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Triaxial Testing for the Short Term Evaluation of Cold-Recycled Bituminous Mixtures

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ABSTRACT. The experimental investigation described in this paper refers to the performance-related characterization of cold-recycled bituminous mixtures employed for the construction and maintenance of road pavements. One of the most critical issues that have to be examined for these mixtures is their short term behaviour under loading, since in the early phases after laying they are more similar to unbound granular materials than to traditional hot bituminous mixtures. In such a context, the authors carried out triaxial tests on a reference cold-recycled mixtures by employing the equipment generally recommended for subgrade soils and foundation materials. Slender laboratory compacted specimens, prepared by means of a gyratory shear compactor, were subjected to triaxial tests for the determination of resilient modulus and of shear strength parameters at three different temperatures (20, 40 and 60°C) and in three different curing conditions (short term, intermediate and full curing). The obtained results were analyzed according to models already available in literature and were discussed by taking into account the internal structure and composition of the mixture.

KEYWORDS: cold recycling, bituminous mixtures, triaxial tests, resilient modulus, shear strength.

1. Introduction

The growing need for sustainable solutions for the construction and maintenance of road pavements has considerably increased, in recent years, the use of various cold-recycling paving techniques which, with the use of specialized equipment and proper operative procedures, can be carried out both in the field and in productions plants (Asphalt Institute, 1983; AASHTO-AGC-ARTBA, 1998; Asphalt Academy, 2002; Wirtgen, 2004). In all cases, bituminous mixtures constituting the top layers of distressed in-service pavements are adequately processed and thereafter mixed with additional binder, either in the form of bituminous emulsion or foamed bitumen. Depending on the adopted recycling method, additional water, active filler and/or supplementary virgin aggregates can also be included in the mixtures which are laid as part of the new pavement. As a result, after being milled off the road, the so-called RAP (Reclaimed Asphalt Pavement) material is no longer a waste product to be disposed of with non negligible costs, but can be considered as a valuable resource for pavement construction. Other advantages associated to these techniques derive from the decrease of energy consumption during paving operations and from the limited emissions which reduce total environmental impact and health hazards for workers.

Cold-recycled mixtures are significantly different from traditional hot-mixed bituminous materials. In order to fully appreciate such a difference, the most important factor which should be taken into account is the presence of a water-based binder which in time, as a result of concurring physical and chemical phenomena, changes its consistency. This is due to the fact that during compaction part of the water (either used for foaming or added together with the emulsion) is expelled from the mix and that thereafter drying and curing phenomena take place, thus leading to a progressive increase of the stiffness and strength of the recycled mixture. Other non negligible differences may be associated to the active role of Portland cement filler, which can also enhance short term mechanical properties as a result of hydration phenomena.

Given the inherent complexity of cold-recycled bituminous mixtures, which undergo a transition from the almost unbound (granular) state to a bitumen-bound (mixture) condition, their characterization, both for mix-design and quality control purposes, requires specific testing equipment and protocols to be developed. This is especially important in the framework of modern pavement engineering performance-based design, which heavily relies on fundamental modeling concepts and only to a very small extent to empiricism (NCHRP, 2004). As a consequence of such observations, the authors have considered the possibility of carrying out short term triaxial tests on cold-recycled mixtures by employing, with some slight modification to standard protocols, the equipment and procedure recommended for subgrade soils and unbound granular materials. This paper contains the results of a preliminary testing program in which the effects of a number of factors, such as temperature and curing, were taken into account.

2. Background

In a number of previous research projects (Santagata *et al.*, 2001; Santagata *et al.*, 2003; Santagata *et al.*, 2004; Santagata *et al.*, 2007), the authors focused on the mechanical characterization of cold-recycled bituminous mixtures, which in most cases, coherently with standard pavement structural modeling, were described in terms of their quasi-elastic response to loading by means of Repeated Load Indirect Tensile (RLIT) tests (EN 12697-26). The issue of failure behaviour, equally important for performance-related evaluation purposes, was treated by referring to quasi-static Indirect Tensile Strength (ITS) tests (EN 12697-23), and only occasionally to Indirect Tensile Fatigue (ITF) tests (EN 12697-24).

Cylindrical specimens, 100 or 150 mm in diameter, have been obtained by making use of two different compaction protocols (Santagata *et al.*, 2003; Santagata *et al.*, 2004). The first one, which has been typically employed in the field, either at the mixing plant or at the recycling site, is a portable static compactor by means of which samples are subjected to a constant vertical pressure of 6.05 MPa for 5 minutes. The second protocol, more useful for laboratory investigations and therefore typically included in mix design activities, requires the use of a gyratory shear compactor operated at the standard vertical pressure of 600 kPa and with a predefined number of gyrations (usually equal to 150). In both cases the excess water which is present in the mixture is allowed to drain vertically through the sample due to the presence of specially designed compaction plates.

The results obtained from RLIT and ITS tests carried out on specimens prepared by means of both the abovementioned compaction procedures have proven to be extremely sensitive to a number of mixture-related and curing-related factors. The former include binder content of the RAP, particle size distribution of the RAP (and of the aggregates contained therein), emulsion type and dosage, percentage of added water, percentage and type of filler, mixture void content (related to compaction effort). Investigated factors belonging to the latter group include time elapsed between mixing and compaction, curing temperature and time (between compaction and testing). Further significant factors, which are common to hot-mix materials and are directly related to test conditions, have proven to be test temperature, speed of loading and, in the case of RLIT tests, target horizontal deformation.

Significant examples of results recorded during the RLIT testing of cold-recycled mixtures are shown in Figure 1, where data codes refer to emulsion type (A or B), compaction mode (G: gyratory, S: static) and waiting time before compaction (30 or 60 minutes) (Santagata *et al.*, 2001). When considering a standard curing temperature of 20°C, it can be observed that as a function of curing time, the so-called elastic stiffness increases almost linearly in a semi-logarithmic plot, reaching a limiting upper value after a time period which is strongly mixture-dependent and is typically comprised between 40 and 90 days. Consequently, stiffness development in the first phase of curing can be described with the following equation:

$$E = E_1 + k_E \cdot log(t) \quad [1]$$

where E_1 and k_E are mixture-dependent factors. E_1 provides an estimate of mixture stiffness after 1 day of curing, when actual RLIT tests are difficult to perform without damaging the specimens. k_E, although not rigorously a curing rate, gives information of the speed with which curing phenomena occur within the mixture.

