Performance Analysis of Mixtures Produced Using Foamed Bitumen

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Synopsis

The decreasing availability of aggregates and the large amount of aggregates needed for the construction and maintenance of infrastructures, have forced research staff, in Italy and in other countries, to seek alternative materials for road constructions. Presently, the use of recycled material becomes thus the key to more efficient and economical road construction. Currently, cold recycling technique presents major advantages due to minimum environmental and energy costs.
In particular, this research involves foamed asphalt process as a possible technique for the cold recycling of flexible pavements. The main task of this work is to investigate the potentiality of foamed asphalt treated mix as a base course material. The work was carried out performing indirect tensile stiffness modulus and fatigue tests on cylindrical specimens prepared with different percentages of cement (1-3%) and foamed asphalt binder (2-4%). Test results showed that the changes in cement and foamed bitumen content resulted in a variation of the mechanical performance of the mix regarding its stiffness properties and fatigue resistance. In particular, the obtained results allow to state that only the choice of a correct bitumen-cement ratio ensures better performance concerning both the stiffness and fatigue properties and there is no univocal relationship between the stiffness properties and fatigue resistance performance regarding the investigated mixtures.

INTRODUCTION : FOAMED ASPHALT PROCESS

Due to the lack of natural materials and large amount of aggregates required for the numerous maintenance operations of road pavements, there is extreme interest in recycling processes of materials coming from damaged pavements (Reclaimed Asphalt Pavement). In Italy and other European countries the present legislation, concerning the treatment of waste materials, considers recycling the key to more efficient road reconstruction even though there are still bureaucratic obstacles and contradictions which prevent its diffusion and practical application.
Recycling can be carried out by means of two different techniques, called “hot” and “cold”. Basically they are different in the way of using the aggregates, with or without previous heating, and the amount of milled material to reuse in the production of new bituminous mixtures. Currently, cold recycling technique presents major advantages due to minimum environmental and energy costs. Such a process simply requires milling the distressed pavement, mixing the reclaimed material with new binder, water, cement, any corrector virgin aggregates and possible regenerating additives and finally laying the pavement layers.
Depending on how the new binder is added and mixed with the aggregates, cold recycling can be divided into two techniques: a cold technique with bituminous emulsion and the one with foamed bitumen. The potential of using foamed bitumen as a cold-mix binder was first realized by Professor Csanyi of Iowa State University in 1957 [1]. His first experiment showed that a steam injection in hot asphalt allowed binder to foam with a low viscosity. This process resulted in improved binder dispersion during the mixing and efficient aggregate coating [2]. This technology was later refined by Mobil Oil Australia which developed the first expansion chamber which mixed hot bitumen with cold water rather than with steam. This method made the asphalt foaming process more practical and less expensive.
“Foamed asphalt treated mixture” is a technical term which refers to a road aggregate blend mixed with foamed bitumen. In particular, foamed bitumen is produced by injecting small amounts of cold water (2-4% of bitumen weight) in heated bitumen inside an expansion chamber. Foamed asphalt is ejected out through specially designed nozzles and mixed, in a transitory state of low viscosity, with the aggregates at ambient temperature in their humid conditions (figure 1) [3, 4].

