# Synthesis of Specimen Preparation and Curing Processes for Cold Recycled Asphalt Mixes

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ABSTRACT: The process of cold recycling (CR) is becoming method of choice for pavement rehabilitation due to significantly added environmental and economic benefits. Understanding and standardization of specimen preparation and curing processes are critical to replicate field conditions in lab. This paper presents an extensive synthesis of various specimen preparation and curing processes for cold recycled asphalt mixes. Topics synthesized include RAP, emulsion/bitumen and aggregate preparation, mixing processes, pre- and post-compaction curing, compaction and mechanical testing. This paper was developed through efforts of cold recycling task group (TG6) of RILEM Technical Committee on Testing and Characterization of Sustainable Innovative Bituminous Materials and Systems (TC-SIB).

## 1. Introduction

Preparation and curing process are the bases of a correct mix design process: only specimens representative of in situ material allow a correct evaluation of performances of in situ material. For this reason the task group on cold recycling (TG6) of RILEM Technical Committee on Testing and Characterization of Sustainable Innovative Bituminous Materials and Systems decided to focus his efforts on that topic. This paper shows the results of a literature review, mainly concentrated on technical manuals and standards, made collecting documents coming from almost all the countries of the world where cold recycling techniques are used.

## 2. Terminology, Process Classification and Definitions

Cold recycling of bituminous pavements involves reusing part of an existing pavement to produce, without (or with a limited amount of) heat, mixtures that will be included in new or rehabilitated pavement layers [1-3].

Similar to Hot Mix Recycling, two methods of cold recycling can be distinguished: Cold Plant Recycling (CPR) and Cold In-place Recycling (CIR). In both cases Reclaimed Asphalt Pavement (RAP) is mixed with a bituminous stabilizing agent and water. Virgin aggregates are often added to meet grading criteria, and active fillers, such as cement, lime, or fly ash, are normally used to accelerate the curing process and improve mixture properties [1,3].

CPR (also referred as Cold Central-Plant Recycling) is performed by hauling RAP material recovered by the Cold Planing process, generally by milling machines, to a central plant where it is selected, pre-treated (crushed and screened) and tested before it is fed in the mixing process. Therefore, central plant recycling allows an optimal control over RAP variability and quality of the recycled mix [1,3].

In CIR all the operations, from milling to mixing, are performed directly on site using single-unit or multi-unit trains. Even if this results in a reduced control of material and mix properties, in-place recycling is generally preferred over plant recycling because the elimination of the haulage yields substantial economic and environmental advantages [1,3].

CIR can be accomplished as partial-depth or full-depth recycling. In the current practice, the term CIR is used to indicate partial-depth recycling, while the term Full-Depth Reclamation (FDR) is used in the second case [1-4].

In CIR pavement milling is limited to the asphalt concrete layers, virgin aggregates may be added to RAP to meet grading requirements and bitumen emulsion is the most commonly used recycling agent. The recycled mix produced by CIR is a Cold Mix Asphalt (CMA) that is generally used for base or binder courses, depending on the traffic type and volume.

In FDR asphalt layers and portions of cement treated or unbound foundation layers are milled, mixed with binder, and placed as a new stabilized course. Modern recycling machines (Recyclers) that combine milling and stabilization capabilities are used to complete the FDR process in a single or more passes. Bitumen emulsion and foamed bitumen[1] are the most commonly used recycling agent and virgin aggregates are usually added to the reclaimed materials to meet specific grading requirements. Active fillers are also employed, in particular Portland cement.

Because of the great variability in aggregate quality and composition, type and amount of recycling agents, recycled mixtures produced by FDR can exhibit a wide range of mechanical behaviors, for example: Cement Treated Materials (CTM) [6,7], Bitumen Stabilized Materials (BSM) [8] and Cement-Bitumen Treated Materials (CBTM) [9,10].

## 3. French Procedure for Aggregate and Bitumen Emulsion Preparation for Making Lab Specimen

A French laboratory procedure to aggregates and bitumen emulsion preparation has been developed [11] and built on the basis of recommendations for the manufacture of the hot bituminous mix and the NF P98-250-1 Standard [12] for the cold mixes.

### 3.1 Preparation of Aggregates (Virgin and RAP)

It is possible to stock aggregates after acceptance, under sealed conditions, in order to preserve their natural water content. One or a few days before cold mix manufacturing, water content must be measured again:

- If the aggregates are wet (water content < 5 % for sand and < 2 % for the fine gravels), they are packaged at the ambient temperature of the laboratory (18 – 25 °C) in sealed conditions. Additional water is then added during manufacturing.
- If the aggregates are too wet (water content > 5 % for sand and > 2 % for the fine gravels), they are conditioned in a low thickness layer in containers at least 12 hours

[1] Actually the term "cold" is sometimes considered misleading when using foamed bitumen because, although the pavement is not heated during the milling process, the asphalt binder used in the foaming process is very hot (i.e., 150°C and 180°C) [5].

before manufacturing at ambient temperature; the second control of the water content of the aggregates can be useful right before manufacturing.

- The use of dry aggregates (water content < 0.5 % for sand) is proscribed. To be used, they will be humidified at least 24 hours before manufacturing and will be preserved in sealed conditions. However, on site, aggregates stocked can presented a dry state because of exceptional weather conditions (summer) and/or of storage conditions (shelter). In this case (rare), all the water will be added before or during mix manufacturing. Aggregates temperature must be around the lab ambient temperature (15 to 25 °C) and representative of that used on the power station.

