Compactability and Thermal Sensitivity of Cement-Bitumen Treated Materials

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ABSTRACT. Full depth reclamation is one of the most used rehabilitation methods for subbase courses in high-traffic roads. The use of both cement and bituminous binder as binding agents for reclaimed pavement materials can lead to mixtures having high bearing capacity and resistance to permanent deformation, avoiding premature cracking due to shrinkage.

This paper focuses on two main topics: compactability and thermal sensitivity of cement-bitumen treated materials (CBTM).

Liquid dosage in CBTM is a key parameter in order to obtain an effective compaction. The volumetric characteristics and the optimum liquid content of CBTM were studied by means of two compaction methods: Proctor and shear gyratory compactor.

The temperature susceptibility of CBTM can be a valuable factor in both design and construction quality control. The influence of temperature on the stiffness modulus of CBTM was investigated using two testing methods: indirect tensile stiffness modulus (ITSM) and ultrasonic pulse velocity (UPV). While ITSM provided reference modulus values at strain levels and rates typical of traffic loads, UPV was used to estimate the Young modulus at very low strain levels and high frequencies.

KEYWORDS: Full depth reclamation, cement-bitumen treated materials, compactability, thermal sensitivity.
1. Introduction

From the early 1990’s, the pursuit of environmentally sustainable and cost effective technologies for asphalt pavement construction and rehabilitation promoted the diffusion of cold-in place recycling technologies. A wide range of cold recycled mixtures has been produced, using different combinations of recycled aggregates, additives and binding agents (Thompson et al., 2009). Each mixture type is optimized to obtain the required mechanical and durability performance with regard to its function in the pavement structure (Maccarrone et al., 1995; Kearney, 1997; Kandhal et al., 1997; Lewis and Collings, 1999; Morton et al., 2002).

At the current state-of-the-practice, two main cold in-place procedures can be categorized.

The term *cold in-place recycling* (CIR) is used to identify procedures where only bituminous layers are milled and incorporated in the recycled mixture. In CIR, reclaimed asphalt (RA), containing high quality aggregates and bitumen, is actually *re-used* adding bitumen emulsion and chemical or mineral additives. Virgin aggregates can also be included to obtain an optimal gradation.

The term *full-depth reclamation* (FDR), is used to identify procedures where recycling machines mill the surface bituminous layers together with the underlying unbounded or cement-treated courses. At the same time, or with a second pass, cement, foamed bitumen or bitumen emulsion are added to improve the properties of the recycled mixture. FDR technologies allow a larger amount of material to be recycled, with considerable environmental advantages over CIR. However, lower quality mixtures are generally produced and must be protected from heavy-load induced stress by thicker asphalt layers. Through FDR a wide range of mixtures, characterized by different mechanical behaviour, can be produced varying the binding agent type and dosage.

At least four cold-recycled mixture families can be distinguished. In figure 1 they are compared to traditional pavement materials using the representation proposed by Asphalt Academy (Asphalt Academy, 2002).
If only cement is added as binding agent, an almost conventional cement treated materials (CTM) can be obtained (White et al., 2002, Ramzi et al., 2002, Paige-Green et al., 2006). CTM including recycled aggregates typically shows high stiffness and tendency to premature cracking (brittle behaviour).

Bitumen Stabilized Materials (BSM) are produced using bituminous emulsion or foamed bitumen as binding agent. The residual bitumen, usually does not exceed 3% by aggregate weight, and up to 1% of cement (by aggregate weight) can be added as “active” filler. The ratio of bitumen content to cement content is greater than 1 (Asphalt Academy, 2009). BSM shows a stress-dependent mechanical behaviour that is similar to granular materials (failure by permanent deformation or shear stress). In fact the bitumen dispersed among the fine aggregate fraction creates “non-continuous” bonds between coarser particles, increasing resistance to fracture, cohesion and shear properties (Jenkins et al., 2007).

For other applications, higher cement contents, up to 2.5% by aggregate weight, can be used. These mixtures, referred as cement-bitumen treated materials (CBTM), are characterized by considerably higher cohesion and stiffness respect to BSM. The basic idea for CBTM is to start from a cement treated material (CTM) and, adding bitumen emulsion, reduce cracking susceptibility and the overall structural stiffness of the recycled layer. This brings to a mechanical behaviour closer to that of a bituminous mixture as thermal dependency and fatigue issues appear. Dosages of
residual bitumen and cement control stiffness and thermal sensitivity of CBTM: these factors must be addressed both in the design and in the construction control phase (Bocci et al., 2010). For instance, in the interpretation of falling weight deflectometer (FWD) tests, the temperature sensitivity of CBTM must be carefully considered (Loizos, 2007, Fu 2007). The use of CBTM, originally considered to be not economically viable, has been documented by various authors (Thompson et al., 2009, Santagata et al., 2009).

