Laboratory Tests for the Characterization of Cold Asphalt Patching Mixtures

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Abstract Cold asphalt patching mixtures are widely employed in pavement maintenance operations due to their technical and economical effectiveness. However, their selection is seldom based on the results of laboratory characterization tests, since there are no standard procedures which are recognized by the international community for such a purpose. The investigation described in this paper focused on the evaluation of the strength and stiffness properties of several cold asphalt patching products which were subjected to analysis in two characteristic compaction states: low compaction, as achieved after placement in the field, and high compaction, as reached under the action of traffic loads. Mechanical characteristics evaluated in the laboratory included indirect tensile strength, California Bearing Ratio, resilient modulus and quick shear strength. Analysis of the obtained results highlighted the existence of significant differences between the various products which were explained by referring to their composition and curing behavior.

Keywords: cold asphalt mixture, patching, indirect tensile strength, California Bearing Ratio, resilient modulus, quick shear strength

1 Introduction

One of the most common distresses occurring in asphalt pavements is represented by potholes. The presence of potholes greatly affects traffic safety, since they may act as a trigger for accidents. Furthermore, when potholes initially occur, they may have a significant impact on user costs as a result of the potential damage to vehicles. Finally, potholes and corresponding repair operations may be concurring factors for the creation of traffic jams, consequently increasing fuel consumption and release of air-borne pollutants (Dong et al., 2013; Naveen et al., 2018).
A pothole can be defined as a steep-sided bowl-shaped cavity of variable size affecting the pavement surface. It derives from the progressive damage of existing distresses and is mainly caused by the simultaneous action of several factors among which traffic and moisture are the most important (Miller and Bellinger, 2003; Chen et al., 2016).

Water seeping into the pavement through existing cracks tends to weaken asphalt layers which can therefore be easily deteriorated by heavy traffic and broken into pieces, thus leading to the creation of a pothole (Liao et al., 2016).

As a result of the frequent occurrence of potholes, one of the most typical pavement maintenance operations is represented by pothole repair, also known as "patching".

Patching activities, which are performed by employing different materials and techniques, are used for temporary and semi-permanent repair operations. In the first case, after being placed on the pothole, the patching material is compacted by means of shovels or by making use of truck tires (the so-called "throw-and-roll" technique). In the semi-permanent practice, the recommended procedure consists in a preliminary cleaning of the distressed area (by removing debris and dust) followed by the thorough compaction of the adopted patching material by means of appropriate equipment (Paige-Green et al., 2010; Biswas et al., 2018). In order to increase the durability of pavement areas subjected to rehabilitation, best practice entails the removal of the upper bituminous layers in a more extended surface (by saw cutting or milling), followed by application of a tack coat and by the laying of a traditional hot-mix asphalt (HMA) mixture compacted by means of steel drum rollers.

Different types of patching materials are available on the market and although it is common to consider HMA mixtures as the most durable, the environmental benefits and speed of use of cold asphalt patching mixes has promoted their widespread diffusion, especially for the repair of small potholes (McDaniel et al., 2014).

Cold patching mixtures are usually manufactured by making use of cutback asphalts or bituminous emulsions and can be easily stored for extended periods of time in appropriate bags or buckets. As reported in the literature, premature failure of cold patching repairs can be related to different factors that include poor short-term strength due to limited curing time, limited resistance to permanent deformation, and insufficient resistance to stripping and debonding in the presence of water (Prowell and Franklin, 1996; Dong et al., 2014; Chen et al., 2016; Liao et al., 2016).

Several studies have been carried out in order to identify suitable laboratory test methods for the assessment of patching mixtures and for their relative ranking in the perspective of gathering information for their rational and cost-effective selection. So far, suggested laboratory tests have been developed by moving away from the classical procedures adopted for the characterization of HMA, and by consequently focusing on methods which can yield relevant information with respect to fundamental performance-related properties such as cohesion, workability and resistance to permanent deformation (Prowell and Franklin, 1996; Estakhri and Button, 1997; Chatterjee et al., 2006; Rosales-Herrera at al., 2007; Dong et al., 2014; Ferrotti et al., 2014; Gómez-Meijide and Pérez, 2014; Biswas et al., 2016; Chen et al., 2016; Liao et al., 2016; Hasanuzzaman et al., 2017).

The goal of the experimental investigation described in this paper was to provide a contribution to the topic outlined above, with the consequent assessment of test procedures for the performance-related characterization of patching mixtures. Activities focused on the evaluation of the strength and stiffness properties of several cold asphalt patching products which were subjected to analysis in compaction states which are believed to be representative of the conditions encountered in service.