### 3.2 Preparation of the Bitumen Emulsion

At the emulsion acceptance, it is recommended to preserve it in a temperature range from the ambient temperature of the laboratory (18° C to 25 °C) up to 40 ° C. Before using, emulsion must be homogenized (mechanical or manual stirring). Emulsion is employed in a temperature range from the ambient temperature of the laboratory to 60 °C. If the emulsion is fresh, a rest period of about 16 hours will have to be observed. The bitumen emulsion must be stocked during several weeks; a stirring action must be done every 15 days.

The procedure suggested for the preparation of the aggregates and bitumen emulsion (Figure 1) is based on the traditional manufacturing conditions according to the plant practices. The various steps of the components preparation are presented in Figure 1.

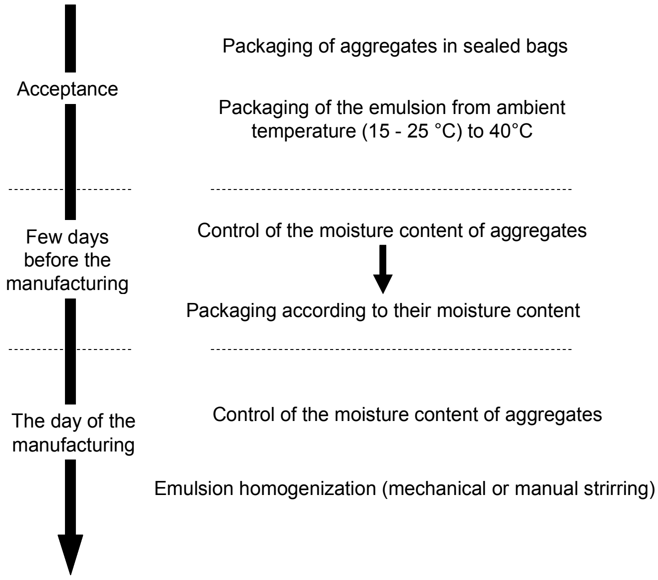


**Figure 1:** Steps of the components preparation in laboratory of aggregate-emulsion (copyright IFSTTAR)

## 4. Laboratory Mixing Process and Mix Composition

The aim of the laboratory mixing process is to distribute the different materials in the RAP mixture homogenously throughout the mixture. In addition, the laboratory mixing process should imitate the field mixing process if possible. In order to ensure relatively constant moisture content, the RAP material is dried prior to mixing. The drying methods include air drying [3,11] and oven drying. The oven drying temperatures vary from round $40^0$C [5] to

$60^0$C [16]. It should be noted that temperatures as high as $60^0$C are above the softening point of the binders and therefore are considered to change the nature of the mix.

Cold RAP mixtures are mixed in the laboratory at specific mixing conditions that may include temperature, mixing order and storage duration before compaction. In general, the mixing process can be divided into mixing conditions for RAP mixtures with and without added bitumen. Table 1 and Table 2 show the laboratory mixing conditions for some of the cold mix design methods considered in this literature review. The tables show the mixing conditions for the RAP mixture with and without bitumen.

**Table 1:** Mixing conditions for cold RAP mixture without added bitumen (i.e. RAP, cement or lime and water)

| Design Method | Temperature ($^0$C) | Mixing Order | Mixing Method | Storage Duration Before Compaction |
|---|---|---|---|---|
| California-foam bitumen [5] | 25 | RAP and cement mixed first. Then mixed with water. | Customized mixer | 0 |
| Norway-emulsion/foam bitumen [11] | Room temperature | RAP and water mixed together at once. | Mixer | At least 12 hours to allow moisture distribution. |
| Wirtgen-emulsion/foam bitumen [3] | Room temperature | RAP and cement or lime mixed first. Then mixed with water. | Mixer | 1 hour to simulate construction conditions. Mix after every 15 minutes. |
| South Africa-Using vibratory compaction [8,12] | Room temperature | RAP and cement or lime mixed first. Then mixed with water | - | 15-30 minutes |

**Table 2:** Mixing conditions for cold RAP mixture with added bitumen (i.e. RAP, cement or lime, emulsion or foam bitumen)

| Design Method | Temperature ($^0$C) | Mixing order | Mixing method |
|---|---|---|---|
| California-foam bitumen [5] | 25 | RAP and cement mixed. Then mixed with water. Foam bitumen added. | Customized mixer |

| | | | |
|---|---|---|---|
| Minnesota-emulsion [13] | 60 | RAP and water mixed. Then mixed with emulsion. | Manual |
| Norway-emulsion/foam bitumen [11] | room temperature | RAP, water and emulsion or foam bitumen mixed at once | Manual/mechanical |
| Wirtgen-emulsion/foam bitumen [3] | room temp | RAP, cement and some water mixed first. Then with foam bitumen. Then rest of the water. RAP, cement, water and emulsion mixed at once. RAP, lime and water mixed at least 4 hours prior to mixing with emulsion or foam bitumen. | Mechanical mixer |
| NYS DOT-proposed specification emulsion [14] | 25 | RAP mixed with water. Then with emulsion. | Manual/mechanical, one specimen mixed at a time, mixing time ≤ 60 seconds |
| South Africa-Emulsion using vibratory compaction [12] | should match field temperature | RAP and cement or lime (if required) mixed. Then mixed with water and stored for 15-30 minutes. Mix with emulsion and store for 40-60 minutes before compaction. | Pug-mill mixer recommended in order to simulate field mixing |
| South Africa-Foam bitumen using vibratory compaction [12] | should match field temperature | RAP and cement or lime (if required) mixed. Then mixed with water. Mix with foam bitumen. | Pug-mill mixer recommended in order to simulate field mixing |

The composition of the RAP mixture depends on the intended characterization test. The characterization tests include optimum moisture content, mixing moisture content (MMC[2]), optimum fluid content (OFC[3]) and evaluation tests for mixtures containing added bitumen. The tables[4] below give an overview of the composition of the cold mix designs considered in this review. Table 3, Table 4 and Table 5 show the mix composition for determination of OMC, MMC and OFC respectively. Table 6 shows the mix composition and evaluation tests for mixtures containing added bitumen.

