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characterization of advanced cold recycling bitumen stabilized pavement solutions

# Report on available test and mix design procedures for cold-recycled bitumen stabilised materials

Deliverable D1.1
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# CEDR Call2012: Recycling: Road construction in a post-fossil fuel society

# CoRePaSol
# Characterization of Advanced Cold-Recycled Bitumen Stabilized Pavement Solutions

# Report on available test and mix design procedures for cold-recycled bitumen stabilised materials

# Deliverable D1.1

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# Executive summary


One of the main objectives of CoRePaSol project is to develop and recommend a harmonized advanced mix design procedure for cold-recycled bitumen stabilized materials, for application throughout Europe.

In fact, several recent research studies concerning cold recycling have emphasised that one factor that is hampering its widespread use is a lack of a suitable and harmonised design procedure. For instance, in the Direct-Mat project (7FP EU) it was concluded that cold in-place recycled mix design approaches and the applied test procedures still vary considerably among European countries (Mollenhauer *et al*., 2011).

Among several mix design approaches, the following key points needing further investigation have been identified:

- Effect of different laboratory compaction methods;
- Influence of different accelerated laboratory curing procedures;
- Evaluation of different performance test methods and mix design requirements.

In order to address these issues, the first work package of CoRePaSol project (WP1 - "Advanced mix design of cold-recycled bitumen stabilized material") focus on the assessment of available mix design procedures, test methods and specifications (standards) for use of cold recycling in pavement rehabilitation and construction.

In this context, one of the first activities of WP1 consisted on collecting world-wide information about mix design procedures with emphasis in European countries.

The purpose of Deliverable D1.1 is to synthesize that information in order to provide an overview on applied mix design procedures.

Based on a comparison of the test methods used and specification limits a holistic synthesis on the available mix design procedures was elaborated. Differences were analysed in terms of the following aspects:

- Type of cold recycling techniques generally used (e.g. type of application and of materials used);
- Requirements on Reclaimed Asphalt (RA) use on cold-recycled bitumen stabilised materials;
- Characteristics of bituminous binders as well as of hydraulic binders (including cement) used on cold-recycled bitumen stabilised materials;
- Typical compositions of cold-recycled bitumen stabilised materials;
- Laboratory test procedures applied for mix design (e.g. type of test specimens, compaction methods, curing procedures, performance test methods)
- Used standards and references.

For planed and widely analyzed assessments various sets of experimentally designed mixes have been used based mainly on use of reclaimed asphalt mineral material and will be continuously used and tested until end of the project CoRePaSol with the target to cover all four key technical options: cold recycled mixes with bituminous emulsion or foamed bitumen (with not more than 1 % cement) and cold recycled mixes with combination of bituminous and hydraulic binder with cement content >1 %. Additionally for some assessments mixes where bituminous binders are used alone or in combination with cement mixes with recycled concrete or recycled granular (unbound) sub-base are tested as well.

# 1 Introduction

The main objective of CoRePaSol project is to develop and recommend a harmonized advanced mix design procedure for cold-recycled bitumen stabilized materials, to be applied throughout Europe.

In fact, several recent research studies concerning cold recycling have emphasised that one factor that is hampering its widespread use is a lack of a suitable and harmonised design procedure. For instance, in the Direct-Mat project (EU FP7) it was concluded that cold in-place recycled mix design approaches and the applied test procedures still vary considerably among European countries (Mollenhauer *et al*., 2011a).

Among several mix design approaches, the following key points needing further investigation have been identified:

- Effect of different laboratory compaction methods;
- Influence of different accelerated laboratory curing procedures;
- Suitable test procedure for water sensitivity assessment;
- Evaluation of different performance test methods and mix design requirements.

In order to address these issues, the first work package of CoRePaSol project (WP1 - "Advanced mix design of cold-recycled bitumen stabilized material") focus on the assessment of available mix design procedures, test methods and specifications (standards) for use of cold recycling in pavement rehabilitation and construction. WP1 is structured into five tasks, including the review on existing mix design procedures and an extensive laboratory study as a starting activity, as follows:

- Task 1.1: Review on specifications and international literature on mix design, comparison of mix designs applied internationally.
- Task 1.2: Selection and characterisation of materials.
- Task 1.3: Comparison of compaction and curing methods.
- Task 1.4: Cold-recycled mixture characteristics and performance.
- Task 1.5: Harmonized advanced mix design procedure.

As previously mentioned, one of the first activities of WP1 consisted on collecting world-wide information about mix design procedures with emphasis in European countries.

Questionnaires have been issued to gather information about common practice on cold-recycling, about used laboratory test procedures and about available standards and legislation. Through these questionnaires, information has been collected from several countries which the partners have been in contact with, given that, apart from their own national responses, each partner has tried to gather information from at least one additional country.

In order to obtain a more widespread international overview, information has also been collected through the following initiatives:

- Review of International existing literature and from recent research projects on the field of cold recycling (e.g. Direct-Mat, Paramix and SCORE projects). One key technical document for CoRePaSol project is the quite recent manual from Wirtgen on "Cold Recycling Technology" (Wirtgen, 2012).
- Internal workshop on "mix design", on 19.04.2013, Munich - Germany, during the second meeting, which included: 1) Review of European mix designs; 2) International

comparison of mix designs. This workshop counted with the presence of the South African expert Kim Jenkins.

The purpose of Deliverable D1.1 is to synthesize that information in order to provide an overview on applied mix design procedures.

Based on a comparison of the test methods used and specification limits a synthesis on the available mix design procedures was elaborated. Differences were analysed in terms of the following aspects:

- Type of cold recycling techniques generally used (e.g. type of application and of materials used);
- Requirements on Reclaimed Asphalt (RA) used in cold-recycled bitumen stabilised materials;
- Characteristics of bituminous binders as well as of hydraulic binders (including cement) used in cold-recycled bitumen stabilised materials;
- Typical compositions of cold-recycled bitumen stabilised materials;
- Laboratory test procedures applied for mix design (e.g. type of test specimens, compaction methods, curing procedures, performance test methods)
- Used standards and references.

# 2 International / European overview on mix design approaches for cold-recycled bitumen stabilised materials

## *2.1 Cold-recycling techniques*

In order to address the common practice in different countries a questionnaire was issued to the partners covering general aspects about cold recycling techniques, such as:

- Type of cold recycling techniques: in-situ/in-plant;
- Type of layers usually recycled: surface/binder/base layers, bound/unbound layers, *etc.;*
- Type of cold-recycled bitumen stabilised layers: surface/binder/base/sub-base layers
- Bituminous binders generally used: bituminous emulsion/ foamed bitumen;
- Hydraulic binders used as secondary binder: cement, lime hydrated, *etc.;*
- Additives used.

Table 1 presents the results obtained for each of the countries where information was gathered.

From the data presented in Table 1 the following conclusions can be drawn:

- Most countries perform mainly in-situ cold-recycling, generally in excess of 90 % (more flexible, time-saving, more cost-effective);
- In general, cold-recycling is commonly applied to a wide range of pavement layers, from sub-grade material or granular base layers to bituminous surface. Therefore, reclaimed asphalt (RA) used in cold recycling terminology can include materials originating exclusively from the asphalt layers, or being a mixture of these with materials from unbound granular layers or even cement/lime stabilized materials;
- The large majority of cold-recycled bitumen stabilised materials are applied in base or binder courses;
- As regards to bituminous binder, bituminous emulsion and foamed bitumen are used by all analyzed countries except by Finland (not using emulsion) and Portugal and Spain (not using foamed bitumen);
- As secondary binders, cement and hydrated lime are commonly used for most countries. On the contrary, Finland or Sweden doesn’t use any of these, but reports the use of corrective materials (aggregates, i.e. gravel). Nevertheless in general there are also efforts to use other mineral binders (fly-ash, dust filler especially if containing calcium, slag). It is worth to mention that other countries also use other corrective materials besides cement and lime (for instance, natural aggregates /filler to adjust the grading curve);
- Some countries reported the use of additives such as foaming agents, adhesion promoters and/or fly ashes.

**Table 1: Type of cold recycling techniques generally used**

| Country | Type of cold recycling | What structural layers predominately | What is recycled (original structures) | Binders used | | Additives used |
|---|---|---|---|---|---|---|
| | | | | primary | secondary | |
| Czech Republic (Slovakia) | in-situ (90%)<br><br>in-plant (10%) | • base courses<br>• binder course | • binder and/or base asphalt layers<br>• cement and/or lime stabilized base layers<br>• macadam<br>• granular base layers<br>• soil stabilization | • bituminous emulsion<br>• foamed bitumen<br>• combination with cement | • cement<br>• lime hydrated | Foaming agents or adhesion promoters not used in cold recycling |
| Finland | in-situ (much):<br>2-3 mil. m² per year,<br><br>in-plant (less) | • base courses<br>• binder courses | Asphalt pavements<br>• Class I only hot recycling/remixing applies (over 5 mil. m² per year)<br>• Class II and III | • foamed bitumen<br>• bituminous emulsion | • cement only for increased bearing capacity<br>• Gravel 0-32 mm<br>• Gravel 0-55 mm Depending on fine contents to correct -> to much fines = to much water content | Sometimes fly ashes |
| France | Mainly in-situ , but also in-plant<br>2009: It has been planned that in 2012 will be 60% of RAP recycled using cold and hot technologies.<br>*Note: The annual volume of RAP in France is about 5 millions tons.*(1) | • base courses<br>• binder course | • Class I: unbound layers and wearing course < 4 cm<br>• Class II and III: 5-12 cm of asphalt layers (Guide technique SETRA, 2003) | • bituminous emulsion<br>• foamed bitumen | • cement<br>• lime hydrated | Foaming agents sometimes used |

[1] Bitume info" 2009 (France)

| Country | Type of cold recycling | What structural layers predominately | What is recycled (original structures) | Binders used | | Additives used |
|---|---|---|---|---|---|---|
| | | | | primary | secondary | |
| Germany | mainly in-situ | • base course | • binder and/or base asphalt layers<br>• specially optimized method for tar contaminated layers<br>• cement and/or lime stabilized base layers<br>• granular base layers<br>• soil stabilization | • bituminous emulsion + cement<br>• foamed bitumen | • hydraulic road binders<br>• cement | adhesion promoter (if required) |
| Ireland | In Ireland cold-mix materials were traditionally manufactured using virgin aggregates and used on low-traffic rural roads. In recent years the practice has changed to promote cold-recycling, but the national experience is still at an early stage. | | | • bituminous emulsion<br>• foamed bitumen | • cement<br>• lime hydrated | Foaming agents & adhesion promoters |
| Norway | • Recycled Asphalt Pavement: (approx. 85 %); in-plant (approx.15 %).<br>• Unbound aggregate: in-situ (99 %); in-plant: (1 %) | • levelling course<br>• base courses<br>• binder course | • asphalt wearing course<br>• base asphalt layers<br>• granular base layers<br>• old gravel wearing course | • bitumen emulsion<br>• foamed bitumen<br>• lignin (ligno-sulphonate) | • water added to asphalt granulate: improved mixing and compaction | • active adhesion agent (amine) in foamed bitumen |
| Portugal | in situ (100 %)[2],[3] | • Base courses<br>• Regulating / binder courses | • Surface, regulating/binder and/or base asphalt layers (including bituminous macadam)<br>• Surface dressing<br>• Cement stabilized base layers (hydraulic macadam)<br>• Granular base layers | • Bituminous emulsion | • Cement<br>• Hydrated lime | - |

2 From 1992 to 2008

3 In 2013 large Portuguese construction company has bought a new asphalt plant, which allows in plant recycling with foamed bitumen using up to 50 % of RAP, and therefore in plant cold/half-warm recycling is expected to take place next years.

| Country | Type of cold recycling | What structural layers predominately | What is recycled (original structures) | Binders used | | Additives used |
|---|---|---|---|---|---|---|
| | | | | primary | secondary | |
| Spain | in situ (90 %)<br>in plant (10%) | • base courses<br>• binder courses | • Surface, regulating/binder and/or base asphalt layers (including bituminous macadam)<br>• Surface dressing<br>• Cement stabilized base layers (hydraulic macadam) | • bituminous emulsion<br>• cement | • hydrated lime | - |
| United Kingdom | in-situ (95 %); ex-situ not specific but reports suggest between 30 – 70 %. In-plant recycling in UK is very small [(4)] | • structural course (roadbase)<br>• foundation platform (sub-base) | Foundation or main structural layer of a road pavement, such as:<br>• bituminous surfacing,<br>• roadbase,<br>• sub-base,<br>• capping<br>• subgrade material. | • bituminous emulsion<br>• foamed bitumen | • cement<br>• lime hydrated<br>• Pulverised Fuel Ash (PFA)<br>• Granulated Blast Furnace Slag | Foaming agents |
| South Africa | in-situ (70 %)<br>in-plant (30 %) | • predominantly base layers | Thin surfacing (asphalt or surface dressing) and high quality granular base | • foam bitumen | • cement<br>• lime hydrated | Generally not used |

4 Ref. Asphalt Surfacing, Ed. J.C. Nicholls.

## 2.2 Materials used and typical compositions

A questionnaire was issued about the materials commonly used in asphalt cold-recycling and about typical compositions. In this context, two tables were prepared (Table 2 and Table 3). This part does not deal with using cold recycling techniques for non-bituminous materials, especially cement/lime stabilized materials or reclaimed cement concrete.

Table 2 presents the Reclaimed Asphalt required characteristics in order to be cold-recycled.

Table 3 presents requirements on binders used as well as its typical contents in the final recycled mix.

Gathered information shows that generally there are requirements for grading of reclaimed asphalt material or for the final granular mix composition. Nevertheless, requirements on its quality are rather unusual and hardly possible, since this material will be always classified as heterogeneous (effect of milling different layers together, impact of local repairs during the pavement life-time, effect of possible overlays etc.)..

Figure 1 presents recommended grading envelopes for cold bitumen stabilised mixes according to Wirtgen manual (2012). Figure 1 shows typical reclaimed asphalt grading curves as well.

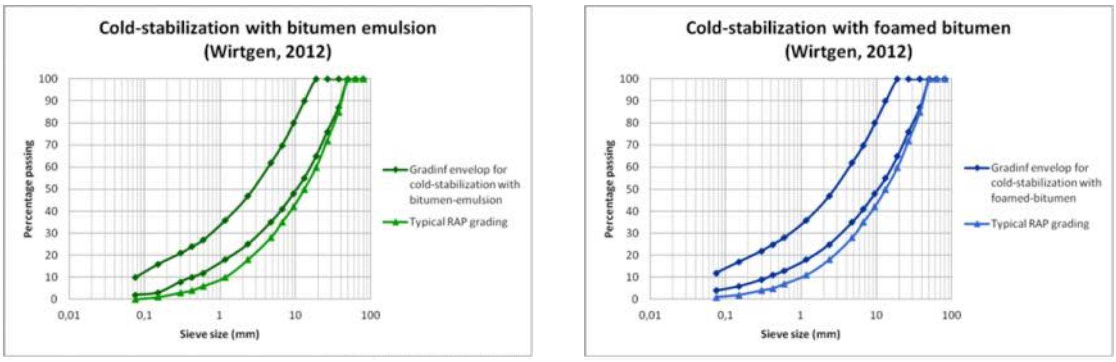



**Figure 1 – Recommended grading envelops for bitumen stabilisation (Wirtgen, 2012)**

Generally, requirements for the material to be cold recycled using bituminous binders (alone or in combination with hydraulic binders) consists on using a well-graded material that should fit in the grading envelops such as the ones presented in Figure 1. This secures sufficient cohesion of the mix and leads to allowed voids content and necessary strength properties.

**Table 2: Requirements on reclaimed asphalt pavement used**

| **Country** | **Reclaimed asphalt pavement material for cold recycling (RAP)** | | | |
|---|---|---|---|---|
| | Fine particles content | Fine particle quality | Grading oversize | References |
| Czech Republic | Cement: $f_{15}$<br>Emulsion/foam + cement: $f_{15}$<br>Emulsion/foam: $f_6$ | Cement: Ip ≤ 17<br>Emulsion/foam + cement: Ip ≤ 17<br>Emulsion/foam: not required | Cement: 10 %<br>Emulsion/foam + cement: 10 %<br>Emulsion/foam: 10 % | Reclaimed asphalt material: CSN EN 13108-8<br>Recycled aggregates: CSN EN 13242+A1<br>Cold recycling: TP208 (technical specifications of the Ministry of Transport) |
| Finland | < 0,063 mm: ≥ 4%, ≤ 8 % or ≤ 10 % when water sensitivity is proven for the resulting mixture | | 15 % | Päällysrakenteen stabilointi. Tiehallinto 2007 |
| Germany | **in situ:**<br>Emulsion/foam + cement:<br>• < 0,09mm: ≥ 2 % and ≤ 10 %<br>• < 2mm: ≥ 20 %<br>Foam:<br>• < 0,063mm: ≥ 3 % and ≤ 12 %<br>• < 2mm: ≥ 25 %<br>**in plant:**<br>Emulsion/Foam + cement<br>• < 0,063mm: 4-9 %<br>• 0,063mm – 2mm: 20-30 % | - | Emulsion/foam + cement: 10 %<br><br>Foam: 10 % | M KRC – Merkblatt für Kaltrecycling in-situ im Straßenoberbau<br>M VB-K – Merkblatt für die Verwertung von pechhaltigen Straßenbaustoffen und von Asphaltgranulat in bitumengebundenen Tragschichten durch Kaltaufbereitung in Mischanlagen |
| Ireland | - | - | - | NRA Specification for Highway Works – Series 900, Clause 947. |
| Portugal | **In situ:**<br>Sieve 0,063mm: 0%-3%<br>Sieve 0,250mm: 0%-10% | - | - | CETO-EP (Type Specifications for Construction of Portuguese Road Administration) |
| Spain | **In situ:**<br>Sieve 0,063mm: 0%-3%<br>Sieve 0,250mm: 0%-10% | - | - | PG-4 – Art.s 20 & 21 (General Specifications for Maintenance of Spanish Road Authority) |
| United Kingdom | - | - | - | Specification for Highway Works – Series 900, Clause 947 |
| South Africa | **In situ:**<br>BSM-Foam<br>• Sieve 0,075mm: 2-9% (ideal)<br>• Sieve 0,075mm: 9-20% (less suitable)<br>BSM-Emulsion<br>• Sieve 0,075mm: 4-10% (ideal)<br>• Sieve 0,075mm: 10-20% (less suitable)<br>• In practice: 0,063mm: 2%; <2mm: 25 to 35% | -- | - | TG2 as reference to SANS draft 4.2 |

**Table 3: Requirements on binders and typical compositions**

| Country | Primary binders (bituminous binders) | | | | Secondary binders (hydraulic binders) | | | |
|---|---|---|---|---|---|---|---|---|
| | Bituminous emulsion | | Bitumen (to be foamed) | | Cement | | Hydraulic road binder | |
| | type | content | type | content | type | content | type | content |
| Czech Republic (Slovakia) | C60B7; C65B7<br>(for partial recycling C60BP7 or C65BP7)<br>*Emulsion cement stability g<2*[5] | Emulsion + cement: 2-3,5% of residual binder<br>Emulsion: 0,9-1,6% of residual binder | 50/70; 70/100; 100/150; 160/220<br><br>Expansion: ≥ 10ml/g<br>Half time: ≥ 10s | Foam + cement: 2-3,5% of residual binder<br>Foam: 0,9-1,6% of residual binder | CEM I 32,5 N (R)<br>CEM I 42,5 N (R)<br>CEM I 52,5 N (R) | Only cement: 4-6 %<br>Emulsion/foam + cement: 2,5-5% | HRB 22,5 E<br>HRB 32,5 E | not prescribed |
| Finland | emulsion with 160/220 | ≥ 0,8 % residual binder; total bitumen content (including RA): ≥ 3,0 % | 160/220 | ≥ 0,8 %; residual binder; total bitumen content (including RA): ≥ 3,0 % | CEM I, II or III | 1/3 of bituminous binder | - | - |
| Germany | C60B1-BEM | Emulsion: 2,0-6,0% of residual binder | 50/70; 70/100<br>Expansion: min. 10-fold<br>Half time: min. 10 s | Foam: 2,5-5,0% of residual binder | CEM I – V<br>(DIN EN 197-1) | Only Cement: ≥ 3,0 M.-%<br>Cement + Foam: 1,0-3,0 M.-%<br>Cement + Emulsion: 3,0-6,0 M.-% | HRB 12,5 E<br>HRB 32,5 E<br>(DIN 18506) | - |
| Ireland | - | **In-plant mixing:**<br>Minimum 3% for QVE and SVE<br>**In-situ mixing:**<br>Minimum 4% for QVE and SVE | Grade 160/220 or harder | **In-plant mixing:**<br>Minimum 3% for QVE and SVE<br>**In-situ mixing:**<br>Minimum 4% for QVE and SVE | CEM I as per IS EN 197-1 | **In-plant mixing:**<br>QH[6]: 2% minimum<br>QVE: 1% minimum<br>SVE: no CEM I<br>**In-situ mixing:**<br>QH[7]: 3% minimum<br>QVE: 1% minimum<br>SVE: no CEM I | - | - |

[5] According to CSN EN 12848

[6] QH: Quick hydraulic: CEM I Portland cement as the main binder; QVE: Quick visco-elastic: bituminous binder but also including some CEM I; SVE: Slow visco-elastic: bituminous binder but excluding CEM I

[7] QH: Quick hydraulic: CEM I Portland cement as the main binder; QVE: Quick visco-elastic: bituminous binder but also including some CEM I; SVE: Slow visco-elastic: bituminous binder but excluding CEM I

| Country | Primary binders (bituminous binders) | | | | Secondary binders (hydraulic binders) | | | |
|---|---|---|---|---|---|---|---|---|
| | Bituminous emulsion | | Bitumen (to be foamed) | | Cement | | Hydraulic road binder | |
| | type | content | type | content | type | content | type | content |
| Norway | C60B5-7, C65B5-7<br>Emulsion shall be fitted to the actual aggregate and mix | Residual binder content 2-4 mass % of a mix with 16 mm max. aggregate size | Emulsified: 160/220, 330/430, V12000 or V6000<br>Foamed: 160/220, 330/430 or V12000 | | | | | |
| Portugal | C60B7(Rec) | ≥ 1,5% of residual binder (≈ 2,5% bitumen emulsion) | | | | ≤ 1%<br>≤ 2% when recycling also granular layers | - | - |
| Spain | C60B7 REC<br>C60B6 REC | ≥ 1,5% of residual binder | | | | ≤ 1% when bitumen emulsion is used | 32.5 usually | >3% |
| United Kingdom | As per 434-1 | **Ex-situ mixing:** Minimum 3% for QVE and SVE<br>**In-situ mixing:** Minimum 4% for QVE and SVE | Grade 160/220 or harder | **Ex-situ mixing:** Minimum 3% for QVE and SVE<br>**In-situ mixing:** Minimum 4% for QVE and SVE | CEM I as per IS EN 197-1 | **Ex-situ mixing:**<br>QH[5]: 2% minimum<br>QVE: 1% minimum<br>SVE: no CEM I<br>**In-situ mixing:**<br>QH[6]: 3% minimum<br>QVE: 1% minimum<br>SVE: no CEM I | - | - |
| South Africa | SABS309 (anionic)<br>SABS 548 (cationic) | - | 80/100 as per SABS307 spec | < 2,5% | CEM II 32.5 as per SANS 50197-1:2000 | < 1% in any case less than bitumen content | - | - |

Some countries, such as Spain and Portugal, only apply specifications on the reclaimed asphalt material (Figure 2). Both countries specify two different grading envelopes: one (RE1/I) for applications in higher thickness layers (≥ 10 cm) and other (RE2/II) for layers' thicknesses between 6 cm and 10 cm.

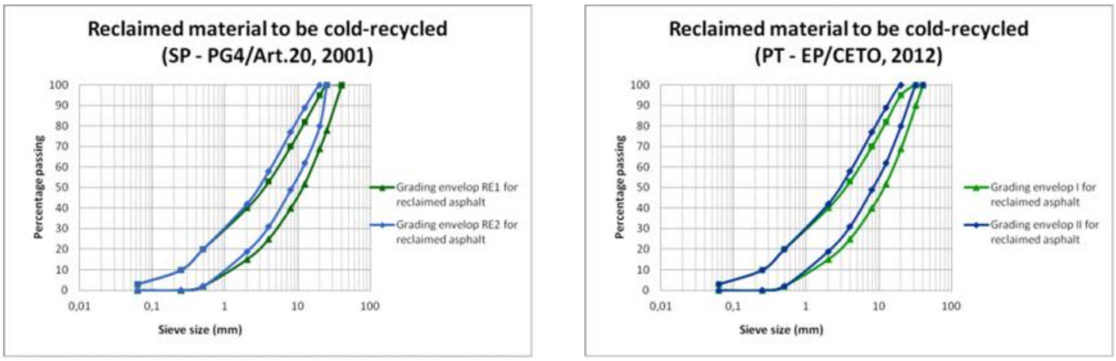



**Figure 2 – Requirements for reclaimed asphalt grading from Spain (PG4 – Artículo 20, 2001) and from Portugal (EP-CETO, 2012)**

In order to achieve the desired grading curve fitting a given envelope, usually additionally imported material (e.g. crushed aggregates/filer) needs to be added to the reclaimed material. As stated in section 2.1, natural aggregates / filler are typically used as corrective materials with the purpose of adjusting the grading curve. Other corrective materials such as cement or lime are also added to the reclaimed asphalt, so that the final granular mixture presents the desired characteristics. That is because, the addition of cement or lime can also aim at increasing early age stiffness of the recycled layers and to decrease both its water sensitivity and curing time, especially when the reclaimed material includes unbound granular layers (Mollenhauer *et al.*, 2011b).

Another solution could be to increase thickness of recycled layer with respect to incorporating also a portion of the bottom layers (i.e. unbound granular material in base course). This however can lead to the presence of cohesive materials (e.g. clay) in the reclaimed asphalt, which should be avoided. In this case, it is preferable to incorporate new materials. For in-situ recycling, that can be made by pre-spreading those materials as a layer on the surface before recycling (Wirtgen, 2012). This has been done e.g. for one of the trial sections monitored within the CoRePaSol project in Finland.

With respect to the typically used binders, gathered information shows that:

- **Bituminous emulsion**: Slow setting bitumen emulsions produced with at least 60 % of paving grade bitumen (C60B6 and C60B7) are the most popular. In some countries, such as Norway, the use of medium setting bitumen emulsions with modified binders (C60BP5 and C65BP5) is also allowed. In the Czech Republic, bitumen emulsions produced with polymer modified bitumen (C60BP7 and C65BP7) are also used for partial recycling (in-plant recycling).
- **Foamed bitumen**: A wide range of paving grade binders according to EM 12591 (50/70; 70/100; 100/150; 160/220) can usually be used to produce foamed bitumen. Climatic conditions have a major influence on the selection of the bitumen. In practice, Southern European countries generally use harder grades and Northern countries softer bituminous binders.

- **Cement**: Majority of countries require Portland cement or Portland slag cement (CEM I) to be used in cold recycling. For high cement contents, the use of low resistance cement class (with less heat of hydration) may be recommended in order to minimize the occurrence of shrinkage. As such, it is usual recommended to use 32.5 cement strength class. However, CEM I 32.5 is not marketed or even produced at the present in most countries as Portland cement, being then replaced by 42.5 resistance strength Portland cements (CEM I 42.5) or as an alternative Portland-Limestone cements/Portland slag cement (CEM II 32.5).
- **Special hydraulic road binders**: Some countries, such as Czech Republic and Germany, have specifications for hydraulic road binders other than cement (e.g. lime or HRBs) to be used in road paving construction. In this case, 32.5 or lower resistance class is recommended.

Additionally it is possible to use also other alternative binders or mineral additives like slag or fly-ash. Other ongoing research activities are looking in the opportunities to activate dust particles gained during aggregate production or use pulverized recycled concrete (especially its fine particles with increased content of hydrated cement mortar).

With respect to binder contents, collected information shows a geographical distribution among European countries, with Central European countries using bituminous binder combined with relatively high contents of hydraulic binder (≈ 3 – 5 %) – because of using cold recycling for increasing bearing capacity of base/binder courses, and Southern countries (e.g. Portugal and Spain) using only bitumen emulsion or emulsion combined with low content of hydraulic binders (≤ 1 %), whereas hydraulic binder is used just to increase slightly the content of fines. Some Northern countries don't apply cement at all.

These differences in applied binder contents result in different types of cold recycled material approaches. One approach is to increase the bearing capacity by high contents of cement binder in the cold recycled layer, resulting in hydraulically dominant mix properties. By adding bituminous binder the flexibility of this material can be increased. With high binder contents a complete covering of the reclaimed granulate material is reached which enables the recycling of environmental hazardous (e. g. tar-containing) road materials. Lower bitumen contents (residual binder content ≤ 3 %, i.e. low to moderate bitumen contents) result in discontinuously bond materials which are referred to as "Bitumen stabilised Materials (BSM)", which inhibits material properties which combines the performance of flexible bound and unbound as well as rigid pavements influenced by the binder contents.

The effect of variation of bitumen and cement content on the mechanical properties can be explained by Figure 3 which allows the classification of BSM as well as other cold recycled materials.

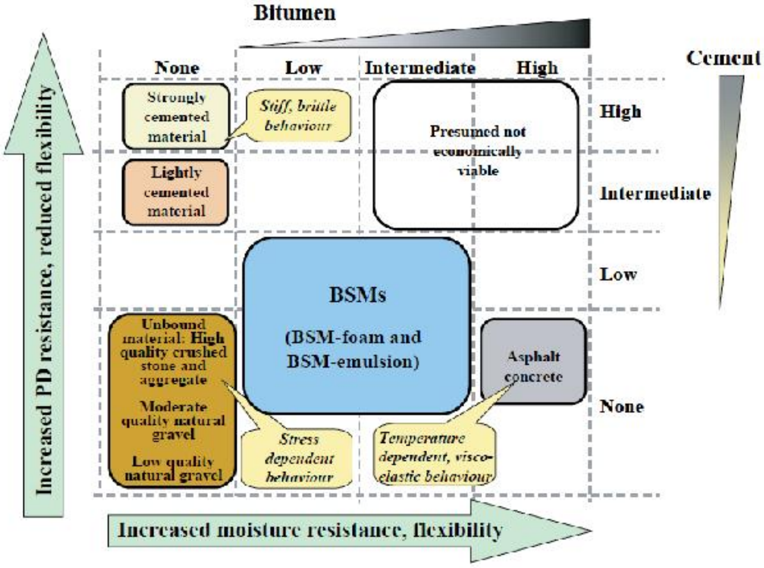



**Figure 3 – Conceptual behaviour of pavement materials (Collings et al., 2009)**

These differences in mix design approaches also result in considerably diverting experiences with cold-recycled materials within Europe. During Direct-Mat project, a total of 21 case studies on cold recycling procedures were gathered. The applied binder contents vary considerably throughout the collected case studies - though some general trends can be observed (Figure 4):

- In case studies from Sweden no cement and low bitumen contents (< 2 %) were applied;
- Case studies from Spain and Portugal are characterised by moderate bitumen content (2 – 3 %) and low cement content (≤ 1.5 %);
- In case studies from Germany, Poland and Slovenia moderate bitumen contents were applied (2 – 3.5 %) combined with higher cement contents (2 – 4 %).