2 Experimental investigation

2.1 Materials

Materials considered in the experimental investigation included four commercially available cold asphalt patching mixtures (CAPMs) deemed to be representative of the wide range of products normally employed for routine maintenance operations.

CAPM-1 is produced by using a polymer-modified bitumen with SBS and SBR derived from end-of-life tires, conveniently fluidized by means of selected vegetable oils, blended with high quality sand and gravel. CAPM-2 is composed of selected aggregates mixed with a patented binder that hardens in contact with water. CAPM-3 contains aggregates of unknown mineralogy and a fluxed bitumen. Finally, CAPM-4 is made by mixing basaltic aggregates with a patented bitumen emulsion. According to the information provided by suppliers and users, CAPM-1 and CAPM-3 have a positive performance record for temporary patching in urban areas, while CAPM-2 and CAPM-4 are promoted for use in heavy-duty semi-permanent applications.

In order to obtain accurate information on their composition, each CAPM was subjected to preliminary characterization for the evaluation of maximum density (ρ_{mv}, EN 12697-5, 2018), binder content (EN 12697-39, 2012), aggregate gradation (EN 12697-2, 2015) and particle density of extracted aggregates (ρ_p, EN 1097-6, 2013).

Results obtained in this phase of the investigation are provided in Table 1, which also shows the maximum aggregate size (D_{max}) and dust-to-binder ratio (DR, ratio between the content of particles finer than 63 μm and that of employed binder) of each CAPM. Aggregate gradations are displayed in Fig.1, where they are also associated to their values of the uniformity coefficient C_u, defined as the ratio between the particle sizes corresponding, respectively, to a passing of 60% and 10% (EN ISO 14688-2, 2018).

It can be observed that the four mixtures exhibited a wide variation of ρ_{mv} as a result of different binder dosage and ρ_p of extracted aggregates. Measured binder content, which was comprised between 5.9% and 8.3% by weight of aggregates, was inclusive of the additives employed by producers in order to guarantee a satisfactory workability of the mixtures at low temperatures. Aggregates extracted from the mixtures were characterized by similar values of particle density, with the exception of those contained in CAPM-4, which showed the highest ρ_p as a result of their basaltic nature.

Table 1 Composition of investigated CAPMs

Mixture	ρ_{mv} (kg/m^3)	Binder content[(1)] (%)	ρ_p (-)	D_{max} (mm)	DR (-)
CAPM-1	2466	6.4	2.720	10	0.64
CAPM-2	2400	8.3	2.732	10	0.51
CAPM-3	2513	5.9	2.765	8	0.46
CAPM-4	2684	6.3	2.946	12.5	0.37

[(1)]By weight of dry aggregates

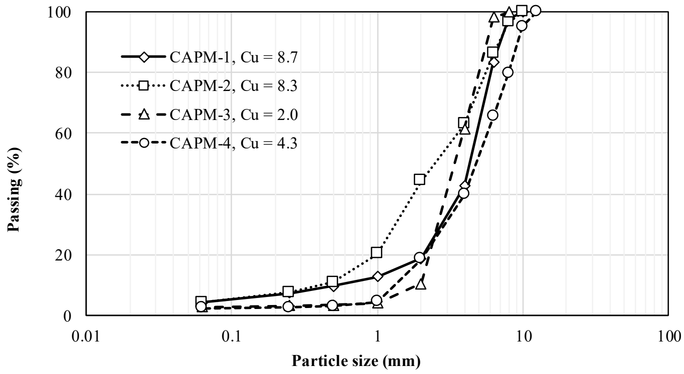

Fig. 1 Gradation curves of investigated CAPMs

As clearly displayed in Fig. 1, significant differences were recorded among the various CAPMs in terms of the shape of aggregate gradation curves. In particular, CAPM-1 and CAPM-2 presented a medium-graded aggregate distribution (C_u comprised in the 6-15 range), while CAPM-3 and CAPM-4 were characterized by even-graded gradations (C_u lower than 6).

2.2 Methods

Specimens of each CAPM were prepared at room temperature by means of the gyratory shear compactor as per EN 12697-31 (2019). Although this method is normally used for the compaction of hot-mix asphalt, in the past it has been successfully adopted by the authors for cold asphalt mixtures (Santagata et al, 2007, Santagata et al., 2010). Two compaction states of the CAPMs were considered in the investigation with the purpose of reproducing characteristic conditions which are encountered in service. Short-term compaction, achieved after placement and before opening to traffic, was mimicked by applying 50 gyrations. Long-term conditions, reached as a result of further densification due to traffic loads, were replicated by applying 180 gyrations.