Cold asphalt mixtures (CAM) are produced using high bitumen dosage and a limited cement addition (“active” filler). Although, CAM are significantly different from traditional hot mix asphalt (HMA), their mechanical behaviour can be analysed following similar approaches (Montepara and Giuliani, 2002, Santagata and Chiappinelli, 2003). CAM are generally suitable for base or binder courses and often share the same specifications of HMA.

Mix design procedures for cold-recycled mixtures are generally adapted from those employed for conventional hot bituminous mixtures (Maccarrone et al., 1995, Santagata et al., 2004, Recasens et al., 2000, Mallick et al., 2001). Mixture grading and the dosages of residual bitumen, water, additives and active filler, are optimized through the assessment of the volumetric, mechanical and durability properties of the compacted mixtures. Static, Marshall, Proctor, gyratory and vibratory compaction have been used to prepare laboratory specimens.

The presence of a water-based binding agent makes the total amount of liquids in the mixture essential to obtain workability at ambient temperatures. Indeed, especially for emulsion stabilised mixtures, liquids act as lubricants during the compaction phase. A proper liquid dosage and a suitable emulsion formulation are therefore crucial to avoid premature breaking, that could lead to non-homogeneity in the mixture and compaction difficulties.

Both cationic and anionic emulsions have been used for cold recycling. An improved emulsion composition (over-stabilized emulsions) is essential, especially for FDR, while the use of rejuvenating agents is only occasional. In some countries polymer modified binders are used to improve fatigue properties of the recycled mixture.

The amount and quality of fines (fraction passing the 0.063 mm sieve) in the pulverized material is extremely important. In particular, if foamed bitumen is used for the stabilisation, the bitumen droplets and the fines form a mastic that acts as binder for the coarser aggregates. A minimum amount of fines, generally greater than 5%, is therefore required. When bitumen emulsion is used the amount of fines is less critical, since the bitumen partially coats the coarser aggregates.
2. Objectives

The study presented in this paper focuses on two important aspects of CBTM design and performance: compactability and thermal sensitivity.

In the first part, the influence of liquids content (emulsion and water) on CBTM compactability has been studied using two standard compaction methods: Proctor and Shear Gyratory Compactor (SGC). These methods have been selected because they represent the current standards for granular and bituminous materials. The objective was to evaluate the influence of liquids content, also comparing different compaction methods and energies. Compaction tests have been analysed using a volumetric approach similar to that of bituminous mixtures.

In the second part, the thermal sensitivity of CBTM mixtures has been studied focusing on modulus and fracture resistance. Based on the results of the first part, mixtures with different residual bitumen dosage have been prepared at optimum liquids content using a SGC. The same mechanical tests have been carried out on an additional mixture, sampled at a FDR project jobsite. The objective was to evaluate the influence of bitumen content on thermal sensitivity, also considering the different origin of the mixtures (laboratory and field).

3. Volumetric analysis of CBTM

CBTM composition can be extremely variable. In fact, several fractions of natural and recycled aggregates can be blended, and dosages of bitumen, cement and water need to be adjusted for each project. Hence, an accurate definition of CBTM volumetric properties is necessary to analyse the mixture in its “fresh” state (mixing and compaction phases) and after curing (in service).

In the mixing and compaction phases, bitumen emulsion and additional water work together as a single liquid phase that reduces internal friction facilitating the homogenization and densification processes. Indeed, the use of over-stabilized emulsions cannot be overemphasized as the use of standard emulsions would lead to early breaking and the formation of bitumen clots inside the mixture.

A fraction of the total water incorporated in the mix is absorbed by aggregates, the remaining part, together with the emulsion (before breaking), contribute to the compaction process as a free liquid phase. Note that during FDR, when additional water is required, it must be added before emulsion and cement, to allow for moisture homogenization and particles saturation. In order to evaluate CBTM volumetric characteristics, the free water content \( W_F \), the absorbed water content \( W_A \), the residual bitumen content \( B_R \) and the free liquids content \( L_F \) can be defined as follows:

\[
W_F = \frac{M_{w,F}}{M_{R,R} + M_S} \times 100
\]  

(1)
\[ B_R = \frac{M_{B,R}}{M_{B,R} + M_S} \times 100 \]  
\[ L_F = \frac{M_{B,R} + M_{W,F}}{M_{B,R} + M_S} \times 100 \]

where \( M_{W,F} \) is the mass of free water (water not absorbed by aggregates, either added separately or part of the bituminous emulsion), \( M_{B,R} \) is the mass of residual bitumen in the emulsion and \( M_S \) is the total mass of solids (aggregates and cement).