[2] MMC = moisture content at maximum dry density in specimens composed of RAP, water and emulsion or foam bitumen.
[3] OFC = total fluid content (i.e. water + emulsion/foam bitumen) at maximum dry density in specimens composed of RAP, water and emulsion or foam bitumen.
[4] In these tables, (co) refers to constant quantity while (v) refers to varying quantity.

**Table 3:** Composition of cold RAP mixtures – Optimum moisture content (OMC)

| Method | Composition |
|---|---|
| California-foam bitumen [5] | RAP + water (v) + cement (1%) or lime (2%) |
| Norway-emulsion/foam bitumen [11] | RAP +water (v) |
| Wirtgen-emulsion/foam bitumen [3] | RAP + water (v) + cement or lime: cement or lime = (2-6%) by dry weight of RAP |
| South Africa [12] | RAP + water (v), cement or lime added if required. |

**Table 4:** Composition of cold RAP mixtures – Mixing moisture content (MMC)

| Method | Composition/comment |
|---|---|
| California-foam bitumen [5] | RAP + water (v) +cement or lime(co) +foam bitumen: foam bitumen = 3% by weight of dry material & MMC = 0.75 to 0.9 OMC |
| Norway-emulsion/foam bitumen [11] | MMC between OMC and (OMC-0.5%) |

**Table 5:** Composition of cold RAP mixtures – Optimum fluid content (OFC)

| Method | Composition/comment |
|---|---|
| Wirtgen-emulsion [3] | RAP + water (v) + emulsion (co): bitumen content in emulsion =2-3% by dry weight of RAP, specimens compacted using AASHTO T-180 |
| Wirtgen-foam bitumen [3] | OFC = OMC for foam bitumen mixes |
| South Africa-Emulsion [12] | RAP+ water (v) + emulsion (v): cement or lime added if required. |

**Table 6:** Composition of cold RAP mixtures – Optimum fluid content (OFC)

| Method | Composition {Intended Test} |
|---|---|
| California-foam bitumen [5] | RAP + foam bitumen (v) + water (MMC) {Indirect tensile test CT 371} |
| Method | Composition {Intended Test} |
| Minnesota–emulsion [13] | RAP + water (v) + emulsion (v): total water = 4% by total weight of mixture, emulsion <3% |
| Norway-emulsion/foam bitumen [11] | RAP + water (MMC )+ emulsion: emulsion = 2-3% {Indirect tensile test HB014 14.554} |
| Wirtgen-emulsion/foam bitumen [3] | RAP (co) + cement or lime (co) + water (v) + emulsion (v): water + emulsion = OFC<br>RAP (co) + cement or lime (co) + water (co) + foam bitumen (v): water = 0.9OMC for 100 mm diameter specimens or water = OMC for 150 mm diameter specimens.<br>{Indirect tensile test, unconfined compression strength} |
| Modified Marshall -emulsion ([15], AASHTO T-283) | RAP + water(v) + emulsion(v): total water = 3% {Maximum specific gravity}<br>RAP + water (v) + emulsion(optimum) {air voids content} |
| NYS DOT-proposed specification emulsion [14] | RAP + water (co)+emulsion (v): emulsion=0.5-4% by dry weight of RAP, water = 1.5-4.5% {Marshall stability at 400C} |
| South Africa – Emulsion [8] | RAP + water (v) + emulsion (v) + cement/lime (if necessary): total water = OFC, {Indirect tensile test for level 1 and 2, triaxial tests for level 3} |
| South Africa – Foam bitumen [8] | RAP + water (co)+ foam bitumen (v) + cement/lime (if necessary): water = 65 to 85%OMC, {Indirect tensile test for level 1 and 2, triaxial tests for level 3} |

## 5. Pre-Compaction Curing and Specimen Compaction

Cold Plant Recycling and Cold In-Place Recycling (CIR) of asphalt pavements are characterized by specific equipments and practices. The mixing phase of CPR is followed by transportation, laying and compaction, whereas mixtures produced by CIR are mixed and immediately compacted in-situ. The same rollers are generally employed for compaction in both technologies and pre-compaction procedures differ mainly in working time.

Cold Recycled Mixtures (CRM) produced by plant recycling and CIR are physically and mechanically similar, and their laboratory pre-compaction and compaction processes share the same equipments and follow the same operating steps. However, time and temperature effects, along with production-related aspects, should be taken into account.

Currently a universally accepted compaction procedure for CRM is not available. At the state of the practice, two main categories of laboratory procedures can be distinguished. The first one uses impact compaction (Marshall and Proctor method), the second one applies kneading or vibratory stress on the material (shear gyratory compactor and vibratory compactor) simulating the effect of rollers and facilitating aggregates reorientation.

The compaction energy to be applied and the selection among these methods and depend mainly on the specific role of CRM in the pavement structure and technical experiences. When CRM is used as an improved granular material impulsive compaction could be more reliable, whereas when it is used as surrogate of a bound mixture the kneading or vibratory compaction could be more effective.

Cold recycled asphalt mixtures without added bitumen are mainly compacted using the Proctor or AASHTO T-180 method while mixtures with added bitumen are mainly compacted using the Marshall or gyratory compaction. Table 7 shows a summary of some of the compaction methods used for cold RAP mixtures with and without bitumen.