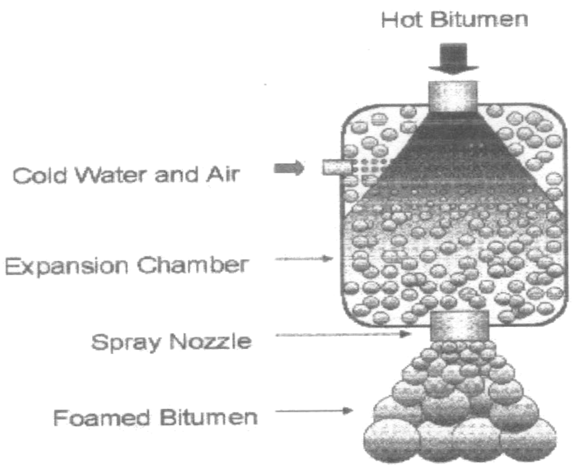

Figure 1: Asphalt Foaming Process

The physical properties of bitumen are temporarily altered when cold water is injected in hot bitumen (heated at 170-180°C). In fact, the water transforms into steam and favours rapid expansion of bitumen in a large number of small bubbles. The foam increases the specific surface of bitumen and highly reduces its viscosity allowing intimate coating when it is mixed with cold and wet aggregates [5]. The produced foam dissolves in less than a minute and the binder recovers its original properties, so it is important that bitumen is injected into the aggregates when it is still in a foaming state.
Usually the phenomenon of foaming is characterized by two typical parameters: expansion ratio ER_m (ratio between the maximum volume of foamed bitumen and the volume of original bitumen) and half-life $t_{1/2}$ (the time taken for the foamed bitumen to settle to half of the maximum volume attained) [6]. These parameters, which respectively express the capacity of bitumen to expand its volume by foaming process and the physical stability of foamed bitumen, play a fundamental role during the production process of foamed asphalt treated mixes. Indeed, experimental works showed that changes of these two parameters modify the viscosity of bitumen during mixing. This affects the bitumen dispersion grade and particle coating and hence the quality of mixture [6].

A further parameter, foamed index (FI), can be determined to take into account the combined effects of expansion (ER_m) and stability ($t_{1/2}$) of the foamed bitumen. Normally, the expansion ratio is plotted versus time on a graph [7], the area subtended by the decay curve represents the foamed index. A proper choice of foamed index permits to improve the foaming properties of bitumen and obtain a final product with higher performance.
The peculiarity of this technique is that it is possible every kind of bitumen to foam, regardless of penetration-grade and origin, by using an appropriate combination of water, air, high pressure injections of asphalt and a specially designed nozzle. Moreover the foamed bitumen can be mixed with a wider variety of aggregates ranging from aggregates with different size gradation and plastic index to recycled materials [5, 7, 8, 9, 10].
The increasing use of foamed asphalt treated mixtures around the world is due to other factors too. The main advantages, besides those mentioned above, are represented by a reduction in air pollution and health hazards of the workers because the hydrocarbon emissions into the atmosphere are almost nil (not having to heat the aggregates) and the use of solvents to reduce the viscosity of the asphalt is not necessary. This technique also allows to totally recycle the milled material, thus reducing construction costs, both in terms of procurement of natural material and transport costs. Furthermore, according to the literature, the foamed asphalt process requires an optimal binder content lower than that of mixes made with bituminous emulsion to ensure similar performance [3]. In fact, the increase of binder dispersion and particle coating due to the foaming process provides a higher resistance to permanent deformation and better durability of the mixes. Lastly, once the recycling work is completed and the layer well compacted, the recycled layer has an adequate resistance offered by the mix and the road can be opened to traffic immediately unlike when bituminous emulsions are used [11]. On the contrary, foamed asphalt technique requires trained technical staff, both during the mixing and during the laying, in order to obtain a good product and makes it difficult to define a correct cost-benefit analysis due to lack of reliable information regarding long-term performance of the pavements produced by using this technique.
Recently, foamed asphalt technique in cold recycling has gained more and more acceptance in the United States, Europe and Asian Countries not only for the reliability resulting from the above mentioned advantages but also because high technology equipment has been designed for a correct application of this process.
The main task of this research work was to reach a better understanding of the mechanical behaviour of cold recycled bituminous mixtures treated with foamed bitumen. In particular, the influence of binders (bitumen and cement) on the stiffness and fatigue properties of the mix was investigated in order to reach useful information regarding its performance to define a correct mix design procedure.

EXPERIMENTAL PROGRAM

The study of this research work was to evaluate the potential use of the cold recycling technique with foamed asphalt and cement to produce asphalt mixture as a base course material. The main topic of this study was to asses the effects of the different constituents of the mix on its mechanical performance. In particular, the stiffness and fatigue properties [12-16] of the mix were investigated changing the foamed bitumen and cement content in order to define a correct mix design procedure.
The experimental program included a preliminary laboratory work to characterize the recycled material regarding its composition and gradation. Then, a mix design procedure was conducted to obtain the cold mixes and finally, dynamic tests on all foamed asphalt treated mixes were carried out to determine the stiffness modulus and fatigue resistance.