\( a) \) constituents by mass

\( b) \) constituents by volume

**Figure 2.** Constituent materials and volumetric characteristics of CBTMs
The solid phases of CBTMs generally consist of Reclaimed Asphalt (RA), Recycled Aggregates (RAg) from cement bounded layers or unbounded layers, Virgin Aggregates (VAg) of different petrographic nature, fillers, and Cement (C). Permeable voids of aggregate particles should be considered to correctly state weight-volume relationships, and the relevant particle density should be used. For example, in the laboratory, where aggregates are weighted separately, their volumetric dosages can be evaluated using the apparent particle density $\rho_{a}$, defined in clause 3.3 of the EN 1097-6. Whereas, for the volumetric analysis of a compacted mixture, the use of saturated surface dry density of particles $\rho_{ssd}$, defined in clause 3.4 of the EN 1097-6, can be more convenient as it includes the weight of absorbed water.

CBTM composition can be characterized by the maximum density $\rho_{m}$ which represents the mass per unit volume of the mixture, at zero voids:

$$\rho_{m} = \frac{\sum M_{i}}{\sum V_{i}} \quad (4)$$

where $M_{i}$ represent the mass of constituent materials (Figure 2a) and $V_{i}$ is their volume (Figure 2b). Water shall not be included in the calculation of $\rho_{m}$ since moisture changes during compaction, curing and service life of CBTMs. The maximum density can be obtained using the procedures described for bituminous mixtures (EN 12697-5), for example applying the mathematical procedure:

$$\rho_{m} = \frac{100}{\sum_{i} \frac{P_{i}}{P_{i}}} = \frac{P_{VAg} + P_{RAg} + P_{C} + P_{B,R}}{P_{VAg} + P_{RAg} + P_{C} + P_{B,R}} \quad (5)$$

where $P_{i}$ represent the content of each constituent material, as percent of the total mixture mass, and $P_{i}$ is its density (the apparent particle density $\rho_{a}$ is used for aggregates). In equation (5) only Residual Bitumen added with the emulsion, is explicitly considered, whereas the bitumen content of RA is already included in the value $\rho_{a,RAg}$. Similarly to bituminous mixtures, the maximum density of CBTMs can be considered as a constant value throughout the service life; its variability is obviously larger in CBTM respect to bituminous mixtures because of larger uncertainties in the constituent materials densities.

The bulk density of the CBTM mixture ($\rho_{b}$) is defined as:

$$\rho_{b} = \frac{\sum M_{i}}{V_{T}} \quad (6)$$

where $M_{i}$ represents the mass of each constituent material, including water, and $V_{T}$ is the total volume of the mixture, including air voids.
The bulk density can be used to evaluate the degree of saturation of the mixture, especially in the compaction phase when water and bitumen work together as a single liquid phase. After the emulsion breaking this liquid phase does no longer exist: residual bitumen coalesces coating aggregates and gives its contribution to mechanical performance (effective bitumen); water reacts with cement during the curing process and afterwards its content varies during service life.

The compaction of unbound mixtures, CTM and BSM is usually evaluated through the dry density ($\rho_d$): the ratio of the total mass of solids to the total mixture volume. Although during CBTM compaction emulsion bitumen acts as a liquid in reducing internal friction, its bitumen content remains constant and influences the mixture performance during service life. Therefore, for the dry density computation, the mass of residual bitumen should be added to the solids:

$$\rho_d = \frac{M_S + M_{B,R}}{V_T} = \frac{M_{Vig} + M_{Rd} + M_{Rbg} + M_C + M_{B,R}}{V_T} \quad (1)$$

where the symbols of Figure 2 have been used.

The use of $\rho_d$ to evaluate CBTM compactability can be misleading when different mixtures need to be studied, typically for mix design. For example, comparing dry densities of mixtures having different fractions of virgin and recycled aggregates is not appropriate since the particle densities usually differs and this affects the maximum density, as showed by equation (3).