**Table 7:** Compaction methods used for cold RAP mixtures with and without bitumen

| Method | Mixture without bitumen | Mixture with bitumen | Moulds-bituminous mixture |
|---|---|---|---|
| California-foam bitumen [5] | AASHTO T-180 (method D) | Marshall 75x2 blows | 4 inch x 2.5 inch (diameter x height) |
| California-emulsion [16] | - | Marshall 75x2 blows/30 gyrations | |
| Minnesota–emulsion [13] | - | Gyratory 600 kPa, 1.250 degree | 101.6 mm diameter |
| Norway-emulsion/foam bitumen [11] | Modified Proctor | Gyratory 600 kPa, 10, 30 rpm, indirect tensile test specimens compacted to 96% of density at 200 gyrations. | 100 mm diameter |
| South Africa foam bitumen level 1 [8,17] | Modified AASHTO | Marshall/vibratory hammer | 100 mm diameter |
| South Africa foam bitumen level 2 [17] | Modified AASHTO | Vibratory hammer | 150 mm diameter by 127 mm Proctor mould |
| Wirtgen-emulsion/foam bitumen [3] | AASHTO T-180 | Marshall 75x2 blows or vibratory compaction | - |
| Modified Marshall - | - | Marshall 50x2 blows | 4 inch diameter |

| | | | |
|---|---|---|---|
| emulsion ([15], AASHTO T-283) | | | |
| NYS DOT-proposed specification emulsion [14] | - | Marshall 75x2 blows or 30 gyrations at $25^0$C | 4 inch diameter |

One of the aims of specimen preparation in the laboratory compaction is to compact specimens in a similar manner to field compaction. However, the extent to which any of these mix design methods simulate field compaction is not clear. As way forward, the mix design method or methods in TG-6 investigations should be chosen through consensus.

The following is a general discussion of various steps involved in both CPMR and CIPR pre-compaction and compaction procedures.

The ARRA guidelines [18] do not consider any specific pre-compaction phase but suggest three methods of compaction for CIR design. Two of these methods use specimens compacted with 50 blows (per face) of the Marshall hammer. In the third method, developed by Oregon State University, CRMs are placed and rodded in a split mould (diameter of 101.6 mm, height of 292.1 mm) in two lifts. Samples are gradually compressed in a hydraulic device to a load of 172,400 kPa for one minute. The whole process of mixing and compaction is standardised at ambient temperature.
The South African guidelines [8] do not discriminate between CIR and CPR. For bitumen stabilised materials (BSM) the determination of the optimum fluid content and maximum dry density is carried out in accordance with the modified Proctor test. After mixing, the bitumen treated material is transferred into a container and immediately sealed to retain moisture. To minimise moisture loss from the prepared sample, specimens are compacted as soon as possible following the relevant procedure AASHTO T-180 for either 100 mm or 150 mm diameter specimens.

For BSM three mix design levels are provided in relation to the traffic intensity and each mix design level allows two different laboratory compaction methods to be used.

The Level 1 mix design requires the Marshall or vibratory compaction (mould diameter of 100 mm). The Marshall equipment must not be heated but kept at ambient temperature. A sufficient material to achieve a compacted height of 63.5 mm ± 1.5 mm has to be weighted, poured into the mould and poked with a spatula (15 times around the perimeter and 10 times on the surface) leaving the surface slightly rounded. The sample is compacted by applying 75 blows per face with the Marshall hammer.

The vibratory compaction method for 100-mm diameter mould follows a similar preparation procedure. However in this case a loading weight of 25 kg (total mass of assembly: hammer + foot + surcharge) is used. When the vibratory hammer is moved into the mould, 15 seconds of vibratory compaction has to be applied for each face.

The Level 2 mix design provides the Modified AASHTO T-180 or vibratory compaction (mould diameter of 150 mm). Using modified AASHTO T-180 method the material is placed in an airtight container immediately after mixing. Samples are compacted using a 150 mm diameter split-mould, applying modified AASHTO T-180 compaction effort (5 layers approximately 25 mm thick, 55 blows per layer using a 4.536 kg hammer with a 457 mm drop).

The vibratory compaction method for 150-mm diameter mould uses a loading weight of 30 kg (total mass of assembly: hammer + foot + surcharge). A sufficient material to achieve a compacted height of 47.5 mm ± 1.5 mm has to be poured into the mould (first layer). A 25 seconds of vibration for bitumen emulsion stabilised materials and a 35 seconds of vibration for foamed bitumen stabilised materials is applied. Using a chisel, the entire surface area of the top of the compacted layer has to be scarified to a maximum depth of 10 mm. For the second layer a sufficient material to achieve a compacted height of 95 mm has to be added into the mould (second layer). Once again a 25 seconds of vibration for bitumen emulsion stabilised materials and a 35 seconds of vibration for foamed bitumen stabilised materials is applied.

The Level 3 mix design establishes additional compaction procedures for triaxial testing. By using modified AASHTO T180 compaction effort, 12 layers, each approximately 25 mm thick, are compacted with 55 blows using a 4.536 kg hammer with a 457 mm drop. By using vibratory compaction, specimens are manufactured in 5 layers, each approximately 60 mm thick, using a hammer assembly of 30 kg total mass. Each layer is compacted for 25 seconds for BSM-emulsion, or 35 seconds for BSM-foam.

Californian guidelines [5] for full-depth pavement reclamation with foamed asphalt require to seal the mix in a suitable container and to prepare specimens with a diameter of 100 mm and a height of 63.5 mm, complying with the Marshall method of mix design. Seventy-five compaction hammer blows are applied on each face of a specimen. All compaction must be completed within 8 hours of the mixes being prepared. However, the reference dry density is determined according to method D in AASHTO T-180.

Austroads [17] for foamed bitumen stabilization recommends compaction of test cylinders is undertaken using gyratory compaction (80 gyrations) or Marshall (50 blows per face) compaction. The mould shall not be heated.

