend upon mastic type.

Similar observations can be made when considering the stiffening effects produced by increasing the filler-bitumen ratio. These consist in an increase of the compression strength (of the order of 25-30%), and in a very slight reduction of the corresponding strain at failure (of the order of 2-6%).
Other interesting information can be derived from the analysis of the stress-strain curves and from the visual assessment of the shape of the specimens at failure. As shown in Figure 5, stiffening effects due to a change in temperature or in the filler-bitumen ratio were reflected by the slope of the rising portion of the curves, whereas in the descending portion of the curves at each temperature the two mixtures tended to a common asymptote. At 0°C the specimens exhibited a more uniform state of deformation (both in the vertical and radial direction) and the corresponding stress-strain curves were recorded as very smooth and repeatable. On the contrary, at 20°C barreling end-effects were not completely eliminated and the recorded response curves tended to be more irregular and dispersed.
Finally, the data shown in Table 7 was compared to the results obtained in a previous research project focused on the analysis of the failure behaviour of fine wearing-course mixtures [6]. For these mixtures it was observed that at the same temperatures (0 and 20°C) and with the same speed of compression (4.0 mm/min) the ultimate strength is sensibly higher (between 1.6 and 3.8 N/mm^2 at 20°C; between 6.5 and 9.3 N/mm^2 at 0°C) with a corresponding lower strain at failure (comprised between 1.00 and 1.6% at both temperatures). As already highlighted when considering the results obtained in phase 4, these differences are due to the peculiar structure of the sealing mixtures which is characterized by the absence of aggregate interlock and by the presence of a very high binder content.