Referring to the current practice for bituminous mixtures, a volumetric evaluation of CBTMs could be more appropriate. With this purpose, the use of voids in the aggregate (VA) is proposed:

$$VA = \frac{V_V + V_{W,F} + V_{B,R}}{V_T} \cdot 100 \quad (2)$$

where $V_V$ is the volume of air voids, $V_{W,F}$ is the volume of free water (not absorbed by aggregates), $V_{B,R}$ is the volume of residual bitumen, and $V_T$ is the total mixture volume (Figure 2b). Voids in the aggregate give a volumetric evaluation of solid skeleton packing achieved with compaction. Using equations (1), (2) and (7), equation (8) can be rewritten as:

$$VA = V_m + \frac{\rho_d \cdot B_R}{\rho_g} \quad (3)$$

In equation (9), $V_m$ represents the content of air voids and free water (volume of the “not structural part”) in the total mixture volume:
During compaction water fills part (unsaturated condition) or all (saturated condition) this volume, however water should not be considered when characterising CBTM or evaluating the compaction effectiveness. Therefore $V_m$ has to be calculated taking into account the dry density ($\rho_d$, equation 7) and not the bulk density ($\rho_b$, equation 6):

$$V_m = 100 \cdot \frac{\rho_w - \rho_b}{\rho_d}$$  \hspace{1cm} (11)$$

Another important parameter to evaluate CBTM volumetric properties before emulsion breaking, is the fraction of $V_A$ that is filled with effective liquids, water and bitumen. This can be evaluated by the volume of voids filled with liquids (VFL):

$$VFL = \frac{V_{w,f} + V_{b,f}}{V_f + V_{w,f} + V_{b,f}} \cdot 100$$  \hspace{1cm} (12)$$

Using equations (1), (2) and (7), equation (12) can be rewritten as:

$$VFL = \left( W_f \frac{\rho_d}{\rho_w} + B_a \frac{\rho_b}{\rho_w} \right) \frac{100}{VA}$$  \hspace{1cm} (13)$$

and, assuming $\rho_w = \rho_b$:

$$VFL = \left( L_f \frac{\rho_d}{\rho_w} \right) \frac{100}{VA}$$  \hspace{1cm} (14)$$

The VFL value computed with equation (13) or (14) is similar to the degree of saturation, except that particle voids that are permeable to water are considered saturated.
4. Experimental program

4.1 Materials

The recycled aggregates used to prepare CBTM laboratory samples were obtained from a FDR project performed for the structural rehabilitation and upgrading of a 42 km section of an Italian motorway (Santagata et al., 2009).

The RA was sampled after the milling of the asphalt concrete of the existing emergency lane. The RA was characterized in terms of density and gradation (Figure 3, “RA” curve). The particles apparent density ($\rho_a$) was evaluated as 2,490 kg/m$^3$ and the water absorption $WA_{24}$ was equal to 0% (EN 1097-6). In accordance with the EN 13108-8, the RA used was designated as 25 RA 0/14.

Two crushed limestone fine aggregate sizes (0/2 and 0/4 according to EN 13242) having the same origin and physical properties ($\rho_a = 2,730$ kg/m$^3$, $WA_{24} = 1.53\%$) have been added to the RA to obtain the final aggregate blend for laboratory prepared samples.

The binding agents were also taken from the aforementioned FDR project: a cement type II/B-LL 32.5 R and an over-stabilised bituminous emulsion C 60 B 5 (EN 13808). The emulsion (Table 1) has a slow setting behaviour and acts as lubricant during the compaction phase. Its special formulation was designed to mix high fines contents, therefore, long workability times and stability can be achieved.

Dosages of the binding agents in the mixtures are given respect to dry aggregate weight (Table 2).

<table>
<thead>
<tr>
<th>Emulsion characteristics</th>
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<tbody>
<tr>
<td>Water content (EN 1428)</td>
<td>40%</td>
</tr>
<tr>
<td>pH value (EN 12850)</td>
<td>3</td>
</tr>
<tr>
<td>Settling tendency @ 7 days (EN 12847)</td>
<td>8%</td>
</tr>
<tr>
<td>Breaking value (EN 13075-1)</td>
<td>180 g</td>
</tr>
<tr>
<td>Mixing stability with cement (EN 12848)</td>
<td>0.2 g</td>
</tr>
<tr>
<td>Application temperature</td>
<td>5 - 80°C</td>
</tr>
<tr>
<td>Characteristic of the extracted bitumen</td>
<td></td>
</tr>
<tr>
<td>Needle penetration (EN 1426)</td>
<td>70 dmm</td>
</tr>
<tr>
<td>Softening point (EN 1427)</td>
<td>50°C</td>
</tr>
</tbody>
</table>
Table 1. Characteristics of the over-stabilised bituminous emulsion

| Fraass breaking point (EN 12593) | -10°C |

4.2 Mixtures

Two types of aggregate blends (mixes A and B) have been studied in this research (Table 2). Mix type A was produced in the field during the cited FDR project, whereas mix type B was prepared in the laboratory blending RA sampled from the FRD project, and virgin aggregates.

