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Classification of Recycled Asphalt (RA) Material

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ABSTRACT: Use of recycled asphalt pavements (RA) in pavement rehabilitation processes is continuously growing as recycling techniques, such as cold recycling (CR), are being utilized in increasing magnitude. The focus of this paper is on developing a state of the art and state of the practice summary of processes used for classification of RA. A variety of topics were explored through an exhaustive literature search, these include RAP production methods, definition of RA materials, stockpiling practices and industrial operations. 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

The purpose of this literature research was to identify the factors or RA mix characteristics that can be used in the description of the RA in order to give sufficient information during mix design or production or laying of the cold RA. Typically, the term “RA” is used for three different materials: milled recycled product, mix used for the pavement, and reclaimed asphalt. The term “RA” in this paper is in context of milled recycled product (recycling asphalt granulate) used for cold recycling.

2. RA Production Methods and Characterization

The production of recycling asphalt granulate is not defined by any standard but is generally produced in two ways, either the pavement is milled with a milling machine or is removed in slabs with an excavator.

Cold milling machines are used particularly for in-place recycling or when only a part of the pavement has to be reconstructed. This technique allows the separation of different layers with high precision to obtain RA of different type and quality. The quality of the RA Milling is influenced by the milling parameters like direction (up or down-cutting), milling speed, type and wear degree of the teeth, type of milling drum including configuration of point attach tools and the amount of water used against dust formation [1]. In addition, ambient temperature, binder viscosity and pavement type have an impact on RA production. Especially fines are produced by the milling process however it is not fully understood, which of the above-mentioned impact parameters dominate.

For the removal of whole pavements excavators are preferred due to the lower costs. The asphalt slabs produced by this method are commonly broken in-plant with a jaw or impact crusher. The RA size can be adjusted to obtain different gradations. Often the material produced by the cold milling machine is reduced in size in the same way. In smaller companies the milled asphalt of different sources are stocked together with asphalt slabs on large stockpiles. From time to time a mobile crusher is utilized to produce RA, which has to be homogenized afterwards.

One of the most basic definitions of reclaimed asphalt pavement (RA) can be found in the Washington pavement association. The Washington pavement association defines RA as a collection of old asphalt pavement in loose form. The RA can also be a collection of loose asphalt and granular layers. In full depth reclamation process, some granular material is removed from the base and blended with the old asphalt at the top.

Homogeneity in terms of size, mineral type, binder type etc. is the most crucial quality criteria of RA. Still, for cold recycling, homogeneity requirements are rarely demanded, except in the Netherlands, where standard deviations are defined for aggregate size distribution, binder content and penetration value of the recovered binder [2], however only for the use in hot recycling. In the ideal case, RA is coming from only one source and one layer. Often this is not possible and RA is mixed together from different pavements and locations. Sampling of large stockpiles is difficult because the inside of the stockpile is difficult to access. The European standard EN 932-1 defines the number of minimum samples but offers only limited practical help [3].

In order to increase the homogeneity or if different RA sizes are required, an additional screening operation is needed. In Norway, it is recommended for plant mixing to produce fractions like 0-4 mm and 4-11 mm, 0-6 mm and 6-11 mm, 6-16 mm or 0-8 mm and 8-16 mm. The use of sieves smaller than 4 mm can be difficult due to moisture in the RA [4]. The maximum particle size of RA is generally defined and varies between 30 and 50 mm [5-7]. The European standard EN 13108-8 leaves it open to the countries to define a maximum particle size for RA [8].

Once the proper RA is produced, care has to be taken to prevent RA to re-agglomerate or congeal in large piles. Recommendations for the size, cover and other criteria for stockpiles are different according to states and institutes [4,5,9].

Summing up, the RA production process for cold recycling is not precisely stipulated and requirements for important properties like homogeneity are regulated only in few countries.

3. RA Cleanliness and Foreign Matter

3.1 Typical Foreign Matter to be Detected and/or Removed Prior to Milling [10]

Tar: Environmental and health problems raised by PAHs are critical when heating tar-contaminated asphalt. Hence, a selective milling is highly desirable if one of the old asphalt layers contains tar. Two qualitative screening identification techniques are commonly used in the field: the tar test spray PAK-Marker® and the staining test with toluene. For a precise assessment, quantitative laboratory methods are used but they are expensive and time-consuming (High Pressure Liquid Chromatography and Gas Chromatography with Mass Spectrometric). Testing on PAH in RA is mandatory in several European countries like Germany, Netherlands and Switzerland. However, the use of tar containing is still possible under special regulations.