Materials

A typical 80/100 penetration-grade asphalt binder was used to make foamed asphalt. According to technical standards it ensures:

- Expansion ratio (ratio between the volume of foamed bitumen and the volume of original bitumen) greater than 20;
- Half-life (the time taken for the foamed bitumen to settle to half of the volume attained) greater than 25 seconds.

The optimal expansion characteristics of asphalt were obtained by the producer ranging the temperature between 170°C and 190°C and the water between 1% and 4% of bitumen weight.
A Portland cement 32.5 R., was used.
A recycled aggregate blend coming from the milling of a distressed asphalt pavement was considered. The blend was composed of recycled asphalt pavement (RAP) and crushed aggregates coming from the pre-existent subbase course. The size gradation of this blend conformed to typical technical specifications for base bituminous mixes and thus it was not convenient to add any corrector virgin materials.
In addition, pure and organic substance-free water was used.

Preparation of the mix

The cold recycled mixes stabilised with foamed bitumen and cement were produced through a procedure, laboratory equipment permitting, that closely simulated full-scale production in site.
The recycled materials were mixed with the adequate amount of foamed bitumen, cement and water always using a water-cement ratio equal to 1. Foamed bitumen was directly pulled out from the expansion pipe of a mixer machine, WR 2500 Wirtgen, and immediately mixed with the other materials in order to avoid changes in its expansion properties. Nine foamed asphalt treated mixes were obtained combining adequately the different binder contents. In particular, bitumen contents selected in this study ranged from 2 percent to 4 percent while cement contents ranged from 1 percent to 3 percent of the aggregate weight both with 1 percent apart.
Subsequently, foamed asphalt mixes were compacted in conformity with CNR standards to obtain Marshall cylindrical specimens. After compacting each specimens was placed inside a dry site without thermal changes and cured for two months at room temperature.

Testing program

The mechanical characterisation of foamed asphalt treated mixes was conducted by means of Nottingham Asphalt Tester (NAT). This equipment permitted to carry out repeated load indirect tensile tests in order to measure the stiffness modulus and fatigue resistance of the mixes [17-22].
The stiffness modulus tests are carried out in a controlled stress or strain mode by applying five compressive load pulses along the vertical diameter of cylindrical specimen and the resultant displacements on horizontal diameter measured by means of suitable linear transducers (LVDT) (Figure 2). The software makes it possible to select a proper stress target as well as the loading frequency (rise time). A proper selection of test conditions like horizontal stress, rise time and temperature, allows to consider the material as a quasi-elastic, isotropic and homogenous material and thereby measuring the stiffness modulus of the specimen by the following simple expression:

$$E = \frac{P}{\Delta \cdot t} \cdot (0.273 + \upsilon) \qquad (1)$$

where P is the applied vertical load, t is the thickness of the cylindrical sample, Δ is the total deformation measured along the horizontal diameter and ν is Poisson's ratio usually assumed to be 0.35.
In particular, during this experimental work the indirect tensile stiffness modulus tests were carried out in a controlled stress mode at 25°C. The maximum horizontal stress target was 50 Kpa, in order to avoid high viscous deformation on a horizontal diameter, the rise time was 124 ms and the pulse repetition period was 3.0 s.

Figure 2: Indirect tensile modulus set up

Figure 3: Indirect tensile fatigue set up

Indirect tensile fatigue tests are carried out in controlled stress mode (Figure 3). The principle of this test is similar to indirect tensile stiffness modulus: a compressive repeated load is applied along the vertical diameter of the cylindrical specimen. Specimen failure is due to the repeated applications of the vertical load that results in a crack along the vertical diameter. During the fatigue test permanent vertical displacements are measured by means of a linear vertical transducer inside the load actuator. Test results is the relationship between the vertical permanent deformation and the number of load pulses (N). This curve allows to evaluate the development of permanent vertical deformation in the time.
Particularly, the indirect tensile fatigue tests were conducted at 25°C applying 40 Kpa as horizontal stress target with a rise time of 124 ms and a pulse repetition period of 1.5 s. The selected horizontal stress was low due to operative reasons. In fact, higher horizontal stress levels would have led to rapid disintegration of the mixes due to their brittle behaviour of some mixes (in particular mixes made with high cement content and low asphalt content) without reaching significant results.