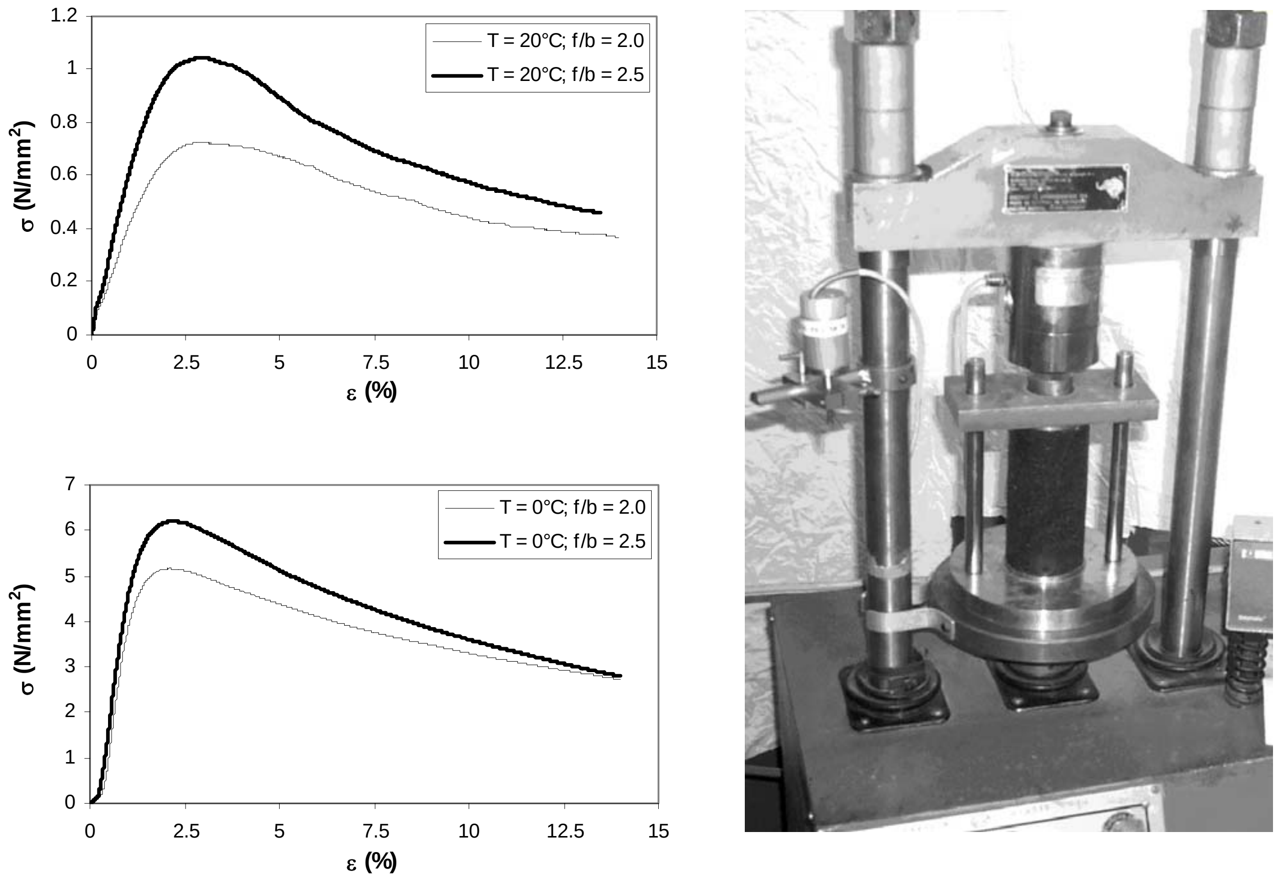

Figure 5 – Simple compression test equipment and results

Direct tension tests
The specimens used for direct tension testing were prepared in the gyratory compactor by employing a special mould, with a dog-bone shaped cavity, previously developed in another research project [6]. The prescribed amount of mixture is introduced in the mould and compaction is carried out by imposing the number of gyrations necessary to reach the prescribed final height (150 mm). Demoulding is then carried out by opening the mould in half by making use of the system of pins and screws specifically designed for this purpose.
In the early phases of the experimental investigation, problems were encountered in the demoulding operations since the bituminous mastic tends to adhere very strongly to the inner surface of the mould: as a result, during their removal from the two semi-moulds the specimens were severely damaged and could not

be used for direct tension testing. After a number of attempts, an additional operation was therefore added to the specimen preparation protocol. It consists in coating the inner surface of the mould with a film of silicone oil (distributed with a brush) and with a thin layer of calibrated sand (totally passing at the 0.18 mm sieve and totally retained on the 0.075 mm sieve). The mould can then be reassembled and conditioned in the oven before the introduction of the mixture to be compacted. Care should be taken in eliminating the sand in excess since a very thin coating is desired, and conditioning in the oven should be carefully controlled (not more than 20 minutes) since downward flow of oil and sand should not take place. Adhesion to the lower and top plate can be prevented by using clear plastic sheeting discs which can be easily strapped off the specimen after demoulding.
After compaction the specimens were allowed to cool down and demoulding operations were carried out at a temperature comprised between 45 and 40°C. At temperatures above this range it was observed that the specimen could be easily detached from the mould but was not sufficiently stiff and could therefore deform under its own weight; at temperatures below the prescribed range problems could arise due to the adhesion between the mastic and the mould in those points where the coating had not maintained its efficiency.
The specimens which result from these operations have a dog-bone shaped longitudinal section (with a length of 150 mm) and a circular transverse section (70 mm in diameter in the terminal parts, 55 mm in diameter in the central part). Their geometry is compatible with the particle size of the aggregates and ensures that failure occurs in the central part of each specimen.
As in the case of simple compression specimens, the dog-bone shaped specimens were allowed to cool down to room temperature and before being subjected to testing they were then conditioned for at least 12 hours in a climatic chamber set at test temperature.
The equipment used for direct tension tests is constituted by a specifically-designed loading system of the "push-to-pull" type which can be mounted on the same simple mechanical testing machine used for compression tests. The "push-to-pull" system is constituted by two steel cages which allow the compressive action of the testing machine to be converted into traction. Specimens are connected to the loading platens by means of metal inserts which on one side have a spherical self-alignment system and on the other are glued to the specimen by means of a thin layer of resin.
Tests were carried out with at a relative speed of elongation equal to 4 mm/min (which corresponds to quasi-static loading conditions). During elongation vertical load and deformation were recorded by means of a system composed by a load cell, an LVDT and a multi-channel data acquisition unit. Figure 6 contains a picture of the test equipment and examples of the stress-strain curves obtained after data processing.