As shown in Figure 2, in the early phase of curing similar linear models can be fitted to ITS test results, with the corresponding use of factors ITS_1 (strength at 1 day curing) and k_{ITS} (strength "curing rate"):

$$ITS = ITS_1 + k_{ITS} \cdot log(t) \quad [2]$$

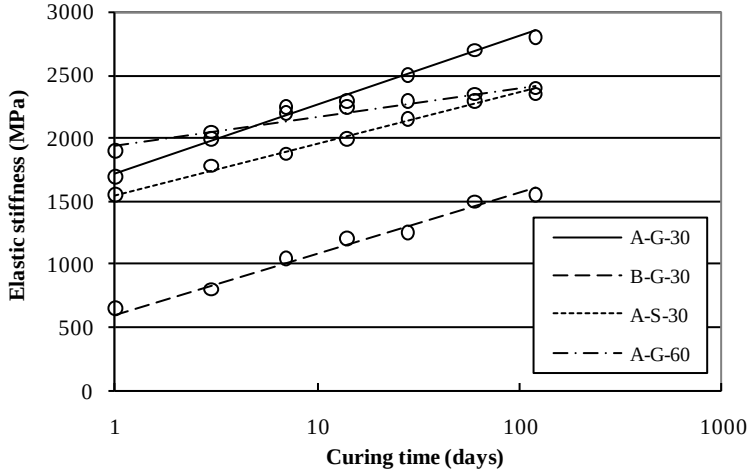

Figure 1. *Typical RLIT test results as a function of curing time*

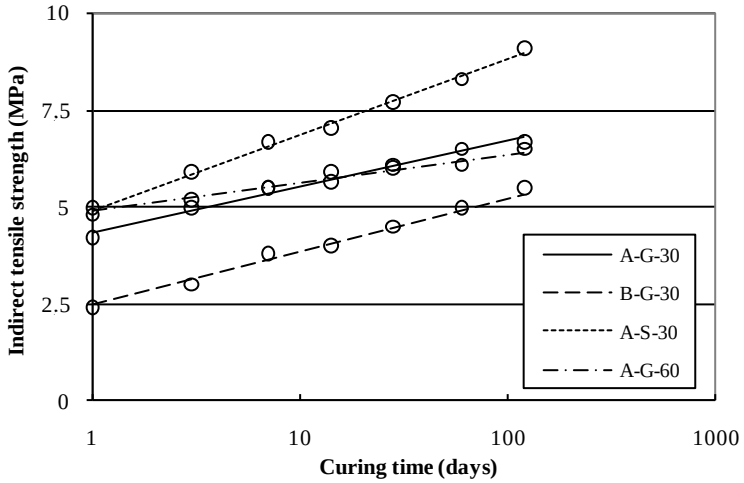

Figure 2. *Typical ITS test results as a function of curing time*

Based on past experience it can be stated that in the long-term cold-recycled mixtures, especially when properly designed both with respect to RAP selection and dosage of components, can reach stiffness and strength values which are comparable to those of standard hot-mix materials (Santagata *et al.*, 2001) . However, short term stiffness and strength are usually extremely limited, and this can lead to serious problems in the field both during pavement construction, when heavy equipment can overload the cold-recycled layer, and in the early stages of pavement life immediately after opening to traffic. In such conditions, significant permanent deformations can occur and in some cases failure conditions, which thereafter affect pavement performance irreversibly, can be reached.

In order to investigate on the short term behaviour of such mixtures, thereby providing indications on the optimal (or at least minimum) curing time which should elapse before traffic loading, practical problems should be taken into account. In the first place it should be mentioned that the linear log(t)-E and log(t)-ITS functions provide a general description of the time evolution of stiffness and strength, but their extrapolation below a certain curing time may not be totally reliable. In fact, indirect tensile tests performed immediately after compaction and/or in the first 12 to 24 hours of curing, are in most cases impossible since the specimens of cold-recycled mixtures may not have reached a state in which they maintain the cylindrical shape under their own weight. In other cases testing can be carried out but the scattering of the corresponding results is generally quite high.

Due to the critical importance of obtaining information on the mechanical response of cold-recycled mixtures in the short term, and as a consequence of the fact that in most cases indirect tensile tests prove to be inadequate for such a purpose, the authors decided to resort to the use of a triaxial equipment as in the case

of unbound granular materials and subgrade soils (Hornych *et al.*, 1999). Thus, stiffness was assessed by measuring the resilient modulus (M_r) under cyclic loading, while tensile strength was replaced by a more realistic shear strength derived from quasi-static compression tests with a constant confining pressure. A similar approach was adopted by Ebels *et al.* (2006) for the characterization of bitumen stabilised materials which were subjected to monotonic and long duration triaxial tests.

The following paragraphs contain details of the employed testing equipment and procedure, of the materials used in a preliminary investigation, and of the corresponding results obtained at various stress levels, test temperatures and curing conditions. Comments are also made on the most adequate modeling that should be carried out in order to correctly interpret test results.

3. Experimental Investigation

3.1. *Characterization of component materials*

Available RAP material, sampled from a production plant where it had been subjected to preliminary crushing, was initially oven-dried and then divided into three size fractions (10/25 mm, 5/10 mm and 0/5 mm) which were evaluated in terms of their binder content and of the size distribution of their particles (after extraction). The corresponding results are shown in Table 1, which also contains the data derived from the analysis of the employed filler (Portland cement of the R32.5 type).

The emulsion used for the preparation of mixtures, of the unmodified type with a nominal 60% binder content, was provided by a local supplier. It was subjected to the evaluation of binder content (%B) according to ASTM D244 (average value, calculated on three test samples, equal to 63.2%), and the resulting residue was tested for determination of penetration at 25°C (54 dmm) and ring and ball softening point (51°C).

Dosages of RAP fractions and of other mixture components (cement filler, emulsion and added water) were calculated by considering a target aggregate size distribution and reference values of total fluid phase and binder content obtained in previous studies performed on similar materials (Santagata *et al.*, 2001). The corresponding mixture composition data, which were kept constant throughout the investigation, are given in Tables 2 and 3 and in Figure 3. Filler, emulsion and water dosages are expressed as a percentage of total RAP dry mass.