TEST RESULTS

During initial data analysis all tests providing anomalous results were discarded. In particular, those specimens which showed mechanical behaviour, concerning stiffness and fatigue properties, much different from that of the specimens related to the same group, were not considered.

Stiffness modulus results

All experimental data are synthesized in Table 1 which shows the elastic modulus results obtained by calculating the average on remaining specimen of each type of mix.

Table 1 : Elastic Moduli (Mpa)

		cement content (%)		
		1.0	**2.0**	**3.0**
foamed bitumen content (%)	**2.0**	2328	4146	7558
	3.0	7257	7031	7654
	4.0	4237	5840	6401

By plotting (figure 4) the elastic modulus data versus the percentage of bitumen on a graph it is interesting to note that the results show a bell shaped curve similar to a Proctor dry density curve of granular materials. This tendency is mostly visible for foamed asphalt mixes which are poor in cement.

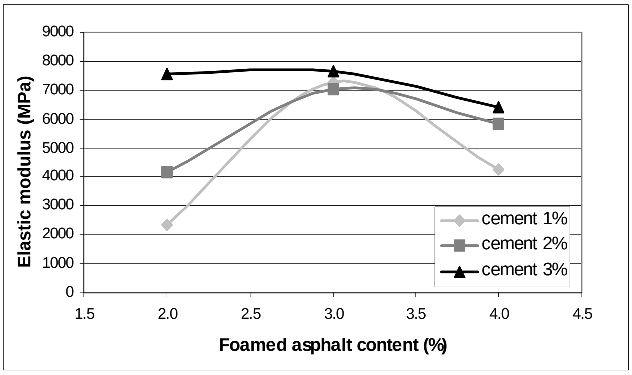

Figure 4 : Elastic modulus vs. bitumen content

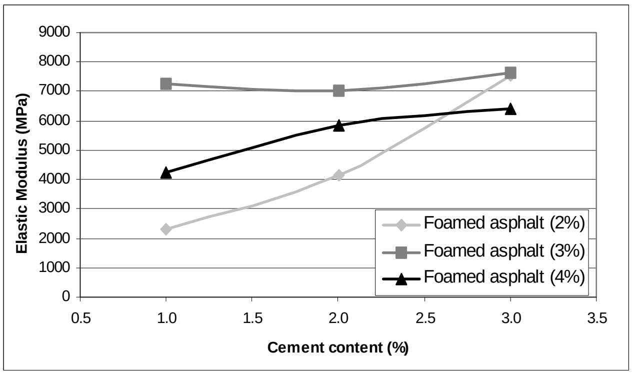

Figure 5 : Elastic modulus vs. cement content

A possible explanation of the effects of bitumen on stiffness properties of the mixes is that a small amount of bitumen (2%, by mass) is not able to ensure an efficient particle coating. Consequently, the thin film of bitumen does not allow sufficient interparticle adhesion inside aggregate skeleton. This aspect results in a low stiffness properties of material.
Figure 6 shows a typical diametral section of a foamed asphalt sample poor in bitumen (2%, by mass), which shows that the foamed bitumen is not well distributed but concentrated in localized areas of the sample.