For mix type A an aggregate blend consisting of about 50% RA and 50% cement-treated and unbound aggregates was obtained from the FDR jobsite (Figure 3, “Mix A” curve). The FDR procedure involved a two-phase milling sequence: the asphalt concrete layers were milled during the first recycler pass, while the underlying cement-treated layer and unbound foundation were milled with a second recycler pass. The milling sequence and successive construction phases are described in detail elsewhere (Santaga et al., 2009). The binding agents employed for mix type A were 2% Portland cement and emulsion with 1.8% residual bitumen; accordingly, mix A was named B18C2 (Table 2). The CBTM mixture was sampled and compacted directly at the FDR jobsite, and had 5.5% water content.

For mix type B the aggregate blend consisted of 50% RA, 42% of virgin fine aggregate and 8% of natural filler (Figure 3, “Mix B” curve). The fine aggregates were blended in order to produce a continuous graded blend respecting the guidelines for grading of BSM (Asphalt Academy, 2009). A high filler content was selected in order to improve the cohesion of mastic and to reproduce the maximum density curve for a maximum aggregate size $D = 20$ mm (Figure 3, “D20” curve). The binding agents employed for mix type B were: 2% Portland cement and four amounts of bituminous emulsion with 1.5%, 2.0%, 2.5% and 3.0% of residual bitumen. Therefore, four type B mixes were studied, namely B15C2, B20C2, B25C2 and B30C2 (Table 2). For each mix, specimens at different water contents were prepared, as specified in section 6 (Table 3). For the preparation of laboratory mixtures, a water amount corresponding to the water absorption of aggregate blend was initially added to the dry aggregate. To obtain a homogeneous humidity before binder addition, the blend was sealed and kept in a plastic bag for 12 hours before compaction. Each sample was then thoroughly mixed with water, as required by the test program (from 4% to 8%). The water added to the mixture by the bituminous emulsion was subtracted from this quantity. Finally, the required amounts of cement and bituminous emulsion were added and mixed in sequence, for two minutes. A visual evaluation of coating was made after mixing to check for homogeneity and verify that mixture breaking did not take place. To simulate the FDR procedure, no pre-compaction curing was done.
Figure 3. Mixture and RA gradations

<table>
<thead>
<tr>
<th></th>
<th>Mix Type A</th>
<th>Mix Type B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preparation:</td>
<td>FDR Jobsite</td>
<td>Laboratory</td>
</tr>
<tr>
<td>Aggregate blend:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Virgin Aggregate, VA (%): &gt;3</td>
<td>0</td>
<td>42</td>
</tr>
<tr>
<td>- Reclaimed Asphalt, RA (%): &gt;3</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>- Recycled Aggregate, RA (%): &gt;3</td>
<td>50</td>
<td>-</td>
</tr>
<tr>
<td>- Filler (%)</td>
<td>-</td>
<td>8</td>
</tr>
<tr>
<td>Binding agents:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Cement, C (%)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>- Residual Bitumen (%)</td>
<td>1.8 (B18C2)</td>
<td>1.5 (B15C2)</td>
</tr>
<tr>
<td>Water, added + emulsion (%)</td>
<td>5.5</td>
<td>Variable</td>
</tr>
</tbody>
</table>

Table 2. Mixture identification and composition summary
5. Equipment and procedures

5.1 Compaction

The influence of liquids content on mixture compactability was studied using Proctor (EN 13286-2) and Shear Gyratory Compaction (EN 12697-31). The SGC was also used to prepare specimens for mechanical tests.

The Proctor compaction tests was carried out using modified energy (about 2.7 MJ/m³) and mould B (diameter 150 mm, height 120 mm). Moulds routinely used for asphalt concrete were employed; no sealing was provided therefore, when approaching saturation, water was free to get out during compaction.

For the SGC a 150 mm diameter mould was used. Other SGC parameters were: vertical pressure of 600 kPa, gyration speed of 30 rpm, energy of 180 gyrations and angle of 1.25°. In the compactability study 4.5 kg specimens were prepared in order to obtain a final volume similar to Proctor specimens. For the mechanical tests, 2.7 kg specimens were compacted at 100 gyrations to obtain a suitable height (about 70 mm).

After compaction, CBTM specimens were sufficiently stable to allow extrusion immediately, than specimens were stored in a climatic chamber at 20°C above 70% of relative humidity.