Table 1. *Results of the preliminary tests carried out on RAP fractions and filler*

D (mm)	Percentage passing (%)			
	10/25	5/10	0/5	Filler
25	100	-	-	-
20	86.1	-	-	-
15	67.9	-	-	-
10	20.7	100	-	-
5	13.2	21.9	100	-
2	10.8	14.6	65.3	-
0.4	6.8	9.8	26.2	100
0.18	4.5	6.6	15.6	45.0
0.075	2.5	3.7	7.9	13.9
%B	2.19	3.02	6.60	-

Table 2. *Design RAP dosages*

Fraction	Percentage (%)
RAP 10/25 mm	34.3
RAP 5/10 mm	23.5
RAP 0/5 mm	42.2

Table 3. *Design component dosages*

Component	Percentage (%)
Cement filler	2.5
Emulsion	3.5
Added water	2.5

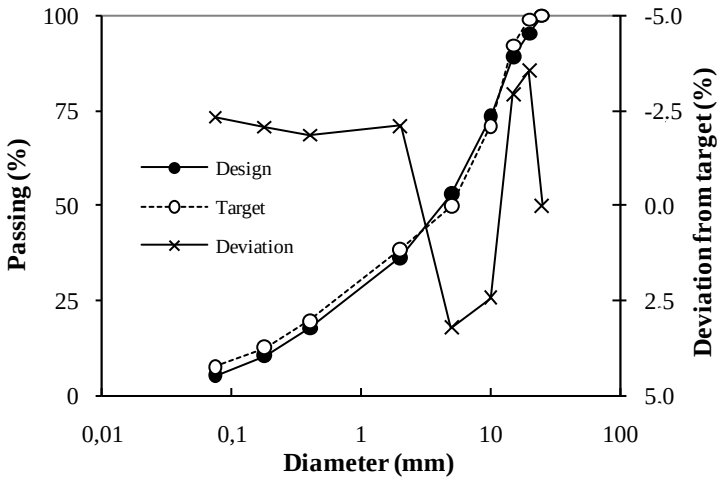

Figure 3. *Target and design particle size distributions*

3.2. *Mixing, compaction and curing*

Since it was planned that triaxial testing would be carried out at three different temperatures (20, 40 and 60°C), and due to the fact that previous experience proved that cold-recycled mixtures can be extremely sensitive to compaction temperature, all components, tools and accessories were conditioned at the given test temperature for 18 to 24 hours prior to mixing. Care was also taken in representatively sampling RAP fractions, which after drying and separation were kept in sealed plastic bags. Immediately before preparation of the mixture, the bituminous emulsion was homogeneized in its storage container, thereby preventing any phase separation to bias test results.

After weighting all components on a precision scale, hand-mixing was carried out in a metal bowl by starting from the RAP fractions and cement filler and by thereafter adding emulsion and water to the batch. Mixing was continued until a homogeneous coating of the RAP material was obtained but in all cases it was checked that mixing time did not exceed 2 minutes in order to prevent possible early breaking of the emulsion due to mechanical action.

The time elapsed between mixing and compaction (also referred to as “waiting time”) was carefully controlled since previous studies indicated that it may significantly affect volumetric and mechanical properties. During all the investigation, waiting time was therefore kept constant, equal to 15 minutes. In this phase, in all cases a clear transition of the colour of the mixture, from brown to black, was observed, thus revealing the initiation of the breaking process of the emulsion.

Compaction of the mixture was performed by making use of a gyratory shear compactor complying to European and SUPERPAVE specifications (1.25° angle, 30 rpm, vertical pressure 600 kPa) (Harrigan *et al.*, 1994). However, the adopted compaction protocol differed substantially from the standard one used in the case of hot mixtures: as mentioned in the previous section, a bottom perforated plate was used in order to allow the excess fluid phase to uni-directionally seep through the specimen. Moreover, since resilient modulus testing requires slender specimens (with a height-to-diameter ratio of at least 2), further modifications to the compaction protocol were implemented.

Given that the largest particles in the mixture had characteristic dimensions comprised between 20 and 25 mm (Table 1), gyratory moulds with an inner diameter of 100 mm were considered adequate for specimen preparation. As a consequence, a target height of 200 mm was selected. However, a homogeneous mixture structure was not expected to be formed by compacting all the necessary material in a single lift. Thus, the compaction procedure was broken down in two consecutive phases: in the first one, a bottom layer is compacted to the prescribed density; in the second one, more material is introduced in the mould above the compacted bottom lift and once again is subjected to vertical stress while gyrations

take place at the normal test speed. In order to avoid the effects of different waiting times before compaction for the two layers, the necessary quantities were separately mixed (in two consecutive batches).

Both specimen layers were compacted by employing a carefully weighted quantity of material, calculated in order to obtain half-specimens 100 mm in height with a theoretical geometrical dry density of 2.170 g/cm^3. Such a value was chosen by examining results obtained in a previous laboratory investigation when the reference cold-recycled mixture was compacted in a single layer by following the standard protocol (Santagata *et al.*, 2001).

Preliminary compaction tests highlighted the fact that the separation plane between the two half-samples is indeed visible. Density gradients were also envisioned and were directly evaluated during the investigation as described further on in this paper.

Compaction properties of both layers were assessed by looking at the progression in time of the specimen height. However, true compaction curves (i.e. curves expressed in terms of percent compaction as a function number of gyrations) were not created since specimens subjected to triaxial testing cannot be used for preliminary density determinations. This is due to the fact that they can neither be submerged in water, as required in the case of the saturated-surface-dry protocol (ASTM D2726), nor can they be coated with paraffin, as indicated in the alternative ASTM D1188 standard. In fact, in both cases, due to the water-based binder of the mixture and as a result of the relatively low stiffness and strength, the specimen would be irreversibly damaged by the density test. As a consequence of these limitations, compaction curves were calculated for the bottom layers only by referring to geometically calculated volumes, to theoretical dry weights and to the Theoretical Maximum Density (TMD) of the mixture at 25°C which was measured as prescribed by ASTM D2041 (with an average value, calculated from two independent determinations, equal to 2.538 g/cm^3).

After completing compaction, each specimen was extracted from the cylindrical mould and subjected to one of the three types of curing process which are synthetically described in Table 4. In the first phase of the investigation, specimens were transferred to a climatic cell set at the same temperature at which pre-conditioning of materials and tools was carried out (either 20, 40 or 60°C). Preliminary trials indicated that the conditioning period required to reach stable temperature conditions ranged between 1 hour (in the case of 20°C) and 2.5 hours (for 60°C). Each specimen was thereafter moved to the triaxial cell, enclosed in a temperature cabinet which was set at the same temperature chosen for the two previous conditioning treatments.