Figure 6 : Localized areas of bitumen

Subsequent increase of bitumen in the mix, on one hand produces a lubricating effect promoting the reciprocal movement between the aggregates, while on other ensures a better particle coating making interparticle bonds stronger. This double effect, due to an increment of asphalt binder content, results in a high increase of stiffness characteristics of the mix. In fact, the elastic modulus reaches a maximum value in correspondence to an optimal percentage of bitumen (3%, by mass). It is possible to suppose that with 3% of bitumen, the greatest density conditions of the mix and the strongest adhesion intergranular bonds coexist. These two conditions allow a low deforming capacity and as such creating high stiffness.
By adding further asphalt binder more than this optimal content the elastic modulus tends to decrease. It is important to consider that the strain behaviour of the mix does not only depend on the intergranular adhesion but also cohesion properties of mastic. In fact, a high amount of bitumen if, on the one hand, guarantees total particle coating, on the other, generates a very deformable mastic. In these conditions, the obtained results mean that the strain behaviour of a mix is mainly influenced by the strain behaviour of the mastic rather than the strenght of adhesion intergranular bonds.
As regards the cement effect (figure 5), the test results show that generally this binder leads to an increase in the stiffness modulus for developing pozzolanic bonds and its effect becomes greater with the increasing amount in the mix. However it is necessary to state that, with the same bitumen content, the effect of the increase in cement quantity on stiffness is different in the mixes poor in bitumen from those rich in bitumen.
As shown in Figure 5 when the bitumen content is low (2%, by mass), the increase in cement results in a significant increase in elastic modulus because the cement compensates for deficiency of bitumen by producing strong aggregate bonds. At the optimum bitumen content (3%, by mass) it seems that changes in cement content do not improve the stiffness of mixes. In fact, results show that elastic modulus remains almost steady. It is likely that such a percentage of bitumen ensures a high density mix whose effect on the stiffness is higher than that due to the cement bonds. Finally, we examine the results regarding all the mixes rich in bitumen (4%, by mass). Also this time further additions of cement result in increase in the stiffness modulus of the mix, but it is less marked than that noticed on mixes poor in bitumen (Figure 5). It would seem that the stiffness properties of the mix depends on the stiffness of the bituminous mastic and not on adhesion bonds produced by cement. In fact, the large amount of bitumen could hinder, in part, cement to bond so that the cement would play the role of a simple filler inside the mix. According to this supposition the increase in cement would be equivalent to the addition of the filler, which would make the mastic harder with a consequent increase in the stiffness of the mix.

Fatigue resistance results

In order to investigate the fatigue properties of the material the number of load pulses to failure and accumulated permanent deformation at the 10,000th load applications of each type of mixture were considered. This number of pulses was selected as reference load repetition for evaluating the strain behaviour of the material over primary creep area, so as to avoid considering only density effects due to the load application. Moreover, it was necessary to have a strain level on which no specimen had reached failure in order to correctly compare the obtained results.
In figures 7 and 8 the vertical strain at the 10,000th load pulse data versus foamed asphalt and cement content are shown, while in figures 9 and 10 the number of load repetition to failure data versus foamed asphalt and cement content are shown.