Asbestos: In the 80s asbestos fibres were sometimes used in asphalt pavement to improve fatigue behaviour. As asbestos can be harmful to health when inhaled, it is important that their presence in bituminous mixes is detected prior to milling. In case of doubts, Polarised Light Microscopy (PLM) and Transmission Electron Microscopy (TEM) are the most commonly used method for the analysis of bulk samples of RA.

Road Markings: As they can affect the properties of the RA, thick thermoplastic road marking should be removed before milling the old pavement.

3.2 European Standardization

In the European standardization, the RA properties are only mentioned in the context of hot in-plant recycling. The EN 12697-42 [51] specifies a visual method for determining the amount and components of coarse foreign matter in RA. Coarse foreign matter is defined as “matter in reclaimed asphalt not derived from asphalt pavements or surplus production, and cold asphalt produced with cut-back bitumen”. The following values are determined through a visual sorting of the particles greater than 8 mm diameter from the sample of RA:

- Content of material derived from asphalt;
- Content of cold asphalt produced with cut-back bitumen; and,
- Content of coarse foreign matter not derived from asphalt, divided into site materials and other materials.

Following note gives examples of site and other materials:

- Site materials: “cement concrete and cement concrete products; bricks; unbound pavement materials including fine natural aggregate, from secondary sources; cement mortar.”
- Other materials: “metals; synthetic materials; plastic; wood.”

For RA feedstock requirements, the EN 13108-8 [8] defines two groups of foreign matter:

- Group 1: Cement concrete including cement concrete products, bricks, sub base material (excluding natural aggregate), cement mortar and metals.
- Group 2: Synthetic materials, wood and plastics.

Then the RA shall be classified in 3 categories:

- F1: Content of group 1 material $\leq 1\%$ and content of group 2 material $\leq 0.1\%$
- F5: Content of group 1 material $\leq 5\%$ and content of group 2 material $\leq 0.1\%$
- Fdec: Content and nature of all foreign matter declared.

The discordance between the “site materials” and “other materials” definitions in EN 12697-42 and the “group 1” and “group 2” definitions in EN 13108-8 should be noted. In France, for example, the EN 12697-42 is not commonly used in practice.

4. RA Grading Evaluation

According to the EN 13108-8 [8] the maximum size of the RA particles (noted as U) should be declared and the grading curve of the aggregate in the RA should be determined after extraction of the binder. For a given RA stockpile one sample should be tested for every 500 ton with a minimum of 5 samples. The grading homogeneity of the stockpile is one of the key parameters for further recycling processes.

5. RA Bitumen Content and Characteristics

In hot mix asphalt containing RA, the aged bitumen in the RA is often considered as a part of the bitumen in the new asphalt mixture composed of the RA material. However, this is not always the case in cold asphalt mixtures containing RA. Some agencies factor the contribution of the aged bitumen in the mix design while others do not take the aged bitumen in consideration. Table 1 shows a summary of some the properties of the bitumen in the RA that are commonly considered in mix design.

Methods such as the Oregon method [11] consider the penetration at 25⁰C and absolute or dynamic viscosity at 60⁰C of the extracted bitumen in the estimation of the required bitumen content. In other methods such as California foam bitumen mixes [12], the aged bitumen is not factored into the binder content since the recycling temperatures are significantly below the minimum temperature required to soften the aged bitumen.

One of the questions that may need to be addressed is the effect of the properties of the aged bitumen in the RA on the properties of the added bitumen. The other question is how this effect affects the required bitumen content. These two questions could be addressed by examining blends of emulsions or foam bitumen and bitumen extracted from the RA material.

Table 1: Properties of bitumen in the RA

Design Method	Comment on aged bitumen in the RA
California-foam bitumen [12]	Aged asphalt in the RA not considered in the bitumen content since cold recycling temperatures are lower than the minimum temperature required to soften the aged bitumen
Minnesota – emulsion [13]	PG class of the extracted bitumen determined. Evaluation of a blend of extracted bitumen and emulsion in relation to the Minnesota DOT requirements recommended.
Oregon [11]	Penetration at 25 ⁰ C and dynamic viscosity of the bitumen extracted from the RA considered in the estimation of the required amount of bitumen.
Wirtgen-emulsion/foam bitumen [14]	RA is classified as active or inactive depending on the penetration value of extracted bitumen at 25 ⁰ C. Active RA has higher levels of cohesion than inactive RA or natural materials.
New York State DOT, proposed specification [15]	The bitumen used to make the emulsion should meet the bending beam requirements of AASHTO M 320 and PG specifications. Aged bitumen in the RA not considered in the bending beam and PG requirements.