In the second phase of the investigation, which included tests carried out at 20°C only, two different conditioning procedures were considered. In the first case, referred to as the "intermediate curing" condition, specimens were conditioned at 20°C for 7 days and were thereafter subjected to triaxial testing. In the second case,

by following a procedure which was experimented in previous research projects, "full curing" conditions were mimicked by transferring the specimens after compaction in a forced draft-oven set at 40°C, where they were kept for 6 days. They were then moved to the climatic cell set at 20°C were they were conditioned for 1 day and then fitted to the triaxial equipment and subjected to testing.

Table 4. *Curing procedures adopted in the investigation*

Phase	Curing process	Pre-conditioning of materials	Curing of specimens	Test temperature
1	Short term	18 to 24 hours at 20, 40 and 60°C	1 to 2.5 hours at 20, 40 and 60°C	20, 40 and 60°C
2	Intermediate	18 to 24 hours at 20°C	7 days at 20°C	20°C
2	Full	18 to 24 hours at 20°C	6 days at 40°C + 1 day at 20°C	20°C

3.3. *Mechanical characterization*

For the analysis of the short term mechanical behaviour of cold-recycled mixtures, the authors employed an electro-pneumatic triaxial cell fitted within a 10 kN loading frame. The entire equipment is contained in a temperature-controlled cabinet, which can be operated between 0 and 80°C.

The size of the cell is such to accommodate the prepared cylindrical specimens (100 mm in diameter and 200 mm in height), which are enclosed in a rubber membrane and are in contact with an upper and a lower porous disc. Vertical forces, which are applied to test specimens by means of metal loading plates, are controlled and measured by means of an electronic load cell, whereas vertical deformations are measured with two spring loaded Linear Variable Differential Transducers (LVDT's) which are connected to the loading piston and are positioned immediately above the test cell.

According to the reference standard (AASHTO TP46) which is generally used to test unbound granular materials for bases and subbases, tests were carried out in drained conditions by applying 15 consecutive sequences of cyclic vertical loads of different magnitude combined with different confining pressures (σ_3). In each sequence, 100 loading cycles of the haversine shape are applied to the specimen, with 0.1 seconds loading time and 0.9 seconds rest period. Vertical stresses transferred to the specimen by means of the loading pulses are composed of a constant contact stress ($\sigma_{contact}$) and a cyclic (deviatoric) stress (σ_{cyclic} or σ_d). Resilient modulus (M_r) values are calculated as the ratio between cyclic stress (σ_{cyclic}) and resilient axial strain (ε_r) only for the last 5 cycles, when quasi-elastic response conditions are reached. Before starting the actual testing sequences, a preliminary conditioning phase is carried out during which 500 vertical pulses are

applied with a given confining pressure (equal to 103.4 kPa) in order to obtain a uniform contact between the loading plate and the specimen and to eliminate any undesired bias which derives from the phenomena occurring between compaction and testing. Stress conditions of the sequences which compose the AASHTO protocol are synthesized in Table 5.

Table 5. *Stress conditions during triaxial resilient modulus tests*

Sequence	σ_3 (kPa)	σ_{cyclic} (kPa)	$\sigma_{contact}$ (kPa)
0	103.4	93.1	10.3
1	20.7	18.6	2.1
2		37.3	4.1
3		55.9	6.2
4	34.5	31.0	3.5
5		62.0	6.9
6		93.1	10.3
7	68.9	62.0	6.9
8		124.1	13.8
9		186.1	20.7
10	103.4	62.0	6.9
11		93.1	10.3
12		186.1	20.7
13	137.9	93.1	10.3
14		124.1	13.8
15		248.2	27.6

After the completion of the last cyclic loading sequence, each specimen was subjected to the so-called “quick shear test”. This consists in evaluating the stress-strain response until failure under the effect of a constant confining pressure of 34.5 kPa and of an axial strain which increases linearly in time with a rate of 1% per minute. Results which are typically extracted from stress-strain curves are the deviatoric stress and axial strain at failure (σ_f and ε_f). However, secant or tangent moduli can also be calculated by considering the stress-strain response measured in various portions of the test.

4. Experimental Results

4.1. *Composition and volumetrics of test specimens*

In order to check the uniformity of test specimens, after triaxial testing the upper and lower portion of two cylindrical samples, selected randomly, were subjected to ignition treatment according to EN 12697-39, with the subsequent evaluation of binder content and aggregate size distribution (wet process). The corresponding results are synthesized in Table 6, where they are compared with those of the design recipe. Results obtained on the two half-specimens (respectively identified with codes B5 and B1) were very similar and only minor deviations from the reference aggregate size distribution of the design mixture were observed. Binder content values of the two half-specimens were also very close to each other (equal to 6.47% for specimen B5 and to 6.44% for specimen B1) and only slightly higher than the target value of the design mixture (equal to 6.30%).

Table 6. *Composition of the actual test specimens*

D (mm)	Design	Specimens	
		Lower B5	Upper B1
25	100	100	100
20	95.4	94.5	93.6
15	89.3	88.4	84.7
10	73.4	72.6	73.2
5	53.0	52.0	53.7
2	36.3	36.3	36.2
0.4	17.7	17.8	17.6
0.18	10.5	7.1	9.1
0.075	5.3	2.9	4.6

Since compaction of each specimen was carried out in two layers, doubts remained with respect to homogeneity. Thus, three supplementary specimens were prepared for each of the conditioning temperatures (20, 40 and 60°C) in order to be subjected, after a conditioning period of 3 days at 40°C in a forced-draft oven, to evaluation of dry density by means of the paraffin-coating procedure (ASTM D1188). The first specimen, 200 mm in height, was prepared in two layers according to the protocol described in the previous section. The second specimen was compacted in the same way as the first one, with filter paper between the top and bottom part. The function of the filter paper was to separate the two portions more easily after compaction, thus allowing the subsequent evaluation of the density of the upper and lower part of the specimen. Finally, the third specimen represented the lower portion only, and therefore had a target height of 100 mm. Density data, and corresponding void content values, are shown in Table 7.

As expected, by increasing mixing and compaction temperature, even though the target (geometrical) density was kept constant, an increase of compaction effects was obtained. This is proven by the void content values both of the slender 200 mm specimens (V1, V4 and V7) and of the shorter 100 mm ones (V3, V6 and V9). The recorded variation, when passing from 20 to 60°C, was of the order of 0.4 to 0.6%. The smaller specimens were also compacted to a greater degree, with void content differences with respect to the slender ones comprised between 1.2 and 1.4%.