In short-term low-compaction conditions, the function of a CAPM placed in a pothole is to prevent premature failure due to loss of material and excessive deformation. Thus, laboratory tests which were selected for the assessment of CAPMs in this state included Indirect Tensile Strength (ITS) and California Bearing Ratio (CBR) tests.

ITS tests were carried out at 20 °C as per EN 12697-23 (2017), with an imposed displacement rate of 50.8 mm/min until failure. In order to analyze the development of strength in time, specimens were cured in a climatic chamber set at 20 °C and were subjected to testing after curing periods of 1, 3, 7 and 28 days. For each curing condition, ITS tests were carried out on 3 specimens for each CAPM and average results were considered in the subsequent analyses.

Although CBR tests are normally used for subgrade soils, during the investigation they were employed for the assessment of the overall resistance to loading of CAPMs in

low-compaction conditions, in which these mixtures may exhibit a very low cohesion, similar to that of granular materials. Specimens were prepared by means of the Proctor procedure (EN 13286-2, 2010) and were then subjected to loading as per EN 13286-47 (2012) with no surface surcharge and no preliminary soaking. Prior to testing, specimens were cured for 24 hours at 20 °C in the abovementioned climatic chamber.
In long-term high-compaction conditions, a CAPM exhibits a response under loading in service which is similar to that of a standard asphalt mixture and depends upon both bulk structure and developed cohesion. Thus, laboratory tests which were considered appropriate to characterize CAPMs in these conditions included triaxial resilient modulus (M_r) and quick shear strength (QS) tests.
M_r tests were performed at 20 °C by following AASHTO T 307-99 (2017), which entails the application of various combinations of confining pressure (σ_c) and vertical deviatoric stress (σ_d) to slender cylindrical specimens (100 mm in diameter, 200 mm in height). Gyratory-compacted specimens were obtained by introducing material into the mold in three superposed layers, each of which was compacted to desired height and predefined target density (equal to that achieved with 180 gyrations in ITS specimens). Tests were carried out on 4 specimens for each CAPM and average results were considered in the subsequent analyses. In order to simulate long-term curing conditions, prior to testing specimens were cured for 28 days at 20 °C. For comparative purposes, tests were also carried out after a curing period of only 24 hours.
After being tested for M_r evaluation, CAPM specimens were subjected to QS tests, in which a vertical strain rate of 0.01 min^{-1} was imposed in the absence of any confining pressure. Stress-strain were recorded during testing with the consequent identification, in peak load conditions, of quick shear strength (σ_{qss}) and strain at failure (ε_f).

3 Results

3.1 Volumetric properties

Voids content of gyratory-compacted specimens prepared in the two characteristic compaction states and of Proctor-compacted specimens are listed in Table 2.
It can be noticed that significant differences were recorded when comparing the CAPMs with each other for any of the three selected compaction procedures. This is probably due to the combined effects of variations of the viscosity of employed binders, of the degree of uniformity of aggregate gradations, of the binder and filler dosages, and of the corresponding DR value. Mixtures characterized by medium-graded gradations (C_u values greater than 6) and higher DR values (CAPM-1 and CAPM-2) formed, as expected, structures which were denser than those exhibited by patching products with an even-graded gradation (C_u values lower than 6) and lower DR values (CAPM-3 and CAPM-4). Consistently with expectations, the lowest value of voids content was recorded for CAPM-2 which showed the highest binder dosage (8.3%) and filler content (4.2%).

Table 2 Voids content of compacted CAPMs

Mixture	Voids content (%)		
	50 gyrations	180 gyrations	Proctor
CAPM-1	20.5	16.1	19.3
CAPM-2	7.5	4.4	8.8
CAPM-3	27.8	24.7	23.9
CAPM-4	22.8	19.5	28.8

When focusing on the results obtained on gyratory-compacted specimens, it can be observed that for most of the considered CAPMs (i.e. with the exception of CAPM-2) measured voids contents were significantly higher than those which are considered typical for standard hot asphalt mixes. However, values listed in Table 2 are consistent with those reported in literature for similar cold asphalt mixtures (Chatterjee et al., 2006; Gómez-Meijide and Pérez, 2014; Hasanuzzaman et al., 2017).
An assessment of the tendency of the CAPMs to densify under the action of traffic loading in service can be made by comparing voids content values recorded at 50 and 180 gyrations. The absolute variation of voids content for all mixtures was comprised between 3.0% and 4.5%. However, it was found that the highest traffic densification potential was exhibited by the mixtures with medium-graded gradations, with a relative reduction in the voids content equal to 21.5% and 41.3% for CAPM-1 and CAPM-2, respectively. Smaller reductions were recorded in the case of the mixtures characterized by even-graded gradations, with values equal to 11.2% and 14.5% for CAPM-3 and CAPM-4, respectively.
Finally, it should be underlined that the voids content of specimens compacted by means of the Proctor procedure were in good agreement with those obtained with the gyratory compactor at 50 gyrations (i.e. in the so-called low-compaction state).