These different experiences must be taken into account when comparing the applied mix design approaches and formulating future harmonized design manuals for this type of rehabilitation techniques.

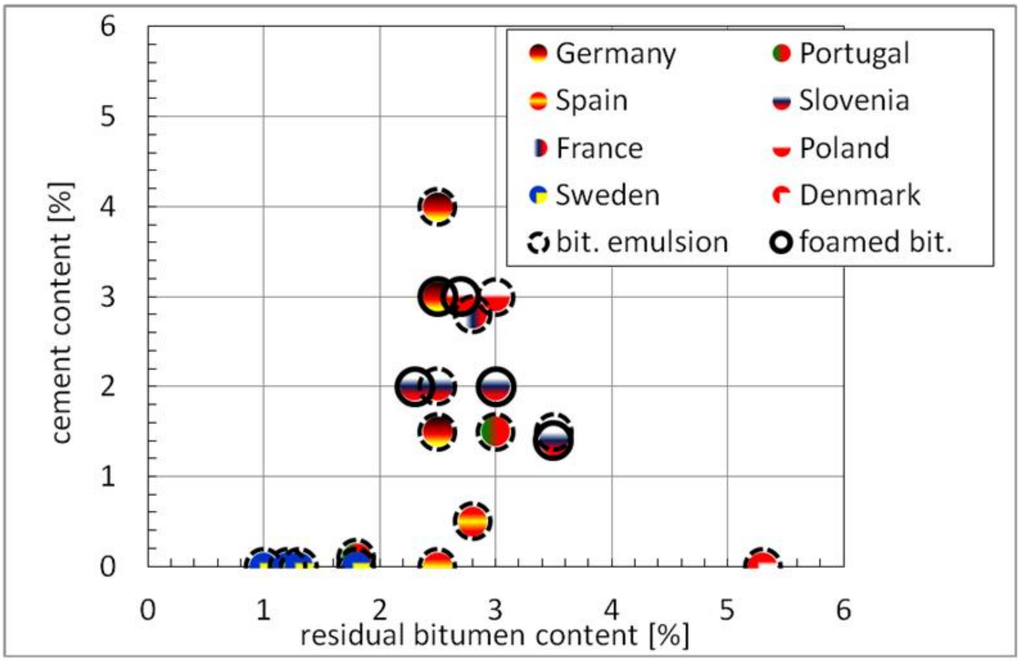



**Figure 4 – Binder contents of cold recycling case studies gathered during Direct-Mat project**

Grille *et al*. (2012) define four kinds of cold-recycled materials:

1. Cement-treated materials (CTM) without any bitumen.
2. Bitumen stabilised materials (BSM) which contain bituminous emulsion or foamed bitumen as bituminous binder (residual binder content ≤ 3 %) and may contain some cement binder as active filler (≤ 1 %)
3. Cement-bitumen-treated materials (CBTM) with residual bitumen contents ≤ 3 % and cement contents ≤ 2.5 %.
4. Cold asphalt mixtures (CAM) with high bitumen contents (≥ 3 %) and possibly cement as active filler.

Figure 5 shows cold recycling concepts as defined by Grilli *et al*. (2012) in combination with the different binder contents applied in selected European countries according to Table 3.

| Country | Bituminous binder | | | | | Hydraulic Binder | |
|---|---|---|---|---|---|---|---|
| | Bituminous binder | | | Foamed bitumen | | Cement content | |
| | | emulsion content | residual bitumen | | | | |
| Czech republic (Slovakia) | Emulsion (+cement) | 3,2-5,6% | 2,0-3,5% | Foam (+cement) | 2,0-3,5% | cement(emul./foam) | 2,5-5,0% |
| | Emulsion only | 1,4-2,6% | 0,9-1,6% | Foam only | 0,9-1,6% | cement only | 4,0-6,0% |
| Germany | Emulsion (+cement) | 3,2-9,6% | 2,0-6,0% | Foam (+cement) | 2,5-5,0 | cement (+foam) | 1,0-3,0% |
| | | | | | | cement (+emulsion) | 3,0-6,0% |
| | | | | | | cement only | ≥ 3,0% |
| Ireland / United Kingdom | Emulsion (+cement) | ≥ 6,4% | ≥ 4,0% | Foam (+cement) | ≥ 4,0% | QH | ≥ 3,0% |
| | | | | | | QVE | ≥ 1,0% |
| Norway | | 3,2-6,4% | 2,0-4,0% | | | | |
| Portugal / Spain | Emulsion (+cement) | ≥ 2,4% | ≥ 1,5% | - | | cement (+emulsion) | ≤ 1,0% |
| Wirtgen Manual | Emulsion (+cement) | < 3,0% | <1,8% | Foam (+cement) | < 3,0% | cement (+emulsion) | ≤ 1,0% |

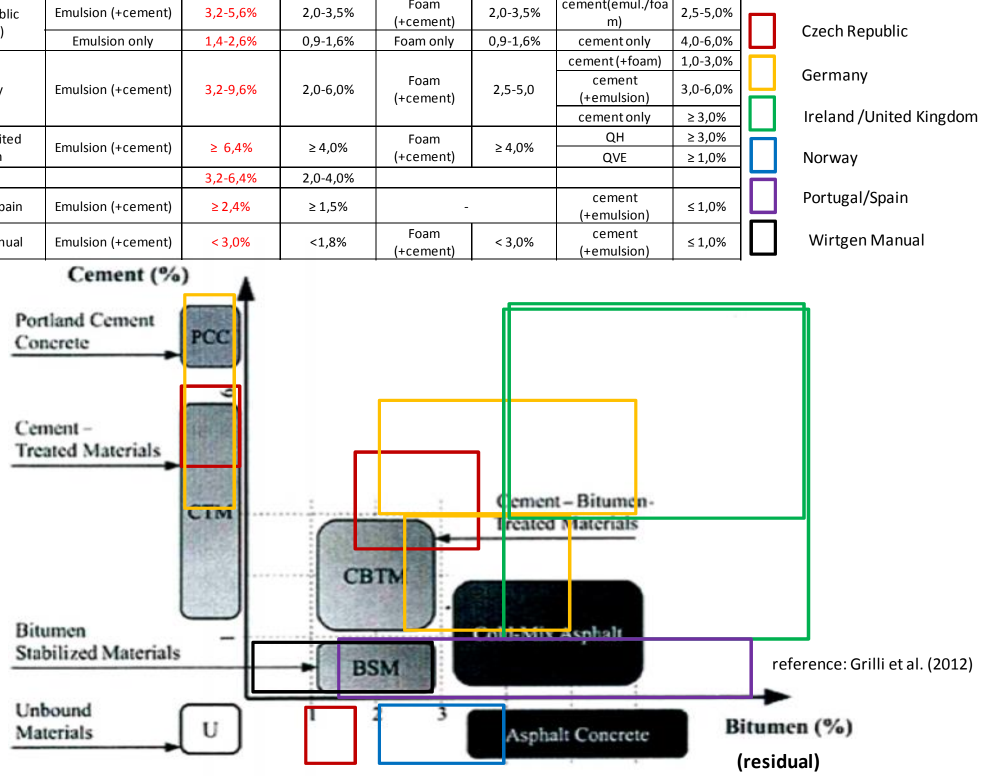



**Figure 5 – Different binder contents of European countries**

From Figure 5 it is evident, that the binder contents applied in Europe show some deviation from the cold recycling concepts as defined by Grille *et al*. (2012). Only the mix specifications as applied in Portugal, Spain and Norway can clearly be classified as bitumen stabilised material (BSM) according to Grille *et al*. (2012). For the other countries, higher contents of cement and higher residual bitumen contents are applied which can not be always assigned exactly to cold recycling types defined by Grilli *et al*. (2012).

These differences may result to some extent from historical reasons. For instance, in Germany cold recycling technique is used for recycling tar containing pavement layers. Therefore, higher bituminous binder content is provided to ensure a complete covering of these aggregates and good immobilization. On the contrary, in Portugal coal tar had barely been used in asphalt pavement applications, even during World War II, thus not enforcing the use of higher bituminous binder content.

Obviously it is difficult to give performance grades of cold recycling materials, which can be clearly distinguished according to the resulting mechanical material properties. These differences demand for varying mix design procedures as discussed in following section.

## 2.3 Laboratory test procedures applied for mix design

After establishing the correct granular composition (RA + corrective materials if required) and selecting bituminous binder to be used, mix design procedures comprise:

- Determination of water content for optimization of the mix workability and the layer compaction during construction;
- Determination of optimum bitumen residue content (or setting required bituminous emulsion/bitumen foam content) in order to ensure the desired mix stability and strength during the pavement's service life.

Previous research projects, such as Direct-Mat (Batista *et al*., 2012), concluded that the optimal water content can be estimated according to laboratory Proctor test results. In contrast, there is no consensual method for detecting the optimum bitumen residue content.

Even though the selection of the bitumen content being usually based on the mechanical properties of the mixture, the correspondent test procedures differ considerably worldwide, namely with reference to compaction methods and specimens dimensions, curing procedures, testing conditions and required quality parameters.

In order to address the laboratory tests and quality control procedures generally applied for mix design in different countries a questionnaire was issued to the partners covering these aspects. Tables 4 and 5 present the results obtained, respectively in terms of applied procedures and existing standards and references.

**Table 4: Laboratory tests and quality control procedures applied for mix design**

| Country | Test specimens | | | | Testing conditions |
|---|---|---|---|---|---|
| | Compaction method | Specimens dimensions | Curing procedure | Quality characteristics | |
| Czech Republic (Slovakia) | Static pressure (5 MPa compression stress for Ø150mm specimens). | ITS: Ø150 mm, height 125 mm (at least 3 specimens for each test) | • cement: 100% moisture at 20°C<br>• emulsion/foam + cement: 90% moisture at 20°C for 2 days then 40-70% moisture<br>• emulsion/foam: air curing at 20°C | **Cement:**<br>- min. air voids not required;<br>- compression strength after 28 days ($R_c$) $C_{3/4}$;<br>- water and frost susceptibility – 85% of $R_c$;<br><br>**Emulsion/foam + cement:**<br>- min. air voids not required;<br>- indirect tensile strength after 7 days ($R_{it}$) 0,30-0,70 MPa;<br>- water susceptibility after 7days dry and 7 days wet curing – residual $R_{it}$ 75%;<br><br>**Emulsion/foam:**<br>- min. air voids 6-14% vol.;<br>- indirect tensile strength after 7 days ($R_{it}$) min. 0,30 MPa;<br>- water susceptibility after 7days dry and 7 days wet curing – residual $R_{it}$ 60%. | **ITS:**<br>- temperature 15°C;<br>- loading speed 50 mm/min.<br>**Water immersion:**<br>- water bath temperature – ambient.<br>**IT-CY[8]:**<br>- temperature 15°C;<br>- strain control test (5 microns defl.);<br>- rise time 125 ms. |
| Finland | Proctor | Ø150 mm | • without cement: 7 days & 28 days @ room conditions<br><br>• with cement: 7 days & 28 days @ 95 % humidity, 20 °C | ITS (1 day) ≥ 80 kPa<br>ITS (28 day) ≥ 500 kPa<br><br>ITSR after frost conditioning: ≥ 40 % | **ITS:**<br>- temperature 10 °C;<br>- loading speed 50 mm/min |

8 Not included in technical specification. Stiffness testing is possible only at TU Prague and TU Brno. Standard conditions used for stiffness testing.

| Country | Test specimens | | | | Testing conditions |
|---|---|---|---|---|---|
| | **Compaction method** | **Specimens dimensions** | **Curing procedure** | **Quality characteristics** | |
| France | Gyratory<br>Class II and III:<br>25 % @100 rotations<br><br>(also static compaction according to Duriez test method) | | Curing 18 °C<br>7 days at air,<br>7 days under water | Class I<br>r/R ≥ 0,55, Rc(14 days) ≥ 1,5 MPa<br><br>Class II<br>r/R ≥ 0,65, Rc(14 days) ≥ 3,0 MPa<br>m ≤ 15 %,<br><br>Class III<br>r/R ≥ 0,70, Rc(14 days) ≥ 5,0 MPa | Compression test<br>(Duriez Method B of EN 12697-12, previously NF P 98 252-4)<br>Static compaction<br>Φ = 120 mm |
| Germany | **Static pressure [9]:**<br>2,8 MPa for Ø150 mm specimens | **ITS [2]:**<br>Ø150 mm, height 125 mm (at least 3 specimens for each test) | **Emulsion+cement[2]:**<br>95% moisture at +20°C for 2 days then 40-70% moisture at +20°C | **Emulsion/Foam + cement (in situ) [2]:**<br>- Void content 8-15 vol.-%<br>- Indirect tensile strength after 7 day ($\beta_{SZ,7}$)at +5°C:<br>• ≥ 0,50 N/mm²<br>• ≤ 0,80 N/mm²<br>- Indirect tensile strength after 28 days ($\beta_{SZ,28}$ ) at +5°C:<br>- ≥ 0,75 N/mm²<br>- ≤ 1,20 N/mm²<br>- Difference in tensile strength between dry specimens ($\beta_{SZ,28}$ ) and after 14 days of water immersion: < 30 %<br><br>**Emulsion/Foam + cement (in plant) [10]:**<br>- Void content 5-15 vol.-% (for material containing tar max. 10 vol.-%)<br>- Indirect tensile strength after 7 days ($\beta_{SZ,7}$) at +5°C: 0,6-0,8 N/mm²<br>or<br>Indirect tensile strength after 28 days ($\beta_{SZ,28}$) at +5°C : 0,7-1,0 N/mm² | **Water immersion [2]:**<br>- water bath temperature +20°C.<br><br>**ITS [2]:**<br>- temperature +5°C;<br>- loading speed 50 mm/min. |

[9] M KRC – Merkblatt für Kaltrecycling in-situ im Straßenoberbau.

[10] M VB-K – Merkblatt für die Verwertung von pechhaltigen Straßenbaustoffen und von Asphaltgranulat in bitumengebundenen Tragschichten durch Kaltaufbereitung in Mischanlagen

| Country | Test specimens | | | | Testing conditions |
|---|---|---|---|---|---|
| | **Compaction method** | **Specimens dimensions** | **Curing procedure** | **Quality characteristics** | |
| Ireland | • Compaction to refusal (as per EN 12697-9)<br>• Can be impact, gyratory or vibratory<br>• Duriez (as per NF P 98-251-4) | • Ø 150 mm; height 70-75 mm<br>• Duriez Ø 120mm, height 135mm | • 28 days at 40°C for materials containing a pozzolanic binder<br>• 28 days at 20°C for materials not containing a pozzolanic binder<br>• Duriez procedure – 14 days at 18°C at a relative humidity of 50 – 55 %. | **Particle size distribution:**<br>- As per target grading zone<br>**Moisture content:**<br>- All individual results to be ±2% of target<br>**Relative in situ density:**<br>- All individual results to be minimum of 93% of required density<br>- Mean result to be minimum of 95% of required density<br>**Layer thickness:**<br>- All individual results ±25 mm of specified<br>- Mean result ±15 mm of specified<br>**Mechanical performance:**<br>Mean stiffness value of:<br>- 1,900 MPa (Class B1)<br>- 2,500 MPa (Class B2)<br>- 3,100 MPa (Class B3) | **IT-CY:**<br>- As per EN 12697-26<br>- As per NF P 98-251-4 |
| Norway | Static pressure (8 tonne, 2 minutes)<br>Gyratory compactor (1 ° angle, 600 kPa static pressure, 30 gyrations/min). Number of gyrations that gives 96 % of the density of 200 gyrations. | ITS specimens: Ø100 mm, height 50-60 mm (at least 3 specimens for each test) | 3-12 hours storage: in plastic bag at room temperature.<br>12 hours-14 days storage: in plastic bag at ca. 5 °C<br>Conditioning<br>a) Dry storage in ventilated oven: 7 days at 40 °C<br>b) 8 freeze-thaw cycles (4 cycles pr. day). Thawing in cold water. | **Emulsion/foamed bitumen:**<br>- Range of water content in aggregate: Modified Proctor Optimal moisture content:<br>$W_{opt.}$ to $W_{opt.}$ – 0,5 x binder content (%)<br>- indirect tensile strength 25 °C, after 7 days dry storage + 8 freeze-thaw cycles. ITS testing shall give a structural coefficient (a) of minimum 1,5, where $a = 0,38 \cdot \sqrt[3]{ITS}$ | |

| Country | Test specimens | | | | Testing conditions |
|---|---|---|---|---|---|
| | **Compaction method** | **Specimens dimensions** | **Curing procedure** | **Quality characteristics** | |
| Portugal | <u>For bituminous **emulsion** mixtures</u>:<br><br>• Static compaction with double plunger (21MPa/170kN & Ø101,6mm/h=101,6 mm specimens)<br><br>Portuguese research studies recommend:<br>• **Static compaction** with double plunger (**8MPa**/65kN for Ø101,6mm) | Specimens dimensions for determination of unconfined compressive strength (NLT 161 / ASTM D 1074) of dry and wet specimens:<br>• Ø101,6mm & h=101,6mm | Bituminous emulsion binder (+ cement/lime ≤ 1-2%):<br>• 3 days @ 50 °C | Characteristics from **immersion-compression tests** (NLT 162 / ASTM D 1075 + laboratory accelerated curing):<br><br>Bituminous **emulsion** binder (+ cement/lime ≤ 1-2%):<br>• Unconfined compressive strength, dry<br>- ≥3,0MPa (≈24kN), high traffic volume (T0/T1)<br>- ≥2,5MPa (≈20kN), low traffic volume<br>• Unconfined compressive strength, wet<br>- ≥2,5MPa (≈20kN), high traffic volume (T0/T1)<br>- ≥ 2,0MPa (≈16kN), low traffic volume<br>• Retained strength, wet spc./dry spc.<br>- ≥ 75%, High traffic volume (T0/T1)<br>- ≥ 70%, Low traffic volume<br><br>Some Portuguese research studies seem to indicate that the referred minimum values for unconfined compressive strength are too high. | **Immersion-compression tests** (NLT 162 / ASTM D 1075):<br>• Procedure 1 – immersion at 49ºC<br>- Dry specimens: 4 days in air/oven @ 25ºC + 2h in water @ 25ºC<br>- Wet specimens: 4 days in water @ 49ºC + 2h @ room temperature + 2h in water @ 25ºC<br>*or*<br>• Procedure 2 – immersion at 60ºC (alternative)<br>- Dry specimens: 24h in air/oven @ 25ºC + 2h in water @ 25ºC<br>- Wet specimens: 24h in water @ 60ºC + 2h @ room temperature + 2h in water @ 25ºC<br><br>Uniaxial **compression test** (NLT 161 / ASTM D 1074):<br>• Rate of deformation: 0,05mm/min per mm of specimen height (e.g. for h=101,6mm specimens, v=5,1mm/min.)<br>• Test temperature: 25ºC |

| Country | Test specimens | | | | Testing conditions |
|---|---|---|---|---|---|
| | Compaction method | Specimens dimensions | Curing procedure | Quality characteristics | |
| Spain | Mixtures with **emulsion**:<br><br>• Static compaction with double plunger (21MPa/170kN & Ø101,6mm/h=101,6mm specimens)<br><br>Spanish research studies recommend:<br>a)<br>• **Static compaction** with double plunger (9,8MPa/**80kN**) for **Ø101,6mm & h=60mm** specimens<br><br>b)<br>• **Static compaction** with double plunger (7,4MPa/**60kN**) for **Ø101,6mm & h=60mm** specimens<br>*or*<br>• **Gyratory compaction** (**0,6MPa & 1,25º**) for **Ø101,6mm & h=60mm** specimens | Mixtures with **emulsion**:<br><br>Specimens dimensions for determination of unconfined compressive strength (NLT 161 / ASTM D 1074) of dry and wet specimens:<br>• Ø101,6mm & h=101,6mm | Mixtures with **emulsion**:<br><br>Bituminous emulsion binder (+ cement/lime ≤ 1%):<br>• 3 days @ 50 °C<br><br>Mixtures with **cement**:<br>• 7 days | Mixtures with **emulsion**:<br><br>Characteristics from **immersion-compression tests** (NLT 162 / ASTM D 1075 + laboratory accelerated curing):<br><br>Bituminous **emulsion** binder (+ cement/lime ≤ 1):<br>• Unconfined compressive strength, dry<br>- ≥3,0MPa (≈24kN), high traffic volume (T1/T2)<br>- ≥2,5MPa (≈20kN), low traffic volume (T3/T4)<br>• Unconfined compressive strength, wet<br>- ≥2,5MPa (≈20kN), high traffic volume (T1/T2)<br>- ≥ 2,0MPa (≈16kN), low traffic volume (T3/T4)<br>• Retained strength, wet spc./dry spc.<br>- ≥ 75%, high traffic volume (T1/T2)<br>- ≥ 70%, low traffic volume (T3/T4)<br><br>Some Spanish research studies propose (for Ø101,6mm & h=60mm specimens, static compaction 60kN or gyratory compaction 0,6MPa & 1,25º):<br>• Dry **Indirect Tensile Strength@ 5ºC** (after curing 3 days @ 60ºC): ≥ 1,0MPa, high traffic volume (T1/T2)<br>• Indirect Tensile retained Strength, wet spc.(1 day in water @60ºC) /dry spc.: ≥ 75%, high traffic volume (T1/T2) | Mixtures with **emulsion**:<br><br>**Immersion-compression tests** (NLT 162 / ASTM D 1075):<br>• Procedure 1 – Immersion at 49ºC<br>- Dry specimens: 4 days in air/oven @ 25ºC + 2h in water @ 25ºC<br>- Wet specimens: 4 days in water @ 49ºC + 2h @ room temperature + 2h in water @ 25ºC<br>*or*<br>• Procedure 2 – Immersion at 60ºC (alternative)<br>- Dry specimens: 24h in air/oven @ 25ºC + 2h in water @ 25ºC<br>- Wet specimens: 24h in water @ 60ºC + 2h @ room temperature + 2h in water @ 25ºC<br><br>Uniaxial **compression test** (NLT 161 / ASTM D 1074):<br>• Rate deformation: 0,05mm/min per mm of specimen height (e.g. for h=101,6mm specimens, v=5,1mm/min.)<br>Test temperature: 25ºC |
| | Mixtures with **cement**:<br>Vibratory compaction | Mixtures with **cement**:<br>• Ø 152.4 mm, h=177.8mm specimens | | Mixtures with **cement**:<br>• compression strength 2.5 MPa | Mixtures with **cement**:<br>• 0.1 MPa/s rate |
| United Kingdom | Same as in Ireland | | | | |

**Table 5: Standards and references**

| Country | Cold recycling mix | | | Materials | | | | |
|---|---|---|---|---|---|---|---|---|
| | Design | ITT and control testing | Requirements for application | Emulsion | Bitumen | Cement | Lime | Hydraulic binder |
| Czech Republic | National technical specifications TP208 (Ministry of Transport, 2010) | | | CSN EN 13808 | CSN EN 12591 | CSN EN 197-1 | n.a. | ENV 13282 |
| Germany | *National technical specifications (M KRC (FGSV, 2005) [2], M VB-K (FGSV, 2007) [3] | | | DIN EN 13808, TL BE-StB 07 [11] | DIN EN 12591, TL Bitumen-StB 08 [12] | DIN EN 197-1, TL Beton-StB 08 [13] | - | DIN EN 18506, TL Beton-StB 08 [7] |
| Ireland[14] | National Roads Authority (2011). NRA Interim Advice Note 01/11 on Low Energy Pavements. | | | IS EN 13808 | IS EN 12591 | IS EN 197-1 | IS EN 14227-11 | - |
| Portugal | - | - | CETO-EP (Type Specifications for Construction of Portuguese Road Administration) | EN 13808 | NP EN 12591 | NP EN 197-1 | NP EN 459-1 | - |
| Spain | - | - | PG-4 – Art.s 20 & 21 (General Specifications for maintenance of Spanish Road Authority) | UNE-EN 13808 | UNE EN 12591 | RC-03, EN 197 | - | - |
| United Kingdom[15] | TRL 386, TRL 611 and RSTA Code of Practice for In-Situ Structural Road Recycling 2012 | | | BS 434 - 1 | EN 12591 | EN 197 -1 | EN 14227-11 | - |

11 TL BE-StB 07 – Technische Lieferbedingungen für Bitumenemulsion

12 TL Bitumen-StB 08 - Technische Lieferbedingungen für Straßenbaubitumen und gebrauchsfertige Polymermodifizierte Bitumen

13 TL Beton-StB 08 - Technische Lieferbedingungen für Baustoffe und Baustoffgemische für Tragschichten mit hydraulischen Bindemitteln und Fahrbahndecken aus Beton

14 GGBS (IS EN 14227-2); PFA (IS EN 14227-4)

15 GGBS (EN 14227-2); PFA (EN 14227-4)

Data presented in Tables 4 and 5 highlight that requirements in technical specifications of different countries concerning compaction methods, test specimens curing and conditioning procedures as well as the final evaluation of testing vary considerably, making not possible any simple comparison between measured values of visually same/similar specimens. Nevertheless, the analyses of gathered information allow following generic findings:

- **Compaction methods**: More countries perform static compaction to obtain cylindrical test specimens of different dimensions. Some countries are already using gyratory compaction, which procedures are described in an existing European standard for hot bituminous mixtures. It is worth to mention that although the type of compaction may be the same, there are still some differences from country to country, since the referred compaction methods are performed in different ways (e.g. applied loading pressure, loading time, loading procedure...).
- **Specimens' dimensions**: There is a significant difference between dimensions of cylindrical test specimens among each country, not only in terms of the diameter of test specimen (i.e. $\phi$ ≈100 mm, $\phi$ =120 mm and $\phi$ ≈150 mm), but also on the ratio between its diameter and height ($h/\phi=1$; $h/\phi<1$; $h/\phi>1$). This might even differ between bitumen and cement dominated mixture types.
- **Curing procedures**: There are again significant differences between curing procedures across countries, in terms of number of days (covering a range between 3 days and 28 days, with 7 days and 14 days being popular), conditioning temperature (from 5ºC to 50ºC, passing through temperatures around 20ºC) and conditioning relative humidity (some countries not having this requirement and others specifying values from 40 % to 95 %, or even 100 % in the case of sealed specimens). The specified curing times of 7, 14 and 28 days seem to be related with common curing times from cement-based materials (cement concrete).
- **Mechanical evaluation (testing conditions and quality characteristics)**: The existing practice focuses mainly on the effect of water on the mixtures (whether based on indirect tensile tests or compression tests), strength (either indirect tensile strength or compression strength) and stiffness (repeated indirect tensile tests). Even though the mechanical type of testing could be the same, the obtained results can vary significantly depending on the compaction, curing and conditioning of the test specimens. In some sporadic cases, additional performance-based properties are evaluated, such as: a) shear strength properties determined by triaxial test in South Africa and supported by research studies (Collings & Jenkins, 2008); b) fatigue resistance, that was investigated by two-point bending beam tests (2PBT) within SCORE project (with some problems during specimen preparation), by four-point bending beam tests (4PBT) and by indirect tensile tests (ITT) within some recently done research studies (Chamot & Romero, 2009), by indirect tension to cylindrical specimens (IT-CY) tests within Portugal research studies (Batista, 2004) and by indirect tension tests (IDT) within the UK research studies (Khweir *et al*., 2001; Fordyce & Khweir, 2002).

There are several possible explanations for the high variety of cold recycling mixing design approaches around European countries, but historical reasons seem to play an important role on this. For instance, some countries are already adapting existing European standards for hot mixtures (such as the ones on water sensitivity) to cold mixtures testing, but others keep using other standards to perform tests.

In next chapter, further analysis of each of the referred aspects (compaction methods, test specimens' dimensions and curing, mechanical evaluation) is given.

# 3 Synthesis of mix design approaches for cold-recycled bitumen stabilised materials

## *3.1 Compaction procedures*

### *3.1.1 Introduction*

Table 4, presented in chapter 2, gives an overview about the different compaction methods used in European countries.

In order to compact cold-recycled materials in which hydrostatic pressure plays an important role, the majority of European countries apply either static compaction or gyratory compaction.

**Static compaction** is a relatively quick and simple method used in Czech Republic, France (together with gyratory compaction), Germany, Norway, Portugal, Spain and other European countries. The procedures used can however vary a lot, as follows:

- In Czech Republic test specimens are compacted in accordance with TP 208 by two pistons moving against each other. The applied pressure should be of 5.0 MPa. During the compaction it is necessary to compensate repeatedly the axial force until reaching the state when the power is stabilized for 30 seconds at the value of 88.5 ± 0.5 kN for 150 mm diameter specimens. In this respect the procedure is similar to that used e.g. in Germany.
- In France, the Duriez method has been used in the design of cold recycled mixes, in accordance with the French standard NF P 98-251-4. This method comprises the preparation of cylindrical test specimens of 80 mm or 120 mm diameter (Figure 6) by applying a static pressure for 5 minutes. Two different modes of loading may be applied depending on aggregate maximum size (< 14 mm or ≥ 14 mm) and mould dimensions. In its original version, compressive loads of 60 kN or 120 kN are issued, but some research and site experiments have concluded that moulding forces of 20 kN and 40 kN (respectively for D < 14 mm or D ≥ 14 mm) would better reproduce on site densities immediately after field compaction (Serfass *et al*., 2009). On the other hand, it should be noted that in France, besides the Duriez test for water sensitivity evaluation, compaction tests are usually performed using the French Gyratory Shear Compactor (GSC), which will be further described in following paragraphs.
- According to the German procedure of cold recycling mix compaction, a static axial pressure of 2.8 MPa is applied. The plastic behaviour of the cold recycled mixture leads to a stress depression and therefore it is necessary to apply 5-7 loading cycles until reaching the final maximum pressure of 2.8 MPa.
- According to the Norwegian methodology one possibility is to use the static pressure of 4.5 MPa which is applied for 120 seconds.
- Static compaction with double plunger is similarly used in Portugal and Spain. According to NLT 161 Spanish standard (adopted from ASTM D 1074), a stress of 21 MPa (170 kN for specimens of 101,6 mm diameter) is applied during 2 minutes, after gradually increased pressure (from 0 to 21 MPa) during 2-3 minutes. However, some research studies have shown that the standard pressure lead to higher densities than the ones achieved in the field (Batista, 2005; Martínez *et al*., 2007).

