Experimental Investigation for the Analysis of Cold-Recycled Bituminous Mixtures

EXPERIMENTAL INVESTIGATION FOR THE ANALYSIS OF COLD-RECYCLED BITUMINOUS MIXTURES

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Abstract: The Authors present the results obtained in a experimental investigation carried out to provide technical support to the construction of a cold-recycled bituminous sub-base layer of a major Italian motorway.
Compliance of the employed materials and of the resulting recycled mixture to requirements set in Technical Specifications and to the adopted job-mix formula were verified by means of laboratory tests. Field observations focused on the evaluation of the void content of the compacted sub-base layer and on its stiffness evolution in the short term curing phase. Finally, mix design was carried out by following a procedure based on the use of the gyratory shear compactor and on the optimization of the composition of the fluid phase. The procedure was validated by performing volumetric and mechanical tests both on the optimized mixture and on a mixture prepared according to the job-mix formula.

INTRODUCTION

The use of cold-recycled bituminous mixtures in flexible road pavements is currently viewed as one of the most attractive options available to designers, Administrators and contractors. This is certainly due to the environmental benefits which are associated to the adoption of cold-mix recycling construction techniques, but also to the satisfactory performance which has been observed in service (Asphalt Institute, 1983; AASHTO-AGC-ARTBA Joint Committee, 1998). Nevertheless, a number of critical issues still need to be addressed and improvements are absolutely necessary in many aspects of material selection, mix design and quality control.

Coherently with this scenario, the Pavement Research Group of the Politecnico di Torino has worked in the area of cold-recycling for a number of years (Santagata, 1999), focusing both on laboratory characterization and on field evaluation of cold-recycled mixtures (Santagata & Chiappinelli, 2002). In this paper a further contribution is given to both topics, by showing the results obtained in a experimental investigation which was carried out to provide support to the construction of a cold-recycled bituminous sub-base layer of a major Italian motorway.

Mixtures were produced in a plant by employing reclaimed asphalt pavement (RAP) material, preliminary processed through a crusher and thereafter sieved on a 25 mm screening deck, and a 60/40 modified emulsion. No virgin aggregates were added to the mixture. The job-mix formula, declared by the contractor and based on the assumption that RAP had approximately 3% water content, included 3.0% bitumen emulsion, 1.0% added water and 1.5% Portland cement.

EXPERIMENTAL INVESTIGATION

The goals of the project were to evaluate the compliance of the materials to requirements set in Technical Specifications (SATAP, 2004) and to provide suggestions to improve field performance. Based on the Authors' previous experience in other research projects (Santagata & Chiappinelli, 2003 and 2004), this latter aspect was addressed by performing additional tests both in the laboratory and in the field, and by carrying out a full mix design of the recycled mixture according to a specifically devised procedure.

Laboratory compliance testing

Requirements included in the Technical Specifications referred both to the plant-produced mixture and to its components (RAP, aggregates extracted from the RAP, emulsion, water, cement), which were therefore sampled at the production plant and from the paver.

Due to the fact that it was stockpiled with no protection, RAP material had a high water content (average value equal to 4.27%). Such a result is considered acceptable by Specifications provided that no extra water is added to the recycled mixture. Average binder content was equal to 5.75%, lower than the maximum acceptance limit (6.5%).

Average particle size distributions and Specification limits, both referred to RAP and to extracted aggregates, are given in Table 1, which also contains the results obtained for the recycled mixture. Violations to the upper and lower acceptance limits were observed for both materials.

Table 1. Particle size distribution test results

	RAP		Extracted aggregates		Mixture
D (mm)	P (%)	P_{min}-P_{max} (%)	P (%)	P_{min}-P_{max} (%)	P (%)
25	100	80-100	100	95-100	100
15	91.2	60-90	95.7	75-95	94.1
10	78	40-80	86.6	60-85	85.4
5	52.3	25-55	65.6	45-60	63.3
2	32.8	15-40	48.8	30-45	46.0
0.4	6.0	7-20	19.5	13-22	20.2
0.18	1.4	4-15	8.6	7-16	10.3
0.075	0.3	2-8	3.4	4-9	4.6

Control of the emulsion, cement and water dosage was carried out by considering the results obtained from the analysis of the recycled mixture (Santagata & Chiappinelli, 2003). The average values of both total binder content (7.40%) and total water content (5.80%) were acceptable when compared to Specification upper limits, respectively equal to 8% and 7%. However, both contents were lower than those calculated from the job-mix formula (respectively equal to 7.54 and 6.26%) considering the average water and binder contents of the RAP. Thus, it was concluded that the production plant provided an underdosage of emulsion (of the order of 2.7%), while variations of the water content of the RAP were presumably responsible for the deficiency of total water content. Cement dosage on the contrary was found to be very precise since calculations lead to identical values of the target and measured values of the percent aggregate passing the 0.075 mm sieve.