6. Aggregate Properties

RA particles often consist not of a single aggregate particle but are conglomerates of smaller aggregates glued together by the mastic (Figure 1). The Wirtgen Guide differentiates between inactive or “black rock” RA particles with a binder penetration value below 18 mm and active RA with penetration values above 25 mm [14]. However, this classification is valid only for cold recycling at ambient temperature and not for recycling at elevated temperatures with foam bitumen as the with the lower viscosity, the blending of the binders becomes better.



Figure 1: From the outside of a RA particle it is difficult to suggest its composition, which can be very different (From left to right: RA particle from the outside, cross sections of possible compositions of a RA particle: single coated aggregate, two major aggregates with some mastic, conglomerate of small aggregate particles and mastic)

Inactive RA particles coated with aged binder act similar like pure aggregates, because only the surface film of the old binder up to a depth of 0.1-0.3 mm will mix with the new binder [1]. Active RA particles are softer and have the tendency to break down further when subjected to mixing and compaction forces. Therefore, for cold recycling requirements for aggregate properties itself are less important in comparison to hot recycling, where the angularity of mineral aggregates plays an important role. However, grading curves and sometimes shape and angularity are generally available from original construction data or cores, as pavements are analysed prior to destruction [16].

7. RA Moisture Content

7.1 Preliminary Remarks on RA Moisture Importance

Moisture content is not always recognized nor considered as one of the most important parameters to be evaluated on RA aggregate, even though it is clear that the water content and moisture resistance become the most important properties to be checked when such an aggregate is re-used in hot or cold recycled mixtures. The reason for this contradiction can perhaps be traced back to the erroneous belief that asphalt pavements are basically dry, and it only becomes important to take into account the role of water in the aggregate when they are milled and recycled.

An asphalt pavement is subject to recycling when it is affected by extended distresses, wide and deep degradations which alter the surface integrity and permit the entry of water into the body of the structure. In these cases, the pavement to be reclaimed is potentially wet and the moisture content, depending on the surface damage, is crucial in order to choose the most suitable in-situ or in-plant recycling process.

Where distresses are frequent and severe, full-depth reclamation (FDR) or cold in-place recycling (CIR) are usually the most common solutions; in this case RA is frequently moist and can be used "as it is", provided that the moisture fits the purpose. In this circumstance, whatever the binder (emulsion or foam), bitumen is used with a reduced viscosity so it can be easily mixed with cold moist material, as RA can be.

When foamed bitumen is used, RA moisture content can be relatively high (aggregate can be at ambient temperature with in situ moisture content [17]), but it needs to be accurately checked, since the consequence could be the underestimation of the role of moisture in the final mixture. In foamed bitumen stabilized materials (BSM-Foam), the moisture in the mix, prior to the addition of the binder, plays an important role in dispersing the bitumen during mixing. It separates and suspends fines, making them available to bitumen during mixing, then acts as carrier for bitumen droplets.

When RA is a component of a bitumen emulsion stabilized material (BSM-Emulsion), its moisture plays an important role in: reducing absorption of emulsion water into the aggregate; dispersing the emulsion and preventing a premature breaking during the mixing (likely at low temperatures, when the evaporation rate of the excess moisture in the material is slow); delaying curing. Moreover, in recycling projects, when the moisture content of the in situ material is relatively high (also due to a wet climate), the addition of emulsion can increase the total fluids content to beyond the zero-voids limit, when compaction energy is applied.

Where hot in-place recycling (HIR) is planned, which is used when damage is minimal, the aggregate is usually quite dry. Moreover, HIR surfacing equipment is provided with a preheater and/or a preheater-scarifier which radically reduces the RA moisture before its reutilization.