Comparative studies on the same type of cold mixes have lead to the recommendation that compressive stress loads from 7 MPa to 8 MPa should be applied, resulting in compressive forces for 100 mm diameter specimen about 60 kN, which should be applied in order to obtain densities of the same order as those typical for in situ measures.

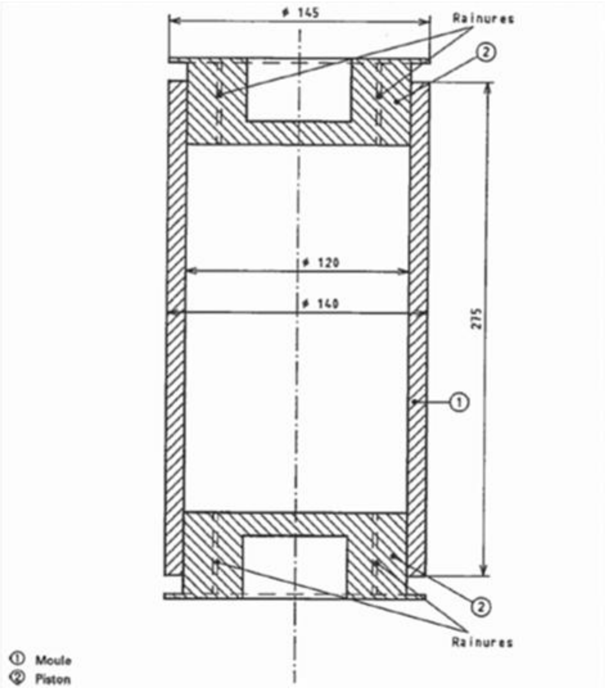


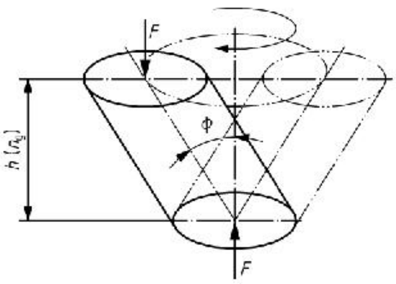

**Figure 6 – Mould and compression piston for cold mixtures with bitumen emulsion (D ≥ 14 mm), according to Duriez test method [Source: NF P 98-251-4:1992]**

As stated before, countries like France, Ireland, Norway and Spain have already begun to use **gyratory compaction**, as it has become more popular in last two decades. Gyratory Shear Compactor (GSC) is used for testing of some mechanical properties and for determination of volumetric properties of the compacted specimens (e.g. voids content and bulk density). The principle of the gyratory compaction is based on the combination of a static compression on the sample and a shearing action resulting, respectively, from a constant axial force and from the motion of the axis of the sample (Figure 7). Some of the procedures that comprise this type of compaction are the following:

- In France, the GSC (PCG - Presse à Cisaillement Giratoire) has been used (in accordance with the French standard NF P 98-252 or, more recently, the European standard EN 12697-31) for optimizing the granular composition and approximate the percentage of voids that will be obtained on site for conventional bituminous asphalt mixes (i.e. HMA - Hot Mix Asphalt). This is not the case of emulsion stabilized graded aggregate layers, since it is considered that GSC test does not realistically reproduces field densities for this type of materials (Serfass *et al*. 2009; Olard *et al*.; 2009). Nevertheless, according to Serfass *et al*. (2009) “GSC is still considered as an useful tool for comparing and optimizing mixture formulas in terms of aggregate gradation, binder and moisture contents”;
- Norwegian methodology prescribes compaction with 1° angle of gyrations at 600 kPa static pressure and standardized angular speed of 30 gyrations per minute. Usually

one set of specimens is prepared – test specimens compacted at number of gyrations that gives 96 % of the density of 200 gyrations.

- Some Spanish research studies (Martinez *et al*., 2007) refers that gyratory compaction (0.6 MPa and 1.25º, 30 rpm, 300 gyrations) is suitable to obtain cold recycled mixtures test specimens with equivalent densities to the ones obtained by static compaction (60 kN on 100 mm diameter specimens).




**Key**

$F$ axial resultant force

$h\ (n_g)$ height of specimen after a number of gyrations

$\phi$ angle

**Figure 7 – Test specimen motion diagram, according to the test method [Source: EN12697-31:2007]**

Still in respect to gyratory compaction, it should be noted that there are more factors influencing cold-recycled mixtures compaction than in the case of HMA. For instance, the compaction of cold-recycled mixtures is strongly affected by its water content. In fact, the water drainage during compaction usually prevents an accurate determination of the mix composition. Other factors, such as the type and content of the used binder as well as the aggregate properties also play important roles concerning GSC tests. In addition, a good correlation between cold-recycled mixtures densities of specimens produced in laboratory and of *in situ* compacted layers is generally very difficult to find.

With respect to the **impact compaction**, the focus is essentially concentrating on Marshall and Proctor compaction. The first decided as the only compaction method for cold recycled mixes in Poland, the latter one then used in Finland.

Despite of **Marshall compaction** being one of the most worldwide used methods for preparation of HMA specimens, it is not so popular for cold mixtures. There are similar standards specifying this type of impact compaction method (e.g. EN 12697 30, ASTM D6926 and AASHTO T245). According to this type of compaction, a given number of impact blows (typically 50 or 75), delivered by a compaction hammer, are applied on both faces of cylindrical specimens. In some countries, such as Portugal, the use of Marshall impact compaction for cold-recycled materials is faced with some reservations. One reason for this is due to the presence of fluids (water + bituminous emulsion) in cold mixtures composition during compaction, thus requiring a compaction method that releases hydrostatic pressure, which is essentially achieved by water drainage. Some previous research studies showed that Marshall compaction could lead to loss of fines entrained in water "splashes", resulting in high variability of specimens densities and in lower levels of compaction (Batista, 2004).

Conversely, the **modified Proctor compaction** is a common procedure to determine the optimum water content of bitumen stabilized materials (BSM). The main reason for this is related to the fact that, during compaction, such materials act as unbound stabilized materials, presenting in some extend a similar behaviour to granular materials, where shear properties play a stronger role. In fact, this type of compaction is worldwide used for determining the optimal moisture content and the correspondent maximum dry density of soils and aggregates. This test generally consists of compacting unbound materials into a standardized cylindrical mould using a given compaction effort for different levels of moisture content. Usually the unbound material is compacted into the mould to a certain amount of equal layers (5 for the modified Proctor test), each receiving a number of blows from a standard weighted hammer at a specified height. Currently, the procedures and equipment details for the modified Proctor compaction test are specified in the European standard EN 13286-2 (which also comprises the original Proctor test, that is commonly known as the “standard Proctor compaction test”), as well as in other standards, such as ASTM D1557 and AASHTO T180.

In spite of Proctor compaction test being not referred in Table 4, its “modified” version is often used as a complementary compaction method for an initial estimation of optimal water content, which later on is adjusted on field (Batista *et al*., 2012). Furthermore, this type of compaction is also generally accepted outside Europe as best practice test to achieve a reference density for BSM (Collings *et al*., 2009; Wirtgen, 2012).

In the following sub-sections 3.1.2 to 3.1.4 different compactions used in each of country members of the project are further described.

### *3.1.2 Method used in Czech Republic*

The compaction method of static pressure according to technical specifications of Czech Ministry of Transportation (TP208) is used to prepare primarily specimens with ø150 mm. The height of the specimens used for further strength testing should be at least 125 mm, especially if used for compression strength assessment. The required slenderness ration as know more from soil or concrete testing has to be at least 0.8. The specimens are compacted by axial pressure of 88.5 kN (this corresponds with a compressive pressure of 5.00 MPa). When the force is exerted, there is due to the plastic and flexible behaviour of the cold recycling mix a decrease in the tension; therefore, it is necessary to repeatedly increase the tension to the required value usually in 30-second intervals until the tension stops decreasing below a value approx. 5 kN lower than the required compacting force. According to the experience gained during many field applications of cold recycling in the Czech Republic the final tension is usually reached after 6 to 8 cycles depending on the moisture content and character of the cold recycled mix (used binders, used RAP and its grading). Used compaction procedure is very similar to the method used in Germany and described in part 3.1.3.

### *3.1.3 Method used in Germany*

According to German mix design standard (FGSV, 2005) a static compaction for cold recycling mixtures with 45 mm maximum aggregate size is used (with a maximum of 10 % oversized grains).

Compaction form according to DIN 1048 with Ø 149.6 mm and h = 300 mm is used with four grooves for drainage by double piston principle (Figure 8).

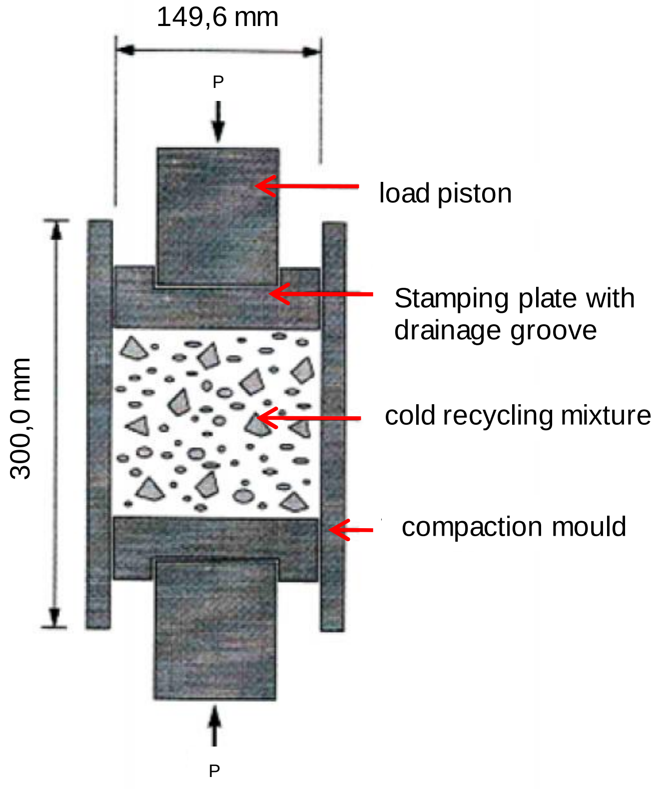



**Figure 8 – Form of compaction Ø 150 mm and stamping plate Ø 149,6 mm with four drainage grooves for drainage (M KRC)**

After placing the mould into the static loading device, the load pistons are moved together up to a compression force of 49 kN (2.8 MPa). Due to consolidation of the mix the force decreases. At a compression force of not less than 28.3 kN the load pistons are moved together again up to a compression force of 49 kN. Afterwards, these cycles of consolidation and compaction are repeated. Starting next compression if the stress does not fall further or the load limit in Figure 9 is reached. Otherwise maximum load is applied again after two minutes but normally end load will be reached after 5 to 7 load acts. One day later the specimens are demoulded and the weight and height are determined.

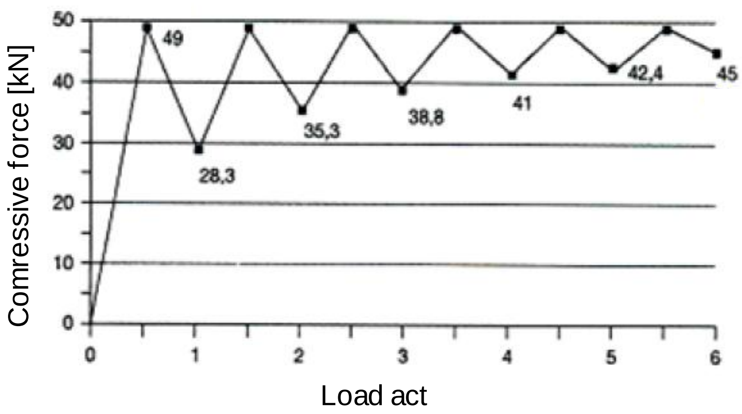
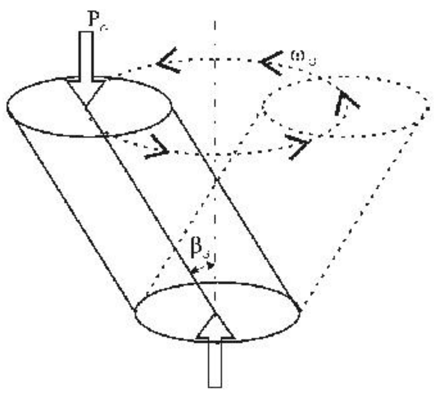



**Figure 9 – Load-time-curve at static pressure (M KRC)**

### *3.1.4 Methods used in Ireland*

In Ireland laboratory test specimens for cold-recycled BSM design are usually prepared using gyratory compaction, which is conducted in accordance with EN 12697-31 standard. As referred before, the procedure uses the kneading motion in the compaction process, whereby a simultaneous static compression and shearing force, resulting from the rotation of the top surface of the mould, is used to compact the mixture. The static compaction pressure is set at 0.6 MPa with an angular velocity of 30 gyrations per minute and the gyratory angle set at 1.25°. Figure 10 a) illustrates the kneading compaction in the gyratory compaction process. Figure 10 b) shows the Coopers Technology gyratory compactor.



**$P_G$ - compaction pressure (0.6 MPa)**

**$\beta_G$ - gyratory angle (1.25°)**

**$\omega_G$ - angular velocity (30 gyrations/minute)**

**a)**

**b)**

**Figure 10 – Basic gyratory compaction concept with insert of Coopers Technology gyratory compactor**

Due to the large nominal size of the aggregates in cold recycled mixtures, moulds with a diameter of 150 mm are used for the production of test specimens. Also due to the high fluids content (water) slotted moulds are advised to be used for the compaction of the cold asphalt mixes. The slotted moulds incorporate narrow (approximately 1 mm) slots running vertically up and down the mould. The slotted moulds are shown in the Figure 11. This concept is similar to the perforated moulds with annular inlets not large than 2 mm in diameter.

**Figure 11 – 150 mm diameter slotted moulds**

For the cold asphalt mixtures the compaction moulds don't have to be pre-heated to an elevated temperature prior to the compaction, instead they should be maintained at ambient room temperature.

### 3.1.5 Method used in Portugal and Spain

In Portugal and Spain, laboratory test specimens for emulsion cold mixes design are usually prepared using static compaction with double plunger action, based on the Spanish specification NLT 161 (which was adopted from ASTM D1074). According to this standard, the moulding of bituminous test specimens comprises firstly an application of an initial compression of 1 MPa, in order to slightly settle the mixture into the mould. Then, the definitive compaction of the mixture takes place by applying a full double-plunger action, with an increasing load pressure (with a velocity as uniform as possible) in order to reach the entire moulding load of 21 MPa in 2-3 minutes, and maintaining this maximum load for further 2 minutes (Figure 12).

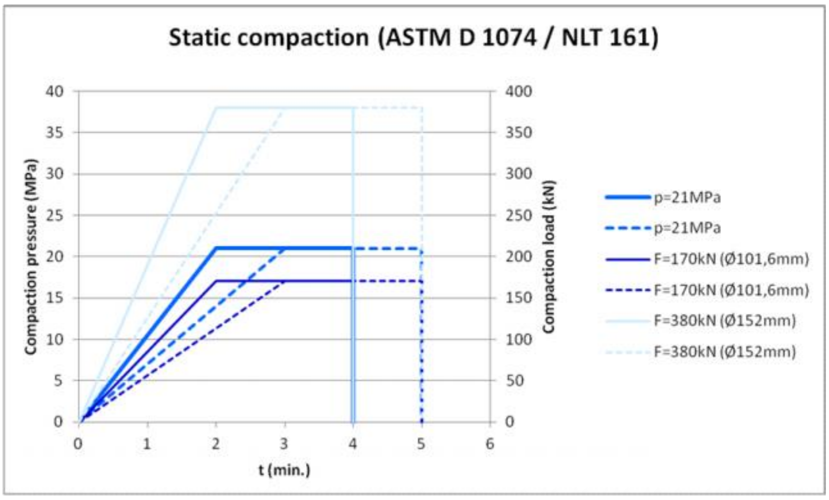



**Figure 12 – Static compaction according to ASTM D 1074 / NLT 161**

As referred before, in both Portuguese and Spanish research studies it has been found that the standard static compression of 21 MPa led to specimen densities well above the field densities. Some of this studies (Batista & Antunes, 2002; Martínez *et al*., 2007) have lead to the recommendation that compressive stress loads from 7 MPa to 8 MPa (resulting in compressive loads of approx. 60 kN for 100 mm diameter specimen) should be applied in order to obtain densities of the same order as those obtained in situ (Figure 13).

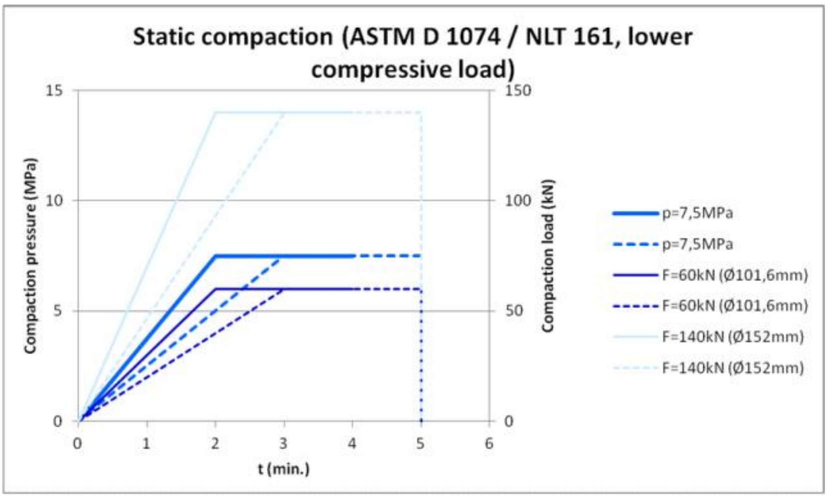



**Figure 13 – Static compaction based on ASTM D 1074 / NLT 161, but modified to lower compaction energy**

Both NLT 161 and ASTM D1074 present the same dimensions for standard test specimens (cylinders of 101.6 mm in diameter and in height, i.e. slenderness ration of 1), allowing cylindrical specimens of dimensions other than 101.6 mm providing that the relation between its diameter and height remain the same (ø ≈ h) and its diameter is not less then four times the nominal size of the largest aggregate particles.

### *3.1.6 Compaction methods to be addressed*

For compaction of test specimens, both static compaction with double plunger and gyratory compaction are considered to be suitable methods in Europe for cold recycled and stabilized materials, and will be further addressed within CoRePaSol extended experimental study. Some comparison tests between the referred compaction methods will be carried out using the same materials and mix composition.

Since Proctor compaction is generally assumed as being a useful tool to complement laboratory design of cold-recycled mixtures and for comparing the results with other applied methods mentioned before, a comparison of these compaction methods is also given in chapter 4. At the same time it will be recommended not to use impact compaction for standard Marshall specimen since no reliable correlation was found with specimens compacted by the other methods.

## *3.2 Test specimens dimensions*

An overview about the dimension of cylindrical test specimens used in cold recycled mix design is given in Table 4 (Chapter 2). The data in this table highlighted the existing differences across European countries both in terms of specimen diameter (Ø ) and of the slenderness ratio between its height and diameter (h/ Ø ), as summarized below:

- Ø ≈ 100 mm, h ≈ 50-60 mm ⇒ h/Ø ≈ 50-60 % (Norway)
- Ø ≈ 100 mm, h ≈ 100 mm ⇒ h/Ø = 100 % (Portugal & Spain)
- Ø ≈ 120 mm, h ≈ 135 mm ⇒ h/Ø ≈ 113 % (France for Duriez method)
- Ø ≈ 150 mm, h ≈ 70-75 mm ⇒ h/Ø ≈ 47-50 % (France & Ireland for gyratory)

- Ø ≈ 150 mm, h ≈ 125 mm ⇒ h/ Ø ≈ 80-85 % (Czech Republic & Germany)

The minimum dimensions of the test specimens are usually related to the maximum dimension of the particles of the granular material (D), as follows:

- NLT 161 Spanish standard (used in Portugal and Spain for static compaction) establishes that the diameter shall not be less than four times the nominal diameter of the largest aggregate particles, i.e. Ø ≥ 4 x D; and refers that generally test specimens are cylinders of 101,6 mm diameter.
- EN 12697-34 specifies that the maximum aggregate size of the mixtures for specimens of 101,6 mm diameter and 63,5 mm height shall not exceed 22,4 mm, i.e. Ø ≥ 4,5 x D and h ≥ 2,8 x D.

Generally, asphalt laboratories are prepared to test Marshall specimens, i.e. specimens of about 102 mm diameter and 64 mm height (h/Ø ≈ 60-70 %). However, grading of reclaimed asphalt for new mixtures can frequently exceed 0/22 mm going up to 0/45 mm grading curves. In this case, a diameter of 150 mm is recommended. Currently, gyratory compaction is becoming also available in more asphalt laboratories, whereas for this case generally test specimens of 150 mm in diameter and about 125 mm in height (h/ϕ ≈ 80-90 %) are usually prepared.

Taking into account this information, in this study, besides local special specimens dimensions, the following dimensions will be addressed when considered appropriate and feasible:

- Ø ≈ 102 mm, h ≈ 64 mm ⇒ h/Ø ≈ 63 %
- Ø ≈ 150 mm, h ≈ 95 mm ⇒ h/Ø ≈ 63 % or Ø ≈ 150 mm, h ≈ 125 mm ⇒ h/ Ø ≈ 83 %

## *3.3 Laboratory accelerated curing procedures*

### *3.3.1 Laboratory curing procedures currently used*

After cold in-situ recycling or after placing in-plant cold stabilized mixtures in the pavement, the compacted material firstly passes the so-called “curing” process, during which the cohesion and the resistance of the mixture increase. At the end of the curing process, a continuous cohesive film that holds the aggregate in place with a strong adhesive bond must be achieved (Asphalt Institute MS14, 1990).

In the field, the curing time at which the cold mixture attains a “stable” condition usually can take several months, depending not only on the properties of recycled material itself or on pavement layer characteristics, but also on external conditions, such as climatic conditions and traffic level causing rate of pavement structure loading. Another factor might be the moment when the cold recycled material is overlaid by next layer. According to Serfass *et al.* (2004), in temperate climate and under medium traffic at least one complete cycle of seasons is usually necessary for emulsion stabilized cold mixes to reach such “stable” condition.

Curing of cold mixtures has a great influence on the evolution of the material properties and consequently on the performance of the entire pavement and quality check.

Therefore, it's of major importance to simulate correctly in the laboratory field curing process. Nevertheless, taking into account, among others, time restrictions related to road closures and available equipment, laboratory curing procedures should be as short as possible, but without causing any significant ageing of the bituminous binder; they should reproduce as close as possible the curing stage in the field; and should employ only usual equipment, i.e. equipment not too complex (Serfass *et al.*, 2004). If applicable they should be accelerated to simulated suitably the properties of the mixture after certain time interval giving values equal to the real pavement layer performance after even longer period.

As stated in 2.3, laboratory curing procedures vary considerably different across analyzed countries, not only in terms of number of days (generally ranging between 3 days and 28 days), but also in terms of conditioning temperature (from 5 ºC to 50 ºC) and conditioning relative humidity (from no requirement to values of minimum 40 % or 100 %). Some examples of currently applied accelerated curing procedures are given bellow:

- Czech Republic: 90-100 % humidity at (20±2)°C for mixtures only with hydraulic binder; 90-100 % humidity at (20±2)°C two days and then 40-70 % humidity at (20± 2)°C for mixtures with combined binder (bitumen and cement) or only curing at (20± 2)°C for mixes where only foamed bitumen or emulsion is used.
- Germany: 2 days @ 20°C, 95% humidity (sealed in the mould) + 26 days @ 20 °C @ 40-70 % humidity (room conditioning).
- Ireland and UK: 28 days @ 40°C (for emulsion mixtures).
- Portugal and Spain: 3 days @ 50 °C (for emulsion mixtures).
- France: curing at constant temperature of 18°C in an environment with relative humidity of 40-70 % until strength or stiffness testing.

In most cases, these differences are not only due to climatic conditions and other geographical specific circumstances (e.g. available materials and their typical characteristics), but also because of historical reasons. For instance, in the years 1990-2000, cold asphalt techniques became quite popular firstly in Spain and later also in Portugal, causing that similar or even identical mix design procedures are used by both countries since then. With regard to the mix composition, laboratory studies were carried out based on standards developed for hot bituminous mixtures, but adapted to cold mixtures that require a curing conditioning period prior to testing. In 1998, Fernández del Campo recommended that after compacting cylindrical test specimens, they were subjected to laboratory accelerated curing of 24 h @ 60ºC. Nevertheless, the common practice in Spain and in Portugal in the latest 90's was to perform a laboratory accelerated curing procedure immediately after compaction of "2 h in the mould at ambient temperature + extraction + 24 h @ ambient temperature + 3 days in oven @ 60ºC". Meanwhile, several research studies took place, and for example, the study carried out by Tijeda (1999) found that the resistance obtained in "immersion-compression tests" on specimens cured at ambient temperature for 21 days was similar to the resistance obtained on specimens subjected to accelerate curing of 1 day at ambient temperature and 3 days at 50°C. This has been proven also during so far done tests and comparison studies within this project. As a consequence, in 2001, the Spanish Road Administration issued a new technical specification document for recycling (PG4), establishing that after compacting, cylindrical test specimens should be submitted to laboratory accelerated cure of 3 days @ 50ºC previously to the "immersion-compression tests".

### 3.3.2 Laboratory curing procedures to be addressed

The analysis of the collected data allows for the following comments:

- Besides historical and geographical reasons, most of the differences among curing procedures seem to be related with the presence of cement besides bituminous binder on the cold-mixtures, leading to higher curing times (7, 14 and 28 days), relatively low conditioning temperatures (around 20ºC) and maximum levels of humidity (95% to 100%) in earlier stages of curing. In fact, cold recycled mixtures with added cement are sensitive with respect to high temperatures and low humidity level which may inhibit their required hydration process.
- A laboratory curing of 28 days is too long for practical reasons, mainly in the case of site-produced material and reasonable quality check or even mix design before starting the in-situ rehabilitation.

Taking these into account, it was decided to address the following studies on accelerated curing procedures in the laboratory and deeply assess the possible recommended procedures for harmonized testing protocols within Europe:

- Comparative curing studies on mixtures with emulsion and foamed, **no cement** or small amounts of cement (≤1%) acting as a reactive filler:
  - 4 days in total: 24 h for demoulding + 3 days @ 50°C
  - 7 days in total: 24 h for demoulding + 6 days @ room temperature and humidity (40% - 70% HR)
  - 14 days in total: 24 h for demoulding + 13 days @ room temperature and humidity (40% - 70% HR)

  Afterwards:
  - ITS according to EN12697-23
  - Moisture susceptibility according to EN12697-12 and modified AASHTO 283 protocol.
- Comparative curing studies on mixtures with bituminous binder and cement (>1%):
  - 7 days in total: 24 h for demoulding + 6 days @ room temperature and humidity (40-70 % HR – unsealed conditions) → verify if $ITS_7 > (0.3 – 0.5)$ MPa & $ITS_7 \leq 0.75$ MPa
  - 7 days in total: 24 h for demoulding + 6 days @ room temperature and 100% HR (sealed specimen conditions with humidity almost 90-100 %) → verify if $ITS_7 > (0.3 – 0.5)$ MPa & $ITS_7 \leq 0.75$ MPa
  - 14 days in total: 24 h for demoulding + 13 days @ room temperature and humidity (40-70 % HR)
  - 14 days in total: 24 h for demoulding + 13 days @ room temperature and 100 % HR (sealed specimens)
  - 28 days in total: 24 h for demoulding + 27 days @ room temperature and humidity (40-70 % HR) → verify if $ITS_{28} > 0.75$ MP
  - 28 days in total: 24 h for demoulding + 27 days @ room temperature and 100 % HR (sealed specimens) → verify if $ITS_{28} > 0.75$ MPa

## 3.4 Laboratory test procedures for determination of mix composition

### 3.4.1 Introduction

For enhancing cold-mixtures design several countries developed strategies separately from each other:

- In Czech Republic, usually requirements for cold emulsion/foamed mixtures (with or without very low content of cement) refer to the indirect tensile strength (ITS) of specimens with 7 days curing and to their retained resistance after immersion in water after additional 7 days curing in water bath. In addition, stiffness has also been assessed by IT-CY and by 4PB test methods at various temperatures, resulting in recommended values of 3500-4500 MPa at 15°C (Valentin, 2009).
- In France, the mix design of cold emulsion stabilised materials usually relies on the following tests:
  - The CGS (or PCG) test, which is mainly used to optimize the mix composition (namely, its granular gradation) as well as to supply additional information on the voids content of the compacted mixtures;
  - The Duriez test (unconfined compression test on Duriez test specimens conditioned with/without immersion), that is usually applied in order to investigate the mixture compressive strength and its water resistance.
    The Duriez test is also recognised as being able to deliver similar void contents as those obtained on site immediately after construction, providing that a reduced static load (of one third of the conventional compression load) is applied during compaction of the cold-mixture (Serfass *et al*., 2009; Claudel *et al*., 2012; Eckman *et al*., 2012).

  The mix design of this type of cold mixtures often also comprise a manual test in which the coating quality of the granular material by the bitumen emulsion (for several total water contents and residual bitumen contents) is visually evaluated (CFTR, 2007).
  Moreover, several studies have been undertaken assessing the stiffness of cold recycled mixtures. For instance, in a study conducted in the sequence of the European SCORE project, the stiffness of lab specimens produced with the same mix composition as in-situ recycled materials (either with foamed bitumen or with bituminous emulsion) using the static Duriez compaction (at two different compression loads: the conventional one and 1/3 of this), resulted in stiffness values of about 1500-4000 MPa (depending on the designed type of the recycled asphalt layer) (Eckman & Soliman, 2010).

- In Germany, mix design studies generally comprise the stiffness evaluation of the cold bituminous mixtures, namely by indirect tension tests (IDT) with continuous loading according to EN 13286-43 (“Unbound and hydraulically bound mixtures - Part 43: Test method for the determination of the modulus of elasticity of hydraulically bound mixtures).
- In Ireland, by designing cold recycled mixes indirect tensile strength at 25°C is usually required together with stiffness assessment. Alternatively Duriez test is done with determination of compressive strength and moisture sensitivity assessment. If Duriez procedure is not applied, the test specimens are sealed and cured at 40°C for given time period.
- In Portugal, usually requirements for cold bitumen-emulsion mixtures refer to the unconfined compressive strength of cured specimens and their retained resistance

after immersion in water. Besides, stiffness values in the order of 3000 MPa at 20ºC (IT-CY tests) have been reported in some research studies (Batista, 2004).