Field testing

Technical Specifications required static plate loading tests to be performed on the sub-base layer 24 hours after compaction with a minimum acceptable value of the deformation modulus set at 60 MPa. However, in order to monitor the curing process in the short term, the Authors resorted to Light-Weight Drop Tester (LWDT) tests, which yield the so-called dynamic modulus (E_d), calculated by means of the following equation:

$$E_d = 22.5 / s \quad (1)$$

where the dynamic modulus (E_d) is expressed in MPa and the vertical displacement of the loading plate (s) is expressed in mm.

Tests were carried out on a test section which had a length of approximately 400 m and was laid in two different days. Dynamic modulus was measured in 68 test points, homogeneously distributed on the test section. Pavement and air temperature, respectively equal to 5 and 5.5°C, were constant throughout the investigation. The average dynamic modulus measured on the underlying unbound foundation was equal to 106 MPa. Experimental results, derived from statistical analysis, are shown in Table 2.

Dynamic modulus was reported to increase in the first 24 hours due to the progressive curing of the bituminous mastic, with a corresponding reduction of the dispersion of measured values, revealed by the decrease of standard deviation and coefficient of variation (COV). The layer was not overlaid immediately, and as a consequence of the cold weather and of intense rain, after 1 week of curing the modulus exhibited a slight decrease and a greater variability.

Table 2. Dynamic modulus results

	Dynamic modulus E_d		
Curing time	Average (MPa)	Std. Dev. (MPa)	COV (%)
~ 20 min	118	17	14.5
~ 2 hours	144	15	10.4
~ 24 hours	154	15	9.4
~ 1 week	123	21	17.0

In order to have information on the level of compaction obtained in the field, cores were taken from the test section and thereafter subjected to laboratory tests for the determination of dry density at 25°C and Theoretical Maximum Density of the loose dry mixture. Unfortunately, even though coring operations were carried out after 2 months of curing, recovery of undamaged cores proved to be quite difficult. The corresponding test results yielded an extremely high value of the average void content, equal to 19.6%.

Mix design

The two-stage mix design procedure followed during the investigation is based on the use of the gyratory shear compactor (GSC) and of specially designed moulds in which a uni-directional flow of the fluid phase (water and emulsion) is induced (Santagata & Chiappinelli, 2004). In the first phase of design the optimal fluid content ($\%FF_{opt}$) of the mixture is evaluated by compacting mixtures made of RAP and cement, with an added water content variable within a conveniently wide range: the resulting cylindrical samples are subjected to density evaluation and the optimal fluid content is defined as the value at which density reaches its maximum. The conversion of such a value in water and emulsion dosage (%W and %E) takes place in the second stage, in which the composition of the mixture is defined according to the following relationship:

$$\%FF_{opt} = \%W + (a + K \cdot b) \cdot \%E \tag{2}$$

where: a and b correspond to the weight ratios of the water and bitumen phase, respectively, to the total emulsion; K is a fluidity index which quantifies the type of contribution which the bitumen phase gives to compaction when compared to water (variable between 0 and 1).
By considering a number of combinations of %W and %E which satisfy the above given relationship, different mixtures are prepared, compacted in the GSC and thereafter subjected to the evaluation of volumetric and (optionally) mechanical properties. Based on the comparative analysis of the corresponding results, the design mixture is finally defined.

During the investigation, mix design was carried out by employing materials sampled from the production plant. In order to simulate the winter conditions in which construction was being carried out (December), before mixing and compaction all materials, tools and moulds were conditioned at 5°C. Each GSC sample was prepared by following an internal test protocol which requires a total of approximately 3200 g of material, a 150 mm diameter mould and 100 gyrations. For all mixtures the cement dosage was kept constant, equal to 1.5%, which was also the maximum value accepted by Technical Specifications.

The average density values obtained in the first and second stage of design are given in Table 3. Tests were carried out after a preliminary conditioning phase during which specimens were dried in a forced-draft oven at 40°C for 4 days. Subsequently, dry density (G_{dry}) at 25°C was measured by following the procedure which requires paraffin specimen coating.

Table 3. Results of density tests carried out in mix design

	First stage			Second stage			
%W (%)	4.0	5.0	6.0	2.88	2.45	2.03	1.60
%E (%)	-	-	-	2.5	3.0	3.5	4.0
G_{dry} (g/cm^3)	2.107	2.147	2.107	2.132	2.139	2.154	2.145

It can be observed that the optimal fluid phase content calculated at the end of the first design stage, equal to 5%, was converted in the second stage, by adopting a value of K equal to 0.75, to an emulsion dosage (%E) of 3.5% and a corresponding water content (%W) of 2.03%. Thus, it is shown that according to the results of the mix design procedure, the job-mix formula used at the production plant is characterized by a slight emulsion underdosage (equal to 3%) but also by excess total water (4.0%, approximately twice the optimal dosage). This latter observation is coherent with previous findings of the Authors, who have frequently noted that contractors tend to overdose water, either as a result of the need of keeping the plant and dump trucks sufficiently clean or as a consequence of unprotected stockpiling of the RAP.

The project included an experimental validation of the results of the mix design procedure. This was carried out by comparing the volumetric and mechanical properties of the newly designed mixture with those of a reference mixture proportioned according to the job-mix formula. To eliminate the effects caused by production variability, the second mixture was replicated in the laboratory by following the same mixing and compaction procedures adopted for the optimized one.