The same temperature-dependency described above was recorded in the case of the two-layer specimens prepared by using an intermediate paper filter (V2, V5 and V8). However, it was noted that temperature affected only to a limited extent the density of the upper portion, with void content values comprised between 12.9 and 13.4%, while it influenced to a greater degree the compaction of the lower part of the specimens (void content values ranging between 8.9 and 10.3%).

When focusing on the issue of homogeneity, it can thus be concluded that in all cases the lower portion of the specimens was clearly more dense than the upper part, with an absolute difference, expressed in terms of void content, which increased with temperature, ranging between 3.1 and 4.3%. This is clearly due to the supplement of compaction which the lower part is subjected to while compacting the upper layer. Such an effect can be clearly highlighted by comparing the results obtained on the lower portions of specimens V2, V5 and V8 with those of the corresponding 100 mm specimens (V3, V6 and V9). The surplus of compaction leads to an additional reduction of the void content which increases with temperature and falls within the 0.5 to 1.5% range.

Table 7. *Results of the volumetric tests*

Specimen	Temperature (°C)	Density (g/cm^3)	Void content (%)
V1 (200 mm)	20	2.228	12.2
V2 (upper portion)		2.197	13.4
V2 (lower portion)		2.278	10.3
V2 (average)		2.237	11.9
V3 (100 mm)		2.263	10.8
V4 (200 mm)	40	2.237	11.9
V5 (upper portion)		2.210	12.9
V5 (lower portion)		2.289	9.8
V5 (average)		2.250	11.4
V6 (100 mm)		2.271	10.5
V7 (200 mm)	60	2.244	11.6
V8 (upper portion)		2.204	13.1
V8 (lower portion)		2.313	8.9
V8 (average)		2.259	11.0
V9 (100 mm)		2.275	10.4

Further information on the compaction of the specimens was obtained by analyzing the data retrieved from the gyratory shear equipment. Thus, the lower and upper portion were compared in terms of the number of gyrations required to reach target geometrical dry density, whereas true compaction curves were derived for the bottom portions only.

As indicated by the data given in Table 8, the compaction effort required to reach target conditions for both portions of the specimens is a function of temperature. This is clearly due to the fact that as temperature is increased, the bituminous coating of the RAP becomes softer and that the added binder derived from the broken emulsion also decreases its viscosity. It can also be noted that there is a significant difference in the number of gyrations needed to compact the lower and upper portion of the slender specimens (N_{lower} and N_{upper}). In fact, as the upper portion is subjected to vertical stresses, part of the compaction energy is dissipated by the presence of a deformable support. As expected, such a difference between the two layers is reduced by increasing compaction temperature, since smaller pressures are transferred to the bottom of the upper layer.

Compaction curves of the lower portions of the slender specimens, plotted in terms of percent compaction (C) as a function of the number of gyrations (N_g), were derived by considering the progressive height data recorded by the gyratory equipment and the density values obtained from the 100 mm specimens (V3, V6 and V9, see Table 7). This is shown in Figure 4, which contains selected results (one specimen per temperature).

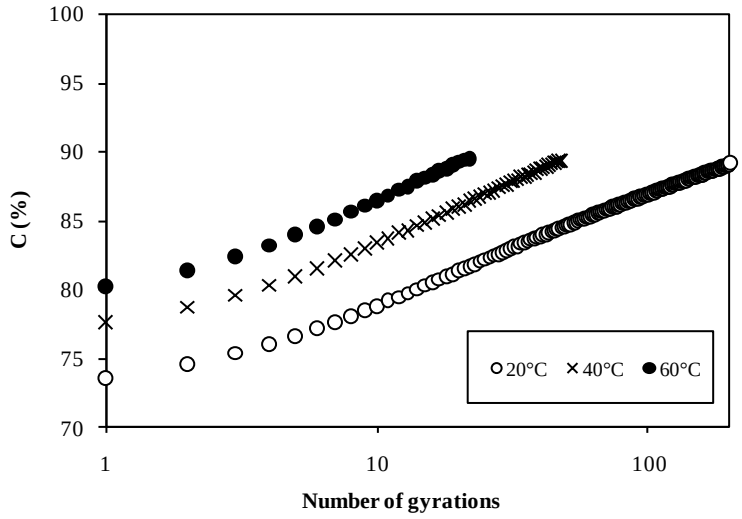

Figure 4. *Compaction curves of the lower portion of the slender specimens*

Each set of compaction curves was synthesized by referring to the average percent compaction at 1 gyration (C_1, also termed as "self-compaction") and to the average slope of the curve in the semi-logarithmic plot (k, also referred to as "workability") calculated by curve fitting by considering the data recorded from 10 gyrations onwards. The calculated average values of these parameters are given in Table 8.

Table 8. *Average values of compaction parameters*

T (°C)	N_{lower}	N_{upper}	C_1 (%)	k
20	194	671	74.0	7.6
40	55	75	77.7	8.6
60	28	41	79.4	9.1

It is interesting to note that by raising temperature, both self-compaction and workability parameters increase significantly. While variations of C_1 should be related mainly to the abovementioned softening of the bituminous coatings of the RAP, the non-negligible increase of k may be also a function of the reduced viscosity of the added binder. In such a context it should be noted that according to the authors' experience in the characterization of both traditional hot and cold-recycled mixtures, variations of mixture composition and/or compaction conditions generally lead to results which are different from those herein reported. In fact, when the self-compaction of the mixture increases, final conditions will usually be reached with a reduced workability since the aggregates in the mixture cannot be easily rearranged during compaction.

4.2. *Resilient modulus*

Cyclic loading triaxial tests carried out in drained conditions according to the previously summarized testing program yielded values of the resilient modulus comprised within an extremely wide range. As shown in Table 9, this depends on the fact that the elastic response at regime of these mixtures is not only dependent on stress conditions, but also, due to the visco-elastic and time-dependent nature of the binder, on temperature and curing.

Table 9. *Resilient modulus ranges at different test temperatures*

Temperature (°C)	Curing	M_r range (MPa)	ε_r range
20	Short term	177.6 to 625.0	6,80E-05 to 4.54E-04
40	Short term	172.4 to 631.2	6,70E-05 to 4.87E-04
60	Short term	163.7 to 427.7	9,90E-05 to 6.00E-04
20	Intermediate	247.6 to 796.8	7,60E-05 to 3.40E-04
20	Full	290.6 to 894.0	5,60E-05 to 3.29E-04

Interpretation of the resilient modulus data was performed by referring to the so-called k-θ model, typically adopted for unbound granular materials or coarse-grained soils (Brown *et al.*, 1967; Hicks *et al.*, 1972). Such a model takes into account the stress dependency of the elastic response by expressing resilient modulus as an increasing function of the first stress invariant (θ) as follows:

$$M_r = k_1 \cdot \theta^{k2} \qquad [3]$$

where k_1 and k_2 are material-dependent parameters.