- In United Kingdom, dynamic stiffness modulus has been assessed at 20°C resulting in values for the foam bitumen stabilized materials of about 1,500 MPa (e.g. Khweir *et al*., 2001).

In the following sub-sections 3.4.2 to 3.4.4 different mix design procedures used in each of country members of the project are further described.

### *3.4.2 Method used in Czech Republic*

The Czech design manual for cold recycled mixes differentiates 4 types of cold recycled mix which can be realized in-situ or mixed in plant:

- Use of recycled material in unbound base layers for re-profiling and homogenizing of such layers or improving grading of existing material;
- Use of cement or another hydraulic binder in combination with reclaimed asphalt material or any other material from the existing pavement structure. The resulting cold recycled material can be tested for compressive strength or ITS;
- Bitumen stabilized materials or cold recycled mixes with residual bitumen content from newly added binder up to 4 % by mass of the recycled mix;
- Cold recycled mixes with combined binder of bituminous emulsion/foam and hydraulic binder (usually cement), whereas two subgroups can be defined depending on cement or bitumen dominant mixtures.

For the pavement structure full-depth recycling or partial cold recycling for selected pavement layers can be realized. Especially for the full-dept recycling it is required to use minimum 30-70 % of the existing pavement material in the recycled mix with additional corrections depending on the final grading. For granular material gained during cold recycling of existing pavement requirements according to Table 6 are set.

**Table 6: Recommended requirements on recyclable aggregates for stabilized mixtures**

| **Characteristic** | | **Requirements on recyclable granular material for bitumen or hydraulic binder stabilized mixtures** | | |
|---|---|---|---|---|
| | | **cement or another hydraulic binder** | **cement + bit. emulsion or foamed bitumen** | **Bit. emulsion or foamed bitumen** |
| Mix notation | In-situ recycling | 0/32; 0/45; 0/63 | | 0/32 |
| | In-plant recycling | 0/16; 0/22; 0/32; 0/45; | | 0/16; 0/22; 0/32 |
| Maximum content of fines | | $f_{15}$ | $f_{15}$ | $f_6$ |
| Quality of fine particles | | $I_p \leq 17$ | $I_p \leq 17$ | --- |
| Oversize | | 10 % | 10 % | 10 % |

Cold recycled mixtures are further specified by their grading curves. Especially for the combined use of bituminous binder and the cement the envelope is set very wide and minimum correction are usually necessary. On the other hand especially for purely bitumen stabilized materials addition of fine grained material might be required and especially for bitumen foam mixtures is required to secure sufficient mix quality

The optimum water content of cold recycled mixtures is investigated and declared according to EN 13286-2 ("Unbound and hydraulically bound mixtures - Part 2: Test methods for laboratory reference density and water content - Proctor compaction").

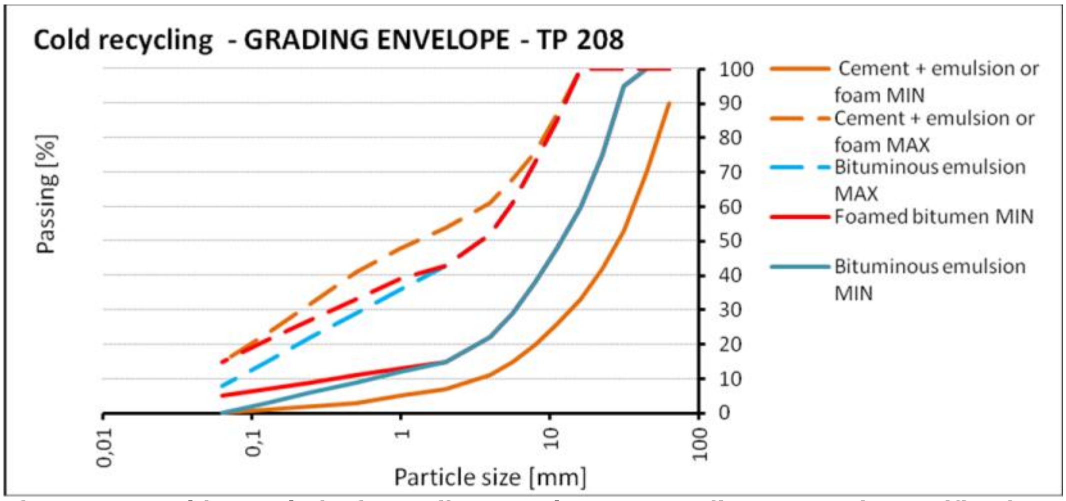



**Figure 14 – Cold recycled mix grading envelopes according to Czech specifications**

After the optimum water content is defined and the grading checked 6 specimens are produced for assessment of strength properties. The specimens are left sealed for 2 days with relative humidity of 90-100 %. For all mixture types indirect tensile strength (@15°C) is required with following threshold values:

- 0.3-0.7 MPa after 7 days curing at relative humidity of 40-70 % (after unsealed) for cement stabilized recycled mixtures or mixtures with combined binder (cement and bituminous emulsion or foam). The test specimens are stored at temperatures (20±2)°C;
- min. 0.3 MPa after 7 days curing at relative humidity of 40-70 % (after unsealed) for bitumen stabilized materials. The test specimens are stored at temperatures (20±2)°C;
- 25 % decrease of ITS after additional 7 days curing in water bath with temperature of (20±2)°C.

For purely cement stabilized cold recycled mixtures it is alternatively possible to declare compressive strength after 28 days curing at relative humidity of 40-70 % and room temperatures of (20±2)°C. The minimum quality criterion has to fulfil the C3/4 class of cement stabilized materials. Additionally the resistance to freezing and thawing has to be performed and the decreased value of compressive strength has to reach a level not lower than 85 %.

### *3.4.3 Method used in Germany*

According to German mix design standard (FGSV, 2005) a mix design is carried out for reaching requirements in void content, indirect tensile strength and water susceptibility.

Before preparing samples, particle size, aggregate size and binder content of the reclaimed asphalt have to be analysed. If the requirements for the grading envelope are not reached, specific aggregates must be added to the mixture.

According to German design guide, the mixtures must reach following requirements:

- For mixtures with bituminous emulsion:
  - content of fines (< 0,063 mm) between 2 % and 10 % by mass
  - content of aggregates < 2 mm: ≥ 20 % by mass
- for mixtures with foamed bitumen:
  - content of fines (< 0,063 mm) between 3 % and 12 % by mass
  - content of aggregates < 2 mm ≥ 25 % by mass.

The optimum water/fluid content of cold bitumen-emulsion mixtures is often investigated according to EN 13286-2 ("Unbound and hydraulically bound mixtures - Part 2: Test methods for laboratory reference density and water content - Proctor compaction") with load compaction for 1.5% hydraulic binder. Within this procedure the influence of the bitumen emulsion and moisture of asphalt granulate is evaluated. In some studies, the following equation is used in order to determine the amount of water to be added to the bitumen stabilised material:

$$W_{water} = W_{OFC} - W_{air\text{-}dry} - W_{em} - 0,5 * PRB \quad (1)$$

Where:

$W_{water}$ – percentage of water to be added (%)
$W_{OFC}$ – optimum fluid content (%)
$W_{air\text{-}dry}$ – moisture content of air-dried mix variation (%)
$W_{em}$ – water content from bituminous emulsion (%)
PRB – percentage residual bitumen in emulsion (%)

In the case of cold foamed-bitumen mixtures, the following equation is occasionally used:

$$W_{water} = W_{OFC} - W_{air\text{-}dry} \quad (2)$$

Where:

$W_{water}$ – percentage of water to be added (%)
$W_{OFC}$ – optimum fluid content (%)
$W_{air\text{-}dry}$ –moisture content of air-dried mix variation (%)

Afterwards, six specimens have to be prepared with reclaimed asphalt mixture and submitted to a curing procedure according to the German mix design standard (FGSV, 2005). Subsequently, indirect tensile strength (ITS) of the specimens under dry conditions and after soaking is evaluated (Figure 1515).

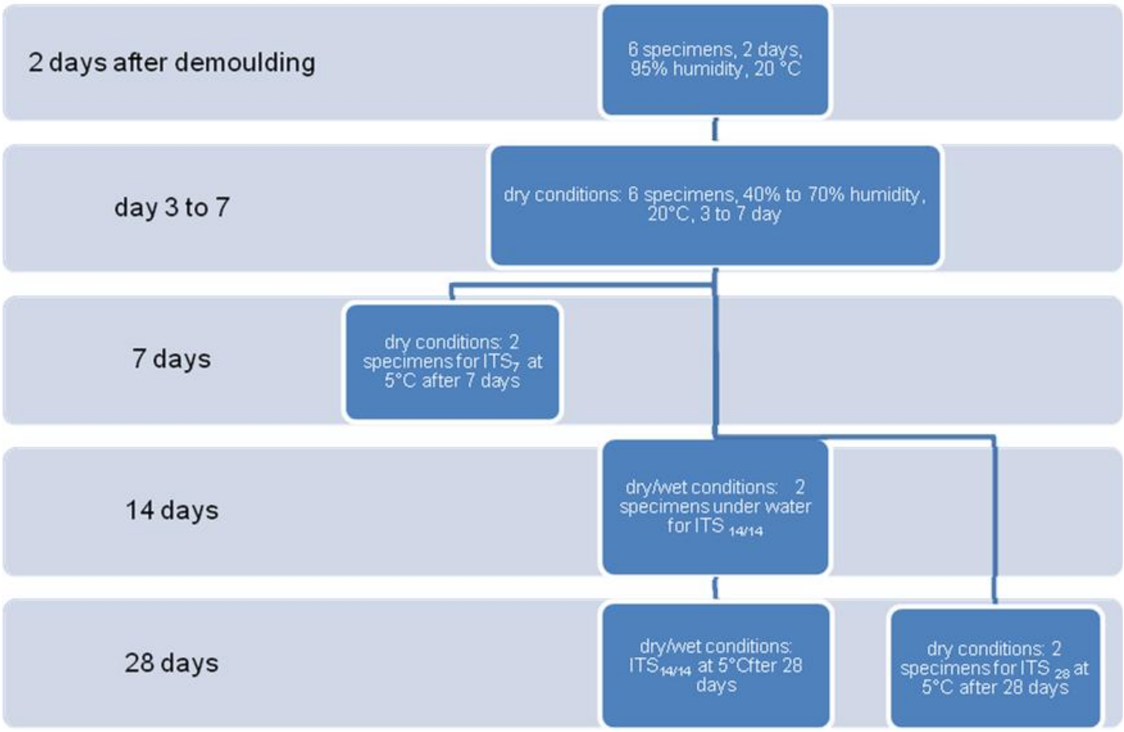



**Figure 15 – Curing method according to German standards after demoulding specimens**

All 6 specimens are firstly stored at 20°C and 95 % relative humidity (i.e. inside the mould) for 2 days. After this period, specimens are de-moulded and its wet density is investigated. Subsequently, the specimens are conditioned at the same temperature (20°C) but at decreased humidity (40-70 % of relative humidity, which are considered to be room conditions in Germany) until 7$^{th}$ day is prevailed. Then, 2 specimens are prepared for testing indirect tensile strength ($ITS_7$) at 5°C. Furthermore, the other 4 specimens are kept under “dry” conditions (not immersed in water).

Reaching the 14$^{th}$ day, 2 specimens of “dry” conditions are soaked under water (water bath temperature 20°C) for the next 14 days. So for these specimens ITS value $ITS_{14/14}$ is tested at day 28 at 5°C.

The other 2 specimens are under dry conditions for the whole time of 28 days. They will be prepared for the ITS value $ITS_{28}$ at day 28 at 5°C, too.

The ITS value $ITS_{28}$ and the reduction of ITS value ($ITS_{14/14}$) after 14 days under water conditions are authoritative values. In exceptional cases, the $ITS_7$ could be used for evaluating the indirect tensile strength.

In Table 7 the requirements for specimens of cold-recycling mixtures are given.

**Table 7: Requirements for specimens of cold-recycling mixtures**

| Characteristic value | Suitability test |
|---|---|
| Void content | • 8-15 Vol.-%<br>• Max 10% 1) |
| Indirect tensile strength after 7 day (βSZ,7) at +5°C: | • ≥ 0,50 N/mm²<br>• ≤ 0,80 N/mm² 2) |
| Indirect tensile strength after 28 days ($\beta_{SZ,28}$ ) at +5°C: | • ≥ 0,75 N/mm²<br>• ≤ 1,20 N/mm² 2) |
| Difference in tensile strength between dry specimens (βSZ,28 ) and after 14 days of water immersion | < 30% |
| E-modulus | For experience collection |

1) if tar containing material is used; compliance with the environmental conditions RuVa-StB
2) for hydraulic-dominant mixtures

The indirect tensile strength test (IDT) is applied to determine deformation behaviour of a mixture during tension. The specimen is temperature conditioned for 20 h at 5°C. Afterwards it is placed between an upper and lower timber plate and the bottom loading strip is raised with a rate of 50 mm/min until failure of the specimen.

### *3.4.4 Method used in Ireland*

As described in section 3.1.4, test specimens for mix design are prepared always by gyratory compaction. Afterwards, the Duriez test (for assessing BSM compressive strength and its moisture sensitivity) is carried out in accordance with the French standard NF P 98-251 4. A schematic representation of the Duriez unconfined compression test is shown in Figure 1616.

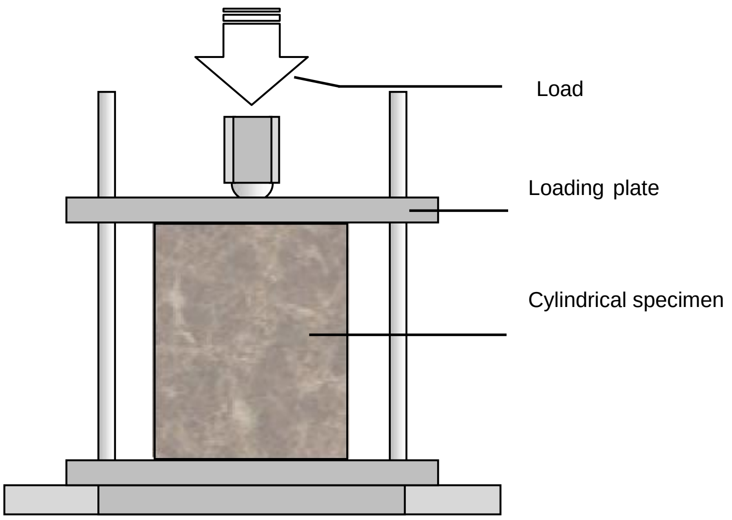



**Figure 16 – Schematic of the Duriez compression test**

The loading rate is of 1 mm.s$^{-1}$ and according to the Irish methodology the maximum load must be obtained in the period between 5 and 60 seconds. It is also necessary to force out water to drain. Similar approach can be found in United Kingdom.

The Duriez compression test is a destructive test and is of two weeks duration. Specimen conditioning accounts for the long duration of the test. Typically, the Duriez test requires specimens to be conditioned at 18°C for 14 days at controlled humidity, prior to testing. While "dry" specimens are kept stored at constant hygrometric conditions (50±10 % RH) during all 14 days, for saturated specimens, the latter week is spent submersed in water at 18°C prior to testing, as follows:

- "Dry" specimens: 14 days @ 18°C & ≈ 50% RH ⇨ compressive strength @ 18°C (R)
- "Wet" specimens: 7 days @ 18°C & ≈ 50% RH + 7 days immersed ⇨ compressive strength @ 18°C (r)

According to this procedure, requirements for cold stabilized material design rely on the strength of "dry" specimens (as an approach to the mix mechanical characteristics), and on the ratio between the strength of specimens with immersion and without immersion (r/R), which refers to mix resistance to water. Thus, these values are checked for compliance with the relevant mix design specification.

### *3.4.5 Method used in Portugal and Spain*

As referred before, traditionally in Portugal, the same procedures like in Spain are used for cold mixtures design (either new dense mixtures treated with emulsion or recycled mixtures).

In both countries, laboratory mix design studies generally consist on performing immersion-compression tests according to the Spanish standards NLT 161 and NLT 162 (respectively, based on the American standards ASTM D 1074 and ASTM D 1075), which were developed for hot bituminous mixtures. As so, some adaptations were made, in order to take into account the specificities of cold mixtures, namely, in terms of the required curing process prior mechanical testing. At the present, both Spanish and Portuguese Road Administration specifications for road works, establish a laboratory accelerated curing procedure for cold emulsion recycled mixtures of 3 days at 50ºC.

In broad terms, the mix design procedures comprise the following steps:

- Adjust the final granulate material (reclaimed asphalt + corrective material when required) in order to meet quality requirements (e.g. grading curve, …);
- Selection of a type and grade of bitumen emulsion;
- Preliminary evaluation of the compatibility of the granulate material with the bitumen emulsion by performing manual coating tests; this can include premixing water content determination in order to achieve a satisfactory degree of coating;
- Water content determination, regarding both the mix workability and the layer compaction, by means of the modified Proctor standard compaction on the final granulate material or, alternatively, on the final granulate material mixed with a pre-estimated amount of emulsion;
- Bitumen emulsion (or bitumen residue) content determination in order to ensure the desired mix stability and strength, by assessing the effect of water on compressive strength of compacted cold recycled mixtures (produced with different emulsion contents), as follows:
    - Preparation of cylindrical test specimens by static compaction with double plunger action (based on the Spanish Specification NLT161 or on the ASTM D1074);
    - Accelerated curing of test specimens by storing them in the oven at 50ºC for 3 days;

- Further test specimens conditioning for water sensitivity tests:
  - “Dry” specimens: 4 days in air @ 25ºC + 2h in water @ 25ºC (or alternatively: 24h in air @ 25ºC + 2h in water @ 25ºC)
  - “Wet” specimens: 4 days in water @ 50ºC + 2h @ room temperature + 2h in water @ 25ºC (or alternatively: 24h in water @ 60ºC + 2h @ room temperature + 2h in water @ 25ºC)
- Uniaxial compression tests (v=5,08mm/min.) in order to determine the average compressive strength of each group of “dry” and “wet” specimens and the correspondent retained strength

It is worth to be noted that, according to the described procedure, the total time between specimens’ compaction and compression strength testing is 7 days, required for the conditioning method commonly used.

The main requirements for cold in situ recycled asphalt (emulsion or emulsion + cement) refer to the unconfined compressive strength of “dry” and “wet” cured specimens (3 days at 50ºC) and their retained strength after immersion in water:

- High traffic volume (T0 / T1)
  - Unconfined compressive strength, dry: ≥ 3,0 MPa
  - Unconfined compressive strength, wet: ≥ 2,5 MPa
  - Retained strength (wet/dry): ≥ 75%
- Low traffic volume
  - Unconfined compressive strength, dry: ≥ 2,5 MPa
  - Unconfined compressive strength, wet: ≥ 2,0 MPa
  - Retained strength (wet/dry): ≥ 70%

### *3.4.6 Methods to be addressed in experimental studies*

From the previous sections it may be inferred that moisture sensitivity tests are the most commonly specified tests for investigate the effect of bituminous binder content. This is the case of France, Germany, Ireland, Czech Republic, Portugal and Spain where requirements for cold bitumen stabilized materials regarding mixture strength (“dry”) of cured specimens and their retained strength after immersion in water (“wet”) are established. Nevertheless, the test procedures are distinct with respect to a number of issues, such as: specimen compaction and preparation, curing, conditioning and testing criteria (especially temperature). As regard to mechanical strength evaluation, apart from specific methods used in a partner country, moisture sensitivity tests based on indirect tensile tests on “dry” and “wet” specimens were continuously carried out since October 2013 within this project to receive as much as possible values and comparable results.

## ***3.5 Quality control procedures***

For in situ cold recycled mixtures, a significant part of the raw material is usually formed by the milled existing pavement layers, which will most likely present more variable characteristics than conventional “new” aggregates due to the milling process itself, local pavement repair treatments, possible changes in the pavement structure in the recycled road section (e.g. change in the thickness of the layers, change of used mix type). For this reason, performance related tests are recommended for quality control, in addition to the usual requirements concerning aggregate gradation, binder content, density and void content. For example: in Germany requirements on bearing capacity are advised; in Portugal and Spain, compressive strength and moisture sensitivity resistance of the cold recycled mixture is required; and in United Kingdom requirements on indirect tensile strength, stiffness and moisture sensitivity are established. In Ireland, stiffness and water sensitivity tests thresholds are specified. In the case that these requirements are not accomplished, then the contractor must determine compliance by taking cores from the pavement after construction and after one year in service. Pavement thickness is measured and the ITSM test conducted on all cores, the mean value for the stiffness must exceed 1.90 GPa. Similar criteria apply in the United Kingdom where a minimum of one core is required per 75 $m^2$ of non-compliant material. The cores are then tested using the dry ITSM test; individual test results must exceed 2.00 GPa and the mean value must exceed 2.50 GPa.

# 4 Experimental studies

## 4.1 Introduction

Various aspects of cold recycling, from characterization of milled materials to formulation of cold recycled mixes and their properties was addressed during a period of almost 12 months through a range of experimental studies. Besides indirect tensile strength, other performance related characteristics, such as stiffness modulus of cold recycled mixes manufactured either with bituminous emulsion or with foamed bitumen was evaluated under various curing conditions. The impact of the addition of small and elevated quantity of cement (depending on the common practice in different parts of Europe) was also assessed.

Assessment of performance based characteristics commonly used and promoted for hot mix asphalt according to EN 12697-series and for hydraulically bound and unbound materials according to EN 13286-series represent key part of a functional mix design but are so far in use for cold asphalt recycling materials only in limited extend and only in some countries. Therefore, in this project it is intended to perform experimental studies using those standards whenever it is considered suitable and feasible. If required, some adjustments to the standards may be adapted in order to attend to specific characteristics of cold recycled mixtures.

## 4.2 Selection and characterisation of materials

### 4.2.1 CTU experimental study including comparison of compaction methods

For the comparison of compaction methods presented in this partial study four cold recycled mixes were designed covering different mix types (bituminous emulsion, foamed bitumen, combinations with cement of >2 % by mass content). The mix composition of two of these mixes is given in the table 6. Mix A contains cationic slow-breaking bituminous emulsion C60B7, which is commonly used in CZ. Mix B is based on foamed bitumen, which was produced by the Wirtgen WLB10S laboratory device. Within the foamed bitumen production water is injected into the 170°C hot bitumen (70/100) and that leads to the foaming effect. The foamed bitumen is then immediately dosed into the two-spindle mixing device with controlled mixing speed, the Wirtgen WLM 30. Additional mixes C and D are similar to presented ones differ only in the absence of hydraulic binder. Table 8 presents the used mix compositions.

The foamed bitumen is characterized by the expansion ratio ER in ml/g and the half-time of the foam settlement $\tau_{½}$ in seconds. Both parameters are strongly dependent on the kind and origin of the bituminous binder, the amount of the added compressed air and the pressure of the water injected into the hot bitumen. The intensity and efficiency of the foaming effect can be influenced by the basic physical conditions such as temperature, moisture and pressure. Optimal amount of the foaming water was specified in order to achieve the maximal expansion ratio (reached value ER=18) and the maximum half-time foam settlement (reached value of 12 seconds) according to the bitumen content. For the optimization of foaming water approach defined by Wirtgen Manual was used.

**Table 8: Used mix designs**

| Mix identification | Mix A | Mix B |
|---|---|---|
| **Reclaimed asphalt material 0-22** | 91,0 % | 88,5 % |
| **Water** | 2,5 % | 4,0 % |
| **Bituminous emulsion** | 3,5 % | --- |
| **Foamed bitumen** | --- | 4,5 % |
| **Cement (CEM II 32.5)** | 3,0 % | 3,0 % |

In total more than 100 cylindrical specimens were compacted from each mix by using the static pressure compactor according to the practice in the Czech Republic, the Marshall hammer and the gyratory compactor. For some variants repeated evaluation has been done to secure high accuracy of the final findings. The diameter of the specimens was 150±1 mm and the height 60±5 mm. In order to know the degree of compaction the bulk density from the specimen dimensions and its weight was calculated for each specimen. The main focus of the experimental testing was then based in the systematic measurement of the ITS and the stiffness modulus at 15°C. Both values were measured on specimens, which were cured for 7 and 14 days in the air with temperature (20±2)°C and also on specimens cured for 7 days in the air and then immersed for 7 days in water.

Part of the specimens prepared within these activities done by the Czech Technical University was compacted by Troxler Superpave Gyratory Compactor, Model 4140, according to CSN EN 12697-31. The gyration angle of the mould was set to 1.25° and the angular speed was 30 revolutions per minute following the standard settings which can be found even in the SUPERPAVE design methodology for hot mix asphalt. The receive data for good comparison of different compaction methods specimens were compacted by the vertical pressure of 600 kPa and 900 kPa, both loads gradually in combination with 40, 60 and 80 revolutions.

***Indirect tensile strength (ITS)***

The following diagrams show the results of the ITS measurement while each column represents the average value for at least three specimens. Apart from ITS values, the following figures also demonstrate the data on the void content of the mixes; the individual compaction methods are sorted according to the value of this important characteristic. The indirect tensile strength values obtained vary considerably. Considering the fact that the specimens were prepared with identical mixes (the same mix design), these variations caused by the compaction methods applied are relatively outstanding and might be explained by the heterogeneity of reclaimed asphalt material. This expected characteristic was the key motivation for the extensive comparison testing. Clearly, the highest ITS values are for emulsion based cold recycled mixes reached for static pressure compaction. In some cases, the values are more than 100 % higher than ITS values for specimens of similar voids content, prepared by different compaction methods which might indicate how important might be the effect of compaction procedure (static vs. dynamic, kneading effect for gyratory compaction etc.). On the other hand if following the foamed bitumen based cold recycled mixes gyratory compaction leads to higher strength values and slightly decreased voids content. It is hardly accountable why the compaction setting of 600 kPa and 80 gyrations has good comparability with 900 kPa loading and 40 gyration, whereas in this latter case increased number of gyrations leads to decreasing strength value and slightly increased voids content. Based on all these findings, we can therefore firmly declare one compaction method may not be easily replaceable by another and not even the identical void content is a guarantee of the same indirect tensile strength.

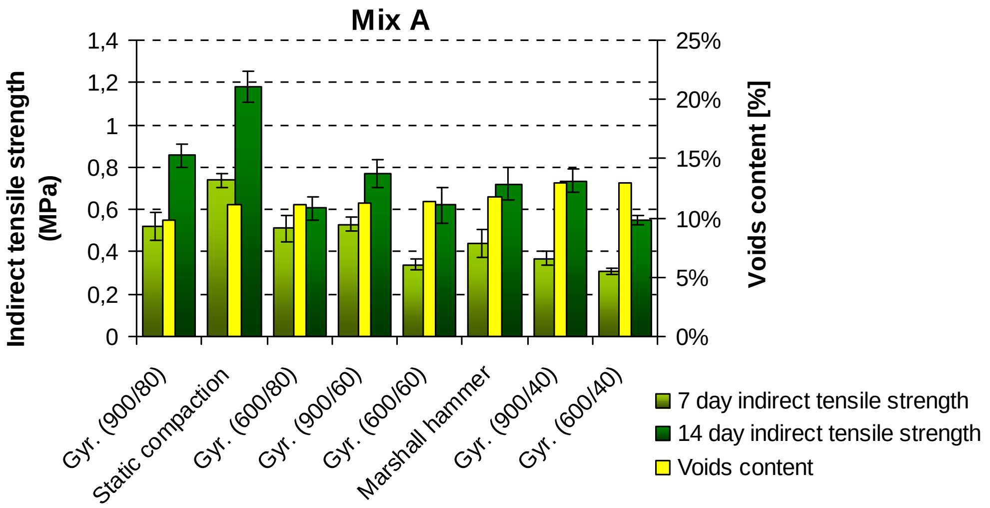



**Figure 17 – Indirect tensile strength (mix A)**

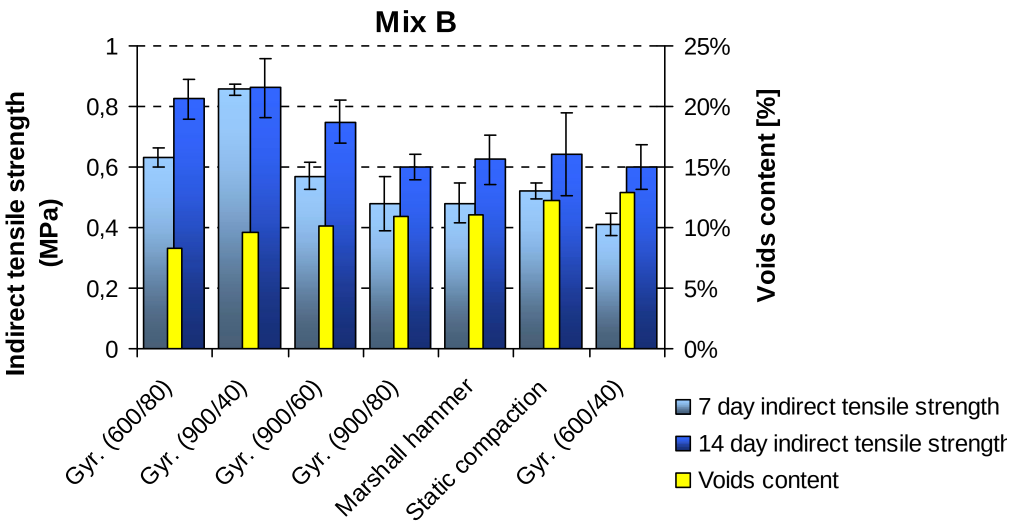



**Figure 18 – Indirect tensile strength (mix B)**

***Stiffness modulus***

Although the Czech technical specifications (TP208, 2009) do not require stiffness modulus validation for cold recycled mixes, it represents an important characteristic with good potential for the future. It stems particularly from the predicative level of the characteristic with respect to the description of the mix behaviour. At the same time, stiffness represents an important parameter for pavement structural design. Therefore it was decided to evaluate the stiffness modulus at 15°C by the repeated indirect tensile stress test according to EN 12697-26 (IT-CY method) for all tested specimens. The values obtained are summarized in figures 19 and 20.