5.2 Mechanical tests

A servo-pneumatic testing machine was used to characterize the mixtures in terms of Indirect Tensile Stiffness Modulus (ITSM), in accordance with Annex C of EN 12697-26. Repeated load pulses were applied along a vertical diameter of the specimen, with rise time of 124 μs, and two LVDTs mounted opposite one another in a rigid frame clamped to the specimen were used to measure horizontal diametral deformation. A target horizontal deformation of 2 μm was applied, whereas the target deformation used for hot mix asphalt is 7 μm. The use of this small value was necessary to avoid specimens failure during the test preconditioning phase.

The propagation velocity of stress wave pulses through a material allow to determine the uniformity (presence of cracks and voids) and the dynamic modulus of elasticity of the material (EN 12504-4, ASTM C 597-02). Ultrasonic Pulses were generated by a transmitting transducer, which is held in contact with one surface of the specimen under test. On the opposite side another transducer receives the stress waves. The time interval elapsed to cover the distance between transmitting and receiving transducer allows to deduce the Ultrasonic Pulse Velocity.

A servo-hydraulic testing machine was used for Indirect Tensile Test (ITT) according to EN 13286-42. The load was applied in a continuous manner to obtain a uniform increase in stress of 0.05 MPa per second.
6. Test program

The experimental program was divided in two phases (Table 3). The first phase aimed to determine the influence of liquids content on CBTM compactability, and compare two laboratory compaction methods (Proctor and Shear Gyratory). The second phase investigated the temperature sensitivity of cured CBTM in terms of ITS and Dynamic Modulus obtained by Ultrasonic Pulse Velocity; the influence of bitumen dosage on Indirect Tensile Strength (ITS) was also verified.

The compactability study was carried out on type B (laboratory) mixes. For each emulsion content specimens were prepared at five different water contents: 4.0%, 5.0%, 6.0%, 7.0% and 8.0%. These moisture values indicate the weight ratio of the total water included in the mix (including emulsion water) to the total solids. A five-point Proctor compaction curve and five SGC compaction curves were obtained for each emulsion content (40 specimens in total).

The thermal sensitivity study was carried out on type A (jobsite) and type B (laboratory) mixes. In particular, type B mixes (B15C2, B20C2, B25C2 and B30C2) were compacted using the SGC at the optimum water content determined in the first phase. Four replicate specimens were tested for each mix. The stiffness was measured at 5°C, 20°C, 35°C and 50°C using ITSM and UPV after a curing time of 35 days at 20°C in a climatic chamber, which supposes the definitive curing been reached (Bocci et al., 2011). All specimens were also tested to assess the influence of bituminous emulsion dosage on strength, by means of ITT at 25°C.

<table>
<thead>
<tr>
<th>Test Methods</th>
<th>Phase I (Compactability)</th>
<th>Phase II (Temperature sensitivity)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Mixes</td>
<td>• Mix type B (B15C2, B20C2, B25C2 and B30C2), each at 5 water contents (4.0%, 5.0%, 6.0%, 7.0% and 8.0%)</td>
<td>• Mix type A (B18C2), at 5.5% water content; • Mix type B (B15C2, B20C2, B25C2 and B30C2), each at optimum water content</td>
</tr>
</tbody>
</table>

Table 3. Test program summary
7. Results and analysis

7.1 Compactability

7.1.1 Proctor compaction

The Proctor compaction test was used to assess the influence of water and bituminous emulsion on CBTM compactability. Results are showed in Figure 4 for mix type B, as dry density (equation 7) and voids in aggregate (equation 8) versus free water content (equation 1) and free liquids content (equation 3).

The typical “bell-shaped” curves were obtained for all samples, with an optimum free water content located around 6%, for all mixtures. However, a unique value of optimum free liquids content was not found: the compaction curves appear to be horizontally shifted by the amount of residual bitumen (0.5% steps). This indicates that, even before emulsion breaking, the effective bitumen did not give its contribution to the compaction process.