One of the main features of the k-θ model is its simplicity, since it relates stress-stiffening effects to the sum of principal stresses, thereby considering the variation of elastic response to be a function exclusively of mass forces exchanged by particles. However, in the case of cold-recycled mixtures other inter-particle forces are due to the presence of the bituminous binder phase which provides the material with a certain degree of cohesion: this observation lead the authors to consider also the model proposed by Uzan *et al.* (1992), which expresses resilient modulus as a function of θ and of deviatoric stress (σ_d) according to the expression:

$$M_r = k_1 \cdot \theta^{k2} \cdot \sigma_d^{\ k3} \qquad [4]$$

where k_1, k_2 and k_3 are material-dependent parameters.

Average M_r and θ values calculated from the results of the last five loading cycles of each test sequence are plotted in Figures 5 and 6.

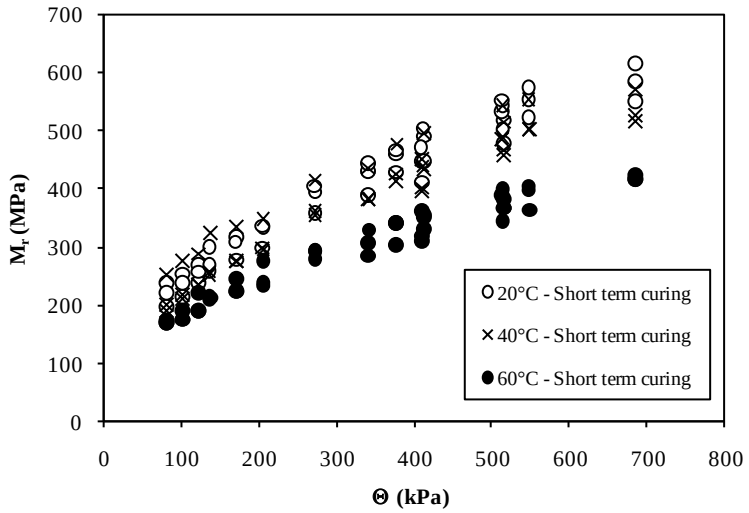

Figure 5. *Results of resilient modulus tests carried out at various temperatures*

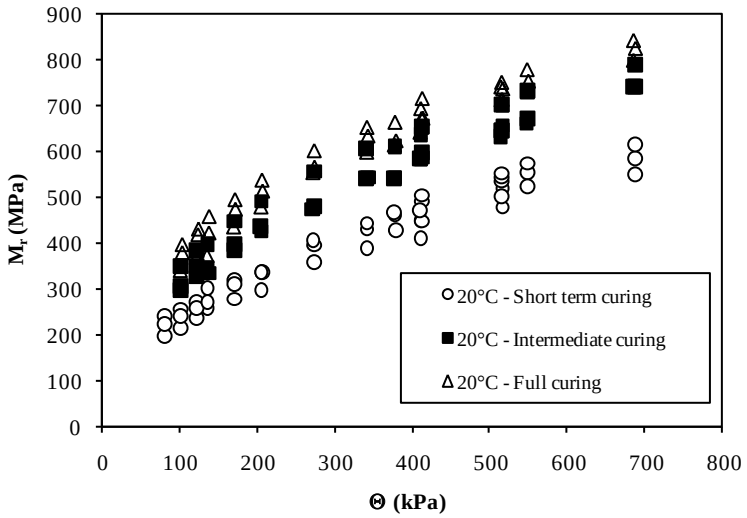

Figure 6. *Results of resilient modulus tests carried out at 20°C after various curing procedures*

Even though it is clear that the mixture exhibits a typical stress-stiffening behaviour, it can be observed that at every temperature and for each curing condition there is a non negligible dispersion of the data which are distributed in bands rather than along curves. This is due not only to material variability and non-homogeneity within samples, but also to the fact that resilient modulus is not necessarily fully controlled by the first stress invariant θ.

Model fitting of the experimental data was carried out by considering each specimen separately and by calculating the corresponding values of k_1 and k_2 (or k_1, k_2 and k_3) by means of the least square regression method. The corresponding results are synthesized in Table 10 which also contains the values of the regression coefficient R^2.

Quite obviously, as shown by the R^2 values, by adding a degree of freedom to the k-θ model, thus including the explicit dependence from deviatoric stress as proposed by Uzan, a better fitting of test data is obtained in all cases; however, R^2 values are extremely high even for the k-θ model, thus indicating that the value of the first stress invariant is indeed strongly correlated with resilient modulus.

Interpretation of the results derived from model fitting should be carried out by considering separately the data obtained in the first and second phase of investigation. In fact, in the short term, when the cold-recycled mixture is still in a state which is very close to unbound conditions, the adoption of the abovementioned models appears to be quite rigorous, with the possibility of relating the results to the structure of the composite material. On the contrary, when curing is allowed to

occur, either in intermediate of in full form, cold-recycled mixtures tend to be more and more similar to traditional hot mixes, for which the use of both the k-θ and Uzan model is quite unusual and perhaps not totally appropriate.

Table 10. *Results of resilient modulus model fitting*

Temperature and curing	Parameter	Specimen 1		Specimen 2		Specimen 3	
		k-θ model	Uzan's model	k-θ model	Uzan's model	k-θ model	Uzan's model
20°C Short term	k_1	717	649	664	620	766	728
	k_2	0.47	0.50	0.48	0.57	0.50	0.54
	k_3	-	-0.06	-	-0.08	-	-0.04
	R^2	0.991	0.994	0.993	0.997	0.994	0.995
40°C Short term	k_1	653	600	637	563	725	612
	k_2	0.49	0.55	0.46	0.55	0.49	0.48
	k_3	-	-0.07	-	-0.10	-	-0.09
	R^2	0.994	0.997	0.990	0.997	0.976	0.984
60°C Short term	k_1	481	569	496	451	513	432
	k_2	0.40	0.26	0.43	0.54	0.46	0.58
	k_3	-	0.14	-	-0.10	-	-0.14
	R^2	0.979	0.998	0.991	0.999	0.981	0.996
20°C Intermediate	k_1	877	913	869	916	949	931
	k_2	0.46	0.47	0.45	0.41	0.44	0.42
	k_3		0.02		0.04		-0.002
	R^2	0.993	0.993	0.994	0.996	0.996	0.997
20°C Full	k_1	977	956	1035	975	981	999
	k_2	0.49	0.45	0.47	0.38	0.43	0.37
	k_3		-0.004		0.0003		0.04
	R^2	0.983	0.983	0.963	0.964	0.982	0.983

When considering the results of tests carried out after short term curing it can be observed that for all specimens, except for one of those tested at 60°C, when adding in the model the explicit dependence from deviatoric stress there is a decrease of k_1 and an increase of k_2. Moreover, parameter k_3 is always negative, thus showing that a minor stress-softening effect controlled by shear forces is superposed to the macroscopic stress-stiffening already highlighted in Figure 5.