Finally, for in-plant applications, RA moisture content is not particularly important, since it can be changed there as required, depending on the construction technique subsequently adopted. Once processed, RA can be handled and stored as a conventional aggregate material. If the mixture is placed in a stockpile, its usability is also influenced by moisture content, which should be close to the optimum moisture content (OMC), in order to avoid the bitumen droplets losing their adhesive capacity when the material dries out. It has been verified that in (horizontal as well conical) stockpiles, RA has the tendency to form a crust (due to heat from the sun) on the surface (200-250 mm circa), which tends to help shed water. RA also has a tendency to retain moisture without draining over time like an aggregate. Low, horizontal and flat stockpiles are subject to greater moisture accumulation than tall, conical ones. 7-8% RA moisture is reported by some authors during the rainy season at facilities using low, horizontal stockpiling techniques [18]. RA stockpiles are generally left uncovered, since covering with tarps can cause condensation and add moisture to the aggregate; RA is preferably stored in an open-sided building, but under a roof. Anyway, to ensure the RA quality in the course of time, the moisture content must be regularly checked.

Obviously, RA can be moist not only for intrinsic reasons but in a wet or rainy climate. In this case neither CIR nor HIR are recommended, especially when 100% of RA is used for cold mixes. When a blend of RA and virgin aggregates is used, the moisture content will be adjusted on basis of the moisture content of virgin aggregate fraction. In the first case, wet weather would compromise the use of emulsion binder and slow down curing; damp pavements also slow the hot recycling construction processes.

7.2 Moisture Testing

Before asphalt is reclaimed, a layer condition assessment is needed. Moisture content and density of the in situ material as well as depths of each layer can be accurately determined from test pits, usually done on approximately 1.0 m in length (across the wheel path) x 1.0 m wide (along the wheel path) x 1.0 m deep [14]. The material removed from the individual layers should be placed in sealed containers or wrapped immediately after excavation, to ensure that samples retain the natural moisture content. Tests are then used to refine in situ trials, like DCP (Dynamic Cone Penetrometer) analyses, and these are important in order to establish a mixing moisture content range for recycling operations [12].

In-place recycling requires field sampling and testing of the existing pavement [19,20]. Field sampling can be done by coring (generally 6-inch diameter cores). Dry coring with compressed air or nitrogen is preferable to wet coring since an accurate determination of moisture content is critical for HIR and CIR recycling projects. Where FDR is being considered, the base and subbase materials also need to be sampled and tested, for moisture content and plasticity index determination (liquid limit, plastic limit and plasticity index should be checked on the basis of ASTM D 4318 and AASHTO T 89/90). In fact, some Agencies set prerequisites for the use of RA, possibly mixed with foundation aggregate, in

specific applications: for instance, in FBSMs, materials should have a maximum PI of 10, while materials with PI up to 20 may be used, if they are pre-treated with lime to reduce their PI to a maximum of 10 (usually not the case with RA).

Laboratory mix design should be carried out using the same moisture content in the RA aggregate, as during production, in order to ensure the significance and reliability of the design [12]. In the mix-design process two alternatives are possible:

- Splitting the material in a moist condition, without previous drying; water can be added beyond the RA “natural” moisture content, in order to achieve the same content as in the mixing plant; this option is recommended for selection of emulsion composition and mix design, if the aggregate is coated with dust.
- Drying, screening and splitting the aggregate, with a subsequent recombination to the prescribed grading; water should be carefully added along the edge of the mixing vat (not directly onto the aggregate) so that fines on the surface of the grains are not washed away; this option guarantees better control over the final grading.

In both cases, the material should remain sealed for 24 hours before any further treatment. It should be noted that the properties of aggregates which have been dried, with the subsequent addition of water, may differ from those of undried materials with the same water content.

The climate and aggregate moisture can be of great importance for the selection of binder when RA is recycled. Where the aggregate materials originally have a high moisture content and the possibility of reducing it through aeration is not envisaged, the use of emulsion can lead to excessive water content in the mix with regard to both optimal compaction and potential emulsion flow problems. In such circumstances, foamed bitumen is preferable; this is also the case in a wet climate, with a high risk of precipitation during laying (it can result in mix instability).

Some Agencies suggest that during the mix-design process from field-sampled materials, RA is pulverized to the desired grading (maximum size 40 to 50 mm) and anyway dried for preparation of laboratory test specimens [21]. Other Authors state that, during laboratory specimen preparation, RA should be dried to constant weight, usually at 40 or 60 °C [22].