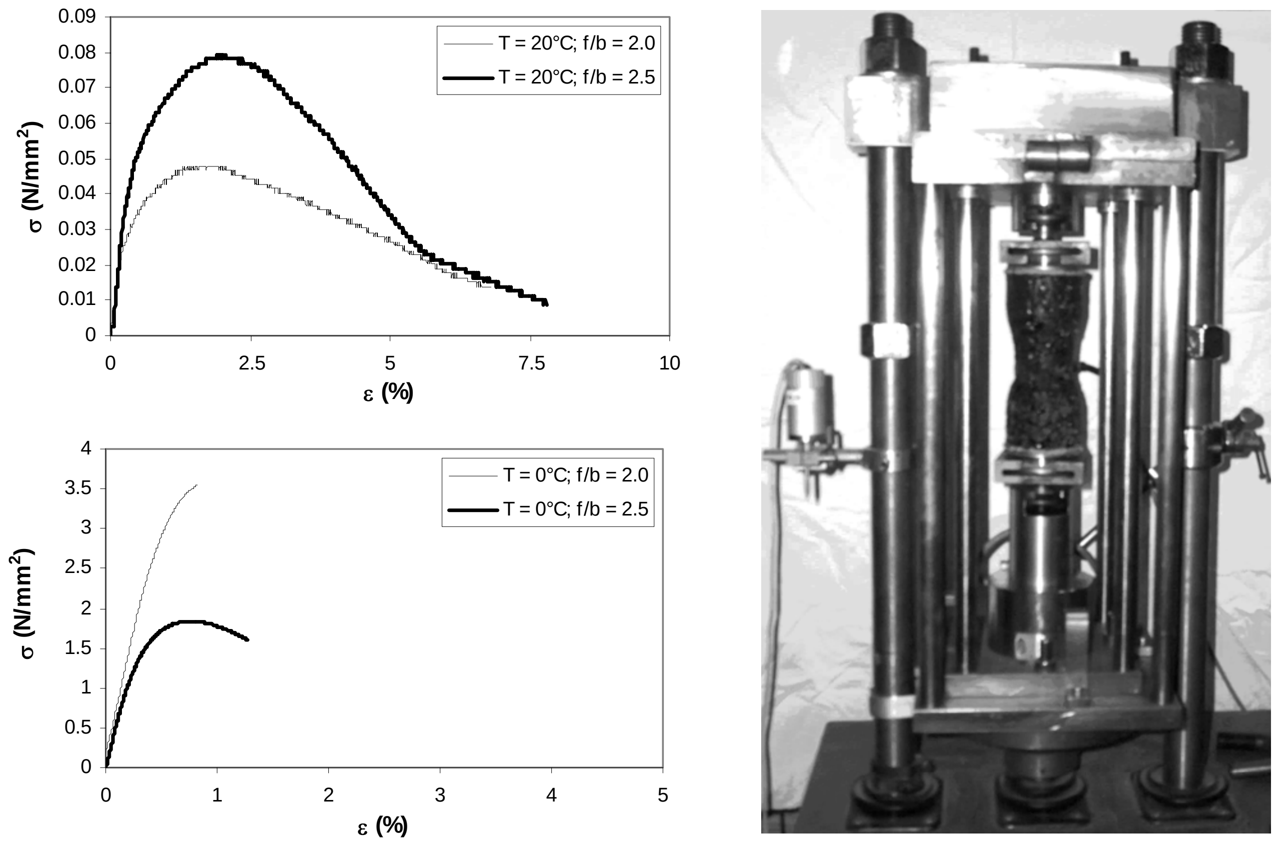

Figure 6 – Direct tension test equipment and results

The results obtained in direct tension tests carried out on the two mixtures are synthesized in Table 8. Four independent tests were performed for each combination of temperature and filler-bitumen ratio. However, at 0°C in many cases it was observed that the resin, due to its stiffening and embrittlement, often failed before the specimen. Only three tests were therefore considered valid for analysis: 2 in the case of f/b equal to 2.0, only 1 in the case of f/b equal to 2.5.
Both mixtures failed in the ductile mode at 20°C with no apparent sign of fracture, whereas at 0°C they exhibited brittle rupture with a clear detachment of the upper and lower portion of the specimen. By inspecting the specimens that failed in the latter mode, it was observed that the fractured surface extends itself both through the bituminous mastic and the aggregate particles. This clearly indicates that at very low temperatures the ultimate response in tension of these mixtures is affected not only by the failure properties of the mastic but also by its adhesion to the aggregate particles. In the case of the specimens which failed in the ductile mode it was observed that only those with a filler-bitumen-ratio equal to 2.5 showed hairline cracks in their central portion.

Table 8: Direct tension test results (phase 5)

	T = 20°C		T = 0°C	
f/b	σ_f [N/mm^2]	ε_f [%]	σ_f [N/mm^2]	ε_f [%]
2.0	0.04	1.96	3.65	1.18
2.5	0.10	1.80	1.18	0.74