This behaviour is significantly different from the one assumed for BSM (Asphalt Academy, 2009) where the Proctor optimum liquid content (water + bitumen) is determined using only water, implicitly assuming that bitumen will behave exactly like water during compaction. The fluidity of the emulsified bitumen can be represented by a simple model proposed for the mix design of cold-recycled bituminous mixtures (Santagata and Chiappinelli, 2004):

\[ \%L_{opt} = \%W + (a + K b)\%E \]  \hspace{1cm} (15)

where \(\%L_{opt}\) is the optimal liquid dosage, \(\%W\) is the added water dosage and \(\%E\) is the emulsion dosage. Coefficients \(a\) and \(b\) correspond to the weight ratios of the water and bitumen phases, respectively, to the total emulsion, while \(K\) is a “fluidity index” comprised between 0 and 1. For \(K = 1\) the bitumen contained in the emulsion has an effect which is equivalent to that of water; for \(K = 0\) the liquids that control compaction are the sum of water added to the mixture and of that contained in the emulsion. The results of the present study show that is possible to consider \(K = 0\). This is also confirmed if the Proctor compaction tests are analysed using a volumetric approach.
The increase of residual bitumen content generally caused a decrease of dry density, as expected, and also led to an increase of VA. Since bitumen volume is part of VA (equation 5), this confirms that, from a volumetric point of view, the effective bitumen added with the emulsion can be treated as a solid phase, and should not be considered a substitute of water.

7.1.2 Shear Gyratory compaction

In addition to Proctor compaction, she SGC was used to study the influence of water and bituminous emulsion on CBTM compactability. For each type B mix (B15C2, B20C2, B25C2 and B30C2), specimens were compacted at five water contents (4.0%, 5.0%, 6.0%, 7.0% and 8.0%) reaching 180 gyrations.
As an example, the compaction curves obtained for B20C2 and B25C2 mixes (2% of cement, 2.0% and 3.0% residual bitumen contents respectively) were reported in Figure 5 and Figure 6. For each water content, VA and VFL were calculated considering the height data recorded during the compaction process and the initial composition of the mixtures. VA and VFL were plotted versus the number of gyrations ($N_g$), on a logarithmic scale.

**Figure 5. SGC test results for mix B20C2 (2.0% cement, 2.0% residual bitumen)**
Two types of compaction curves were identified (figure 7). At lower water contents ($W_1$), a linear relationship between VA and the logarithm of $N_g$ can be assumed up to above 100 gyrations. At higher water contents ($W_2$), the relationship between VA and log $N_g$ becomes bi-linear. Observing Figures 5 and 6, the point of inflection can be located at the number of gyrations corresponding to a VFL of about 90%. This means that, as VA are reduced, liquids tend to fill them (mixture approaches to saturation), then part of the compaction energy is spent to increase pore liquid pressure. The linear portion of the compaction curves can be modelled as:

$$VA = VA_1 + k \log N_g$$  \hspace{1cm} (16)

where $VA_1$ is the voids in aggregate at 1 gyrations and $k$ is the slope of the semi-logarithmic plot. The parameter $VA_1$ is a measure self-compaction of the mixture, while $k$ represents its workability. Observing the experimental values, it is possible to notice that the added water content had limited effect on workability and it mainly influenced the self-compaction (columns of Table 4). Moreover, the residual bitumen content had a limited effect both on workability and self-compaction (rows of Table 4).
Figure 7. SGC test results for sample B30C2 (2.0% cement, 3.0% residual bitumen)

![Graph showing SGC test results for sample B30C2](image)

Table 4. Compaction curves parameters

<table>
<thead>
<tr>
<th>Added water (%)</th>
<th>CBTM mix (type B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$VA_1$</td>
<td>$k$</td>
</tr>
<tr>
<td>4</td>
<td>33.9</td>
</tr>
<tr>
<td>5</td>
<td>34.6</td>
</tr>
<tr>
<td>6</td>
<td>33.1</td>
</tr>
<tr>
<td>7</td>
<td>32.5</td>
</tr>
<tr>
<td>8</td>
<td>33.4</td>
</tr>
</tbody>
</table>

7.2 Influence of temperature

The stiffness modulus values measured with ITSM test are shown in Figure 8. The temperature dependency was described using the following analytical model.

\[
\log S = -\alpha \cdot T + b \tag{17}
\]
where $S$ is the stiffness modulus (or elastic modulus) at temperature $T$, and $\alpha$ and $b$ are experimental parameters depending on the material characteristics. Temperature sensitivity is represented by the slope of the regression curve, that is the parameter $\alpha$. Obviously, the higher the $\alpha$ value, the more temperature sensitive the mixture is.

Results confirmed the thermo-dependence of CBTM (Bocci et al., 2011), showing a decrease in modulus with the increase in temperature. As shown in Table 5, the analytical model allows good fitting to be obtained and the values of $\alpha$ (equation 18) varied as a function of residual bitumen dosage from about 0.006 to about 0.009. Except for B18C2 that was produced in situ, $\alpha$ increases with the increase in residual bitumen dosage (Figure 8). Note that B18C2 has the lowest fine contents and probably the bituminous emulsion does not achieve a good coating of aggregates and the material resulted less thermo-sensitive.