For CIR design the Kansas department of transportation [19] proposes specimens compacted immediately after mixing at ambient temperature with a superpave gyratory compactor (SGC) in a 100-mm mould for 30 gyrations. The mould shall not be heated.

Italian highway specifications for CRM require to compact 4.5 kg samples by means of a shear gyratory compactor (SGC) at 180 gyrations. The SGC protocol requires a 150 mm diameter mould, a constant pressure of 600 kPa, a speed of 30 rpm and an angle of gyration of 1.25°. For in-situ control the CIR mixture has to be sampled after mixing (behind the recycler) and immediately compacted by means of a mobile SGC. Another study (Bocci et. al, 2011) suggested some modifications to obtain a suitable specimen height (about 70 mm) for mechanical tests, such as indirect tensile stiffness modulus. In this case 2.7 kg specimens shall be compacted at 100 gyrations.

It should be noted that the mix design philosophy influences the applicable compaction technique. The SGC is more applicable for asphaltic type mixes (higher BCs) such as cold mix asphalt. The BSM stabilised mixes (lower binder contents) do not respond well to SGC and need vibratory or drop weight compaction.

For cold mixtures produced by full depth reclamation, Mallik et al. [20] proposed a modified SGC mould, characterized by several holes to allow water flow during compaction. An absorbing cloth should be put around the mould to catch the water during compaction. The slots should be cleaned before each compaction. The emulsion treated samples have to be cured for 45 minutes at 40°C and then compacted with the SGC at 75 gyrations.

For CRM with bituminous emulsion, Santagata et al. [21] suggests the use of a SGC operated according to Superpave specifications (1.25° gyration angle, 30 rpm gyration speed, 600 kPa normal pressure) with a 100 mm mould. The bottom plate of the mould has a square grid of 2 mm holes distributed on a 0.85 cm × 0.85 cm grid. A cylinder placed in the mould under the plate allows the water which is expelled during compaction to be gathered.

Specimens are prepared with 100 gyrations. Approximately 1100 g of dry material are employed for each sample. The time elapsed between mixing and compaction should be defined trying to meet the actual conditions in field applications.

## 6. Post Compaction Curing Process

Curing is the process whereby the mixed and compacted material discharge water through evaporation, particle charge repulsion or pore pressure induced flow paths [22]. The reduction in moisture content leads to an increase in strength and rut resistance of the mix.

In the field, curing may take many months. The laboratory process needs to simulate field conditions of curing, but as it is impractical to cure for months, an accelerated method is required to emulate field condition. It should be noted that due to the different in situ conditions of mixing and compacting, as well as the stress condition and the temperature variations during the early life of the pavement, it is chllanging to achieve this in the lab.

According to Maccarone et al. [23], oven curing for three days at temperature of 60°C appears appropriate. From United Kingdom study [24]; both the resilient modulus and creep properties of laboratory specimens cured in this manner were similar to those of field cores taken after 12 months after construction. However, as discussed below, more recently the accelerated curing temperature has been lowered to 40°C.

### 6.1 Austroads [17]

Austroads recommends the following approach to specimens curing:

- Immediately after compaction the cylindrical specimens are tested for modulus without curing. The uncured modulus needs exceed 700 MPa to ensure that the pavement can be opened to traffic;
- The specimens are then oven cured at 60 °C for three days and then tested for indirect tensile modulus;
- The specimens are then soaked in water prior to testing for their soaked modulus ($M_{wet}$). Two methods may be used for soaking the specimens: submerged under water for 24 hours, or in a vacuum chamber for 10 minutes;
- The wet and dry modulus results are then plotted versus bitumen content to define the optimum modulus.
- Note: samples should be prepared with moisture contents such that Mwet/Mdry is 0.5 or more, because bituminous binders will not cure at excessive moisture contents.

Please note that the 60 °C curing temperature is typically higher than the softening point of the binder. On large projects, additional testing may be undertaken including unconfined compressive strength, flexural fatigue and creep.

### 6.2 Queensland Department of Transport and Main Roads [25]

In the TMR (Transport and Main Roads) method, the prepared specimens are tested for modulus in three states as follows:

- Initial modulus after three hours curing at 25±5 °C is determined to provide an indication of susceptibility to permanent deformation early in pavement life. Where the initial daily traffic on opening is 1000 ESA (Equivalent Standard Axle) or more, TMR recommends that this three hour curing time be confirmed by wheel tracker testing;
- Cured modulus where the sample is oven cured at 40 °C for three days to provide an indication of medium term stiffness 3−6 months after construction;

- Soaked modulus where the sample is submerged under water for 10 minutes under a 95 kPa vacuum to provide an indication of the moisture sensitivity of the material.

Based on TMR experience, laboratory cured samples compacted to 50 blow Marshall compaction achieve similar resilient modulus values to the upper half of field cores after 12−24 months field curing.

TMR practice is not to seal the samples during curing.

**6.3 Asphalt Academy (TG 2) [8]**

In the current South African method, the shortcomings of several curing methods in use were discussed as follows:

- Curing at 60 °C in an oven results in lower moisture contents than field equilibrium;
- Characterising materials with secondary binders where curing for 7 days or 28 days resulting in time delays;
- Sealing specimens in plastic bags and curing for 72 hours in an oven at 40 °C retains excessive moisture and gives conservative results;
- Curing for 24 hours at 25 °C (unsealed) followed by 48 hours sealed in a bag and cured in an oven at 40 °C more closely reflects equilibrium moisture content but does not provide evidence that the laboratory stiffness truly reflects field stiffness;
- Interpretation of stiffness from tangent modulus derived from modified Californian Bearing Ratio (CBR) compression tests and determination of curing time at ambient temperature yields modulus values comparable to that used in the mechanistic design – but results in time delays and requires more research;
- Field testing in southern Africa to re-evaluate prediction models for equilibrium moisture content has provided more robust predictions based of optimum moisture content, bitumen content and climate and showed that the 24 hours at 25 °C unsealed and then 48 hours sealed at 40 °C provided the most accurate prediction.