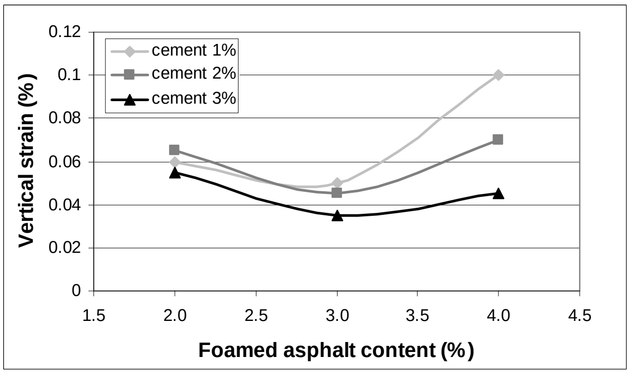

Figure 7 : Vertical strain vs. bitumen content

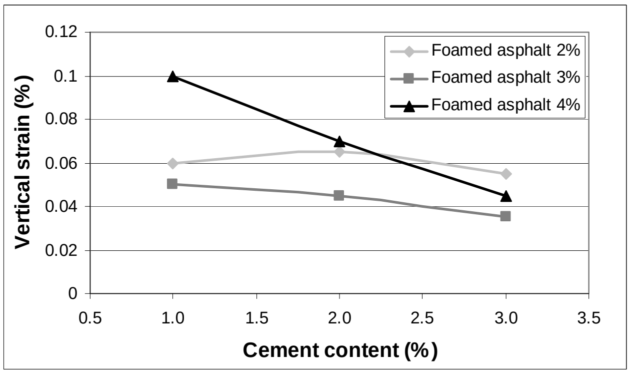

Figure 8 : Vertical strain vs. cement content

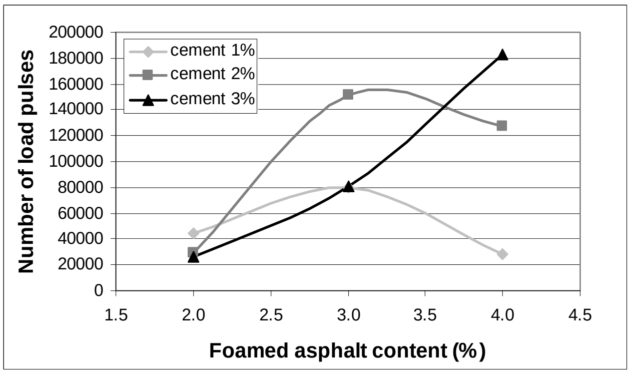

Figure 9 : Load repetitions vs. bitumen content

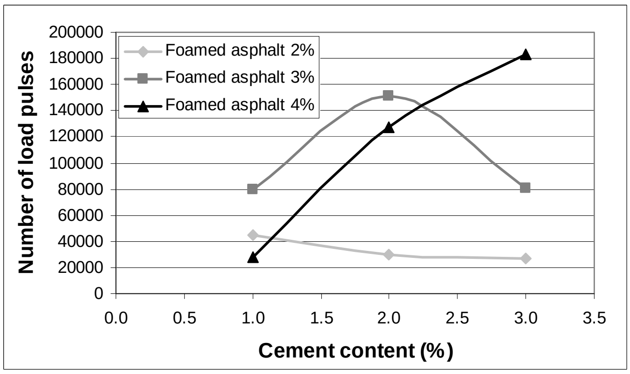

Figure 10: Load repetitions vs. cement content

The analysis of the accumulated permanent strain at the 10,000th load pulse confirms what was found regarding the stiffness properties of the mixes. In fact, as shown in figure 7, by varying the asphalt binder content a concave curve is obtained. This curve is specular to that shown in figure 4 and evidences that the minimum strain, probably due to the maximum density condition, occurs when the bitumen content is equal to 3%.

On the other hand the data plotted in figure 8 show that the effects on the strain behaviour of the mix, due to the increase in the quantity of cement, are different changing the bitumen content in the mix. As explained in the previous paragraph, if there is a scarce quantity of bitumen in the mix (2%, by mass) the bond between the aggregates is mainly due to the cement bonds. In this case it seems that the accumulated permanent strain does not depend on the cement content even if the improvement in the stiffness due to the increase in the cement content (see figure 5) confirms the existence and effectiveness of the cement bond. Otherwise if we increase the quantity of bitumen in the mix it tends to totally coat the aggregates and to absorb the cement. In that case the data confirm the effect of the cement like a filler on the strain behaviour of the mix. In fact, the increase in the cement content results an increase in the viscosity of the mastic and thus in the decrease of the deforming capacity of the mix. This decrease becomes greater with the increase in the bitumen content in the mix.

As regard the fatigue resistance, it is possible to make, in part, similar considerations on the effects produced by two types of binders. As shown in figure 9, the effect of bitumen on the number of load repetitions on the one hand confirms the density effect due to the addition of such a binder, while on the other it supposes the increase in ductility as a further effect of bitumen on the fatigue resistance. The results show a trend that is the sum between a bell shaped curve and an amount that depends on the bitumen-cement ratio. This aspect is probably due to the fact that bitumen produces more ductile and durable bonds as opposed to the rigid and brittle bonds produced by cement, but at the same time it produces high accumulated permanent strains which premature failure. Thus, when the bitumen content is increased, the choice of a proper bitumen-cement ratio is fundamental to obtain a ductile and less soft mastic in order to ensure that the mix has a good fatigue resistance.

Figure 10 shows the effect of cement on the number of load applications. It is possible to note that in the mixes with 2% of bitumen the changes in cement content do not improve the fatigue life of the mix, rather it seems to be penalized. Thus, it seems that cement is not able to compensate for deficiency of bitumen concerning the fatigue life of the mix, contrary to what occurred when the strong bonds due to the cement let the elastic modulus triplicate.

By analysing the mixes with the 4% of foamed bitumen the results show that the addition of cement affects the fatigue life very much. In fact 3% of cement increases the number of pulses to failure by six or seven times. On the basis of what was deduced regarding the study of stiffness properties, considering the mixes which were rich in bitumen (4%, by mass), the positive effects of cement did not come from the effectiveness of the bonds produced by it but its role like a filler. The addition of cement acts on the mechanical properties of the mastic improving its internal cohesion and thus avoiding high strains. The overall increase of stiffness of the mix, due to a harder mastic, results in an increase in the number of load repetition to failure and lower accumulated permanent deformation.