3.2 Low-compaction behavior

Results obtained from ITS and CBR tests are presented in Table 3. No ITS data are available for CAPM-1 and CAPM-3 since the test specimens prepared with these mixtures, characterized by a very low cohesion, failed under the effect of their own weight as soon as they were positioned in the test jig. Such an outcome did not change even when considering specimens cured for a time period as long as 28 days.

Table 3 ITS and CBR of compacted CAPMs

Mixture	$ITS_{1\ day}$ (MPa)	$ITS_{3\ days}$ (MPa)	$ITS_{7\ days}$ (MPa)	$ITS_{28\ days}$ (MPa)	$CBR_{1\ day}$ (%)
CAPM-1	-	-	-	-	60
CAPM-2	0.37	0.42	0.42	0.45	62
CAPM-3	-	-	-	-	38
CAPM-4	0.02	0.03	0.07	0.26	42

The two CAPMs that could be tested in the indirect tensile configuration exhibited significantly different ITS values which were also characterized by a different sensitivity to curing time. Nevertheless, the range of recorded ITS values was consistent with that presented in literature for cold asphalt mixes having similar composition (Biswas et al., 2016; Rezaei et al., 2017).
As a result of its more closely packed aggregate skeleton and of its stiffer binder, CAPM-2 in the very early stages of curing (i.e. after only 1 day) achieved a strength which was one order of magnitude greater than that of CAPM-4 (0.37 MPa instead of 0.02 MPa). Over time the ITS of CAPM-2 increased only to a limited extent, with most of the changes of binder properties occurring in the first 3 days of curing. On the contrary, the time-dependent curing of the bituminous emulsion contained in CAPM-4 led to a build-up of strength which in post part took place after 7 days of curing, with an average ITS of 0.26 MPa reached after 28 days.
As indicated in Table 3, after only 24 hours of curing the CBR index could be measured for all CAPMs due to the lateral restraint that is provided to test specimens by Proctor molds. Obtained results suggest that the CBR index is mainly influenced by the internal structure formed by mineral aggregates, since a clear distinction could be made between the denser mixtures with medium-graded gradations (CAPM-1 and CAPM-2, with CBR values greater than 60%) and those with even-graded gradations (CAPM-3 and CAPM-4, with CBR values of the order of 40%).

3.3 High-compaction behavior

Results obtained from M_r and QS tests performed at 20 °C on the considered CAPMs in their high-compaction state after 1 and 28 days of curing are presented in Fig. 2, Fig. 3 and Table 4. Data were recorded for all mixtures, thereby overcoming the problems which occurred for some of them during ITS low-compaction characterization.
As shown in Fig. 2, in which M_r is plotted as a function of the first stress invariant (θ), in both curing conditions the stiffest response was exhibited by the two CAPMs which were characterized, as previously shown, by a non-negligible ITS (CAPM-2 and CAPM-4, see Table 3). The other two mixtures (CAPM-1 and CAPM-3) showed significantly lower M_r values, comparable to those of compacted granular materials.
With respect to stress-dependency, Fig. 2 indicates that the stiffest mixture (CAPM-2) in both considered curing conditions displayed a true stress-stiffening behavior which is testified by the progressive M_r increase recorded for increasingly high θ values. On the contrary, as a result of their lower cohesion, at all levels of confining pressure (σ_c), the more deformable mixtures (CAPM-1 and CAPM-3) exhibited a slight reduction of M_r with increasing values of applied deviatoric stress (σ_d), thus combining stress-stiffening and stress-softening characteristics. Such an occurrence, which was more evident in short-term curing conditions, is proven by the existence of discontinuities in the plots provided in Fig. 2. CAPM-4, for which the build-up of ITS was found to occur after 7 days of curing (see Table 3), displayed an intermediate behavior, which was fully stress-stiffening after 28 days of curing but of the combined nature (stiffening and softening with respect to σ_c and σ_d, respectively) after only one day of curing.