Coherently with the results obtained in simple compression, the data reported in Table 8 show that the mixtures are sensitive to variations of the stiffness of the bituminous mastic which depend upon temperature and on filler-bitumen ratio. However, it is interesting to note that at 0°C the mixture characterized by a greater filler content (f/b equal to 2.5) yields a relatively low value of tensile strength which could be due to an excessive embrittlement of the mastic. This conclusion is compatible with the whole set of data recorded in the experimental investigation but is unfortunately biased by the fact that in these conditions only one test yielded valid results.
As in the case of simple compression, the experimental results reported in Table 8 were compared to those obtained by performing the same type of tests (at the same temperatures and with the same elongation speed) on fine wearing course mixtures in a previous research project [6]. The differences observed by considering the failure behaviour in tension were even greater than those recorded in compression: this is due to the fact that in direct tension conditions the binding mastic plays a predominant role while the aggregates affect the results mainly through their adhesion to the binder.
At 0°C the sealing mixtures, especially the one characterized by a lower filler-bitumen ratio, proved to be more resistant and ductile than the previously tested fine wearing course mixtures, which exhibited an ultimate strength comprised between 1.1 and 1.4 N/mm^2 and a strain at failure comprised between 0.4 and 0.7%. It can be hypothesized that in these conditions the behaviour in tension is controlled by the stiffness and strength of the binding mastic which in turn is strongly affected by the employed filler-bitumen ratio. In the case of the sealing mixture the adopted values, equal to 2.0-2.5, were sensibly higher than those reported for the wearing course mixtures (comprised in the 0.91-1.06 range).
The comparison between the two types of mixtures yielded a completely different result at 20°C: in these conditions it was observed that the wearing course mixtures exhibit a higher strength (0.2-0.5 N/mm^2) and a lower ductility (0.14-0.29%) than the designed sealing mixtures. These results suggest that at higher test temperatures the factor which mainly controls the behaviour in tension is the percent volume occupied by the binding mastic, which can exhibit viscous flow when subject to loading. Since the sealing mixtures are characterized by extremely high values of this volume (of the order of 38%) it is not surprising that in these conditions they are more easily deformable and less resistant than standard wearing course mixtures.

Indirect tensile tests

The specimen preparation and testing protocols used in this part of phase 5 are identical to those adopted in phase 4. However, this further testing session allowed a description of the stress-strain and failure properties based on a greater number of samples (8, instead of 4) and in a wider temperature range (20 and 0°C, instead of 20°C only). Moreover, the compression speed adopted in the indirect tensile strength tests was reduced from 50.8 mm/min (as in phase 4) to 4.0 mm/min, which corresponds to more severe quasi-static conditions and is identical to that used in direct tension and simple compression tests.
The mean results obtained in this part of the investigation are shown in Table 9.

Table 9: Indirect tensile test results (phase 5)

	T = 20°C			T = 0°C		
f/b	E [MPa]	σ_f [N/mm^2]	ε_f [%]	E [MPa]	σ_f [N/mm^2]	ε_f [%]
2.0	1191	0.11	1.24	11990	1.71	0.38
2.5	1607	0.16	0.34	13783	1.34	0.20

Mean elastic stiffness values were slightly higher than those recorded in phase 4. However, observed variations were not considered as significant since these mixtures are characterized by a high degree of dispersion of the elastic stiffness data when comparing different specimens and/or different loading diameters in each specimen. It was confirmed that the use of a stiffer mastic (i.e. with a greater filler-bitumen ratio), both at 0 and 20°C, leads to a higher stiffness of the mixture. As expected, however, an increase in the dosage of filler reduces the temperature susceptibility of the mixture.

The results derived from indirect tensile strength tests are completely coherent with the previous data sets presented in Tables 6 (indirect tensile strength), 7 (simple compression) and 8 (direct tension). In fact, the failure properties of the mixtures once more proved to be sensitive to variations of the stiffness of the bituminous mastic which depend upon temperature and on filler-bitumen ratio.

As previously observed, stiffening effects consist in an increase of the strength at failure and in a reduction of the corresponding strain. However, as in the case of direct tension tests, this general trend is violated at 0°C by the mixture with a filler-bitumen ratio equal to 2.5 which as a result of its excessive embrittlement yields relatively low values of the indirect tensile strength (i.e. lower than the mixture with f/b equal to 2.0). Indirect tensile strength results also confirmed that even with respect to failure properties an increase in the dosage of filler reduces the temperature susceptibility of the mixture.

CONCLUSIONS

The results obtained in the experimental investigation described in this paper support the conclusion that the proposed mix design method is suited for the analysis of the mixtures used for the sealing of narrow trenches. The method combines a volumetric modeling of the mixtures with a thorough study of the stress-strain and failure properties of the filling mastic and of the compacted mixtures. Most of the employed test equipment, although adequate for the specific design purpose, can be easily available to standard control laboratories and not only to advanced research-oriented facilities. Given the context of the considered problem, this was considered as a necessary requisite for the design method to be truly applicable in practice.