Comparison of results

By analysing the results obtained by means of two types of tests an important consideration can be made, which is fundamental for the structural design of road pavements. There is no univocal relationship between the stiffness properties and fatigue performance. In fact, as an example, the mix produced with the 3% of cement and 2% of bitumen was that characterized by the highest value of elastic modulus but the lowest fatigue life (number of load repetitions to failure).

The explanation of this phenomenon is in the different way of measuring stiffness and evaluating the fatigue life of a mix. The study of the stiffness properties through elastic modulus test investigates on a stress-strain relationship. In this case the strains induced by the applied load are so low that the cement bonds can highly affect the stiffness properties.

In the case of fatigue test the failure of the specimen is due to the repeated applications of the load even if its magnitude is lower than that used in the modulus test. During the continuous repetitions of the load the sample accumulates a strain threshold that compromises the effects of cement bonds. In fact these bonds are very brittle-natured and it is possible to suppose that they break down when a threshold strain level is reached. Thus, it is likely, during the indirect tensile fatigue test, that once the specimen reaches a prefixed permanent strain the effect of cement is lost. After this moment the fatigue performance depends only on the asphalt bonds, which can be more or less strong with regard to their internal cohesion depending on the percentage of cement like a filler.

CONCLUSIONS

The main topic of this research work was the study of the recycling of flexible road pavements damaged due to their exposure to atmospheric agents and traffic loads during their useful life. In particular, this study was performed to assess the potentiality of cold recycling technique *in situ* based on the use of foamed bitumen and cement.

Due to insufficiency of data in literature on the performance of these materials and lack of a proper technical standard to adopt in their practical application, the present work wants to give technical guide lines in order to define a correct mix design to produce foamed asphalt treated mixtures as a base course material.

In particular, the aim of this study was to investigate the structural properties and performance of foamed asphalt treated mixes with regard to the type and amount of binder in the mix. In fact, the obtained results showed that the changes in cement (from 1% to 3%, by mass) and foamed bitumen (from 2% to 4%, by mass) content resulted in a variation of mechanical performances of the mix regarding the stiffness properties and fatigue resistance.

The present study was performed through an experimental investigation during which dynamic tests were carried out by means of Nottingham Asphalt Tester (NAT) for the performance characterization of the materials.

The obtained results allow to suppose that foamed bitumen, as viscous fluid, affects the density properties of the mixtures and this effect provides a bell shaped curve of the stiffness and fatigue properties.

In particular, if the foamed bitumen is in small amount not sufficient to coat all the aggregates of the mix, the cement is able to develop strong and brittle bonds which ensure high elastic modulus values to the mix but at the same time a low number of load pulses to failure (fatigue life).

By increasing the foamed bitumen content the cement has less chances of reacting and in these conditions it is likely that the cement is absorbed by the bitumen thus playing the role of a simple filler. As a consequence, when the foamed bitumen is in a large amount, the addition of cement acts on the viscosity of the mastic and thus on the stiffness properties of the mix.

It is necessary to state that bitumen, unlike cement, in general, provides ductility for the mix and thus better fatigue resistance properties. In fact, the worst fatigue results were obtained using the minimum investigated bitumen content. By using higher foamed bitumen content, the mixture is composed of thicker films of bituminous mastic. In this case the fatigue performance depend on a correct bitumen-cement ratio in order to produce a more ductile and at the some time not much deformable mastic.

Finally, on the basis of an overall analysis of the results, an important remark, which has heavy effects on the structural design of the road pavement, can be made. In fact, it was possible to check that there is no univocal relationship between the stiffness properties and fatigue resistance performance regarding the investigated mixtures. Basically, the reason is that in the elastic modulus test a stress-strain relationship of an integer sample is analyzed, while in the fatigue test the failure of the specimen is investigated. In this case the failure, with regard to reaching a permanent strain limit, depends highly on the brittle or ductile nature of the bonds developed in the mix.

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