In the case of cured mixtures, specific trends when comparing the results obtained with the two models could not be found. Moreover, the use of Uzan's model lead to non repeatable results, with values of parameter k_3 which are very small and in most cases positive. This inconsistency suggested that the use of such a model is not recommended to represent the stress-strain behavior of the cold-recycled mixture once it has reached truly bound conditions as a result of curing.

The average model parameter values calculated for each temperature-curing combination are given in Table 11, which also contains the correlation coefficient

values referred to each set of data. As mentioned above, the first specimen tested at 60°C was considered as an outlier and was therefore eliminated from data analysis, while all other data sets were treated with no filtering. Given the limited number of replicates available, a statistical analysis was not possible; however, in each condition and for each parameter the maximum percentage deviation (Δ) of the results from the average was calculated and is listed in Table 11.

Table 11. *Results of resilient modulus model fitting*

Temperature and curing	Parameter	k-θ model		Uzan's model	
		Average	Δ (%)	Average	Δ (%)
20°C Short term	k_1	715	14.2	666	16.2
	k_2	0.49	6.3	0.54	13.2
	k_3	-	-	-0.06	59.7
40°C Short term	k_1	672	13.1	592	8.3
	k_2	0.48	5.7	0.53	14.5
	k_3	-	-	-0.09	37.7
60°C Short term	k_1	504	3.4	442	4.2
	k_2	0.45	5.0	0.56	7.0
	k_3	-	-	-0.12	34.3
20°C Intermediate	k_1	898	8.9	920	1.6
	k_2	0.45	5.0	0.43	11.0
	k_3	-	-	0.02	237.4
20°C Full	k_1	998	5.8	977	1.9
	k_2	0.47	12.8	0.40	20.4
	k_3	-	-	0.011	370.3

The observations made when comparing the two models fitted to the results obtained on single specimens are confirmed by analyzing average results. However, by looking at the data reported in Table 11, temperature and curing effects can be more clearly assessed and preliminary conclusions on the reliability of the models can be drawn.

As test temperature is increased, for both models parameter k_1 decreases, while parameter k_2 shows a different trend depending upon the employed model. In the case of the k–θ model a slight decrease of k_2 is recorded, whereas in the case of Uzan's model k_2 is more or less constant while parameter k_3, which is always negative, clearly tends to decrease.

Such results can be explained by referring to the internal structure and composition of the cold-recycled mixture. Stress-stiffening effects, associated to the intensity of bulk stress, are mainly due to the coarse aggregate structure of the mixture: thus it is reasonable to assume that as the binder reduces its elasticity and stiffness with increasing temperature, contact forces within the aggregate skeleton of

the mixture can become less effective thereby causing a reduction not only of the stiffness level but also of its stress-sensitivity. This interpretation is coherent with the results obtained by employing Uzan's model, in which the additional stress-softening factor becomes increasingly relevant as test temperature is raised, while the stress-stiffening factor remains almost constant.

As already mentioned in this paper, both models have been previously proposed for use to represent the resilient response of unsaturated unbound granular materials. Thus, it is not surprising that the dispersion of the data, expressed in very simple terms by means of the percent deviation Δ, tends to decrease as the viscosity of the binding matrix is reduced with increasing temperature. Such an observation applies to all parameters and for both models. When comparing the two models it should also be observed that in most cases Δ values for all parameters tend to be greater in the case of Uzan's model; moreover, the additional k_3 parameter is characterized by dispersions (comprised between 34.3 and 59.7%) which are substantially greater than those calculated for all other parameters. This suggests that based on the limited amount of available data, the use of a more complex model is not recommended.

The effects of curing on the resilient modulus of the cold-recycled mixture fit in the same framework on analysis that has been set up for the interpretation of temperature effects. In fact, as curing progresses, the cold-recycled mixture changes its internal structure and moves away from the almost unbound short term condition. Thus, while it can be clearly observed that parameter k_1 increases for both models, no specific temperature-dependency can be highlighted k_2, nor for k_3 which according to calculations assumed positive average values and was characterized by a relatively large scattering of the data. Even in this case the use of the more complex model, characterized by three parameters, seems to lead to possibly misleading results and at the present time, awaiting for further experimental evidence, does not appear to be of any practical advantage.

4.3. *Shear strength*

The so-called quick shear strength tests were carried out, according to the previously described procedure, on all the prepared specimens immediately after completion of resilient modulus loading sequences. While all specimens tested in the short term curing condition were actually failed, thus leading to the evaluation of the deviatoric stress to failure (q) and of the corresponding vertical strain (ε_f), those which were subjected to intermediate or full curing did not reach rupture as the upper limit of the load cell (10 kN) was approached. This gives further proof of the fact that such specimens exhibit a mechanical behavior which is more similar to that of traditional hot mixtures rather than to unbound granular materials.

It should be reported that unfortunately the employed testing equipment did not exhibit an efficient strain rate control. Even though the imposed axial strain rate was set at 1% per minute, it was observed that the speed of the vertical loading piston tended to increase over time, starting from very low values and gradually reaching

strain rates at the onset of failure which were at least double than the target value. This may be due to the fact that the equipment was not specifically designed for the analysis of bound mixtures in which, after a stiff initial response, deformation occurs as a result of the time- and strain-dependent behavior of the binder phase.

By carefully examining the experimental data, two distinct phases of the test could be highlighted. In the first phase, for strains smaller than 0.1%, the average strain rate, calculated by considering all test results (including those obtained on specimens subjected to intermediate and full curing), was equal to 0.41% per minute. In the second phase, from 0.1% strain to failure or to limiting loading conditions, the average strain rate was substantially higher, equal to 1.41% per minute. Moreover, in most cases strain rate was within 20% of the target value for axial strain values comprised between 0.1 and 0.3%. By neglecting the existence of the two phases and by considering all the test results in the entire range of measured strains, the average strain rate was equal to 1.02% per minute.