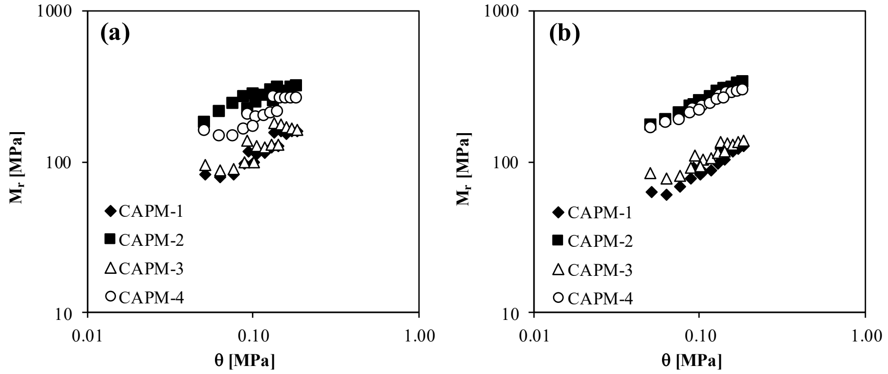

Fig. 2 Resilient modulus of CAPMs after 1 day (a) and 28 days (b) of curing

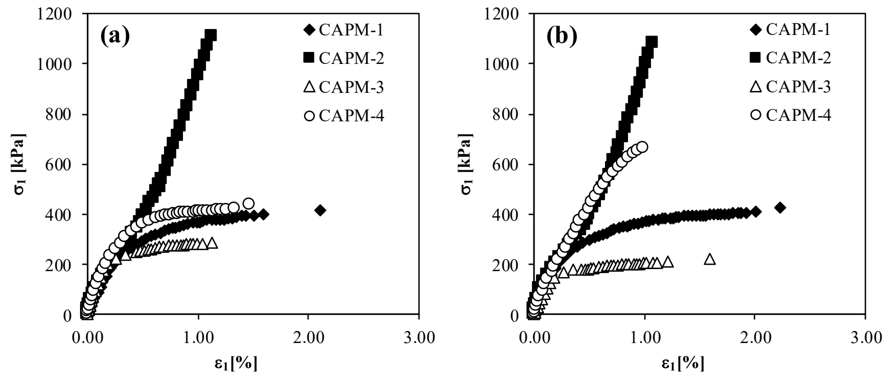

Fig. 3 Stress-strain curves obtained from quick shear tests after 1 day (a) and 28 days (b) of curing

Results obtained from QS tests (Fig. 3) were consistent with the outcomes of M_r tests and in line with those reported by Estakhri and Button (1997) for similar cold asphalt mixtures. As shown in Fig. 3, the behavior of CAPM-2 was different from that of all other mixtures, with a stiff quasi-linear response until brittle failure which can be explained by considering the dense aggregate structure and hardened bituminous binder. On the contrary, mixtures characterized by low cohesion (CAPM-1 and CAPM-3) exhibited a non-linear behavior, reaching failure at very high strains. In particular, CAPM-1 was found to be the most ductile, probably as a result of the presence of polymers in its binder. As a result of its cohesion build-up, CAPM-4 displayed an evolution in time, exhibiting a non-linear ductile response after 1 day of curing and a stiffer response, less ductile and closer to that of CAPM-2, after 28 days of curing.

Average QS parameters synthesized in Table 4 clearly indicate that most of the considered CAPMs did not exhibit any relevant changes in σ_{qss} and ε_f as a function of curing time. The only exception is constituted by CAPM-4, which displayed a 53% increase in strength and a 29% reduction in strain at failure when passing from 1 to 28 days of curing.

Table 4 Average quick shear test parameters of compacted CAPMs

Mixture	Curing time (days)			
	1 day		28 days	
	σ_{qss} (MPa)	ε_f (%)	σ_{qss} (MPa)	ε_f (%)
CAPM-1	0.424	1.982	0.405	1.891
CAPM-2	1.092	1.146	1.082	1.027
CAPM-3	0.265	0.994	0.199	1.043
CAPM-4	0.446	1.516	0.682	1.075

4 Conclusions

Based on the outcomes of the investigation discussed in this paper, it can be concluded that the experimental procedures selected for the characterization of cold asphalt patching mixtures provide meaningful results which highlight the differences between various products. Low-compaction properties, representative of those possessed by mixtures immediately after their placement in potholes, can be assessed for all products by means of CBR tests, while the applicability of indirect tensile strength tests is limited to mixtures in which the binding matrix has a sufficiently high cohesion. High-compaction properties, achieved in long-term conditions under traffic loading, can be described for all mixtures by means of resilient modulus and quick shear tests which provide information on stiffness and type of failure.

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