During mix-design procedures [23], pre-mix RA moisture content is determined for adequate coating, because it influences the curing rate and equilibrium moisture conditions, hence short, medium and long-term effects (for instance, workability, bitumen dispersion, compaction, permanent deformation and moisture susceptibility under traffic loading) [24]. It also contributes to the value of some common indicators of properties such as CBR, DCP penetration [25], plasticity index [26,27] and retained cohesion (MIST), when applied.

7.3 Role of RA Moisture during Mix Design

Preparation of samples for mix-design requires evaluation of the moisture/density relationship, usually according to AASHTO T-180. The Optimum Fluid Content (OFC) and Maximum Dry Density (MDD) of the mixtures are estimated, sometimes completed by the determination of the resilient modulus or other parameters [20].

For FBSMs, the OFC and MDD are usually assumed to be the same as the optimum moisture content (OMC) and MDD of representative samples of the untreated material; actually, the dispersed bitumen can potentially act as a compaction aid, hence the OMC for a foamed mix is generally not the same as that of the parent pulverized material [28,29]. The mixing moisture content (MMC) of a foamed mix is defined as the moisture content in the

pulverized material when foamed asphalt is injected [12]. MMC is practically the same as the compaction moisture content (CMC). MMC and CMC influence the mix properties in terms of binder dispersion and compaction behavior of the material (i.e., density for a given compaction method). No standard test methods currently exist for determining the MMC for foamed mixes, it being typically dependent on the laboratory asphalt foaming unit and mixer used. Experience has shown that typical MMC values are between 75 and 90% of the OMC of the pulverized material; in some opinions [30] the range should be 65 to 85% of OMC as determined by modified AASHTO compaction or even 65 to 95% of OMC [31]. The minimum MMC is the aggregate 'fluff point', i.e. the point at which maximum bulk volume of the loose aggregate is obtained. The optimum percentage of foamant water for laboratory samples varies between 1 to 3.5% [32-34].

For bitumen emulsion stabilized mixes (BESMs), the OFC is the percentage by mass of bitumen emulsion plus additional moisture required to achieve the MDD in the treated material (a minimum of 1 to 2% moisture is required in the aggregate prior to adding the binder, as water acts as lubricant). In this case, a fluid content of 90% of OMC for mixing should be planned [30], even if different approaches are considered for MMC determination.

Wirtgen suggests an iterative process: the OFC is determined by adding a constant percentage of bitumen emulsion whilst varying the amount of water added. The bitumen emulsion is measured as a percentage by mass of the air-dried material; the content of bitumen emulsion to be added is normally between 2 and 3% residual bitumen (e.g. for 3% residual bitumen, 5% of a 60% bitumen emulsion). Bitumen emulsion and water are added to the material and mixed evenly before compaction. OFC and MDD are then determined in accordance with AASHTO T-180 [14].

New York State Department of Transportation [20,31] indicates an emulsion content covering a range typically between 0.5 and 4.0% by dry weight of RA; increments of either 0.5 or 1.0% should be selected. Moisture to be added is typically 1.5 to 4.5%. Mixing of test specimens can be performed manually or with a mechanical bucket mixer. The RA should be mixed thoroughly with water, then with emulsion at ambient temperature (25 ± 2 °C). MMC is 90% of OMC, minus 50% of emulsion content.

Pennsylvania [35,36] uses RA samples from crushed cores. The OMC is determined adding 3, 4, 5, 6, 7% water to mixtures which have 2.5% emulsion content. California doesn't give emphasis to RA moisture content [35,36], since dried material (from crushed core samples) is used, plus 2% water and emulsion. Oregon uses samples obtained by milling; total fluid content is estimated by an analytical method (Oregon's method TM-126) finalized to the optimization of the mix by Hveem stability and resilient modulus [35-37].

In Ontario samples are obtained by cold milling or coring (this solution being preferred). The evaluation of the material consists in determining the RA moisture, because it contributes to the total amount of liquid that should be 4.5% [38].

AASHTO Modified Marshall mix-design [36,39] requires that RA samples are obtained by cold milling. Material evaluation consists mainly in obtaining the moisture content and grading. Mix samples are prepared to achieve 3% total water content (moisture in the emulsion, RA and additional water).