It is interesting to consider that, compared to the indirect tensile strength values the differences between the stiffness modulus values are not so extreme amongst specimens with similar voids content. Some compaction methods even result in similar voids content and stiffness modules at the same time (e.g. specimens compacted by static pressure and specimens compacted using gyratory compactor with 60 revolutions and static load of 900 kPa). This applies to both mixes; especially if observing the mixes stabilized by bituminous emulsion (mix A).

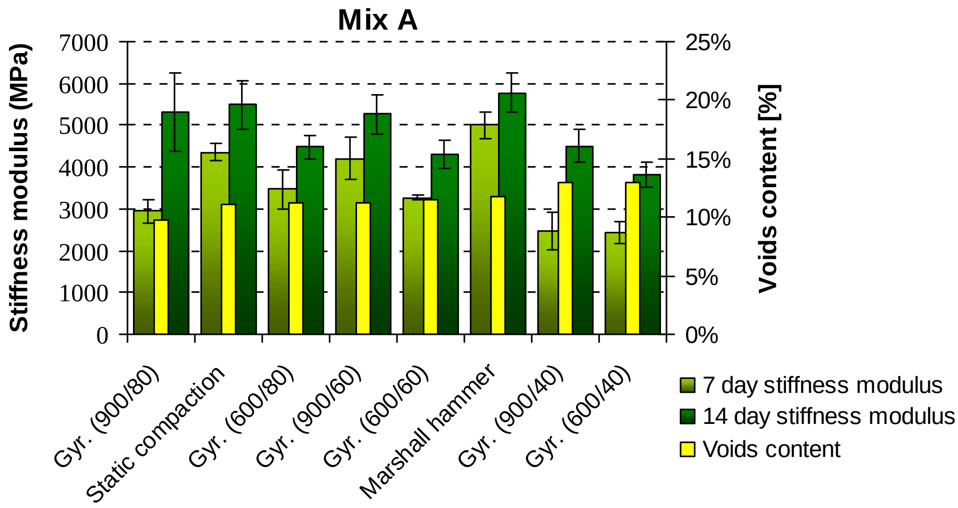



**Figure 19 – Stiffness modulus (mix A)**

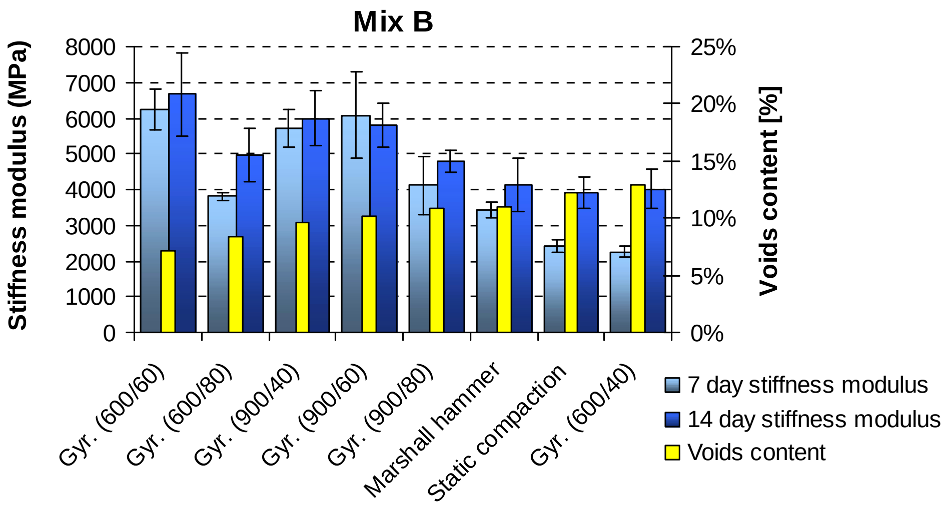



**Figure 20 – Stiffness modulus (mix B)**

From these results it is visible that the methods used for compaction of cold recycled mix test specimen differs significantly based on the requirements given in particular national technical specifications. Nevertheless a common European approach in the field of test specimen compaction method and used curing protocols would help to compare experience and good practice in different parts of Europe, since both compaction and curing have a crucial impact on voids content and other characteristics presently assessed (indirect tensile strength, stiffness). The effort to record all differences caused by the compaction method and curing conditions applied has resulted in this comparative study confirming that the introduction of a unified methodology as opposed to the present state marked by incomparability of values obtained in different countries by different methods used for specimen compaction and curing would be hugely beneficial. The incomparability of results was clearly demonstrated by the variations between the ITS values of the specimens, which were prepared from the same mix but the applied compaction device or the loading was different. Even if the specimens showed similar voids content values, the difference between the ITS values reached in some cases up to 100 % (e.g. static pressure at 5 MPa vs. gyratory compactor with 600 kPa vertical pressure and 60 revolutions for mix A). In the case of stiffness, the variations are markedly lower; some compaction methods even show comparable voids content and stiffness modulus (e.g. specimens for mix A prepared by static pressure at 5 MPa and by gyratory compactor with 900 kPa vertical pressure and 60 revolutions).

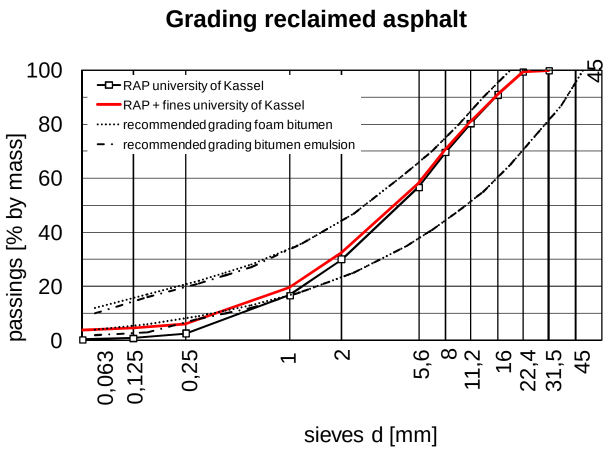
### *4.2.2 Experimental study conducted at University Kassel*

For the comparison of compaction methods two cold recycled mixes were designed with bituminous emulsion and foamed bitumen based on one grading for evaluating suitable compaction and curing procedures.

In order to reach adequate content of fines according to German mix design guide (FGSV, 2005), 3.6 % limestone filler was added to the RA. The RA grading as well as the resulting mix granulate grading after filler addition is compared to Wirtgen Manual (2012) in Table 9. Whereas the mix gradation meets the Wirtgen requirements for emulsion BSM, the applied grading result in lower contents of fine aggregates as recommended by the Wirtgen Manual.

Further the applied binder contents are identified in Table 9. These contents of bitumen and cement represent in a good way the German mix design approach and exceed the recommendations as defined by the Wirtgen Manual.

**Table 9: mix design for reclaimed asphalt mixtures**




| | Bituminous binder | Hydraulic binder |
|---|---|---|
| MIX C | 2.4% residual bitumen (4% bituminous emulsion C60B1-BEM) | 2% cement (CEM I 32.5R) |
| MIX D | 4% foamed bitumen (50/70 Pen grade: penetration 37.8 dmm; $T_{R\&B}$: 55.5°C) | 2% cement (CEM I 32.5R) |

The recovered bitumen characteristics are given in Table 10.

**Table 10: Bitumen characteristics (recovered)**

| | |
|---|---|
| **Bitumen content (% in mass)** | 5.4 |
| **Needle penetration ($10^{-1}$ mm)** | 23.0 |
| **$T_{R\&B}$ (ºC)** | 63.5 |

The bitumen characteristics of the bitumen emulsion are given in Table 11.

**Table 11: Bitumen emulsion characteristics according to EN 13808**

| | | |
|---|---|---|
| **Type of bitumen emulsion** | **C** | Catonic emulsion |
| | **60** | Bitumen content 60% by mass |
| | **B** | Unmodified bitumen |
| | **1** | Class of breaking value |
| **Residual bitumen** | **Penetration grade @ 25° ($10^{-1}$ mm)** | < 100 |
| | **Softening point R&B (ºC)** | ≥ 43 |

For foamed bitumen production water was injected into the 170°C hot bitumen (50/70) leading to the foaming effect by using Wirtgen laboratory foaming unit WLB10S. The foamed bitumen is immediately sprayed into the two-spindle mixing device Wirtgen WLM 30.

According to Figure 21 following parameter were applied for foaming of 50/70 in this study:

- foaming water content 4.5 % by mass
- 180°C bitumen temperature
- 5.5 bar bitumen pressure

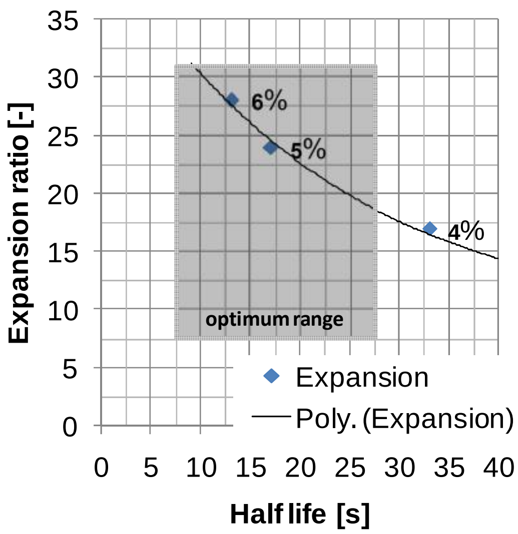



**Figure 21 – Foamed bitumen characteristics for 4; 5 and 6 % of water content**

### *4.2.3 Experimental study conducted at LNEC*

The reclaimed asphalt material used in this study was originated from the milling of the upper layers of a Portuguese National Road pavement, within its rehabilitation works. The grading curve of samples of the reclaimed (RA-S1, RA-S2, RA-S3) as well as its average (RA-Average) is represented in Figure 22. This figure also shows the Portuguese required grading envelope for the reclaimed asphalt to used asphalt layers of at least 10 cm thick (EP-CETO, 2012) and the Wirtgen Manual (2012) recommended grading envelope for cold bitumen-emulsion stabilisation.

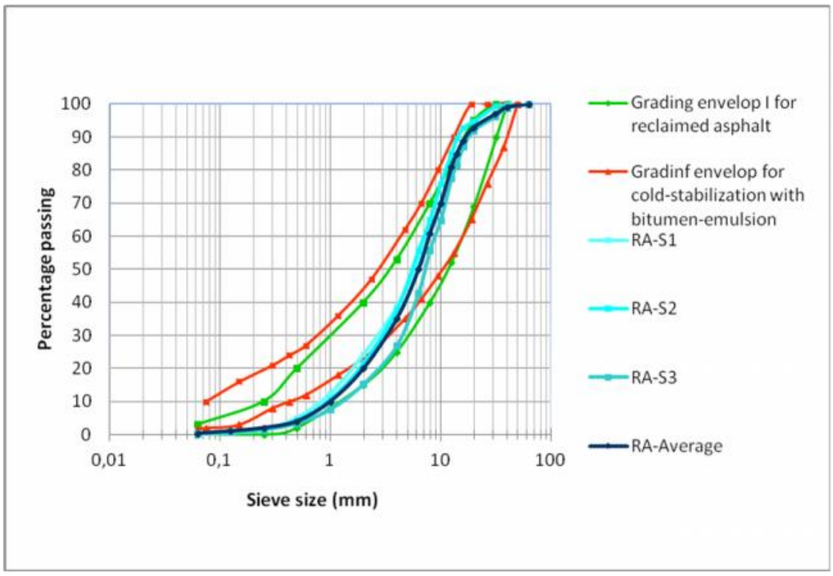



**Figure 22 – Reclaimed asphalt grading curves and cold recycled mixtures envelops**

With regard to achieve a grading curve fitting the Wirtgen Manual recommended envelop, certain amount of filler was added to the mixture, as shown in Figure 23. The adopted granular mix composition comprised 97 % RA and 3 % filler.

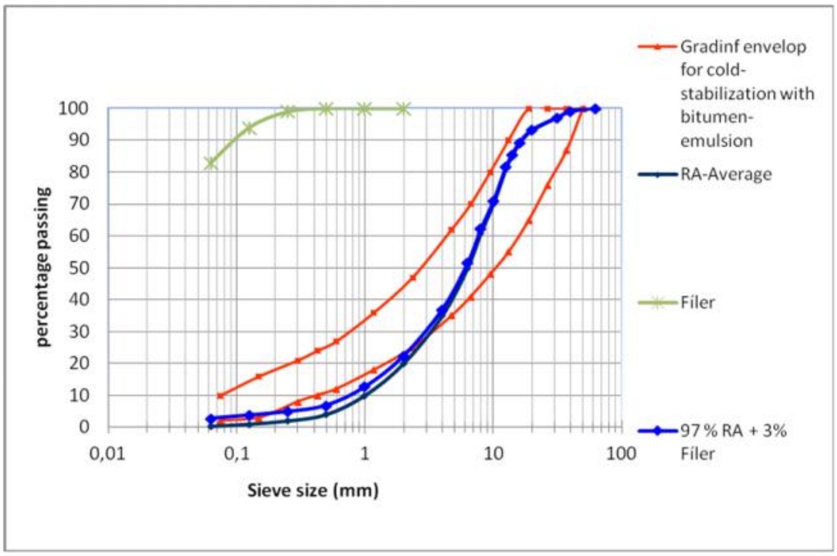



**Figure 23 – Reclaimed asphalt, filler and final granulate material grading curves**

In order to investigate the optimum water content, modified Proctor tests were performed on the granular material (Figure 24).

The Proctor compaction curve is fairly atypical, what may be related both to the type of tested material (which is mainly "reclaimed asphalt"), and to the dimension of its particles (which is mainly defined as "coarse" material). From the results obtained, an optimum water content of 5.7 % (in mass of the granular material) was considered for further testing. Furthermore, the bitumen on the reclaimed asphalt was also recovered and characterized (Table 12).

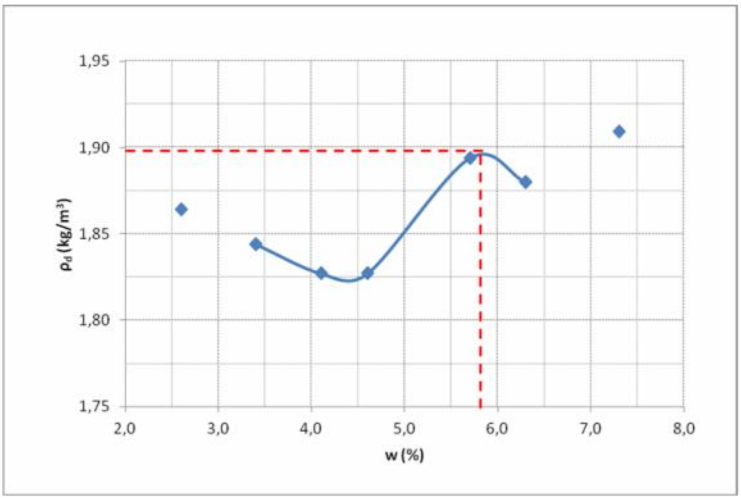



**Figure 24 – Modified Proctor compaction curve**

**Table 12: Characteristics of the bitumen on the reclaimed asphalt**

| | | |
|---|---|---|
| **Bitumen content (% in mass)** | | 4.5 |
| **Properties of the recovered bitumen** | **Needle penetration (EN 1426), $10^{-1}$mm** | 12 |
| | **Softening point by R&B (EN 1427), ºC** | 73.4 |

In the studies developed at LNEC, a cationic slow setting bitumen emulsion (C60B7 according to the older classification given in EN 13808) was selected. Furthermore, a 42.5 resistance strength Portland cements with rapid (higher) early strength (CEM I 42.5 R) was also used.

Table 13 shows the compositions that were adopted for mix design studies.

**Table 13: Used mix compositions for bitumen emulsion stabilized materials and for bitumen emulsion & cement stabilized materials**

| Cold mix ID | | CM-E3 | CM-E4 | CM-E5 | CM-E3C1 | CM-E4C1 | CM-E5C1 |
|---|---|---|---|---|---|---|---|
| **Percentage of each material in the mixture** | **Reclaimed Asphalt** | 91.8 % | 91.8 % | 91.8 % | 91.8 % | 91.8 % | 91.8 % |
| | **Filler** | 2.8 % | 2.8 % | 2.8 % | 1.8 % | 1.8 % | 1.8 % |
| | **Cement** | - | - | - | 1.0 % | 1.0 % | 1.0 % |
| | **Emulsion** | 2.8 % | 3.8 % | 4.7 % | 2.8 % | 3.8 % | 4.7 % |
| | **Added Water** | 2.6 % | 1.6 % | 0.7 % | 2.6 % | 1.6 % | 0.7 % |

For each of the referred six mix compositions, maximum density was determined as shown in Table 14 and Table 15, respectively, for the mixtures with bituminous emulsion and for the mixtures with combined binder of bituminous emulsion and cement. Those results are graphically represented in Figure 25.

**Table 14: Maximum density of bitumen emulsion stabilized materials**

| Cold mix ID | | CM-E3 | | | CM-E4 | | | CM-E5 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Sample | | A1 | A2 | A3 | A1 | A2 | A3 | A1 | A2 | A3 |
| **Maximum density (EN 12697-5), Mg/m³** | $\rho_{mv,i}$ | 2.449 | 2.437 | 2.447 | 2,430 | 2,416 | 2,441 | 2,427 | 2,402 | 2,440 |
| | $\overline{\rho_{mv}}$ /s | **2.444** / 0.278 | | | **2.429** / 0.286 | | | **2423** / 0.289 | | |

**Table 15: Maximum density of bitumen emulsion & cement stabilized materials**

| Cold mix ID | | CM-E3C1 | | | CM-E4C1 | | | CM-E5C1 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Sample | | B1 | B2 | B3 | B1 | B2 | B3 | B1 | B2 | B3 |
| **Maximum density (EN 12697-5), Mg/m³** | $\rho_{mv,i}$ | 2.456 | 2.466 | 2.448 | 2,457 | 2,435 | 2,445 | 2,419 | 2,434 | 2,419 |
| | $\overline{\rho_{mv}}$ /s | **2.457** / 0.272 | | | **2.446** / 0.277 | | | **2.424** / 0.288 | | |

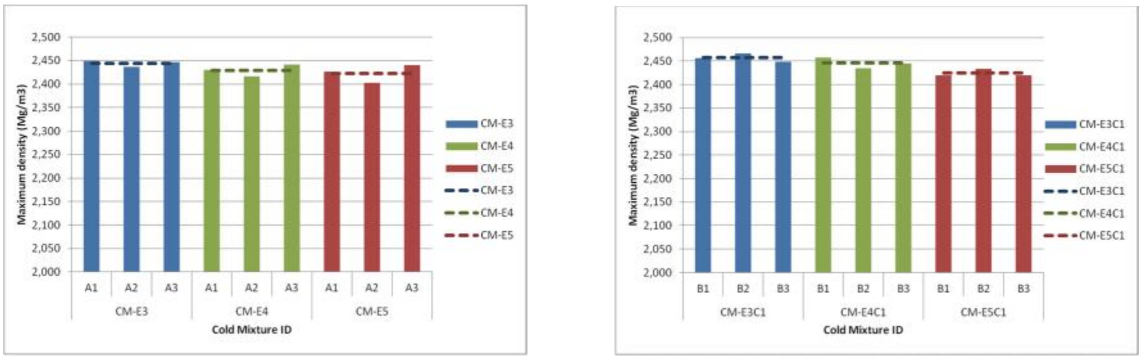



**Figure 25 – Maximum density of bitumen emulsion & cement stabilized materials**

The results previously presented on the maximum density of cold stabilised materials show that:

- There is some variability among the values obtained from different samples of the same mixture, which may be related with the variability of the reclaimed asphalt used to produce each sample of mixture for further testing;
- As expected, there is a tendency to a decrease in the maximum densities of mixtures with an increase of the binder content, as it was expected.

## *4.3 Comparison of compaction and curing methods*

### *4.3.1 Experimental study conducted at CTU*

For cold recycling mixes, curing is an important process during which water released by gradual break-down and consolidation of the bituminous emulsion or drying-up of the consolidated wet mix is drained, or such water is used for cement hydration, thus ensuring gradual stiffening thereof. In this respect lower water content in a mix that only uses bituminous binder (emulsion or foamed bitumen) results in improved strength and resistance to water thanks to better adhesion. Contrastingly, in the case of hydraulic binder content >1 % by mass, it is important that the mix has sufficient moisture level and that such water content can be used for cement hydration. This allows achieving the highest strength characteristics possible. Depending on the surrounding conditions of the environment where the material is curing, the water content in the mix can decrease more quickly or more slowly due to its evaporation; however, that is still not enough for the reclaimed material particles to form very good quality bonds with the bituminous binder. The process requires roughly one to six months when the adhesion barrier is gradually broken due to the residual water film around the particles and a solid bond is formed. This leads immediately to improved strength and stiffness values. The time of the curing process is connected to that; the curing might take months with respect to the fact that reality lacks any ideal conditions that could be used to simulate the curing process in a laboratory. Due to the need to know the predicted development of strength characteristics as soon as possible, accelerated curing procedures of such characteristics that could be used in laboratory assessments while imitating the conditions of curing in construction practice have always been searched for to deliver results that the assessed mix would demonstrate if applied in practice. It is not easy to find such conditions for specimen curing in laboratory environment. At the same time, it should be pointed out that in contrast to a testing laboratory the new structure is influenced (primarily at the beginning of construction) mainly by the weather conditions (temperature fluctuation, negative impact of rain water and frost etc.). The weather conditions, or the specimen curing conditions, have been shown to have a significant effect on mix properties and, therefore, the research of their impact on cold recycling mixes has been one of the main objectives of the measurements taken. Primarily in the case of mixes with higher cement contents, unfavourable curing conditions can result in insufficient hydration during the curing time, or in the occurrence of micro-cracks that deteriorate mechanical properties and overall durability of the work performed.

With respect to the current trend of construction practice where the time factor has been the most important priority for a number of years, waiting 28 days for the strength test results and only paving the subsequent cold recycling layer afterwards is impossible. Instead, the results of measurements after 7 days are used which allow conclusions on the resulting strengths to be achieved by the mix. However, these do not have the exact information value and, therefore, some countries have decided to determine strength characteristics after 14 days of curing. Such values should give a more precise idea of the mix properties, particularly if combined with an assessment of water susceptibility and the strength ratio determination. Within the framework of the results presented further in this sub-chapter, measurements were taken after 7 as well as 14 days for the sake of comparison of curing options in order to give a more precise idea of mix behaviour and to demonstrate the striking difference between them [Forde (2009), Formanová (2011), Wirtgen (2012), Asphalt Academy (2009), Tebaldi et al (2012]. For some curing procedures this has been modified to shorten the period of determining strength and comparing the values reached always after 14 days.

All of the cold recycling mixes assessed were observed for the impact of various combinations of curing procedures in environments of different humidity levels under temperatures of the environments where the specimens were cured. Based on the literature searches conducted within this project, several curing methods which are applied all over the world and represent various approaches were selected for the experimental comparison. These are the procedures established in the Czech Republic, Great Britain and Ireland, France, Australia, South Africa and Portugal. The countries apply different curing methods with distinctive differences in the conditions to which the test specimens are exposed.

***Czech Republic***

The curing procedure for cold recycled mixes is described by national technical specifications, TP 208, which stipulates the temperature, humidity and time frames for test specimens. For mixes bound by cement or other hydraulic binders, test specimens are stored at 90-100 % humidity and temperature of (20 ± 2)°C. In the case of applying cement and bituminous emulsion or foam, the test specimens are stored for 2 days at 90-100 % humidity and temperature of (20 ± 2)°C, followed by storage at 40-70 % humidity and identical temperature (20 ± 2)°C. For mixes bound by bituminous emulsion or foamed bitumen, the test specimens are stored in climatic chamber at (20 ± 2)°C. The reason for the different storage of test specimens is the different impact of individual binders. Storage under 90-100 % humidity can be replaced by the use of an impermeable cover. Contrastingly, 40-70% humidity simulates storage with the relative humidity of air, i.e. without any quick impermeable overlay, Zajíček (2009).

***Great Britain and Ireland***

In the case of the curing method applied in Great Britain the test specimens are left sealed for 28 days to cure at the temperature of 40 °C. For the entire duration of the process, relative humidity of 90-100 % is required (therefore curing in impermeable covers), Tebaldi et al (2012). The reason for this procedure is explained by fast overlay of the recycled layer and by the frequent rains occurring in this part of Europe.

***France***

The curing of test specimens in France is specified by the French national standard, NF P 98-251-4, which also stipulates the static compression testing performed on asphalt mixes including the modified test for cold recycling mixes. The French test method specifies the requirements for cold mixes where the test specimens are stored at constant temperature of 18°C in an environment with relative humidity of 40-70 %, COLAS (2006).

***Australia***

The up-to-date summary “Austroads Technical Report AP-T178/11: 2011” recommends test specimen curing to follow the process where the test specimens are first exposed to the temperature of 40°C for 3 days without any impermeable covers. For the remaining time before the strength testing, the specimens are left at the temperature of (20±2)°C, [Asphalt Academy (2009), Tebaldi et al (2012)].

***South Africa***

In South Africa where cold recycling has long tradition, the curing process has been described within the framework of the Asphalt Academy TG2: 2009, which discussed the inappropriateness of the test specimen curing as applied before (since 1994), using temperature of 60°C. The new specifications have reduced the temperature to 40°C. It has been stipulated that test specimen enclosure in an impermeable cover for 72 hours under the temperature of 40°C maintains excess humidity and delivers very conservative results for the specimens. In contrast to that, the curing of specimens which are first exposed to the temperature of 25°C for 24 hours without being sealed and, subsequently, wrapped in plastic bags and transferred to the drying facility with temperature regulation to 40°C for 48 hours (this method better complies to the steady humidity to be achieved) does not present any evidence that the laboratory measurements are consistent with the actual conditions achieved in practice, [Tebaldi et al (2012), AUSTROADS (2011)].

***Portugal***

The last of the aforementioned procedures described the so-called accelerated curing method which applies higher temperatures than in the preceding cases. Test specimen curing occurs for 1 day at 40-70 % humidity and (20±2)°C and, then, the specimens are transferred to a tempered chamber that maintains the temperature of 50°C, and for the remaining time the specimens are stored under (20±2)°C again. As has been verified by later results of research in progress (not presented here) this is only appropriate for mixes with bituminous binders. In the case of applying hydraulic binders, it results in significant lack of humidity needed for hydration.

<table>
<tr><th rowspan="2">Curing procedure number</th><th rowspan="2">Country</th><th colspan="14">Days</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th></tr>
<tr><td rowspan="4">1</td><td rowspan="4">Czech Republic</td><td colspan="2">sealed</td><td colspan="5">unsealed</td><td colspan="7" rowspan="2"></td></tr>
<tr><td colspan="7">20 ± 2°C</td></tr>
<tr><td colspan="2">sealed</td><td colspan="12">unsealed</td></tr>
<tr><td colspan="14">20 ± 2°C</td></tr>
<tr><td rowspan="4">2</td><td rowspan="4">Great Britain and Ireland</td><td colspan="7">sealed</td><td colspan="7" rowspan="2"></td></tr>
<tr><td colspan="7">40°C</td></tr>
<tr><td colspan="14">sealed</td></tr>
<tr><td colspan="14">40°C</td></tr>
<tr><td rowspan="4">3</td><td rowspan="4">France</td><td colspan="7">unsealed</td><td colspan="7" rowspan="2"></td></tr>
<tr><td colspan="7">18°C</td></tr>
<tr><td colspan="14">unsealed</td></tr>
<tr><td colspan="14">18°C</td></tr>
<tr><td rowspan="4">4</td><td rowspan="4">Australia</td><td colspan="7">unsealed</td><td colspan="7" rowspan="2"></td></tr>
<tr><td colspan="3">40°C</td><td colspan="4">20 ± 2°C</td></tr>
<tr><td colspan="14">unsealed</td></tr>
<tr><td colspan="3">40°C</td><td colspan="11">20 ± 2°C</td></tr>
<tr><td rowspan="4">5</td><td rowspan="4">South African Republic</td><td>unsealed</td><td colspan="2">sealed</td><td colspan="4">unsealed</td><td colspan="7" rowspan="2"></td></tr>
<tr><td>25°C</td><td colspan="2">40°C</td><td colspan="4">20 ± 2°C</td></tr>
<tr><td>unsealed</td><td colspan="2">sealed</td><td colspan="11">unsealed</td></tr>
<tr><td>25°C</td><td colspan="2">40°C</td><td colspan="11">20 ± 2°C</td></tr>
<tr><td colspan="16">* Sealed = moisture 40 - 70 %, Unsealed = moisture 90 - 100 %</td></tr>
</table>

**Figure 26 – Used curing procedures**

***Study results***

Presented assessments of characteristics of cold recycled mixes subjected to different curing methods were performed for cylindrical specimens prepared with four mix designs. Separately recycled mixes with reclaimed asphalt of 0-22 mm and 0-11 mm grading were used. The designs differ in the bituminous binder type and in the presence or absence of a hydraulic binder. The compositions of the individual versions are indicated in Table 13. Mix A and E contains cationic slow-breaking bituminous emulsion C60B7 (according to the older classification in EN 13808) commonly used in the Czech Republic. In mixes B and F, the bituminous emulsion was replaced by foamed bitumen (the base consisted of conventional bitumen 70/100) prepared by means of Wirtgen WLB10S laboratory equipment. These mix types used cement CEM II/B-M 32.5 R, produced in compliance with product standard CSN EN 197-1. The composition of mixes C and G corresponds with the composition of mix A (E) contains cationic bituminous emulsion; there is not hydraulic binder though. The same applies to mixes D and H, which were stabilised by foamed bitumen without cement.

Identically for individual options, a set of selected characteristics was verified which included both determination of bulk densities and calculation of void content in the mix, and verification of the initial moisture content of the mix and determination of strength characteristics by means of an ITS test. Stiffness was determined at the same time by means of the non-destructive method of indirect tensile stress test (IT-CY method).

Four typical variants covering the possible designs used in road practice not only in the Czech Republic were chosen. Tables 17 and 18 state the basic volumetric characteristics – densities – with respect to the type of mix and curing method applied to the individual test specimens. The void contents of the cold recycling mixes was then calculated based on the bulk weights of the specimens and maximum bulk weight of the mixes. Within the framework of the comparisons performed, bulk density is an important parameter which the remaining values measured relate to. As can be noted, maximum density of the cold recycling mixes with reclaimed asphalt 0-22 mm using bituminous emulsion with and without cement (indicated in brackets) are almost identical with slightly higher values in the case of mixes with hydraulic binders. Contrastingly, the maximum bulk weights of mixes using foamed bitumen have a completely opposite trend; the higher values are recorded by mix D where no hydraulic binder has been added.