Whilst research is currently underway in southern Africa, as an interim, the current recommended method is to cure for 24 hours at 25 °C unsealed and then seal and cure for a further 48 hours at a temperature of 40 °C.

In particular, considering the number of variables that need to be addressed in the mix design and the amount of material required to investigate these variables, the mix design procedure involves several steps and one or more series of tests (levels), depending on the magnitude of design traffic. The mix design procedure always starts by testing the material to be treated (preliminary tests) to determine whether it is suitable for treating with bitumen and, if not, the type of pre-treatment or blending required to make it suitable. Following this, the actual Asphalt Academy mix design procedure commences with an initial series of tests (Level 1 Mix Design) that provides an indication of the application rate of bitumen and active filler (if necessary) required to achieve an indicated class of BSM (Bitumen Stabilised Materials). Thereafter, depending on the design traffic, additional tests are undertaken to refine the application rate of bitumen and gain confidence in the performance potential of the treated material (material classification). These are the Level 2 and Level 3 Mix Designs. In summary, the mix design procedure consists of:

- Preliminary tests: These include standard laboratory tests to determine the grading curve, moisture, density relationships and Atterberg limits. Where the results indicate that some form of pre-treatment is required, additional tests must be undertaken after such pre-treatment to ensure that the desired result was achieved;

- Level 1 Mix Design: Level 1 starts with the preparation of samples that will be used to manufacture the specimens required for all levels of mix design testing. 100 mm

diameter specimens (Marshall moulds) are compacted and cured for Indirect Tensile Strength (ITS) testing. Test results are used to:
  - Identify the preferred bitumen stabilising agent;
  - Determine the optimum bitumen content;
  - Identify the need for filler, and, where required, the type and content of filler.

Level 1 mix design is sufficient for lightly trafficked pavements, which will carry less than 3 MESA (Million Equivalent Standard Axle).

- Level 2 Mix Design: This level uses 150 mm diameter by 127 mm high specimens (Proctor specimens) manufactured using vibratory compaction, cured at the equilibrium moisture content and tested for Indirect Tensile Strength to:
  - Optimise the required bitumen content.

  This level is recommended for roads carrying 3 to 6 MESA.

- Level 3 Mix Design: This level uses triaxial testing on 150 mm diameter by 300 mm high specimens for a higher level of confidence. This step is recommended for design traffic exceeding 6 MESA.

Curing of BSMs is the process where the mixed and compacted layer discharges water through evaporation, particle charge repulsion and pore-pressure induced flow paths. Curing process depends on stabilising binder to be used:
- For emulsion bitumen stabilised materials chemistry plays a significant role in the curing process. Water is an intrinsic component of bitumen emulsions. Breaking of the bitumen emulsion needs to take place before curing via migration and evaporation. BSM-emulsion usually requires longer curing times than BSM-foam because of the higher moisture contents.
- For foam bitumen stabilised materials curing take place as a result of migration of water during compaction and continues with evaporation of the water.

The reduction in moisture content leads to an increase in the tensile and compressive strength, as well as stiffness of the mix. It is imperative that this process is realistically simulated in the laboratory for mixes to be assessed for their expected field performance.
The rate of moisture loss from newly constructed BSM layers plays a significant role in determining the performance of the layer. It is in the early period of repeated loading that the majority of the permanent deformation takes place in BSM layers. Where a new BSM layer is to be trafficked immediately after finishing, it is important to minimise the moisture content during construction.

The lower the degree of saturation of the BSM, the greater the resistance to permanent deformation. The temperature of the layer in the field and the loss of moisture with time are the two factors to consider with curing, and hence, stiffness and strength gain. Although a BSM should have sufficient stiffness and strength to withstand moderate levels of early traffic, the layer will continue to gain strength over several years in the field. In order to achieve this, low strain/stress level in the body of the recycled layer is required. The maximum tensile strain in the body of the recycled can be used as the major field curing criterion [44].

<u>The recommended curing procedure differs for the specimen size and bitumen types, BSM-emulsion and BSM-foam.</u> Although the use of active filler has an impact on curing, its inclusion in a BSM does not justify extensions in the curing time as cementation is not one of the desired properties of these materials (cement content should remain under 1%).
For Level 1 mix designs, the <u>100 mm diameter</u> specimens are cured until they reach a constant (dry) mass, typically with moisture contents of less than 0.5%. Testing follows <u>72 hours of curing at 40 ºC without sealing</u> the specimens to determine the $ITS_{dry}$ value. Half the specimens are then soaked for 24 hours before testing to determine the $ITS_{wet}$ value. This procedure is aimed at evaluating the moisture susceptibility of the BSM.

The curing procedure for 150 mm diameter specimens used in Level 2 and Level 3 mix designs typically produces moisture contents of 43 to 50% of OMC (Optimum Moisture Content), which represents the long-term equilibrium moisture content of the material in the field. To achieve this, different curing periods are required for BSM-emulsion and BSM-foam. Unsealed specimens are initially placed in a draft oven at 30 °C to allow the moisture content to reduce. Thereafter, they are individually sealed in loose-fitting plastic bags (at least twice the volume of the specimen) and cured for a further 48 hours at 40 °C. The wet plastic bags must be replaced with dry bags every twenty four hours.

Before the specimens are tested, they should be allowed to cool down to the required test temperature whilst sealed in a new dry plastic bag to prevent any further moisture loss.