The use of the gyratory shear compactor proved to be ideal not only for the preparation of specimens of bituminous mixtures to be subjected to volumetric and mechanical testing, but also to study the mechanics of compaction of the single-size aggregate which constitutes their structural skeleton. By analyzing the shape of the compaction curves and the degradation of the compacted particles, the number of gyrations which corresponds to the obtainment of a stable structure, characterized by well distributed aggregate-to-aggregate contact points, was defined. It was also shown that aggregate packing is affected only to a limited extent by the presence of bituminous filling mastics which are proportioned and dosed according to the proposed design method.

Designed mixtures have an acceptable residual void content (3.40-3.85%) which should ensure an adequate level of impermeability. Their mechanical properties, evaluated both with standard test methods (elastic stiffness and indirect tensile strength) and with mechanistic-based characterization procedures (simple compression and direct tension), are limited if compared to standard paving mixture, but seem to be adequate for the kind of application considered. In fact, these mixture cannot rely upon aggregate interlock and in the field may certainly benefit from the containment and collaboration of the pavement in which the narrow trench is included.

The experimental investigation included the assessment of the effects caused by variations of level of compaction, mastic composition and temperature. The obtained results were coherent with expectations since stiffness and strength (in all the three modes considered) tend to increase as the mixture is compacted to a denser state and/or as the filling mastic is stiffened (either by increasing the filler-bitumen ratio or by reducing temperature). These same effects are generally accompanied by a certain degree of embrittlement which in extreme cases may limit mechanical performance.

The coherency of the results obtained in the investigation gives proof of the overall reliability of the adopted test methods. In particular, the simple compression and direct tension tests, previously developed and employed for the characterization of other function-specific bituminous materials [5-6], yielded repeatable results which allowed a performance-related comparison of the two designed mixtures. It is envisioned that both tests will be useful in the future in the context of other research projects.

Based on the analysis of the whole set of experimental results, it may be concluded that both the mixtures subjected to testing, characterized by a different filler-bitumen ratio (equal to 2.0 and 2.5), may be qualified as acceptable for the special application which has been considered in the study. However, since the stiffer mixture exhibited brittle failure at the lower testing temperature (0°C), it is recommended that the choice of the design recipe to adopt in practice should also take into account the climatic conditions expected in service. Validation of the design method through monitoring of actual field performance is also necessary in order to develop acceptance criteria which in the future may be implemented in technical specifications.

ACKNOWLEDGEMENTS

The research described in this paper was funded by ALPITEL S.p.A. of Nucetto (Cuneo) and by the Italian Ministry of Instruction, University and Research (MIUR).
The experimental investigation was carried out in the Road Materials Laboratory of the Politecnico di Torino. Direct tension tests were performed in the laboratory of the University of Ancona which is part, together with the Politecnico di Torino, of the Italian Experimental Interuniversity Road Research Centre (CIRS).

REFERENCES

[1] SANTAGATA, E. (2003), "Stato dell'Arte e Linee di Sviluppo della Ricerca Internazionale nel Settore delle Pavimentazioni Stradali", *Le Strade,* n. 42, novembre-dicembre 2003, anno VII, pp. 10-17.

[2] SANTAGATA, E. and M.C. SANTAGATA (1999), "Progetto di Ricerca QUICK-Trenching Alpitel. Analisi delle Problematiche Riguardanti i Materiali e le Prestazioni in Opera", *Rapporto di Ricerca QTA.1.1*, Centro Sperimentale Interuniversitario di Ricerca Stradale, Ancona.

[3] SANTAGATA, E., P.P. RIVIERA and M.C. SANTAGATA (2005), "Two-Stage Mix Design of Controlled Low Strength Materials", in *Proceedings of the 3rd International SIIV Conference*, *"People, Land, Environment and Transport Infrastructures"*, SIIV, Bari.

[4] SANTAGATA, E. and E. TORALDO (2004), "Laboratory Characterization of Bituminous Materials Used for Asphaltic Plug Joints", *International Journal of Pavements*, vol. 3, n. 3, September 2004, pp. 51-58.

[5] TORALDO, E. (2001), *Indagine Sperimentale sul Comportamento a Rottura dei Conglomerati Bituminosi*, Tesi di Laurea, Politecnico di Torino.

[6] SANTAGATA, E. and E. TORALDO (2002), "Metodologie di Indagine Sperimentale per la Valutazione del Comportamento a Rottura dei Conglomerati Bituminosi", in *Proceedings of the 12th International SIIV Conference*, SIIV, Parma, Italy, October 30-31, 2002, vol. 2, pp. 453-471.