**Table 16: Designed experimental cold recycled mixes**

| Mix | RAP 0-22 mm | Stabilizing agents / binders | | | Water content |
|---|---|---|---|---|---|
| | | Cement | Bituminous emulsion | Foamed bitumen | |
| A | 91.0 % | 3.0 % | 3.5 % | - | 2.5 % |
| B | 90.5 % | 3.0 % | - | 4.5 % | 2.0 % |
| C | 94.0 % | - | 3.5 % | - | 2.5 % |
| D | 93.5 % | - | - | 4.5 % | 2.0 % |

**Table 17: Basic volumetric characteristics; cold recycled mixes with RAP 0-22**

| Mix | Type of curing | Maximum density [kg/m$^3$] | Bulk density [kg/m$^3$] | Voids content [%] |
|---|---|---|---|---|
| A (C) | Czech Republic | 2 423 (2 421) | 2 124 (2 124) | 12.3 (12.2) |
| | UK and Ireland | | 2 102 (2 102) | 13.3 (13.2) |
| | France | | 2 104 (2 104) | 13.2 (13.1) |
| | Australia | | 2 097 (2 097) | 13.5 (13.4) |
| | South Africa | | 2 140 (2 140) | 11.7 (11.6) |
| | Portugal | | 2 093 (2 071) | 13.6 (14.5) |
| B (D) | Czech Republic | 2 341 (2 346) | 2 116 (2 116) | 9.3 (9.5) |
| | UK and Ireland | | 2 152 (2 152) | 7.8 (8.0) |
| | France | | 2 175 (2 174) | 6.8 (7.1) |
| | Australia | | 2 115 (2 115) | 9.3 (9.5) |
| | South Africa | | 2 121 (2 121) | 9.1 (9.3) |
| | Portugal | | 2 085 (2 072) | 10.6 (11.3) |

**Table 18: Basic volumetric characteristics; cold recycled mixes with RAP 0-11**

| Mix | Type of curing | Maximum density [kg/m$^3$] | Bulk density [kg/m$^3$] | Voids content [%] |
|---|---|---|---|---|
| E (G) | Czech Republic | 2 406 (2 407) | 2081 (2137) | 13.5 (11.2) |
| | UK and Ireland | | 2121 (2157) | 11.8 (10.4) |
| | France | | 2125 (2078) | 11.7 (13.7) |
| | Australia | | 2100 (2064) | 12.7 (14.2) |
| | South Africa | | 2153 (2149) | 10.5 (10.7) |
| | Portugal | | 2058 (2122) | 14.4 (11.9) |
| F (H) | Czech Republic | 2 334 (2 328) | 2118 (2120) | 9.0 (8.6) |
| | UK and Ireland | | 2122 (2099) | 8.8 (9.5) |
| | France | | 2111 (2118) | 9.3 (8.7) |
| | Australia | | 2107 (2100) | 9.4 (9.5) |
| | South Africa | | 2136 (2099) | 8.2 (9.5) |
| | Portugal | | 2118 (2126) | 9.0 (8.4) |

For cold recycled mixes with RAP of 0-11mm grading, different results were gained. Maximum densities for mixes where only bituminous emulsion has been used reach slightly higher values compared to mixes where also hydraulic binder was applied. In the case of foamed bitumen higher maximum densities were reached for mixes with cement. For a complex overview of all results the following Figure 27 summarizes void contents for designed and tested mix variants divided into groups according to curing method which has been used. It should be pointed out, that bulk densities have been determined always before the indirect tensile strength test. Therefore residual water captured in the test specimens plays an important role as well.

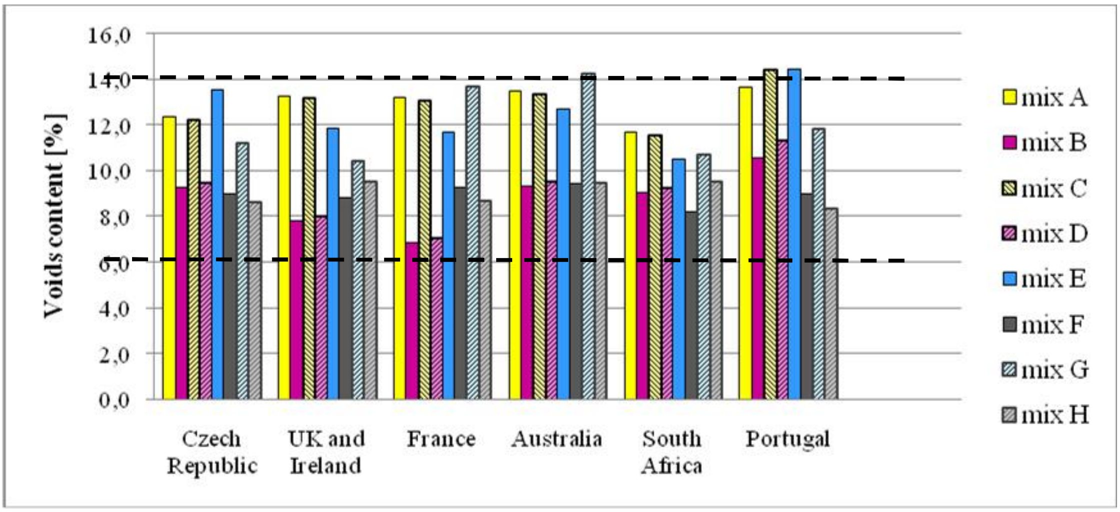



**Figure 27 – Voids contents of compared mixes and curing procedures**

**Curing method impact on ITS**

The determination of indirect tensile strength was performed in accordance with the method stipulated by Czech technical specifications TP208. Cylindrical test specimens of 150 mm diameter and min. 60 mm height are used. As a standard, the test is taken at 15°C. The measurements per se were taken after 7 and 14 days of curing. In total, strength was determined for four types of mixes with different curing methods and times. The average values of the indirect tensile strengths (ITS) obtained are indicated in the following Tables 19-22. The indirect tensile strength values reach fundamentally different results in comparison to the findings related to the bulk densities and void contents that depend on the curing methods chosen. During the research, this presented the motivation to carry out extensive assessment. As ensues from the results presented, the weather conditions (conditions simulated by the curing method) have significant impact on the mix properties and the selection of the right method could have a distinctive influence on material characteristics. The aforementioned fact has been proven also in the case of indirect tensile strengths.

The quality of cold recycled mixes is proved by reaching the required value of the relevant indirect tensile strength as described in sub-chapter 3.4.2. Empirical determination of the values for mix quality assessment is a very simple and fast way of obtaining information on mix behaviour; however, there are certain risks that affect the resulting values. First and foremost, it is the dependence of the parameter in question on various factors, particularly the curing method applied to the test specimens, i.e. the conditions under which the best results were achieved.

**Table 19: Results of indirect tensile strength (ITS) testing for mixes A and C; T=15°C**

| Type of curing | Mix A ITS [MPa] | | Mix C ITS [MPa] | | ITS improvement A vs. C [%] | |
|---|---|---|---|---|---|---|
| | 7 days | 14 days | 7 days | 14 days | 7 days | 14 days |
| Czech Republic | 0.67 | 0.87 | 0.35 | 0.47 | 93.1 | 85.5 |
| UK and Ireland | 0.83 | 1.00 | 0.16 | 0.56 | 404.9 | 79.4 |
| France | 0.84 | 0.65 | 0.44 | 0.51 | 91.5 | 28.6 |
| Australia | 0.85 | 0.87 | 0.63 | 0.68 | 34.9 | 27.3 |
| South Africa | 0.90 | 0.83 | 0.45 | 0.54 | 100.7 | 52.2 |
| Portugal | 0.86 | 0.85 | 0.82 | 0.88 | 4.4 | -3.5 |

**Table 20: Results of indirect tensile strength (ITS) testing for mixes B and D; T=15°C**

| Type of curing | Mix B ITS [MPa] | | Mix D ITS [MPa] | | ITS improvement B vs. D [%] | |
|---|---|---|---|---|---|---|
| | 7 days | 14 days | 7 days | 14 days | 7 days | 14 days |
| Czech Republic | 0.65 | 0.84 | 0.26 | 0.41 | 150.0 | 104.8 |
| UK and Ireland | 0.93 | 1.17 | 0.22 | 0.49 | 325.1 | 139.9 |
| France | 0.88 | 0.95 | 0.33 | 0.46 | 163.2 | 106.0 |
| Australia | 0.91 | 0.95 | 0.52 | 0.63 | 74.3 | 50.5 |
| South Africa | 0.84 | 0.87 | 0.48 | 0.59 | 76.3 | 48.9 |
| Portugal | 1.12 | 1.14 | 0.87 | 1.06 | 28.2 | 7.2 |

When a comparison is made for mixes with RAP 0-22 and identical stabilising agent (e.g. bituminous emulsion with and without cement), the use of cement is noticed to increase the ITS achieved in contrast to the mixes where no hydraulic binder (cement) was applied. In the case of the accelerated Portuguese method, the mix achieved almost identical results with and without cement which is caused by a different effect during hydration. In the cases of the remaining curing methods, the least increase of strength was recorded for the Australian method which delivered an improvement of 35 % in comparison to the mix without cement after 7 days and of 27 % after 14 days. The most marked difference was delivered by the British method where the application of cement resulted in indirect tensile strength increase by over 400 % after 7 days; however, after 14 days, the value only amounted to 79 %. The Czech curing method applied to the mix with added cement improves ITS in both cases, after 7 as well as 14 days, on average roughly by 90 %. If indirect tensile strengths after the final 14 days of curing are compared and it is assessed how the strengths improved due to the added cement, it should be concluded that the most beneficial (i.e. with the highest increase) percentages, is the application of the Czech curing method with an improvement of 85 % after 14 days' curing. The decrease of indirect tensile strength of mix A for the curing method according to the French approach seems illogical within the overall comparison of methods.

Comparing cold recycled mixes using foamed bitumen, the addition of cement seems to improve the indirect tensile strength again. In the case of some curing methods, the improvement is quite significant. Again, like in the preceding case, it is visible that the highest ITS improvement with cement application was achieved by the British curing method where the strength exceeded the mix with no hydraulic binder by 325 % after 7 days' curing; in the case of the 14 days strength, the value was lower but still improved by approx. 140 %. The indirect tensile strengths measured according to the Czech and French curing methods were almost identical; after 7 days, strength improved by roughly 150 % and after 14 days, by an average of 100 %. In the case of the Portuguese method, no significant effect of cement addition to the cold recycling mix was noticed. From the point of view of the 14 days strengths, the effect of the British curing method was demonstrated as the most beneficial.

**Table 21: Results of indirect tensile strength (ITS) testing for mixes E and G; T=15°C**

| Type of curing | Mix E ITS [MPa] | | Mix G ITS [MPa] | | ITS improvement E vs. G [%] | |
|---|---|---|---|---|---|---|
| | 7 days | 14 days | 7 days | 14 days | 7 days | 14 days |
| Czech Republic | 0.47 | 0.58 | 0.37 | 0.49 | 25.7 | 16.7 |
| UK and Ireland | 0.93 | 1.05 | 0.26 | 0.27 | 262.9 | 290.9 |
| France | 0.67 | 0.82 | 0.38 | 0.52 | 76.0 | 58.5 |
| Australia | 0.84 | 0.91 | 0.65 | 0.76 | 30.6 | 19.4 |
| South Africa | 0.78 | 0.81 | 0.55 | 0.61 | 41.1 | 33.6 |
| Portugal | 0.62 | 0.64 | 0.55 | 0.65 | 13.9 | -1.6 |

In the case of comparing cold recycled mix variants with RAP 0-11mm gained results are similar. Influence of cement has a positive effect on gained strength values and mixes with hydraulic binders again reach higher values. The assumption made for mixes with RAP 0-22mm was confirmed. Focusing on comparison of recycled mixes containing bituminous emulsion and cement it can be stated that highest values were gained after British curing method. Cement improved the ITS values after 7 days curing by 263 % and after 14 days curing there was additional slight increase in strength values. If comparing with the remaining coring methods this one leads to most prominent improvements. Czech and Australian curing methods have shown identical values for mixes with cement addition. On the other hand the least suitable curing method if cement is applied might be the Portuguese accelerated curing procedure, where test conditions are not introducing best environment for cement hydration.

**Table 22: Results of indirect tensile strength (ITS) testing for mixes F and H; T=15°C**

| Type of curing | Mix F ITS [MPa] | | Mix H ITS [MPa] | | ITS improvement F vs. H [%] | |
|---|---|---|---|---|---|---|
| | 7 days | 14 days | 7 days | 14 days | 7 days | 14 days |
| Czech Republic | 0.73 | 0.87 | 0.39 | 0.52 | 87.3 | 65.8 |
| UK and Ireland | 0.90 | 1.11 | 0.30 | 0.73 | 204.3 | 51.9 |
| France | 0.74 | 0.79 | 0.40 | 0.53 | 85.3 | 48.6 |
| Australia | 0.93 | 0.95 | 0.62 | 0.67 | 50.6 | 41.2 |
| South Africa | 0.97 | 1.04 | 0.48 | 0.55 | 100.9 | 88.3 |
| Portugal | 1.08 | 0.82 | 0.86 | 0.64 | 25.6 | 28.0 |

If attention is paid only on recycled mixes with foam and cement, improvement is again reached by the British curing method (increase of ITS after 7 days curing about 204 %). In the case of 14 days strength properties the improvement was smaller and shoed only 52 %. On the other hand curing method used in South Africa increased the strength value after 7 days curing about 101 % and after 14 days curing about 88 %. For the latter conditioning time this method seems to be slightly more promising. Almost same improvement level was reached for Czech and French curing method, showing about 86 % increase in strength value after 7 days curing. For 14 days curing the Czech method showed a little bit higher increase level reaching about 66 %.

When assessing the ITS after 14-day curing from the point of view of curing regardless of the bituminous binder applied, the methods used in Australia, South Africa, CZ and Portugal basically deliver comparable results. Minor differences appear in the case of mixes with foamed bitumen. With respect to cold recycling mixes with no cement, the approaches applied in Portugal, South Africa and Australia seem to be comparable. The British method showcases the effect of water which cannot be freely released in the surrounding environment. Primarily the 7-day strengths are low in comparison to the other methods.

**Curing method impact on stiffness**

The requirements applicable to stiffness modules are similar to those of ITS. Czech technical specifications do not require determination of stiffness modulus value and specify no minimum thresholds required; however, the characteristic is examined as a standard within experimental research. Stiffness measurements were taken of all types of mixes designed after 7 and 14 days of curing. A summary of the results is given in Tables 23-26. The measurements were taken under 15°C using the method of repeated indirect tensile stress method. Again, the results had to be compared from the point of view of values reached after 7 and 14 days of curing, with the effect of the curing method applied.

**Table 23: Results of stiffness assessment for mixes A and C; T=15°C**

| Type of curing | Mix A | | Mix C | | Stiffness improvement A vs. C [%] | |
|---|---|---|---|---|---|---|
| | Stiffness modulus [MPa] | | Stiffness modulus [MPa] | | | |
| | 7 days | 14 days | 7 days | 14 days | 7 days | 14 days |
| Czech Republic | 4 212 | 4 997 | 1 594 | 1 838 | 164.3 | 171.9 |
| UK and Ireland | 4 926 | 6 223 | 897 | 2 345 | 448.9 | 165.4 |
| France | 4 486 | 3 803 | 2 073 | 2 108 | 116.4 | 80.4 |
| Australia | 5 038 | 4 448 | 3 359 | 3 411 | 50.0 | 30.4 |
| South Africa | 5 169 | 5 223 | 2 369 | 2 893 | 118.2 | 80.5 |
| Portugal | 5 573 | 6 633 | 4 157 | 5 363 | 34.0 | 23.7 |

**Table 24: Results of stiffness assessment for mixes B and D; T=15°C**

| Type of curing | Mix B | | Mix D | | Stiffness improvement B vs. D [%] | |
|---|---|---|---|---|---|---|
| | Stiffness modulus [MPa] | | Stiffness modulus [MPa] | | | |
| | 7 days | 14 days | 7 days | 14 days | 7 days | 14 days |
| Czech Republic | 3 756 | 4 760 | 1 082 | 1 573 | 247.2 | 202.6 |
| UK and Ireland | 5 174 | 6 389 | 1 116 | 2 108 | 363.6 | 203.1 |
| France | 4 155 | 4 380 | 1 490 | 1 880 | 178.8 | 133.0 |
| Australia | 4 920 | 5 511 | 2 266 | 2 575 | 117.1 | 114.0 |
| South Africa | 4 191 | 4 492 | 2 279 | 2 454 | 83.9 | 83.1 |
| Portugal | 6 304 | 6 673 | 4 698 | 5 327 | 34.2 | 25.3 |

**Table 25: Results of stiffness assessment for mixes E and G; T=15°C**

| Type of curing | Mix E Stiffness modulus [MPa] | | Mix G Stiffness modulus [MPa] | | Stiffness improvement E vs. G [%] | |
|---|---|---|---|---|---|---|
| | 7 days | 14 days | 7 days | 14 days | 7 days | 14 days |
| Czech Republic | 2 891 | 3699 | 1 252 | 1 597 | 130.9 | 131.6 |
| UK and Ireland | 5 500 | 6 385 | 831 | 1 044 | 562.3 | 511.3 |
| France | 3 503 | 4 313 | 1 204 | 1 647 | 191.0 | 161.9 |
| Australia | 4 287 | 5 000 | 2 513 | 2 714 | 70.6 | 84.2 |
| South Africa | 4 611 | 4 165 | 1 983 | 2 163 | 132.5 | 92.6 |
| Portugal | 4 064 | 4 172 | 2 899 | 3 091 | 40.2 | 35.0 |

From the perspective of stiffness modulus development in time, we can note that there is usually a considerable increase of stiffness between the values after 7 and 14 days; however, a slight decrease was recorded for some curing methods. In the cases of the French and Australian curing methods, a rather significant decrease was found and could have been caused, identically to the Portuguese method, by the heterogeneity of the reclaimed material which constitutes a risk that is difficult to control. Therefore, we can conclude that the values obtained after 7 days' curing give just a rough idea of the final mix properties and, therefore, the values obtained after 14 days of curing should be relied on more since they proved to have greater indicative value.

**Table 26: Results of stiffness assessment for mixes F and H; T=15°C**

| Type of curing | Mix F Stiffness modulus [MPa] | | Mix H Stiffness modulus [MPa] | | Stiffness improvement F vs. H [%] | |
|---|---|---|---|---|---|---|
| | 7 days | 14 days | 7 days | 14 days | 7 days | 14 days |
| Czech Republic | 4 189 | 5 127 | 1 749 | 2 038 | 139.4 | 151.6 |
| UK and Ireland | 4 691 | 5 679 | 1 025 | 2 717 | 357.9 | 109.0 |
| France | 3 655 | 4 019 | 1 466 | 1 953 | 149.3 | 105.8 |
| Australia | 4 538 | 4 961 | 2 198 | 2 329 | 106.5 | 113.0 |
| South Africa | 5 135 | 5 519 | 2 270 | 2 410 | 126.2 | 129.0 |
| Portugal | 6 790 | 5 144 | 4 014 | 2 850 | 69.1 | 80.5 |

The results of stiffness copy relatively well the ITS results. Unexpected is the low modulus values for the Czech curing method. The lower values of the British method related to the mixes with no cement just confirm the findings applicable to ITS (negative impact of humidity and condensing water). Contrastingly, in the case of mixes with cement, it is quite obvious that the water enhances cement hydration. The high figures of stiffness modules for mixes with cement that were exposed to the Portuguese curing method seem illogical from the perspective of curing. The lack of water in the mix should have led to poorer results with respect to the cement's limited ability to hydrate. The Australian and South African methods are mutually very well comparable for basically all mix types.

As is obvious from the performed assessments, the selected curing method has a major effect on the resulting characteristics of cold recycling mixes. The choice of a suitable method cannot be made on the basis of historic analogies or acceptance of other countries' approaches. At least three perspectives must be taken into consideration. First, whether the mix is based solely on bituminous binders with a maximum of 1 % by mass of cement, or whether it is a mix with combined binder where cement plays an important role. Secondly, the approach to the structure of the recycled layer from the point of view of its subsequent overlay – if another layer is laid to cover it soon after the cold recycling completion, the phenomenon can be simulated by enclosing the test specimens sealed by plastic bags as the water content will be mostly retained in the recycled layer and the evaporation of the excess water takes much longer. The third point of view is the region where the cold recycling technology is being implemented, and its characteristic climate. Based on these aspects, the accelerated curing method where the test specimens are put in an air-conditioning chamber with temperature >40°C to provide good drying-up and, consequently, faster bituminous emulsion or foam consolidation, seems appropriate for cases where no hydraulic binder is used and regulations allow requiring e.g. 5-7 day technological break. Contrastingly, a different procedure should be applied in case of using hydraulic binders to the quantity of >1 % by mass; with respect to the course of construction and the climate, it is to be discussed whether the test specimens should be left uncovered in an environment with relative humidity of 40-70 % or whether they should be put in plastic bags which is likely to give a better simulation of prompt overlay by the next structural layer. However, it is questionable whether this should occur immediately or for instance after 1-2 days break. In general, we can note that the approach wherein the specimens remain unsealed is more conservative and will yield lower strength and deformation characteristic values. Due to that, the approach appears preferable. Nevertheless, it is important that reasonable simulations of accelerated curing will not be possible for this combination of binders since it is complicated, if not impossible, to accelerate the cement hydration process.

### *4.3.2 Experimental study conducted at University Kassel*

For evaluating the influence of the compaction method on resulting void content and ITS specimens were prepared using Marshall compaction, Proctor compaction, static compaction and compaction using a vibrating table.

**Marshall compaction** is a dynamic compaction according to DIN EN 12697-30 (especially TP Asphalt- StB, part 30 in Germany). Within this method the samples were prepared by 50 and 100 beats each side. **Vibrating table** is a compaction method for unbound and hydraulically bound mixture. The samples are loaded with a defined weight by a frequency of 50 Hz for 3 minutes each side. **Static compaction** is used in most European countries. The University of Kassel compared the Czech standards (5 N/mm²) and the German mix Design standard (FGSV, 2005) with 2.8 N/mm². For mentioned compaction methods, ITS and void content were tested after 7 days of dry curing. **Proctor compaction** is a dynamic compaction method according to DIN RN 13286-2. The samples (diameter 150mm) are compacted by 22 beats each side. Here it was not possible to de-mould specimens and no mechanical tests could be conducted for these compaction methods. The bulk density was evaluated by identifying the specimen volume in the mould.

For each compaction method three specimens were prepared. The compacted specimens were stored in their moulds at 20 °C and 80 % relative moisture for approximately 24 hours and de-moulded afterwards. Then they are stored under room conditions for 7 days. Bulk density is determined 1 day before conducting ITS test (before temperature conditioning 1 day prior the test).

**Table 27: Compaction methods used by university of Kassel**

| Compaction method | Standard | Characteristic | Curing methods and results |
|---|---|---|---|
| Marshall compaction | DIN EN 12697-30 (TP Asphalt-StB, part 30) | 50 and 100 beats each side, dynamic, Ø 100 | Room conditions 7 days, afterwards testing $ITS_{7,dry}$, void content |
| Vibrating table | DIN EN 13286-5 | Vibration f = 50 Hz, t = 3 min each side, top load 10.4 kg, Ø 100 | |
| Static compaction | Czech Mix Design standard | 5.0 N/mm², Ø 100 | |
| | German Mix Design standard (M KRC) | 2.8 N/mm², Ø 100 | |
| Proctor compaction | DIN EN 13286-2 | RA mixture is filled in 3 layers in forms, 22 beats each layer for compacting, Ø 150 | Void content in compaction form |

For evaluation of the effect of the moisture range allowed according to the German standard (humidity span 40 to 70%) on the mechanical properties, specimens were stored in controlled humid conditions using a climate chamber. Therefore, humidity of 40 %, 55 % and 70 % were applied for up to 28 days conditioning. Furthermore, the standard room storage conditions as well as the Portuguese curing procedure (3 days at 60°C) were applied. The procedure is shown in Figure 28. The specimens were composed according to the mix design presented in section 4.2.2 and compacted statically according to German mix design procedure (compare section 3.1.3). ITS was conducted on the conditioned specimen after varied conditioning durations at a test temperature of 25°C.

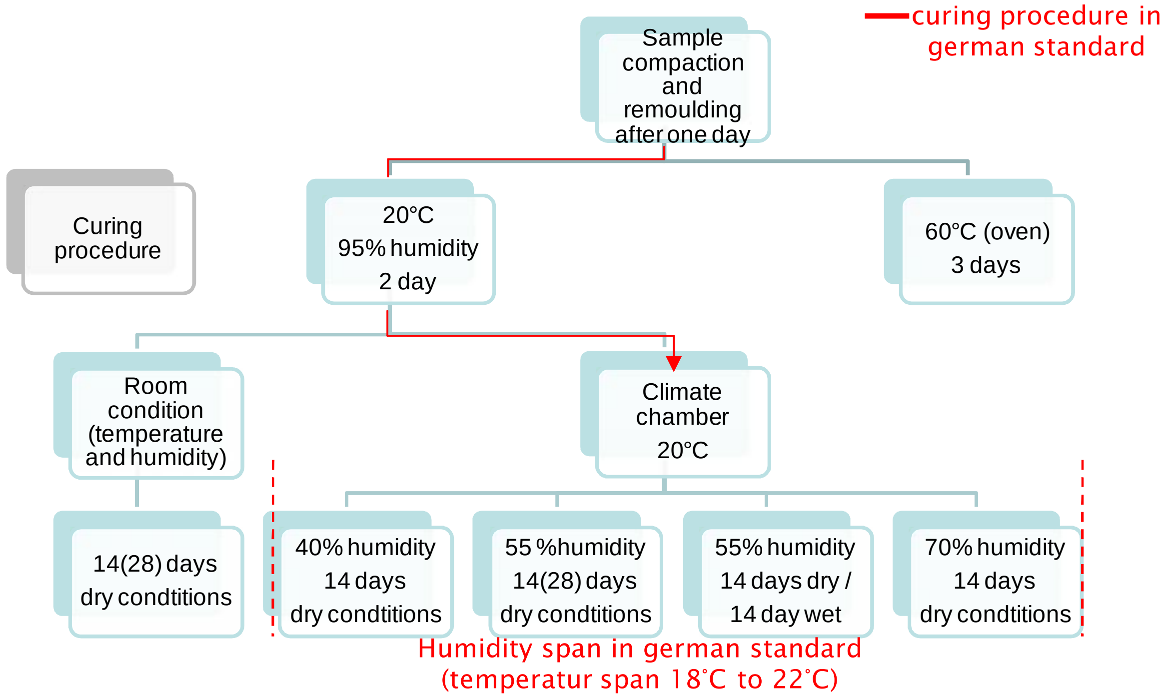



**Figure 28 – Curing procedure University of Kassel**

### 4.3.3 Experimental study conducted at LNEC

Initial studies on this matter carried out at LNEC aimed at comparing the effects of using static compaction but applying a reduced compressive loading (7.5 MPa) instead of the standard one (21 MPa) established in the Spanish standard NLT 161.

Once the granular material (97 % RA + 3 % filler) has a maximum dimension of the particles of 20 mm, it allows for the use of cylindrical moulds of 102 mm internal diameter (NLT 162) and of Marshall test specimens (ø ≈ 102 mm and h ≈ 64 mm).

**Table 28: Bulk density of cylindrical test specimens of bitumen emulsion stabilized materials**

| **Preparation & conditioning of test specimens** | Cylindrical specimens: p = 21 MPa ø ≈ h ≈ 102 mm 5days @ 50ºC | | | | | | Cylindrical specimens: p = 7,5 MPa ø ≈ 102 mm & h ≈ 64 mm 5days @ 50ºC | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Determination of bulk density (based on EN 12697-6)** | Procedure D (Bulk density by dimensions) | | Procedure B (Saturated surface dry, SSD) | | | | Procedure D (Bulk density by dimensions) | | Procedure B (Saturated surface dry, SSD) | | | |
| | $\rho_{bdm}$ (Mg/m$^3$) | | $\rho_{bSSD}$ (Mg/m$^3$) | | w (%) | | $\rho_{bdm}$ (Mg/m$^3$) | | $\rho_{bSSD}$ (Mg/m$^3$) | | w (%) | |
| | $\rho_{bdm,i}$ | $\overline{\rho_{bdm}}$ / s | $\rho_{bSSD,i}$ | $\overline{\rho_{bSSD}}$ / s | $w_i$ | $\overline{w}$ / s | $\rho_{bdm,i}$ | $\overline{\rho_{bdm}}$ / s | $\rho_{bSSD,i}$ | $\overline{\rho_{bSSD}}$ / s | $w_i$ | $\overline{w}$ / s |
| **CM-E3** | 2.300 | **2.306**/ 0.007 | 2.324 | **2.335**/ 0.007 | 0.7 | **0.5**/ 0.2 | 2.159 | **2.158**/ 0.011 | 2.220 | **2.222**/ 0.002 | 1.4 | **1.4**/ 0.2 |
| | 2.311 | | 2.337 | | 0.5 | | 2.163 | | 2.225 | | 1.3 | |
| | 2.304 | | 2.344 | | 0.3 | | 2.155 | | 2.220 | | 1.7 | |
| | 2.317 | | 2.331 | | 0.5 | | 2.158 | | 2.224 | | 1.2 | |
| | 2.303 | | 2.336 | | 0.8 | | 2.173 | | 2.220 | | 1.4 | |
| | 2.299 | | 2.339 | | 0.3 | | 2.140 | | 2.222 | | 1.4 | |
| **CM-E4** | 2.308 | **2.305**/ 0.004 | 2.324 | **2.325**/ 0.005 | 1.1 | **0.7**/ 0.2 | 2.164 | **2.165**/ 0.012 | 2.224 | **2.224**/ 0.005 | 1.1 | **1.1**/ 0.2 |
| | 2.303 | | 2.315 | | 0.5 | | 2.174 | | 2.219 | | 0.9 | |
| | 2.305 | | 2.327 | | 0.7 | | 2.176 | | 2.228 | | 0.9 | |
| | 2.303 | | 2.331 | | 0.9 | | 2.144 | | 2.224 | | 1.3 | |
| | 2.301 | | 2.324 | | 0.5 | | 2.158 | | 2.230 | | 1.3 | |
| | 2.312 | | 2.326 | | 0.4 | | 2.171 | | 2.217 | | 0.9 | |
| **CM-E5** | 2.303 | **2.302**/ 0.006 | 2.322 | **2.316**/ 0.006 | 0.4 | **0.5**/ 0.3 | 2.181 | **2.193**/ 0.013 | 2.225 | **2.232**/ 0.006 | 0.7 | **0.6**/ 0.2 |
| | 2.298 | | 2.306 | | 0.3 | | 2.184 | | 2.231 | | 0.8 | |
| | 2.304 | | 2.316 | | 0.3 | | 2.197 | | 2.239 | | 0.6 | |
| | 2.294 | | 2.320 | | 1.0 | | 2.216 | | 2.239 | | 0.4 | |
| | 2.305 | | 2.316 | | 0.6 | | 2.183 | | 2.227 | | 0.6 | |
| | 2.310 | | 2.320 | | 0.4 | | 2.197 | | 2.230 | | 0.8 | |

In summary, the comparative studies on different compaction procedures initially comprised:

*Standard test method*:

- Static compaction: p = 21 MPa (standard pressure);
- Cylindrical test specimens: ø ≈ h ≈ 102 mm (standard dimensions).