### 6.4 Wirtgen Cold Recycling Manual [3]

The curing procedure recommended by the Cold Recycling Manual is the following: place the specimens in an oven at 40 °C for 20 to 24 hours or until the moisture content has reduced to at least 50% of OMC (Optimum Moisture Content). Thereafter place each specimen in a sealed plastic bag (at least twice the volume of the specimen) and place in an oven at 40 °C for a further 48 hours. Remove specimens from the oven after 48 hours and take out of their respective plastic bags, ensuring that any moisture in the bags does not come into contact with the specimen. Allow to cool to ambient temperature.

### 6.5 University of California, Pavement Research Centre [5]

According the procedure suggested by the University of California, the mix preparation should follow following items:

- Prepare eight samples (25 lb [10 kg] each) of pulverized material, sufficient for testing an untreated control and three asphalt binder contents, each with a replicate. Do not add active filler:
- Place the prepared material into the mixer and begin agitation;
- Add sufficient water to achieve the MMC (Mixing Moisture Content). Keep the mixer running for approximately five minutes to allow the moisture content to equilibrate.
- Spray the specified foamed asphalt content onto the pulverized material (skip this step for the untreated control);
- Seal the prepared mix in a suitable container;
- From each batch, prepare six specimens with a diameter of 4 in. (100 mm) and a height of 2.5 in. (63.5 mm), complying with the specimen preparation procedure described in the Asphalt Institute's Mix Design Methods for Asphalt Concrete (MS-2) (Marshall Method of Mix Design). Seventy-five compaction hammer blows are applied on each face of a specimen. All compaction must be completed within eight hours of the mixes being prepared;
- Extrude the specimens from the mould immediately after compaction and cure in a forced draft oven at 105°F (40ºC) for 72 hours;
- After curing, remove the specimens from the oven and place in a water bath for 24 hours. Water temperature should be between 68°F and 77°F (20ºC and 25ºC). Water depth should be 4.0 in. (100 mm) above the specimen surface. Specimens must not be stacked.
- After soaking, remove the specimens from the water and allow them to drain for 60 minutes and equilibrate to the room temperature. Ambient temperature should be 77°F ± 4°F (25°C±2ºC). Specimens should be covered with a damp cloth to prevent excess evaporation. Care should be taken at all times to prevent damage to the specimens.

### 6.6 ANAS (Agenzia Nazionale Autonoma delle Strade) Italian Road Authority [26]

Subbase specimens made with foam stabilised materials must be compacted in 150 mm mould with 180 rotation of gyratory compactor (600 kPa vertical pressure, rotation angle 1.25° and speed 30 gyrations/min). Sample should be than cured for 72 hours at 40°C and cooled to 25°C for four hours before testing. Same procedure should be followed when rehabilitation is made with bitumen emulsion.

## 7. Test Procedures to Evaluate Curing

### 7.1 Background on Curing Evaluation of Cold-Recycled Mixtures

This section of the paper presents a review on test procedures for evaluation of curing in cold recycled asphalt mixes. The amount of curing in actual field conditions depends on several factors including climatic conditions, amount of moisture in the mix, level of compaction and, drainage and moisture conditions of the underlying layers. As described in previous section on curing procedures a significant amount of curing procedures in the literature are prescriptive in nature, whereby a definite amount of time and temperature is required. In order to standardize procedures for specimen preparations to conduct mechanical and physical property tests it is necessary to have a test procedure to evaluate the curling.

There have been numerous studies that reported physical and mechanical properties of cold recycled mixtures in cured conditions using laboratory curing process. While significant amount of literature is available, very little has been reported on quantitative and qualitative comparisons between material properties and curing of mixes. This literature review is limited to studies where evaluation of curing is presented by series of laboratory tests and not necessarily studies where single set of results are presented for so called cured samples.

The procedures commonly used to evaluate the curing can be divided into two main categories: (1) use of moisture content; (2) use of laboratory measured mechanical tests; and (3) field measurements. Since this paper focuses on laboratory specimen preparation the field measurement techniques are not included in the discussions.

### 7.2 Use of Moisture Content

The moisture content based evaluation can further be broken down to following categories:

- Absolute moisture content [27,28];
- Percent of optimum moisture content from moisture-density relationships [3,5,8,29], and;
- Use of stable weight conditions [19].

The use of moisture content as means to indicate the amount of curing has been mostly based on empirical observations between lab and field moisture conditions. As pointed out by Lee et al. [30], it is very important to determine the mechanical properties of cold recycled mixtures containing emulsion to evaluate curing. The stability and strength of cold recycled asphalt concrete layer in field has most significant effect on pavement performance thus, use of mechanical properties for evaluation of curing seems more reasonable.

### 7.3 Use of Laboratory Measured Mechanical Properties

A number of laboratory measured mechanical properties have been employed by researchers for evaluation of curing, this includes: indirect tensile strength (ITS), indirect tensile modulus or resilient modulus (ITRM), unconfined compressive strength (UCS), Marshall and Hveem stability, and raveling test. The following subsections provides review on use of mechanical tests for evaluation of curling in cold recycled asphalt mixtures.

Indirect Tensile Strength (ITS) Test: Historically the ITS test has been prescribed by numerous cold recycled asphalt mix design procedures to evaluate the potential for moisture induced damage, such as Asphalt Academy Mix Design Procedures [8] and Norwegian Public Roads Administration's Guidelines for Cold Bitumen Stabilized Base Course [11]. As per Asphalt Academy [8], the ITS test is used as an indirect measure of the tensile strength and flexibility of the cold-mixes to reflect the flexural characteristics of the material. The widespread availability of ITS test equipment and its low cost has made it a popular choice for curing evaluation of cold recycled mixes. The ITS test protocols show minor variations between various agencies and researchers. The majority of test procedure follows the standard indirect tensile strength evaluation as per the AASHTO T-283 protocol used for determining moisture induced damage in asphalt mixtures.