Figure 9 shows the linear regression that can be used to determine the $\alpha$ value in a range of temperature from 5 to 50°C for CBTM having 2% of cement dosage and a bitumen dosage from 1.5 to 3.0%. For similar recycled mixtures, the relationship between stiffness and temperature as a function of residual bitumen content can be an useful tool in control phase to shift the back-calculated modulus from field temperature to reference temperature and in design phase to calculate the stress-strain responses as a function of seasonal temperature.

![Figure 8](image-url)

*Figure 8. ITSM values as a function of temperature for all series, rise-time of 124 ms*
The elastic modulus values determined through UPV test are shown in Figure 10. The results from UPV confirm the thermo-sensitivity of CBTM. Also in this case, the value of $\alpha$ (equation 18) generally increases as the residual bitumen dosage increases (Table 6). However, due to higher testing frequency the thermo-sensitivity of CBTM is less evident. Time-temperature superimposition principle seems to be applicable, and the stiffness moduli obtained by UPV can be considered a good estimation of the ITSM at the higher loading frequencies. Thus, taking into account the effect of the loading frequency, the UPV can be used as a practical method for the rapid evaluation of CBTM stiffness.
Figure 10. Elastic modulus values as a function of temperature for all series, frequency of 59 kHz

Table 6. Fitting parameters for all series, frequency of 59 kHz

7.3 Indirect tensile strength

ITT were carried out on the same specimens tested for ITSM after further four hours of conditioning time at 25°C. Figure 11 shows the average of ITS and standard deviation for all series. A t-test, at 95% confidence level, revealed that the difference between the ITS of B20C2 and B25C2 has no statistical significance. Therefore, it can be asserted that the B20C2 and B25C2 series achieved the highest ITS.
The ITS and ITSM results were compared and evaluated with regard to residual bitumen/cement ratio (percentage expressed by aggregate weight). It is interesting to note from Figure 12 that the graph can be divided into four quadrants with regard to residual bitumen/cement ratio. Indeed, residual bitumen/cement ratio less than 1 implies high stiffness and low ITS values, whereas when the bitumen/cement ratio is approximately 1 the mixture provided both high stiffness and ITS values. Finally, if the bitumen/cement ratio is more than 1 the mixture showed low stiffness and ITS values. This means that cement allows high stiffness to be reached and, increasing the residual bitumen dosage, high fracture resistance can be provided, too. However, when higher dosage of bituminous emulsion is used, the mixture becomes more ductile and the stiffness decreases. In this case the cement is included in the mastic and it is not allowed to form stiff bonds with aggregates.

**Figure 11.** Mean values of ITS at 25°C for the series produced in laboratory (lab. aggregate blend)
8. Conclusions

The paper describes an experimental study concerning the compactability and the thermal sensitivity of CBTM. The following conclusions can be drawn:

- a rational approach to the volumetric characterization of CBTM is proposed, considering the heterogeneity of aggregate composition and the effective bitumen role in the mixture;
- the “bell-shaped” curves obtained by means of Proctor compaction showed an optimum free water content for all mixtures. A unique value of optimum free liquids content was not found. This indicates that, even before emulsion breaking, the effective bitumen did not give its contribution to the compaction process;
- the increase of residual bitumen generally caused a decrease of dry density, and an increase of voids in the aggregate. From the volumetric point of view the effective bitumen added with emulsion can be treated as a solid phase, and should not be considered a substitute of water;
- two types of SGC compaction curves were identified: linear (at low water content) and bi-linear (at high water content). The point of inflection of the bi-linear regression is located at the number of gyrations corresponding to a voids filled with liquids of about 90%, indicating that, as VA are reduced, liquids tend to fill them (mixture
approaches to saturation), then part of the compaction energy is spent to increase pore liquid pressure;

- the added water content had limited effect on SGC workability and mainly influenced self-compaction. Moreover, the residual bitumen content had a limited effect both on workability and self-compaction;

- ITSM and UPV results showed the thermo-sensitivity of CBTM;

- the relationship between stiffness and temperature as a function of residual bitumen content can be an useful tool in control phase and in design phase;

- the bitumen/cement ratio controls the stiffness and resistance to fracture of CBTM.

Bibliography


White G. and Gnanendran C., “The characterization of cementitious in situ stabilized pavement materials: the past, the present and the future”, Road and transport research, Vol. 11, No. 4, p. 56-69, 2002.