*Modified test method*:

- Static compaction: p = 7.5 MPa (reduced pressure);
- Cylindrical test specimens: ø ≈ 102 mm & h ≈ 64 mm (Marshall test dimensions).

In this framework, bitumen emulsion stabilized mixtures were produced, according to the compositions presented in Table 13 (CM-E3, CM-E4 and CM-E5). Bulk density of compacted test specimens was determined after curing 3 days in oven at 50ºC. Table 28 and Figure 29 synthesize the results obtained.


**Figure 29 – Bulk density of cylindrical test specimens of bitumen emulsion stabilized materials**

The results presented in Table 28 and Figure 29 are consistent with the expected, since specimens compacted with lower pressure present lower bulk densities. In addition, lower specimens densities correspond, in general, to higher water absorptions during immersion in water (in SSD test procedure), and thus to higher differences between bulk densities determined by dimensions and by immersion in water.

Subsequently, the air void content of each group of specimens was calculated (Table 29, Figure 30).

**Table 29: Voids characteristics of test specimens of bitumen emulsion stabilized materials**

| **Preparation & conditioning of test specimens** | Loose mixture | Cylindrical specimens: p = 21 MPa ø ≈ h ≈ 102 mm 5days @ 50ºC | | | | Cylindrical specimens: p = 7,5 MPa ø ≈ 102 mm & h ≈ 64 mm 5days @ 50ºC | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Voids characteristics (based on EN 12697-8)** | $\overline{\rho_{mv}}$ (Mg/m$^3$) | $\overline{\rho_{bdm}}$ (Mg/m$^3$) | $V_{m,dm}$ (%) | $\overline{\rho_{bSSD}}$ (Mg/m$^3$) | $V_{m,SSD}$ (%) | $\overline{\rho_{bdm}}$ (Mg/m$^3$) | $V_{m,dm}$ (%) | $\overline{\rho_{bSSD}}$ (Mg/m$^3$) | $V_{m,SSD}$ (%) |
| **CM-E3** | 2.444 | 2.306 | 5.7 | 2.335 | 4.5 | 2.158 | 11.7 | 2.222 | 9.1 |
| **CM-E4** | 2.429 | 2.305 | 5.1 | 2.325 | 4.3 | 2.165 | 10.9 | 2.224 | 8.5 |
| **CM-E5** | 2.423 | 2.302 | 5.0 | 2.316 | 4.4 | 2.193 | 9.5 | 2.232 | 7.9 |

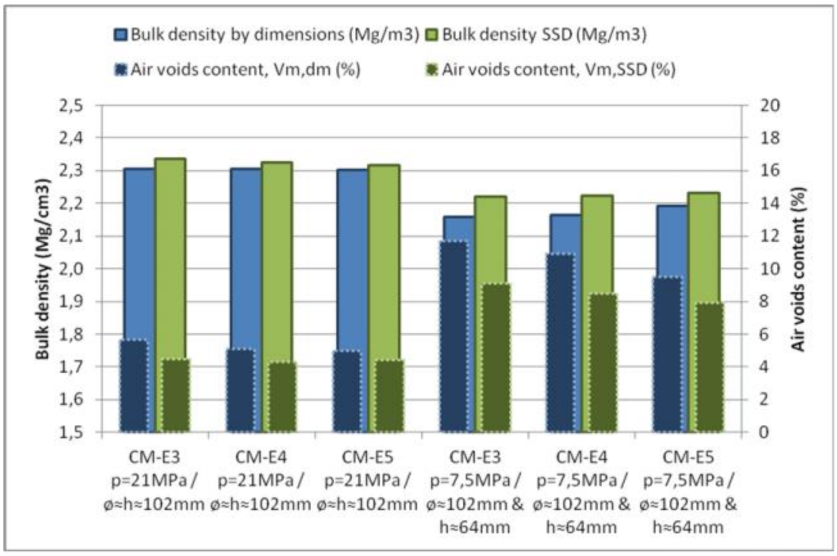



**Figure 30 – Voids characteristics of test specimens of bitumen emulsion stabilized materials**

The analyses of the results presented in Table 29 and Figure 30 allow for the following considerations:

- Air void contents achieved on specimens compacted with the standard pressure of 21 MPa are of about 4 % or 5-6% (for bulk densities determined by SSD procedure and by dimensions, respectively), which are typical values of hot bituminous layers. In contrast, for a reduced compaction pressure (7.5 MPa), air voids ranging from about 8-9 % or from about 10-12 % were obtained (for bulk densities determined by SSD procedure and by dimensions, respectively). These last values are considered to be of the same order of magnitude as the usually achieved on field for cold bitumen-emulsion recycled layers.

These results confirm that a static compression load of 7.5 MPa would be suitable to obtain representative laboratory test specimens of on site compactions.

As regards to the particular method to be used for measuring test specimens' bulk densities, guidance is provided in EN 12697-6. According to this standard, Procedure B (Bulk density – SSD) is suitable for "continuously graded materials such as asphalt concrete (with relatively small pores) with voids contents up to approximately 5 %"; Procedure C (Bulk density – sealed specimen) is "not suitable for reclaimed asphalt (…)" and is less convenient to conduct then the others; and Procedure D (Bulk density by dimensions) is suitable for measuring the bulk density of bituminous specimens "whatever the voids content may be" (or greater than 15 %), providing that specimens have a "regular surface and a geometric shape". Therefore, in subsequent testing, Procedure D (Bulk density by dimensions) was selected for measuring the bulk density of cold recycled specimens.

- While, in the case of using a very high compression load, the air voids content of the three different mixtures are quite similar among them, this is not the case when using a more representative compaction pressure. In fact, the use of a suitable compression allows distinguishing the three mixtures, yielding void contents of about 10 % for CM-E5 mixtures and of about 12 % for CM-3E mixtures.

## *4.4 Cold-recycled mixture characteristics and performance*

### *4.4.1 Experimental study conducted at CTU*

**Relation between compressive and indirect tensile strength**

Czech technical specification allow for some cold recycled mixes to perform either compressive strength test or indirect tensile strength. Similarly in some countries compressive strength (e.g. in form of Duriez test) is preferred. Therefore it was important to utilize a partial study where both tests were compared. In total 16 different mixes with RAP 0-22 mm and different binder content were produced according to mixed designs in the next Table 30. This research was so far focused only on mixes with foamed bitumen (no emulsion assessed). Foamed bitumen was produced from standard distilled bitumen of penetration grade 70/100. The specimens were approx. 60 mm high and had the diameter of 150 mm produced by standard static pressure compaction method.

**Table 30: Tested cold recycled mix variants**

| | Mix D | Mix P1 | Mix B | Mix P2 | Mix V | Mix P3 | Mix P4 | Mix P5 |
|---|---|---|---|---|---|---|---|---|
| Reclaimed asphalt mix | 93,5% | 92,5% | 90,0% | 88,0% | 94,5% | 93,5% | 91,0% | 89,0% |
| Water | 2,0% | 2,0% | 2,5% | 2,5% | 2,0% | 2,0% | 2,5% | 2,5% |
| **Foamed bitumen** | **4,5%** | **4,5%** | **4,5%** | **4,5%** | **3,5%** | **3,5%** | **3,5%** | **3,5%** |
| **Cement** | **0,0%** | **1,0%** | **3,0%** | **5,0%** | **0,0%** | **1,0%** | **3,0%** | **5,0%** |
| Total | 100,0% | 100,0% | 100,0% | 100,0% | 100,0% | 100,0% | 100,0% | 100,0% |

| | Mix K | Mix L | Mix M | Mix N | Mix R | Mix S | Mix T | Mix U |
|---|---|---|---|---|---|---|---|---|
| Reclaimed asphalt mix | 95,5% | 94,5% | 92,0% | 90,0% | 96,0% | 95,0% | 92,5% | 90,5% |
| Water | 2,0% | 2,0% | 2,5% | 2,5% | 2,0% | 2,0% | 2,5% | 2,5% |
| **Foamed bitumen** | **2,5%** | **2,5%** | **2,5%** | **2,5%** | **2,0%** | **2,0%** | **2,0%** | **2,0%** |
| **Cement** | **0,0%** | **1,0%** | **3,0%** | **5,0%** | **0,0%** | **1,0%** | **3,0%** | **5,0%** |
| Total | 100,0% | 100,0% | 100,0% | 100,0% | 100,0% | 100,0% | 100,0% | 100,0% |

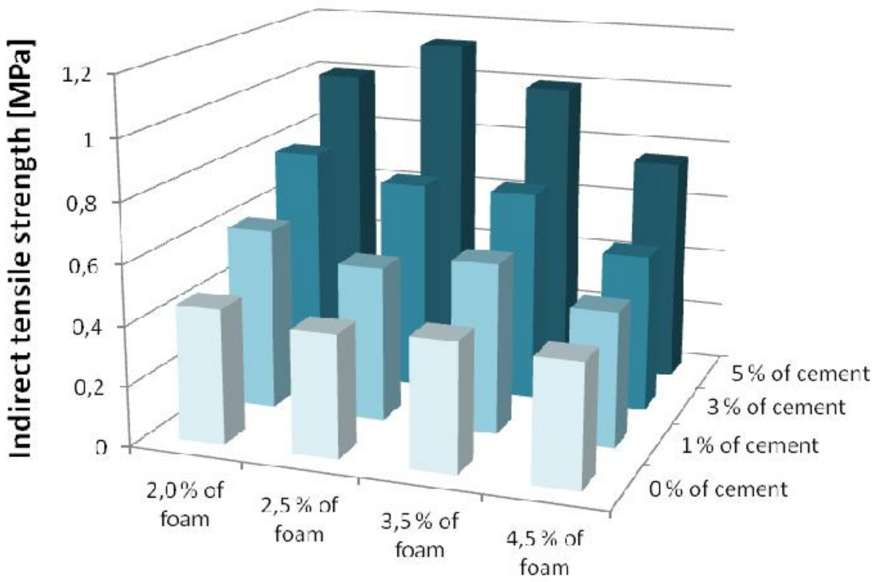



**Figure 31 – Impact of binder content on ITS values at 15°C**

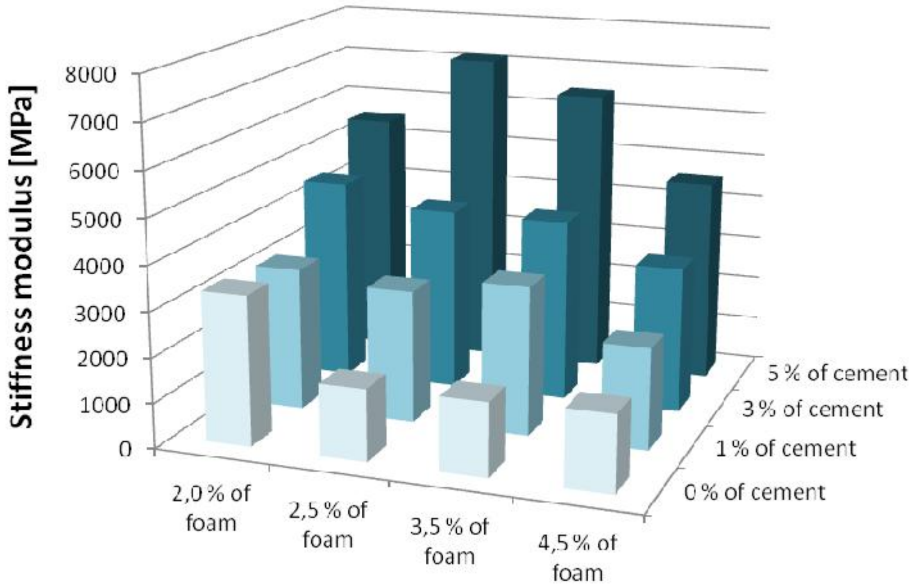



**Figure 32 – Impact of binder content om stiffness at 15°C**

Stiffness modulus values follow the trend of ITS values; compressive strength trends are slightly different. Nevertheless it is clearly visible, that cement plays an important role in all of the assessed characteristics. Foamed bitumen content has a slightly decreasing impact on strength or deformation characteristics if considered without cement addition. If combined binder used then it is visible from ITS and stiffness results that foam bitumen content between 2.5 % and 3.5 % might lead to highest values. Higher foam content had negative influence on all the strength and stiffness values.

In general higher content of cement has more significant influence than higher content of foamed bitumen. Cement content had surprisingly bigger influence on the ITS and stiffness than on the compressive strength values.

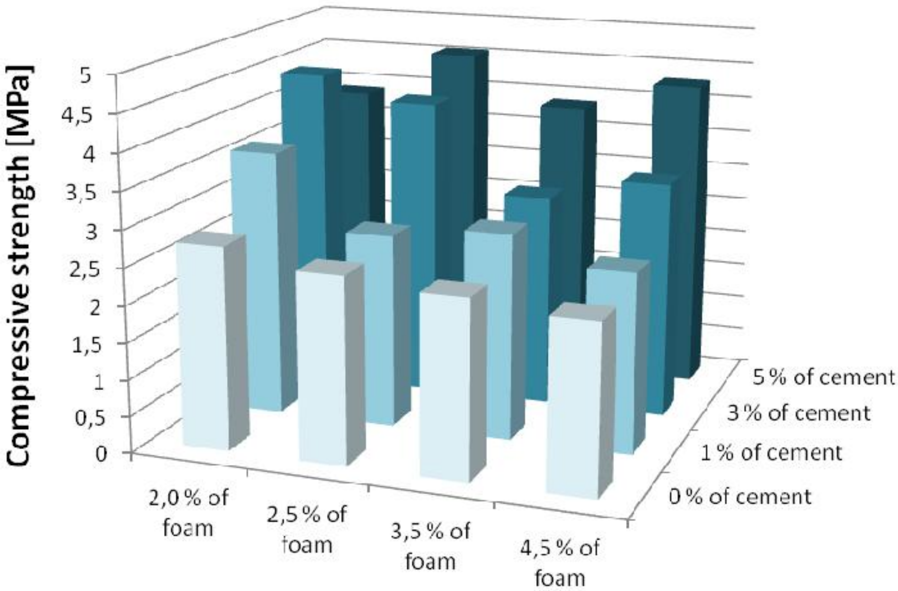
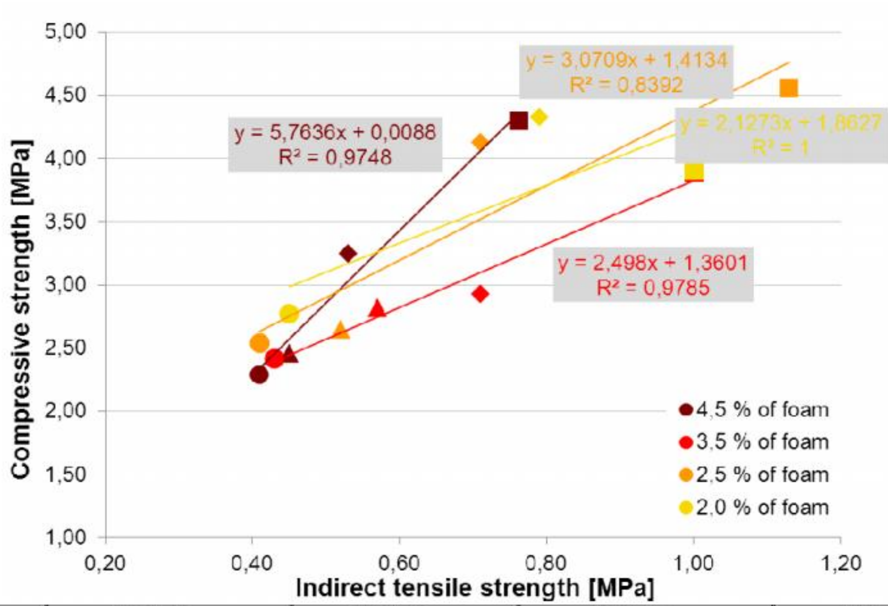



**Figure 33 – Impact of binder content on comprssive strength values at 15°C**

The relation between ITS and compressive strength can be shown on following figure 34. The undergone experiments showed that there might be a linear correlation between ITS and compressive strength values. The regression is steeper for mixes with higher content of foamed bitumen.




| | 2.0 % of foam | | | 2,5 % of foam | | | 3.5 % of foam | | | 4.5 % of foam | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mix | ITS | Rc | Mix | ITS | Rc | Mix | ITS | Rc | Mix | ITS | Rc |
| 0 % of cement | R | 0,45 | 2,77 | K | 0,41 | 2,54 | V | 0,43 | 2,42 | D | 0,41 | 2,29 |
| 1 % of cement | S | 0,61 | 3,65 | L | 0,52 | 2,65 | P3 | 0,57 | 2,82 | P1 | 0,45 | 2,46 |
| 3 % of cement | T | 0,79 | 4,33 | M | 0,71 | 4,13 | P4 | 0,71 | 2,93 | B | 0,53 | 3,25 |
| 5 % of cement | U | 1,00 | 3,90 | N | 1,13 | 4,56 | P5 | 1,00 | 3,89 | P2 | 0,76 | 4,30 |

**Figure 34 – Comaprison and statisticalevaluation between ITS and compressive strength for cold recycled mixes**

**Influence of specimen height on resulting ITS values**

According to Czech technical specification specimens for ITS testing should have a height of 125 ± 20 mm (slenderness ratio of 0.85). The specimens with this height can't be used for IT-CY stiffness modulus testing. Therefore it was assessed if a modified proposal for changed dimensions in the harmonized specifications can be done. This lead to the investigation of the possible influence of specimen height on the ITS values (i.e. experimental prove of the formula from Czech technical specification):

$$R_{it} = \frac{2 \cdot F}{\text{®} \cdot H \cdot D}$$

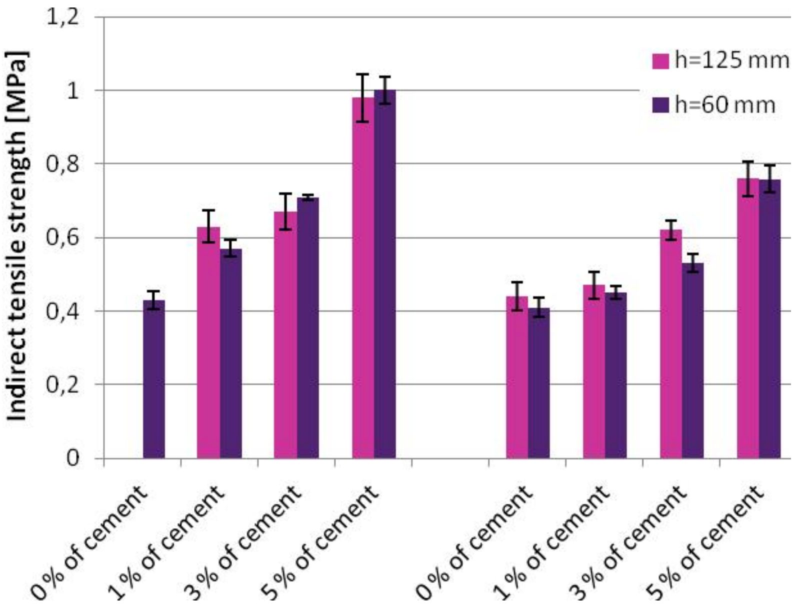



**Figure 35 – Comaprison**

The difference is always just a few percent and can be covered by the accuracy of strength or stiffness testing. Comparison has been done for mixes with bituminous emulsion and foamed bitumen containing different percentage of cement. It can be stated that specimens suitable for stiffness modulus testing can be used also for ITS testing and it doesn't affect the final ITS value.

**Moisture sensitivity tests including accelerated curing procedure**

Within this study firstly accelerated curing has been evaluated with respect to set the relation between ITS/stiffness determined after this curing and same values assessed on specimens of same cold recycled mix which were cured naturally at laboratory conditions. In the latter case indirect tensile strength and stiffness were determined after 7, 14 and 28 days since compaction of the specimen. The specimen were one day left at 90-100 % humidity and then stored at (20±2)°C in an environment with 40-70 % humidity.

For accelerated curing the specimens were first 24h after compaction left at 90-100 % humidity, then immediately put to environmental chamber for 3 days at a temperature of 50°C. After this curing procedure they were tested.

For this comparability study two mixes were designed containing only bituminous binder (emulsion or foam). Table 31 summarizes the used mix design, whereas mixes A and B were used only for the second part of the done assessments (described later). Reclaimed asphalt of 0-22 mm grading was used. All specimens compacted from these mixes had approx. height 60 mm and diameter 150 mm.

**Table 31: Used mix designs for cold recycled mixes**

| Mix components | Mix A | Mix B | Mix C | Mix D |
|---|---|---|---|---|
| Reclaimed asphalt | 91,0% | 90,5% | 94,0% | 93,5% |
| Water | 2,5% | 2,0% | 2,5% | 2,0% |
| Bituminous emulsion | 3,5% | 0,0% | 3,5% | 0,0% |
| Foamed bitumen | 0,0% | 4,5% | 0,0% | 4,5% |
| Cement | 3,0% | 3,0% | 0,0% | 0,0% |

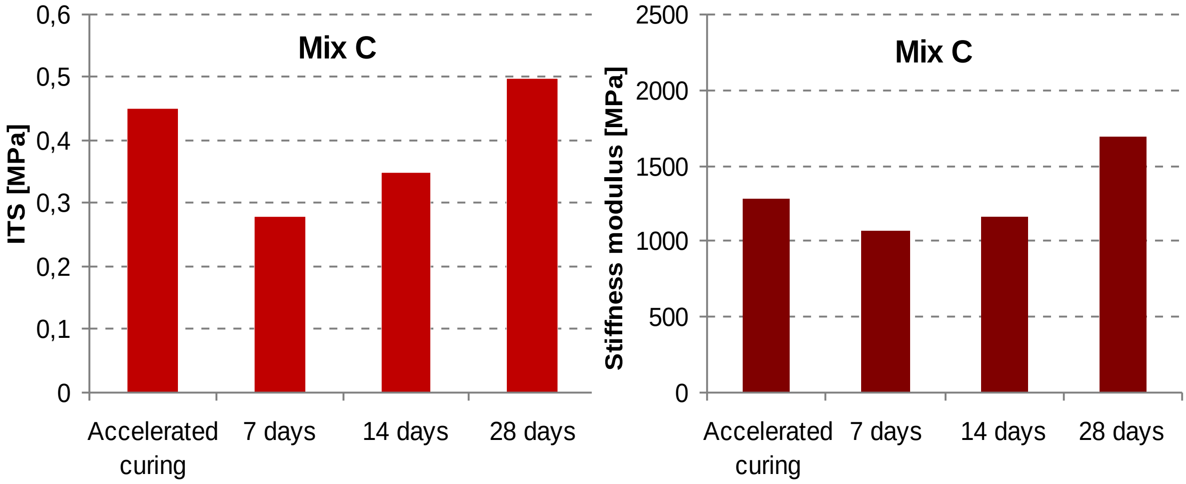



**Figure 36 – Results for emulsion based cold recycled mix; accelerarted vs. natural curing**

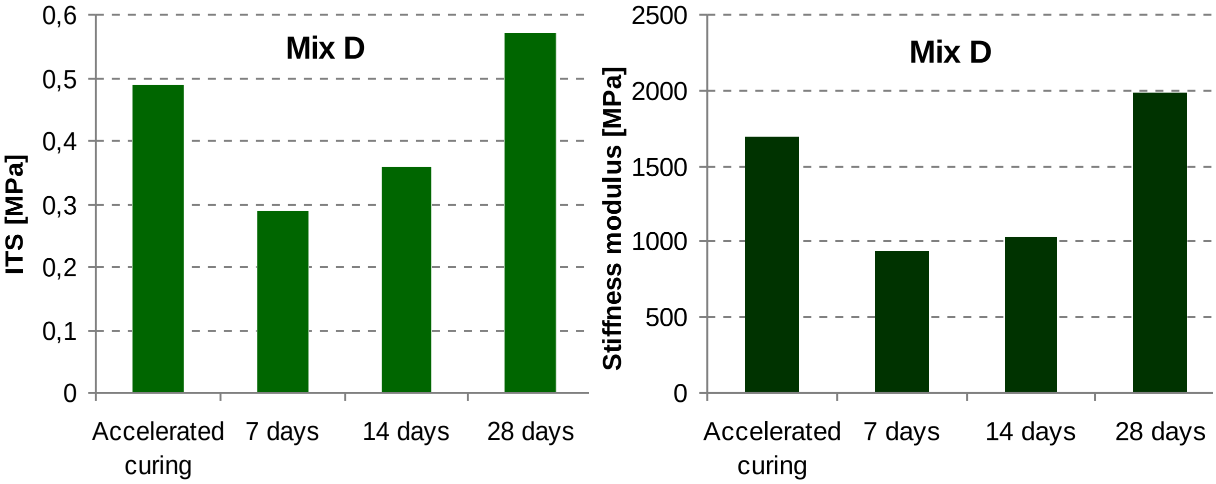



**Figure 37 – Results for foam based cold recycled mix; accelerarted vs. natural curing**

The pre-defined accelerated curing method (24 hours at 90-100 % relative humidity and 20°C storing temperature and after that 3 days at 40-70 % relative humidity and 50°C) was applied only on the cement-free mixes (mix C and D). In general it was so far recommended within this project to use this procedure for mixes with cement content ≤1 % by mass. The assessed characteristics after application of the accelerated curing were in all cases higher than the stiffness end ITS values of specimens which were cured for 14 days (20±2)°C in an environment with 40-70 % humidity. On the other hand these values were always worse than that one of the specimens which were cured at same conditions for 28 days. It can be therefore summarized, that the accelerated curing might represent indirect tensile strength or stiffness values of approx. 21 days natural curing. These findings are in good compliance with findings found e.g. by LNEC in Portugal.

### Moisture susceptibility assessments

Firstly cold recycled mixes without cement were evaluated. Specimens prepared from the mixes C and D (see Table 31) were tested after different time of curing. That was caused by the application of the accelerated curing (24 hours at 90-100% moisture; 20°C and 3 days at 40-70% moisture; 50°C).