Queensland Department of Transport and Main Roads [40] requires that the moisture content for trial mixes is determined from field moisture and the PI (when RA is mixed with base or foundation aggregate) according to predefined rules: when PI is lower than 6%, samples at 70% OMC of the untreated material using Standard compaction; when PI varies from 6 to 10%, test samples at 70% OMC of the untreated material using Standard compaction; where field moisture content is higher than 70% OMC (Standard compaction), test samples at field moisture content.

In general, specimens of bitumen stabilized mixes are prepared with both gyratory press and Marshall equipment; there seems to be no convergence towards a uniform procedure and water content differs. Mix design methods also vary in curing procedures [21], depending on the binder type [7,41,42].

7.4 Relationship between Moisture and Production of Mixtures with RA

It is clear that mix moisture content plays a fundamental role in: reducing friction angle and lubricating for compaction; providing workability of the mix at ambient temperatures; reducing early strength; providing shelf-life for the mix. For this reason, particular attention should be paid to the fluid content of the mix (including hygroscopic moisture, water and bitumen still in suspension in the emulsion), since high values determine surface deformation under compaction. Dry or porous aggregate is subjected to considerable water absorption and premature breaking of the bitumen emulsion.

In Hot or Cold In-Plant Recycling (H/CIPR), RA moisture can have a significant effect on the amount of recycled aggregate used or the quality of the recycled mix, so it is important for the contractor to monitor RA moisture (especially when aggregate is directly exposed to weather changes) and utilize best management practices to minimize its content. Moist RA is also subjected to temperature reduction due to wind chill, which cannot be accepted before mixing. Moreover, when RA is too wet (above OMC) or too dry (< 50% of OMC) a satisfactory mix will not be produced. During periods of unstable or wet weather a constant moisture content must be assured. Further expedients are necessary during transport and laying with graders, in order to avoid moisture losses.

For CIR, the total fluid content (binder and water) during production is important both in terms of the distribution of the binder, mixing (workability) and compaction of the mix [4]. Changes in grading and moisture of RA occur throughout the production process and can result in changes in CIR mix workability. Adjustments in mix water content or recycling agent content will therefore be necessary to promote good coating and workability. When the particles are not sufficiently coated, the mix water content should be increased: the lower the mix moisture, the higher the mix segregation and raveling under traffic or the poorer the density [43]. Excess mix water may facilitate bitumen flushing to the surface and will delay curing. Where the mix is adequately coated, but lacks cohesion, the emulsion content should be increased together with an equivalent reduction in mix moisture, in order to keep the total fluid content constant. When using foamed bitumen, doping the water with about 0.1% active additive has been found beneficial in coating aggregate [44].

In a stockpile, separation can easily take place and the moisture content will often be different on the surface and in the center of the stockpile. Working at ambient temperatures, the aggregate is cold during mixing. New York State Specifications [31] stipulate that CIR is permitted when the existing pavement contains frost, the surface air temperature is below 7 °C or a temperature decrease below 7 °C is expected within 24 hours. CIR is also excluded in some seasons (October to April).

The moisture content and its uniform distribution throughout the recycled material influences the properties of the mix, affecting the binder dispersion, the compaction effort required to achieve density, and the potential for surface cracking. The amount of water added to CIR mixtures [45] will also affect their final properties: high water contents can produce unstable mixtures. For this reason, RA moisture during construction is accurately determined in order to compare it to the water contents used in the laboratory and for future reference during pavement performance evaluation [45]. For recycled layers, the MDD of the material is used as the reference density; it is determined in the laboratory by means of a moisture-density relationship test, which should be referred to the specific site the sample comes from.

Normally for bitumen stabilized layers (BESMs, FBSMs), at least 100% of the MDD is required with RA aggregate.

In the case of in situ recycling, excessive or variable moisture can sometimes be observed in the bituminous pavement. The layers beneath the wearing course are usually moist and an "equilibrium moisture content" (EMC) relative to the OMC of the material is predictable. However, variations of EMC are possible when the surfacing is cracked (higher moisture can be found close to the cracks), the pavement shoulders are unsurfaced (where water penetration is easier), or there is a sag in the longitudinal section. Saturation of pavements with unbound granular foundations can occur where there are several deep asphalt patches. This problem can be overcome by mixing RA with a granular base material, producing a blend that has a lower OMC value than the original base material (which happens when the EMC in the base approximates the OMC, a common condition during wet seasons and where the surfacing is severely cracked). Where the in situ moisture content of the material to be recycled is higher than the OMC, the material must be preliminarily pulverized and dried before any treatment [46].