Despite the lack of full control of strain rate, the strain history imposed to all the specimens was quite repeatable, thus allowing the authors to compare the results obtained at different test temperatures and on specimens subjected to different curing procedures. This is shown in Figures 7 and 8, which contain examples of stress-strain plots, and in Tables 12 and 13, which give average values and corresponding maximum percent deviations of the strength data of short term cured specimens and of the stiffness values of all specimens. Stiffness was expressed in terms of a static modulus (E), calculated from stress-strain plots both as a tangent modulus in the range of strain rates within 20% of the target value ($E_{t,1}$) and as a secant modulus at failure ($E_{s,f}$).

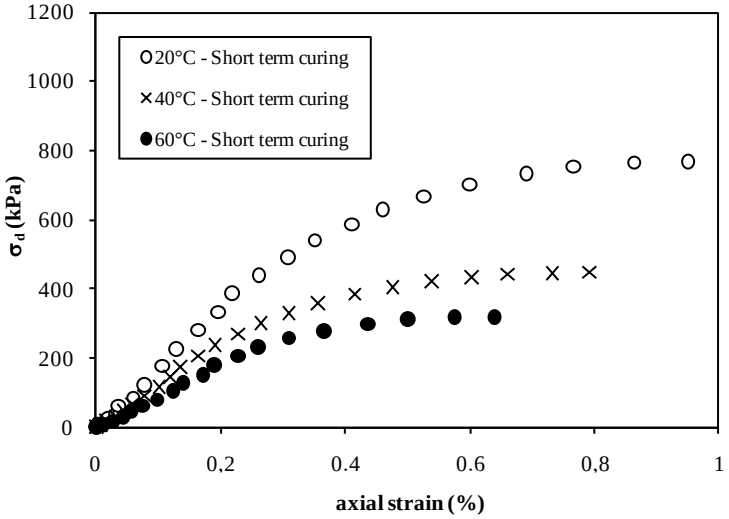

Figure 7. *Results of quick shear strength tests carried out at various temperatures*

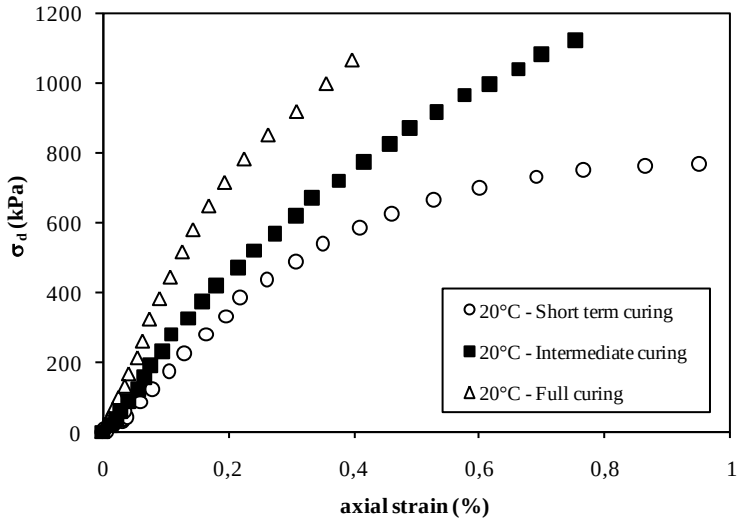

Figure 8. *Results of quick shear strength tests carried out at 20°C after various curing procedures*

Table 12. *Strength parameters at various test temperatures*

	20°C Short term		40°C Short term		60°C Short term	
Parameter	Average	Δ (%)	Average	Δ (%)	Average	Δ (%)
q (kPa)	744	6.5	433	10.7	337	11.4
ε_f (%)	0.969	3.4	0.761	5.6	0.698	14.7

Table 13. *Stiffness values for all testing conditions*

Temperature and curing	$E_{t,1}$ (MPa)		$E_{s,f}$ (MPa)	
	Average	Δ (%)	Average	Δ (%)
20°C Short term	172	15.4	77	9.7
40°C Short term	122	3.0	57	6.1
60°C Short term	117	14.4	48	3.3
20°C Intermediate	179	8.8	-	-
20°C Full	260	9.3	-	-

From the data shown in Figure 7 and in Table 12 it is interesting to note that as a result of test temperature increase not only strength is reduced, but also the corresponding strain at failure is progressively smaller. This indicates that within the structure of the mixture the temperature-dependent viscosity reduction and loss of cohesion of the binder lead to shear strains and distorsions which tend to override effects associated with the enhancement of binder ductility. As proven by the percent deviation data, it can also be stated that as the time-dependent components of binder response are increased (i.e. at higher temperatures), failure conditions occur in a less repeatable fashion, thus revealing the non negligible influence of local flow and distorsion phenomena. As a consequence, stiffness at failure decreases with increasing test temperature (Table 13); however, the corresponding reduction of maximum percent deviation suggests that the occurrence final conditions is increasingly controlled by the viscosity of the binder phase as temperature is increased.

As indicated by the data contained in Table 13, coherently with physical expectations, at a given strain rate (1% per minute ± 20%) stiffness tends to increase with the reduction of test temperature and with the development of curing. However, it is worthwhile observing that only a minor stiffening effect was caused by the intermediate curing treatment, while very small differences were recorded when comparing $E_{t,1}$ values obtained at 40 and 60°C.

5. Conclusions

The first objective of the research program was to develop a series of procedures for the analysis of the short term elastic response of cold-recycled bituminous mixtures in triaxial stress conditions. Procedures included specimens preparation and testing protocol. Based on the results summarized in this paper, it may be concluded that the proposed procedures are indeed adequate, even though further efforts may be needed to improve specimen homogeneity and accuracy of axial strain measurements.

The second objective of the project was to assess the elastic response of the mixtures in a wide range of stress levels, temperatures (comprised between 20 and 60°C) and curing conditions. It was found that the most adequate model which can be used for the description of the stress-strain properties appears to be the so-called k-θ model. Such a model, widely employed for the analysis of unbound granular materials, generates parameters (k_1 and k_2) for which specific trends were highlighted in the case of short term cured specimens. The consistency of the findings was discussed by considering the internal structure and composition of the cold-recycled mixture.

Finally, the third objective of the research study was to evaluate shear strength properties of the considered cold-recycled mixture. Even in this part of the investigation, results were found to be repeatable and their dependency upon test temperature and curing condition was coherent with physical expectations.

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