Determined values for ITS and stiffness showed that whatever immersion in water brings inferior characteristics (all moisture sensitivity methods lead to worse characteristics compared to dry specimens). The longest immersion (TP 208) results in the worst values, but the relevance of comparison of the specimens with so different curing time remains questionable. Using of the RAP 0-11 instead of the RAP 0-22 resulted in higher values of ITS and stiffness modulus.

| **Mixes without cement – used procedures** | | Days of curing |
|---|---|---|
| AC + 3 days air | Accelerated curing + 3 days in air | 7 days |
| AC + EN 12697-12 | Accelerated curing + water saturation under pressure 6,7±0,3 kPa and 3 days in water in 40 °C | 7 days |
| AC + AASHTO T283 | Accelerated curing + 1 freezing cycle according to AASHTO | 6 days |
| TP 208 | 7 days in air + 7 days in water | 14 days |

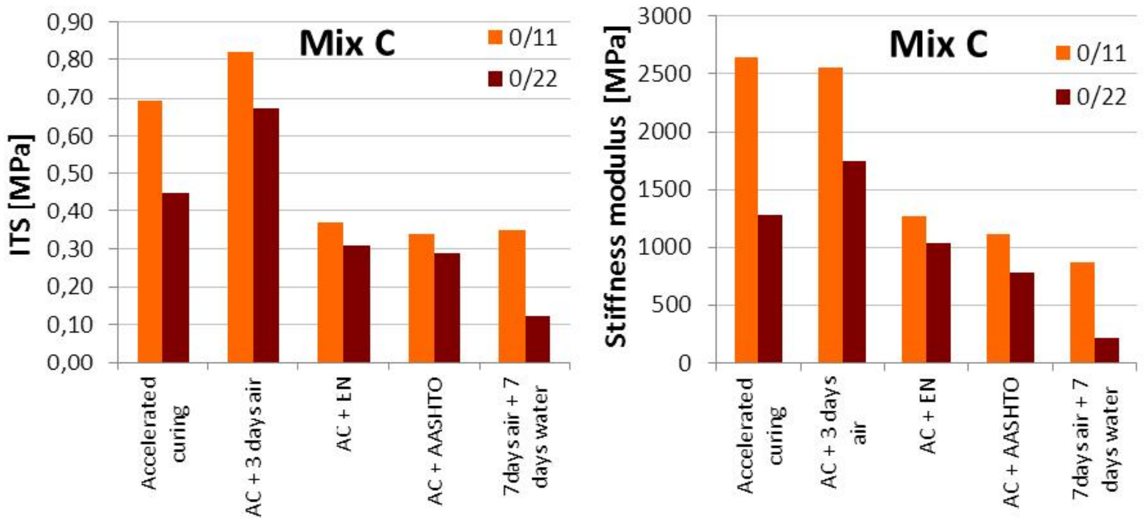



**Figure 38 – Results of moisture sensitivity testing, mix C (emulsion)**

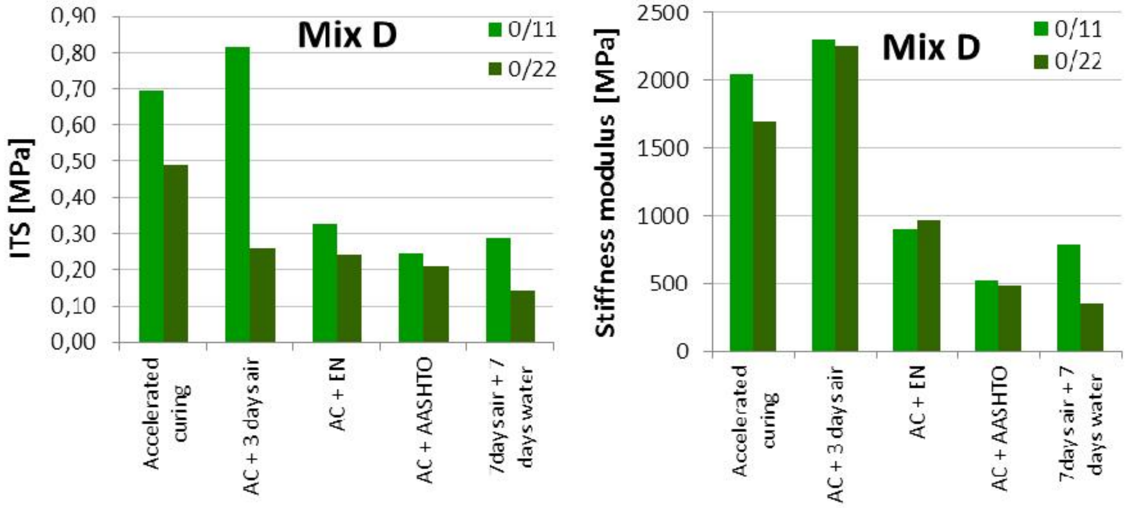



**Figure 39 – Results of moisture sensitivity testing, mix D (foamed bitumen)**

In case of mixes containing higher percentage of cement (typical e.g. for recycling works done in the Czech Republic), all the ITS and stiffness modulus values used for comparison were measured at the specimens naturally cured for 14 days.

| Mixes with cement | |
|---|---|
| 14 days air | 14 days air curing |
| EN 12697-12 | 11 days air curing + water saturation under pressure 6,7±0,3 kPa and 3 days in water at 40°C |
| AASHTO T283 | 12 days air curing + 1 freezing cycle according to modified procedure of AASHTO 283 |
| TP 208 | 7 days air curing + 7 days water curing |

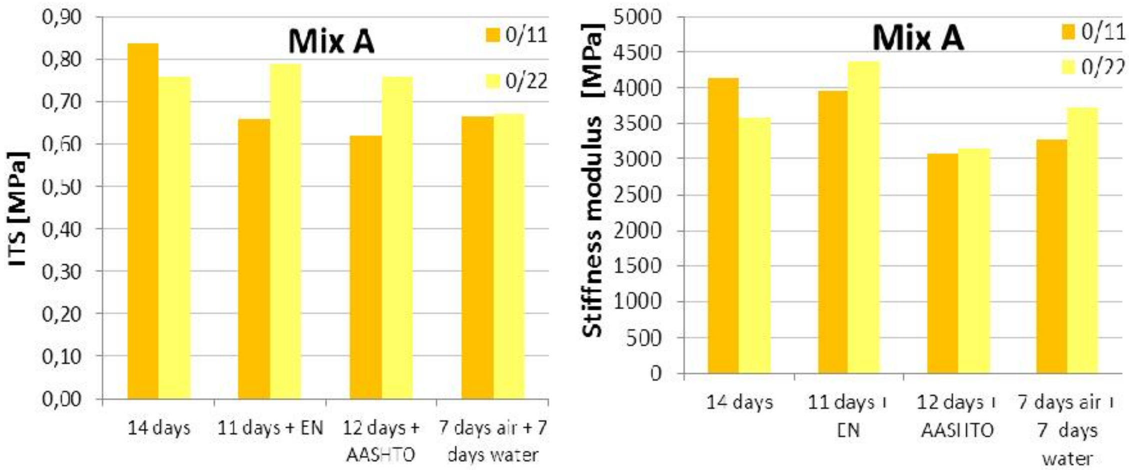



**Figure 40 – Results of moisture sensitivity testing, mix A (emulsion+cement)**

Gained results show that every immersion in water is also detrimental for the specimens, but the difference is not as significant as in the case of mixes with ≤1 % of cement. The specimens conditioned for the moisture sensitivity assessment according to EN had the lowest ITS and stiffness modulus values, even lower than the specimens conditioned according to technical specifications TP 208 (7 days in the air + 7 days in water). The tendency of specimens with RAP 0-22 isn't as obvious as the tendency for RAP 0-11. This is probably caused by high heterogeneity of the RAP 0-22 and this part of the experiment should be repeated.

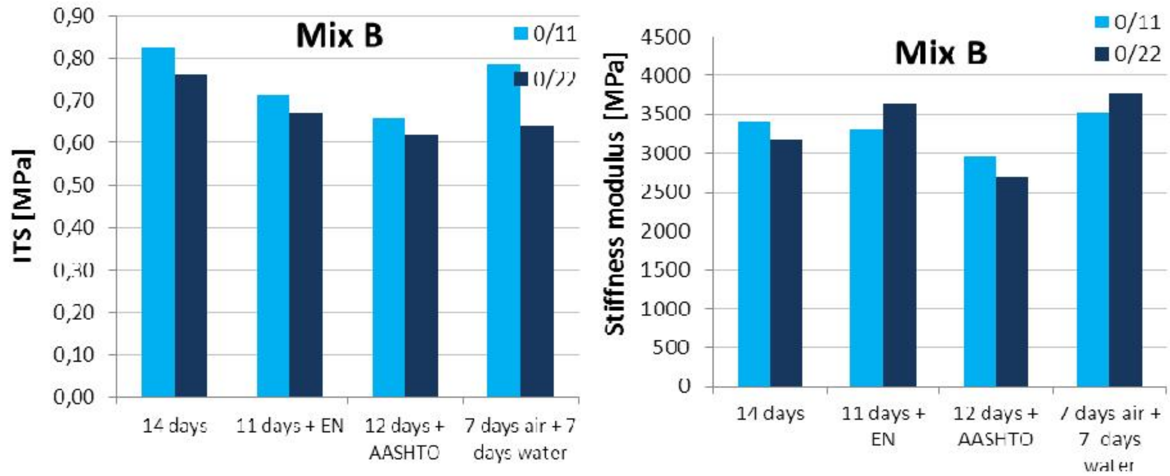



**Figure 41 – Results of moisture sensitivity testing, mix C (foamed bitumen + cement)**

### Difference between sealed and unsealed specimens during curing procedures

Specific issue which has been analyzed is the influence of storing test specimens in sealed or unsealed conditions since in different countries different procedures are defined often requiring sealing the specimens in plastic bags. For this reason two sets of 12 laboratory specimens from mix A (3.5 % of bituminous emulsion and 3 % of cement) were produced. The specimens from the first set (AS) were cured in sealed conditions for the whole time of curing, while the specimens from the second set (AU) were cured sealed only for the first 24 hours and then removed and cured for the rest of their curing time in laboratory conditions. All specimens were produced using reclaimed asphalt 0-22 and had average height of 60 mm and diameter 150±1 mm.

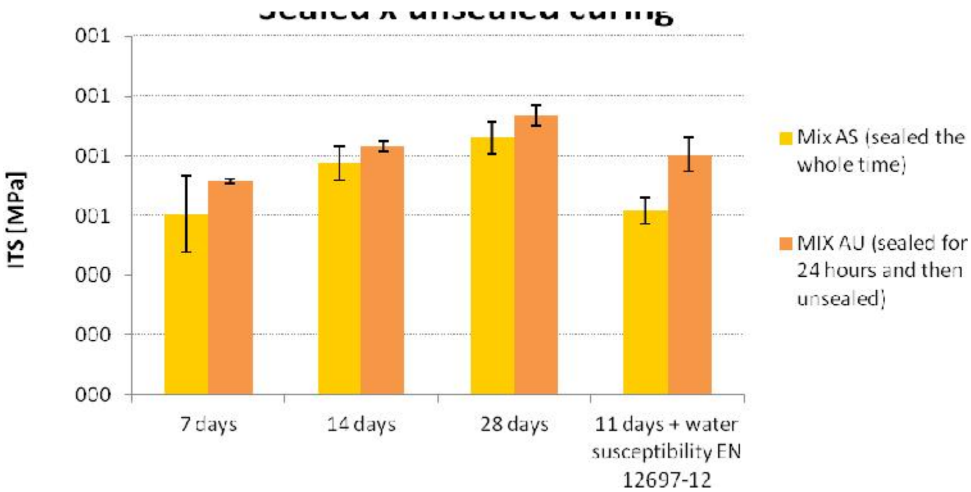



**Figure 42 – Comparison of ITS values between sealed and unsealed specimens, mix A**

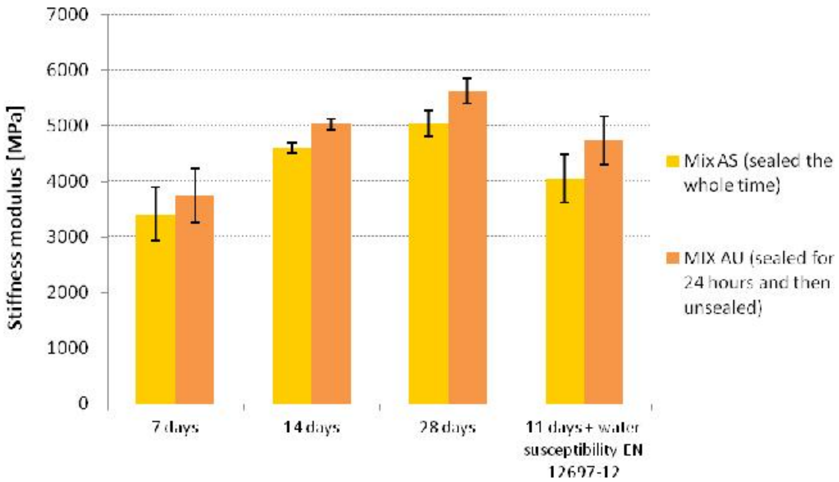



**Figure 43 – Comparison of ITS values between sealed and unsealed specimens, mix A**

Curing under sealed conditions resulted in the case of bituminous emulsion stabilized mix (with higher content of cement) in lower ITS and stiffness modulus values for all curing patterns applied, including the moisture sensitivity assessment. The difference between average values was from 7 % to 30 %. The specimens which were cured according to the moisture susceptibility standard (EN 12697-12) showed the most significant differences depending on the sealed or unsealed curing conditions.

The former research which was performed in the field of curing conditions impact showed that in case of mixes with cement higher moisture brings higher ITS and stiffness values, because the moisture is supportive for the hydration process. On the other hand even then was clear that the moisture value must be regulated. Reason for this necessity is that in general moisture interferes with bonding of the bituminous binder and the aggregate. In this case as well as in other experiments carried out by CTU and by University Kassel the detrimental effect of moisture on the bond was larger than the positive.

když jsme dělali výzkum na vliv způsobu zrání, tak u směsí s cementem vycházela vyšší vlhkost jako pozitivní, to jsme vysvětlili přínosem vlhkosti pro hydratační procesy, ale v dalších měřeních (zvláště u směsí bez cementu ale nejenom a také co vyšlo Dianě) vycházel vliv vlhkosti převážně negativní, což jsme vysvětlili tím, že voda zabraňuje vazbě pojiva s kamenivem, protože se sama naváže na kamenivo (silnější polarita).
Tzn. tady byla myšlenka taková, že zrání v pytlíku po celou dobu už je moc dlouhé a negativní vliv vlhkosti na vazbu převáží pozitivní vliv vlhkosti na hydrataci cementu.
Pokud se Vám to nezdá, tak to klidně změňte, nejsem si jistá, že je to 100 % neprůstřelná myšlenka.

## *4.4.2 Experimental study conducted at University Kassel*

For evaluation between the effect of compaction procedure and void contents or resulting strength properties, an emulsion mix and a foam bitumen mix as described in section 4.2.2 were prepared with varied compaction procedures.

The resulting void contents and ITS values after 7 days curing at room conditions, i.e. 40-70 % relative humidity and temperature of (20±2)°C, are plotted in Figure 44 for the bituminous emulsion mixtures.

From the void content results it can be concluded, that the compaction procedures using Proctor Standard, vibrating table and Marshall method (2 x 50 and 2 x 100 blows) are not feasible to reach adequate void contents (10-15% as recommended by Wirtgen Manual). The void content directly influences the ITS results as also indicated in the figures below. For the vibrating table compaction method and Proctor Standard compaction the specimen didn't obtain enough strength for de-moulding and evaluation of ITS.

The resulting void contents and ITS values after 7 days curing at room conditions, i.e. 40-70 % relative humidity and temperature of (20±2)°C, are plotted in Figure 45 for foamed bitumen mixtures.

As stated for the previous case, compaction procedures using Proctor Standard, vibrating table and Marshall method seem not to be feasible to reach adequate void contents smaller than 15 %. In the present study, that value could only be reached with static compaction conditions used in the Czech Republic.

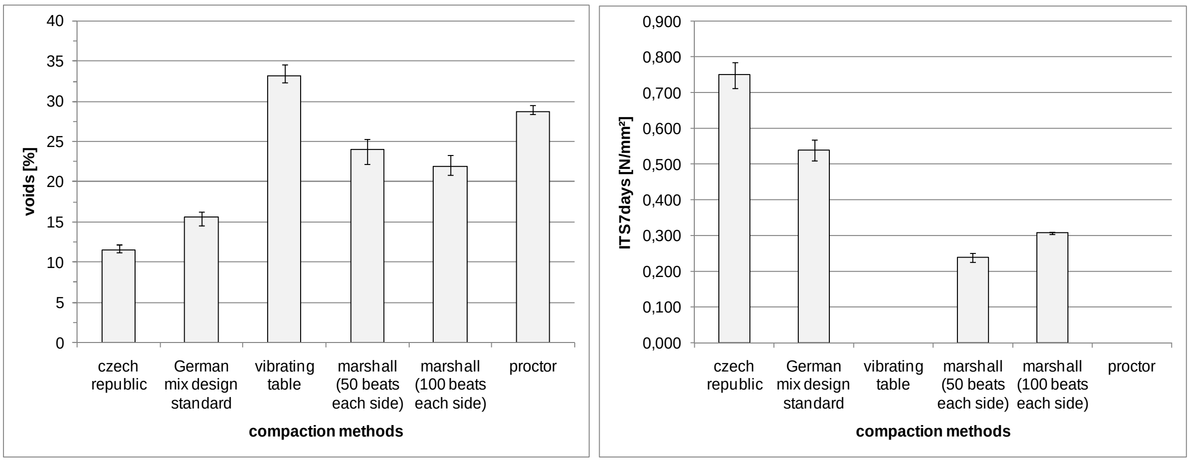



**Figure 44 – Void contents (left) and ITS (right) for emulsion based cold recycled mixtures**

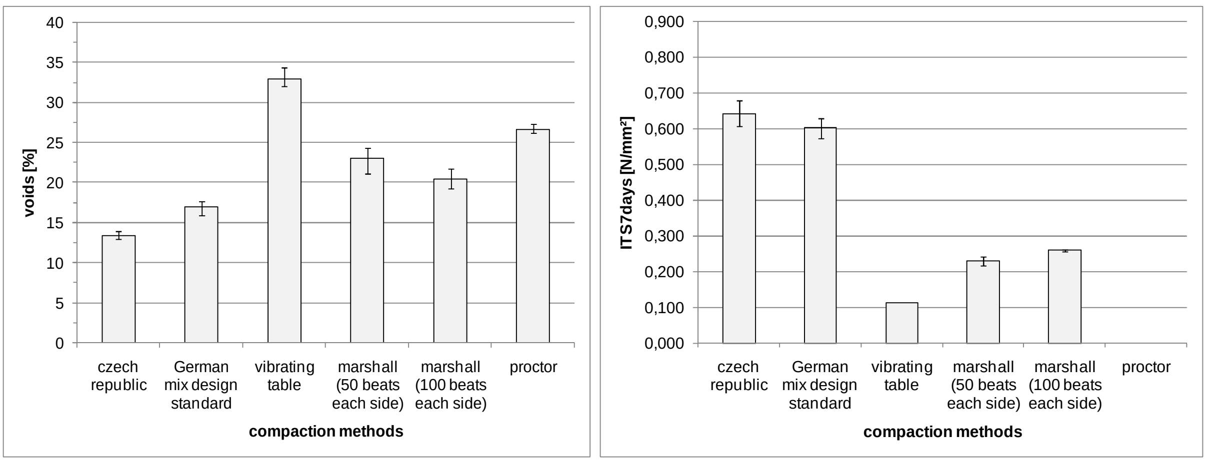



**Figure 45 – Void contents (left) and ITS (right) for foamed bitumen based mixtures**

The ITS results of the specimens if compared to conditioning times applied with different moisture content and temperature conditioning are plotted in Figure 46.

For all conditioning procedures which were conducted at 20°C indirect tensile strength increase can be observed with conditioning time. The conditioning temperature doesn't affect the strength development in the first three conditioning days significantly, as indicated by similar ITS values obtained for the 20°C conditioned and 60°C conditioned specimens after 3 days. For the further interpretation of the results it has to be taken into account, that the tested material contained 2 % cement which is more comparable to the mixes usually applied in Portugal or Spain from where the 60°C conditioning procedure was adapted. The time-dependent strength increase with similar results in dry (40 %) and humid (70 %) conditions show the predominately effect of cement hardening due to hydration.

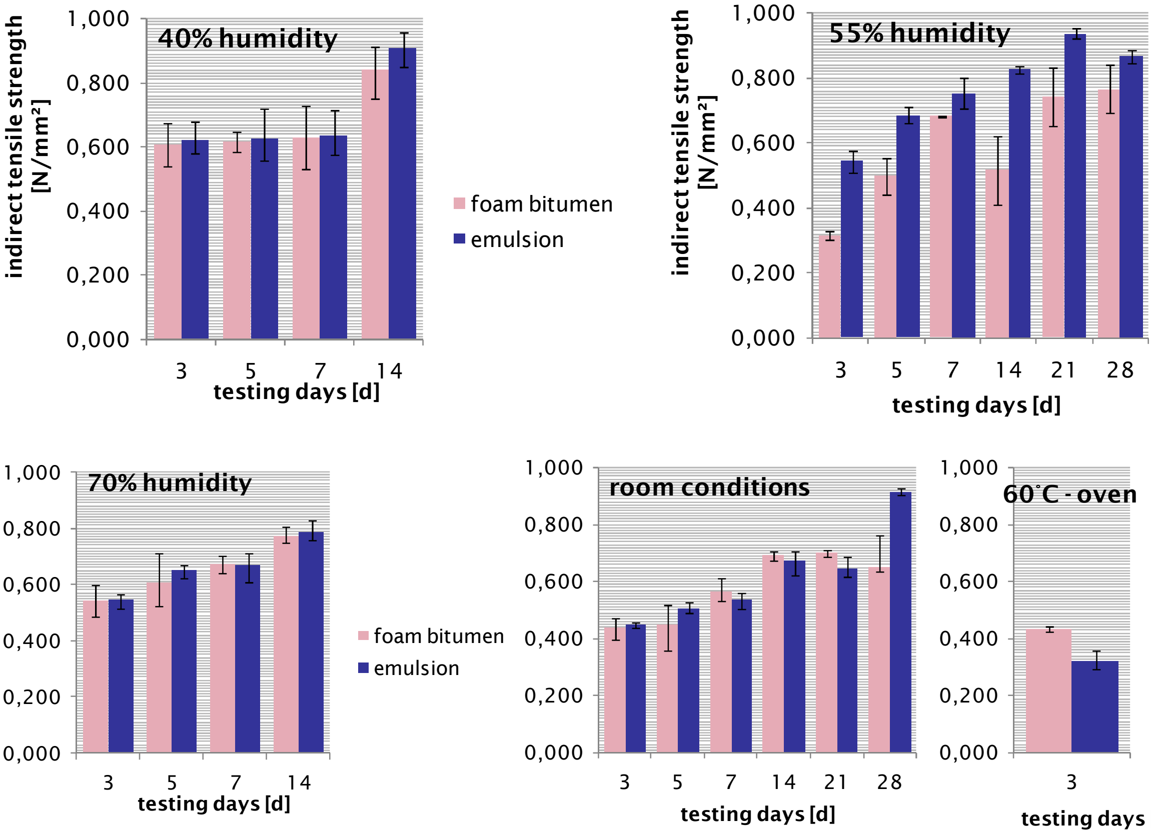



**Figure 46 – Overview results for ITS**

Figure 47 illustrate ITS values after 14 days at conditions with 40 %, 55 % and 70 % humidity at (20±2)°C and at room conditions for foamed bitumen mixture and bituminous emulsion mixture. The controlled humidity in climate chamber conditioning has only a limited effect on the resulting ITS. In general, an increase of humidity at constant temperature (20°C) from 40 % to 70 % will result in slightly decreasing ITS values.

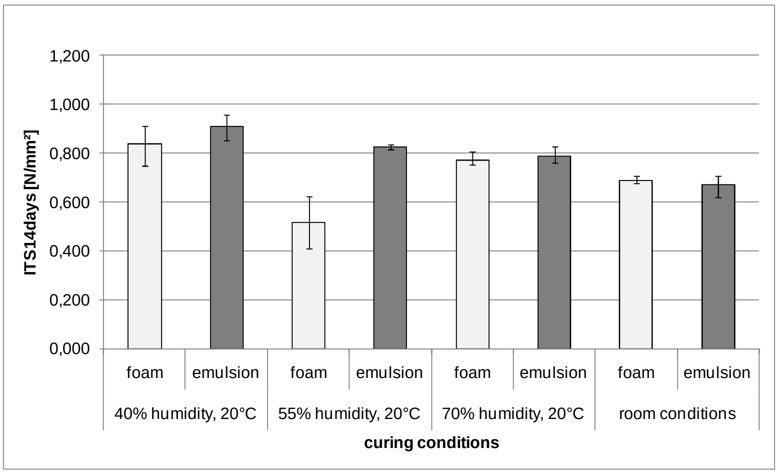



**Figure 47 – Comparison ITS after 14days for different curing conditions**

## *4.4.3 Experimental study conducted at LNEC*

In Portugal and Spain, the design of bituminous emulsion stabilized cold mixes usually rely on the effect of water on the compressive strength of test specimens, based on the Spanish specification NLT 162 (which was adopted from ASTM D1075).

As mentioned in 3.4.5, the determination of "optimum" emulsion/bitumen-residue content is typically based on the following steps:

- Preparation of cylindrical test specimens(ϕ≈h≈101,6 mm) by static compaction with double plunger action, applying a compression load of 21 MPa (based on the Spanish Specification NLT161 or on the ASTM D1074);
- Accelerated curing of test specimens by storing them in the oven at 50ºC for 3 days;
- Immersion-compression tests (NLT 162 standard):
  - "Dry" specimens: 4 days in air @ 25ºC + 2h in water @ 25ºC ⇨ compressive strength @ 25°C ($S_d$)
  - "Wet" specimens: 4 days in water @ 50ºC + 2h @ room temperature + 2h in water @ 25ºC ⇨ compressive strength @ 25°C ($S_w$)

From these conditioning steps then determination of the "Index of retained strength" (IRS), which corresponds to the ratio between the compressive strength of specimens with immersion and without immersion, expressed in percent ($S_d/S_w$ x 100).

Immersion-compression tests were performed according to the specified method, whose results are presented in Figure 48. In this context, bituminous emulsion stabilized mixtures were produced according to the compositions shown in Table 13 (CM-E3, CM-E4 and CM-E5).

Similarly to the Duriez design method (see paragraph 3.4.4), the strength of “dry” and “wet” specimens and the retained strength of specimens after immersion are also checked for compliance with the relevant mix design specification. In this case, the required values are the following:

| | **High traffic volume (T0/T1)** | **Low traffic volume** |
|---|---|---|
| $S_{d,\ minimum}$ | 3.0MPa (⇔ ≈24 kN for ø≈101.6 mm) | 2.5 MPa (⇔ ≈20 kN for ø101.6 mm) |
| $S_{w,\ minimum}$ | 2.5MPa (⇔ ≈20 kN for ø101.6mm) | 2.0 MPa (⇔ ≈16 kN for ø≈101.6 mm) |
| $IRS_{,\ minimum}$ | ≥ 75 % | ≥ 70 % |

Figure 48 also shows the limit values required for the unconfined compressive strength of “dry” and “wet” cured specimens (3 days @ 50ºC) and for their retained strength after immersion in water. From the data presented in this figure, it can be further concluded that the unique mixture that complies all requirements both for low and high traffic levels is the CM-E3 (2.8% in mass of bitumen emulsion on the final mixture).

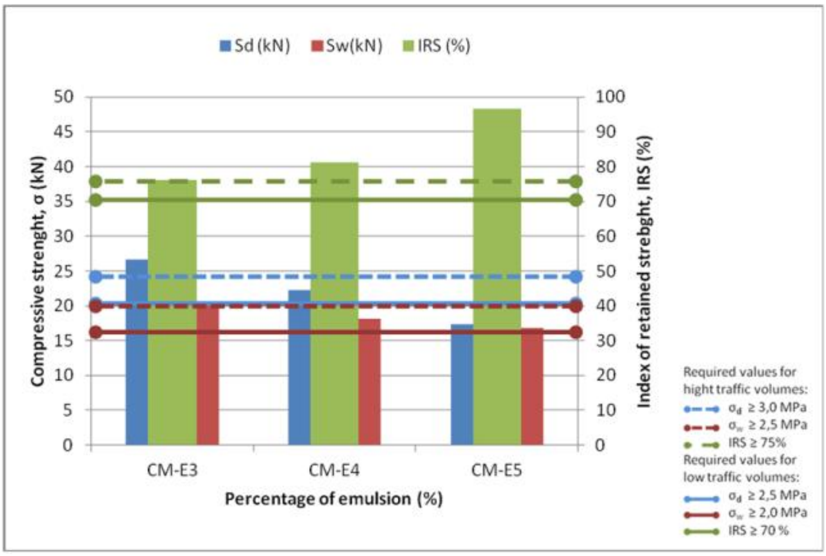



**Figure 48 – Compression-immersion tests according to NLT162**

Afterwards, water sensitivity tests were carried on (Figure 49), but using the following procedures:

- Static compaction with double plunger action, applying a reduced compression load of 7.5 MPa (which was found to be more suitable, as described in paragraph 4.2.3) of cylindrical test specimens of about 102 mm in diameter and 64 mm in height (“Marshall” test specimen dimensions);
- Accelerated curing of the test specimens by storing them in the oven at 50ºC for 3 days;

- Water sensitivity tests, according to method A of the European standard EN 12697-12:
  - "Dry" specimens: 3 days in air @ 20±5 °C ⇨ indirect tensile strength @ 15°C ($ITS_d$);
  - "Wet" specimens: vacuum (30 min. @ 6.7 kPa in water @ 20ºC) + 68-72h in water @ 40ºC ⇨ indirect tensile strength @ 15°C ($ITS_w$).

Based on these conditions then determination of the "Indirect tensile strength ratio" (ITSR), calculated as the ratio of the indirect tensile strength of "wet" specimens to that of dry specimens, expressed in percent ($ITS_d/ITS_w$ x 100).

Figure 49 shows the results obtained for the above described modified mix design procedure. If the same minimum for retained strength was required in the case of the alternative mix design procedure, just mixtures CM-E4 and CM-E5 would meet specifications. In fact, in this case, even a slight increase in ITS of wet specimens is recorded from the mixture with lower emulsion content (CM-E3) to the mixture with higher emulsion content (CM-E5). This is fairly consistent with the results obtained for the bulk densities of the different cold mixtures specimens compacted applying a static pressure of 7.5 MPa (see paragraph 4.3.3).

The so far gained results of the experimental tests carried out at LNEC point out following conclusions:

- Static compaction of cylindrical specimens applying reduced compressive loading of about 7.5 MPa provide fairly representative densities of on site compactions;

- Water sensitivity tests performed according to the European standard EN 12697-12 on cured test specimens are suitable for distinguishing the performance of different mixtures (produced with different bitumen emulsion contents).

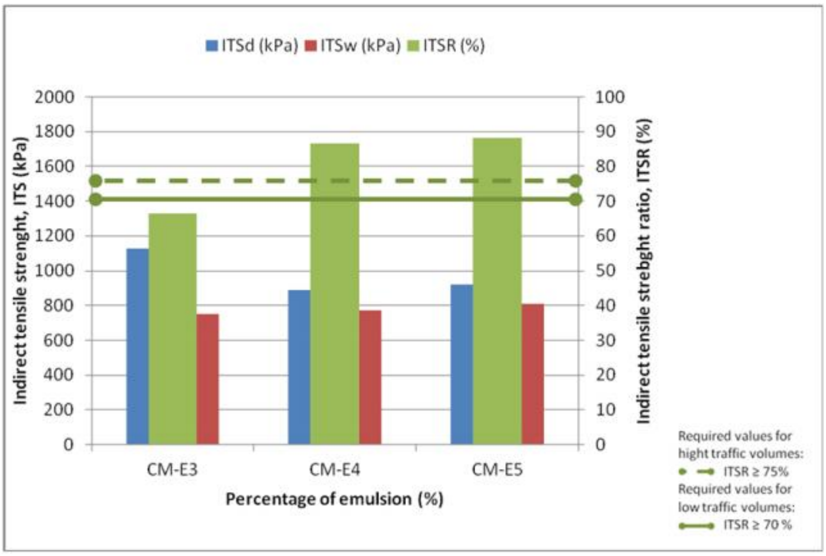



**Figure 49 – Water sensitivity tests (based on EN 12697-12 - method A)**

# 5 Conclusions and further work

In the present report the collected information on currently used mix design procedures and several partial studies on particular phenomena related to cold recycled mixtures were summarized.

Furthermore, wide analysis of the different test methods was presented, highlighting the following conclusions:

- Cold recycling techniques:
  - Most countries perform mainly in-situ cold-recycling, generally in excess of 90 %. It is a more flexible and cost-effective solution for pavement rehabilitation reducing any additional environmental impacts or additional logistic arrangements;
  - Cold-recycling is commonly applied to a wide range of layers, from sub-grade material to bituminous surface. In general it is more common to use cold recycling in full-depth option combining often asphalt layers with granular or differently stabilized materials;
  - The large majority of cold-recycled bitumen stabilised materials are applied in base or binder courses.
- Reclaimed Asphalt (RA) used on cold-recycled bitumen stabilised materials:
  - In general, requirements on the grading curves of reclaimed asphalt material or on the final granular mix composition are specified;
  - Usually, well-graded materials are considered to be suitable for cold recycling;
  - It is important to reflect possible rectifications of grading curves within the mix design. Especially for foamed bitumen stabilized mixes it is crucial to secure in the final grading sufficient content of filler particles (>5 %) for optimal coating.
- Bituminous and hydraulic binders:
  - Most countries use both bituminous emulsion (mainly C60B6 and C60B7 according to the classification used until 2013 in EN 13808) and foamed bitumen (being the most popular the ones produced using 70/100 pen grade bitumen with alternatives either 50/70 or 160/220 depending on the climatic conditions);
  - As secondary binders, cement (mainly, Portland cement CEM II 32.5 or CEM I 42.5) and hydrated lime are commonly used. