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Dissipated energy analysis of four-point bending test on asphalt concretes made with steel slag and RAP

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Abstract

The paper discusses the results of an experimental study and a statistical analysis on the stiffness and the fatigue performance of recycled asphalt concretes, evaluated by the four-point bending test, at 20 °C and 10 Hz. The laboratory study was conducted on five different base-binder bituminous mixtures, made with recycled aggregates, namely Reclaimed Asphalt Pavement aggregate (RAP) and Electric Arc Furnace (EAF) steel slag, up to 70% by weight of the aggregate. In order to evaluate statistically the influence of the recycled aggregates on the stiffness of the mixes, the analysis of variance (ANOVA) has been performed on the modulus data. The fatigue tests were performed in stress and strain control mode, in order to describe completely the fatigue properties of the mixes. A dissipated energy method, based on the internal damage produced within the asphalt concretes, was used for the fatigue analysis. The damage curves, expressed in terms of the Plateau Value of the Ratio of Dissipated Energy Change, for both the stress and the strain control mode, were elaborated and statistically analyzed in order to unify the fatigue analysis. Compared to the control asphalt concrete, made exclusively with natural aggregate, the resulting mixes with RAP and EAF slag were characterized by improved stiffness and fatigue performance.

Keywords: Asphalt concrete; Reclaimed Asphalt Pavement; Steel slag; Stiffness modulus; Fatigue resistance; Dissipated energy

1. Introduction

Laboratory fatigue and stiffness investigations on bituminous mixtures for road pavements can be based on several type of tests: two-point bending tests on trapezoidal and prismatic specimens, three- and four-point bending tests on prismatic beam specimens, as well as repeated indirect tensile strength tests on cylindrical specimens, are some of the most used test protocols in the road laboratories, all over the world [1–5]. For each one of the above mentioned tests, two different loading modes can be adopted, namely based on controlled stress or controlled strain.

Using the conventional methodology in the fatigue analysis, based on the correlation between the initial strain values and the number of cycles to failure, as well as on the 50% reduction of the initial Stiffness of the mix, two different fatigue life evaluations can be obtained, according to the loading mode [6]. The stress control mode is commonly adopted in order to evaluate the fatigue resistance of stiff materials and thick pavements, while the strain control mode is used in case of conventional bituminous mixtures and flexible pavings [7]. However a complete fatigue analysis should provide a unique value of the fatigue resistance, irrespective of the loading mode, in order to effectively support the rational design of a road pavement. In the present experimental and theoretical study, the fatigue resistance of

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high performance asphalt concretes for base courses of road pavement, produced using artificial and recycled aggregates (EN 13242 and 13043), was evaluated by means of both the "stress control" and "strain control" four-point bending test (4PBT), following the methodology originally proposed by Carpenter [8,9] for the analysis of the laboratory data, in order to identify a unique fatigue law, irrespective of the loading mode.

The stiffness properties have been also determined, according to EN 12697-26 Standard, Annex B and statistically analyzed by means of the ANOVA method. The stiffness modulus represents a fundamental mechanical parameter which expresses synthetically the structural properties of a bituminous mix. It is determined by means of non-destructive tests and it is very useful in order to perform statistical evaluations about the effect of one or more components in the mechanical response of the mix [10].

2. Materials and methods

2.1. Materials

2.1.1. Aggregates and bitumen

For the aggregate skeleton of the asphalt concretes, three granular materials have been considered: Reclaimed Asphalt Pavement (RAP) aggregate, steel slags, as well as conventional aggregates, i.e. crushed limestone and sand. The RAP materials have been recovered from the milling of an Italian highway pavement, in the North-eastern part of Italy. The steel slags considered represent a production waste of an Italian steel industry, characterized by the electric arc furnace (EAF) technology. Both the by-products were supplied by Italian private companies, based in the province of Padua (Northeastern area of Italy, Veneto Region), devoted to the recovery, valorisation and re-utilization of industrial wastes, for road pavements. Both the natural aggregates were provided by a local quarry located in the above-mentioned region.

The resulting bitumen content of the RAP material, determined by cold extraction (centrifugation method; EN 12697-1) was equal to 4.3% by weight of the aggregate. The recovered binder presented a penetration of 15 0.1× mm at 25 °C (EN 1426) and a softening point of 74 °C (Ring & Ball Method; EN 1427). A standard bitumen (50/70 penetration grade), with a Ring & Ball softening point of 62 °C (EN 1427), has been adopted as virgin binder for all the asphalt concretes in the investigation.

2.1.2. Asphalt concretes

The composition of the aggregate skeleton of the asphalt concretes is reported in Table 1. The corresponding grading curves are shown in Figs. 1 and 2. Five non-conventional aggregate skeletons were studied, characterized by different combinations and contents of RAP, steel slag and limestone (S0R2, S0R4, S3R0, S3R2, S3R4: S0 and R0 mean no slag and no RAP; S3, 30% slag; R2 and R4, 20% and 40% RAP). One further asphalt concrete, made with a conventional lithic skeleton (S0R0) was studied and considered as a control mix.

Table 2 presents the design binder percentage (by weight of the granular material), bulk density, Indirect Tensile Strength (ITS), for the bituminous mixtures. The bitumen percentage reported in Table 2 concerns the virgin binder added to the asphalt concretes. For the asphalts made with RAP material, assuming a complete blending condition between the aged RAP bitumen and the virgin one, the total bitumen percentage is determined as the sum of the aged binder of RAP and the Optimum Bitumen Content (OBC). The virgin bitumen has been mixed simultaneously with the RAP, the limestone and the steel slags, in a heated lab mixer, for one minute. The RAP aggregates have been preheated for 2 h, at 90 °C, to be mixed with the other materials.

A detailed discussion of the chemical, physical and geotechnical properties of all the granular materials, the mix design and some performance test results were previously presented by the authors [11,12] in other papers.

2.2. Methods

2.2.1. Stiffness Modulus tests

The Stiffness Modulus of the mixtures has been evaluated by means of Four Point Bending tests (4PBT), according to the Annex B of the European EN 12697-26 Standard, with a controlled strain equal to 50 μm/m, at a temperature of 20 °C and frequency of 10 Hz. A stand-alone four-point bending test apparatus, characterized by a digital servo-controlled pneumatic actuator with a 5 kN load cell capacity, has been used for the stiffness evaluation (Fig. 3); the equipment was hosted in a dedicated climatic chamber. The beam specimens used for the 4PBT, were characterized by a size of 400 × 50 × 60 mm. They have been obtained by cutting 300 × 400 × 50 mm slabs, prepared using an electromechanical laboratory compactor, characterized by a vertical load and/or displacement control of the roller segment by a stepper motor, measured directly by a linear transducer (Fig. 4), according to the EN 12697-33 Standard. The target bulk density was assumed equal to that of gyratory specimens involved in the mix design phase, outlined in previous works [11,12]. Four beam specimens were prepared for each asphalt concrete.

In order to evaluate statistically the level of significance of the effect induced by the marginal aggregate on stiffness of the mixes, a multiple factors ANOVA has been applied [10,13] to the modulus data, assuming a normal distribution. The RAP, as well as the steel slag quantities have been considered as factors (a and b, respectively) and their interaction was also analyzed. The response is the Stiffness Modulus.

2.2.2. Fatigue tests

The fatigue study was based on the four-point bending test, assuming as reference the protocol described in Annex