During BESM layers construction, the recycler should be equipped with an appropriate spray bar for water application in order to increase the moisture content of the RA and dilute the bitumen to obtain the required fluid content. If the recycled material is dry, pre-treatment adding only water should be done, so that the moisture regime is suitable to accept the emulsion, added during a second pass.

In CIR processes [11], water may be required to facilitate coating and compaction. The water may be present as natural moisture in the RA or aggregate, or may be added before addition of the recycling agent, or may be a component of the recycling agent (e.g. diluted slow-setting emulsified bitumen). For mixing with bitumen, it is essential that the moisture content of the material to be recycled should be 4-6%, so that the hot bitumen can foam and serve as an aid to coating [47]. For BESMs, the compatibility of water with the emulsion should be checked, in order to avoid any adverse effect, such as premature breaking. Generally, slow-setting (cationic and anionic) and anionic medium-setting bitumen emulsions require moisture for mixing; vice versa, emulsions that contain a quantity of petroleum distillates (HFMS-2s, CMS-2 and 2h emulsions) perform better with dry aggregates, than with wet ones [47]. In any case, a coating test in the laboratory should first be carried out, to determine if pre-mix moisture content is adequate to disperse the emulsion and the amount of water needed.

According to [20], water should be added at the milling head to facilitate uniform mixing of the emulsified recycling agent and cold milled material. Water added by the milling machine should be at a rate of between 0.5 and 5.0% by weight of the RA for the approved mix-design. The quantity of residual binder in the final recycled pavement mixture should not vary due to the addition of water.

Where active fillers are applied (i.e. fillers suitable for chemically modifying the mix properties), their effectiveness is evidenced by moisture that immediately triggers the reactions, promoting adhesion between the fine particles. Additives and stabilizers [39] are added in order to reduce the Plasticity Index, swelling and moisture in RA (especially when mixed with natural base aggregate) and to enhance bitumen dispersion in the mix. Bitumen and cement are normally used and act in a different way. In hydraulic mixtures, cement contributes to quickly remove excess moisture from the pulverized material. Lime (calcium hydroxide) is used when RA is mixed with base materials affected by reactive clay (PI higher than 8, fines content greater than 10% [48,49]). The reduction in plasticity helps to minimize swelling and reduce excess moisture in the pulverized base materials and subsequent moisture damage. When moist RA is present, fly ash can provide improved base strength through a cementitious bonding of the grains. Moisture resistance is improved by a reduction in the permeability of the base materials.

Existing granular shoulders can be incorporated into the CIR process, on the condition that uncoated material should not exceed 25% of the resulting RA. In fact, excessive granular material may lead to increased amounts of binder required, and decreased pavement performance, due to a large portion of the mixture being only partially coated with bitumen.

During FDR processes, a water truck is used for supplying water to the reclaimer when additional moisture is required [50]. However, some rules must be observed: paving shall not be executed in the rain and freezing temperatures for 7 days after works are not permitted. Moisture content before emulsion addition shall be checked by microwave oven (ASTM D 4643), nuclear gauge, direct heating, or infrared. The water content in the full depth shall be checked on the same day that emulsion will be applied (in case of rain after testing and before emulsion addition, moisture content shall be repeatedly checked): moisture content shall be within 1% from the mix design recommendation; if not, it shall be modified by water addition or aeration. After each water content change, an evaluation of moisture is needed. In the same way, on the first day of FDR works, the moisture content should be checked at each of three reclaimer passes (reducing sampling frequency after the first day). Before placing any surfacing, the reclaimed base should be allowed to cure until the moisture content in the material is reduced to 50% or less of the mix-design OMC or lower than 2.5%. Conventional construction equipment is adopted for H/CIPR. Where FBSMs are used, the addition of water and in situ mixing are necessary to achieve a uniform moisture content throughout the layer; any moisture loss due to evaporation must be prevented. Where BESMs are employed, the slow breaking of the emulsion guarantees that all the grains can be coated by binder (assuming that the in situ moisture content of the untreated layer is never too high).

8. Summary and Conclusions

The synthesized literature review results are a compendium of the existing techniques to classify RA. All the collected information will be used in the next steps of RILEM task group (TG-6) on cold recycling activities. In particular this will be the base of a proposal for RA classification, as a part of a general procedure for mix design.

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