Lee and Im [30] provided an in-depth evaluation of curing criteria for cold in-pace recycling, their study focused on use of ITS as a property to evaluate effect of curing. The findings from their study further reinforce the superiority of using mechanical properties for curing evaluation as compared to use of moisture prescribed conditions. The study by Lee and Im [30] involved testing of three cold recycled mixes as seven curing levels and three curing temperatures. The same study also showed a gradual increase in ITS values with reduction in moisture content from 3.5 to 1% as well as continued increase in ITS values of lab samples for as long as 28 days. A related study by Lee et al. [31] concluded that length of curing and moisture content showed most significant effects on the measured ITS values, furthermore even at a constant moisture content the ITS value increases with prolonged curing period.

Martinez et al. [32] showed the applicability of ITS in designing cold recycled mixes. Their study showed cold mixtures show approximately 15% improvement in ITS values for field samples between the duration of six months and three years. Lane and Kazmierowski [33] reported series of ITS results for cold in-place recycled asphalt mixes at various density levels. The test results were reported for ITS tests conducted in dry and wet conditions, the results showed significant improvement in ITS values with increasing density. Linearly increasing ITS values for cold recycled asphalt mixes have been reported by Xu et al. [34] with increasing cement amount and curing times. A study by Salomon and Newcomb [13] conducted series of ITS tests on mixes utilizing recycled materials from three field projects. The study showed that ITS values did not change significantly between one and seven days of curing, however remarkable differences were observed in the failure modes. Specimens that were cured longer showed minimal signs of failure at the point of ultimate strength, whereas significant disintegration is observed for short term cured specimens.

Indirect Tensile Modulus or Resilient Modulus (ITRM) Test: The ITRM is typically measured using similar test configuration as the ITS. The main difference is the measurement of resilient (recovery) modulus under repeated (pulse) loading conditions at a given stress amplitude and loading frequency. The ITRM properties have been measured and reported with varying degree of sophistication. Simple measurements such as instantaneous modulus at a given time and stress amplitude to presentation of creep compliance master-curves developed using measurements at multiple test temperatures and time increments.

The Queensland Department of Transport and Main Roads [35] design method for cold mixes requires measurement of ITRM on uncured and cured samples. Early works by Tia and Wood [36], and Maccarrone et al. [23] showed potential of ITRM in correlating to the amount of curing. Work by Bocci et al. [9] shows that the ITRM values increase considerably with increase in curing time. A model to predict ITRM values as function of curing time and temperature has also been proposed [9]. A study conducted by Thanaya et al. [37] showed that ITRM values for loose mix curing showed reduction over period of time ranging from 0 to

50 hours. However, in compacted form the ITRM values improved significantly over the duration of 24 hours as the specimens were left outdoors for curing.

<u>Unconfined Compressive Strength (UCS) and Marshall/Hveem Stability:</u> Apart from ITS and ITRM the UCS and stability has been most widely reported cold mix property for evaluation of curing in cold recycled mixes. While several studies have shown that UCS and stability values shown good distinction between uncured and cured samples [38,39], no reported studies were found present an in-depth investigation that shows quantitative relationship between curing at various times against these properties.

<u>Ravelling Test:</u> The raveling test has been specified as ASTM D7196 test procedure for determining the potential for ravelling distress in asphaltic paving layers. The test procedure is recommended as optional test for New York State Department of Transportation (NYSDOT) [14] to indicate the level of curing. The incorporation of ravelling test by NYSDOT as indicator of curling level is based on unpublished data from labs at private companies. The only other report showing correlation between level of curing and ravelling test results is by Kim et al. [40-41]. This study showed that for two cold recycled mixes (one with emulsion and other with foamed asphalt) the amount of ravelling loss reduced significantly as the curling time increased from four to eight hours.

<u>Triaxial Test:</u> The triaxial testing has also been recommended by few cold recycling methods to determine the strength gain and extent of curing [8]. The triaxial testing of cold mixes at early age is natural, as the material behaviour is more “granular-like” rather than that of asphalt concrete. The triaxial testing is used to obtain shear properties of the cold recycled materials and their behaviour in confined conditions. The Asphalt Academy (South Africa) design manual for cold mixes [8] recommend triaxial testing for roadways with traffic levels above 6 MESA. Mulusa and Jenkins [42] have proposed simplified triaxial test for cold recycling mixes that involves monotonic loading and specialized cell. The test procedure has shown very promising results and accommodates specimens prepared using the Superpave gyratory compactor (SGC). The work by Ezio et al. [43] further confirms the utility of triaxial test in determining the extent of curing. Their study determined resilient moduli and shear strength of cold recycling mixes at three temperatures and three curing levels.

### 7.4 Summary of Post-Compaction Curing Evaluation Methods

Based on the literature review on topic of test procedures for evaluating curing in cold recycled asphalt mixes it can be found that the indirect tensile strength is most widely accepted test for curing evaluation with most supporting data available in literature. The indirect tensile strength is followed by indirect resilient modulus as an indicator test for evaluation of curing. Triaxial tests have also shown good potential in determining the extent of curing through use of shear strength. Other test procedures have been used and reported in literature however the extent of their usage and availability of published data is not comparable to indirect tensile strength and resilient modulus.

## 8. Summary and Conclusions

The main result of this literature review is the clear evidence that exist a very large spectrum of technical and theoretical approaches to specimens preparation, not always in agreement. This consideration is the base of the strategic plan of task group on cold recycling of Rilem TC-SIB that has as a main goals making a state of the art of cold recycling techniques and to make an as much as possible unified procedure for mix design.

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