Evaluation of the void content of the mixtures was carried out by considering specimens compacted by means of the above described GSC protocol and also by employing a static compactor, which applies a load of 5 tons for 5 minutes on a 3000 g sample contained in a 150 mm diameter mould with a specially designed perforated base plate. The use of the alternative compaction method was deemed necessary since the Authors have frequently used it on site for quality control purposes (Santagata & Chiappinelli, 2002). Moreover, Technical Specifications contained a maximum void content value (%v), equal to 10%, derived from a similar compaction procedure (in which, however, no controlled water drainage from the sample is allowed). A synthesis of the obtained results is given in Table 4 which also includes Theoretical Maximum Density (TMD) values measured on dried mixture samples.

Table 4. Volumetric characteristics of the recycled mixtures

		GSC		Static compactor	
	TMD (g/cm^3)	G_{dry} (g/cm^3)	%v (%)	G_{dry} (g/cm^3)	%v (%)
Job-mix formula	2.500	2.137	14.52	2.145	14.20
Design	2.431	2.169	10.78	2.157	11.27

It should be noted that the mixture prepared according to the mix design results can be compacted to a void content which is significantly lower than that of the mixture selected by the contractor for production. Moreover, a good agreement between the results obtained by means of the two compaction techniques is observed. Finally, by means of the design improvements, the obtained void contents is drawn very close to the maximum value given in Specifications (10%).

Mechanical testing was carried out on GSC compacted specimens and included repeated load indirect tensile tests (RLIT) (at 20°C after 1, 2 and 45 days of curing), indirect tensile strength tests (ITS) (at 25°C after 24 hours of curing) and static uni-axial creep tests (SUC) (at 20°C, after 24 hours of curing). In all cases curing of the specimens took place in a climatic cell set at 20°C. Elastic stiffness values (E) were obtained from RLIT tests carried out with 124 ms rise time and 7 μm target horizontal deformation. As required by Specifications, ITS tests were carried out at 25°C with a displacement speed of 0.847 mm/s. SUC tests were carried out at a relatively low temperature, 20°C, in order to consider worst case conditions in which no curing enhancement occurs as a result of temperature increase; 100 kPa compressive stress was applied for 1000 s and strain recovery was monitored for 3000 s. Results were expressed by referring to compliance calculated after 1 s loading (J_1) and to permanent strain recorded after recovery (ε_p).

Results obtained in this phase of the investigation are shown in Table 5, where the percent differences between the two mixtures are also given. As expected, the denser mixture derived from design exhibited , when compared to the one which replicates plant production, a significant reduction in the short term of compressive compliance and of the corresponding permanent deformation. The more closely packed aggregate skeleton also caused a slight increase of short term indirect tensile strength, which however was in both cases quite low if compared to other reference cold-recycled mixtures (Santagata & Chiappinelli, 2003). Elastic stiffness data provided information on the progression of curing of the bituminous matrix: while in the long term the two mixtures tend to very similar modulus values as a result of complete water elimination, significant differences are observed in the short term. In particular, after 2 days of curing the design mixture, as a result of its lower water dosage, proved to be significantly stiffer than the reference plant mixture. Data obtained after 1 day of curing only seem to contradict this observation, but it should be taken into account that at such low stiffness levels RLIT test results tend to be less reliable and are affected by a greater dispersion.

Table 5. Mechanical properties of the recycled mixtures

	$E_{1\ day}$ (MPa)	$E_{2\ days}$ (MPa)	$E_{45\ days}$ (MPa)	ITS (N/mm^2)	J_1 (mm^2/N)	ε_p
Job-mix formula	594	775	2284	0.059	7.55E-02	1.56E-02
Design	461	1153	2476	0.065	4.98E-02	1.15E-02
Δ (%)	-22.4	+48.8	+8.4	+10.2	-33.4	-26.1

CONCLUSIONS

The results collected during the investigation described in this paper allowed the Authors to provide the highway Administration with a number of suggestions to improve field performance. As a result of the specific particle size distribution of the employed RAP, in order to increase dry density values obtained in the field after compaction it was recommended either to allow the use of additional virgin aggregates or to perform a preliminary separation of the RAP in different size fractions to be separately fed in the mixing plant. RAP protection from environmental precipitations was also highlighted as necessary in order to ensure a closer control of the water content which can adversely affect compaction. Moreover, it was pointed out that the contractor should perform an optimization of the compaction scheme followed by the rollers by means of appropriately monitored trial sections.

Further conclusions were drawn from the results obtained in the mix design phase of the study. With the RAP available at the plant a more easily compactable mixture was obtained by appropriately adjusting the emulsion and water content. Such a mixture was characterized, when compared to the one prepared according to the job-mix formula adopted by the contractor, by a greater stiffness and indirect tensile strength. Moreover, its tendency to accumulate permanent strains was also significantly reduced. As a result of these observations the Authors strongly recommended to included the proposed mix design method in the acceptance procedures indicated in Technical Specifications.

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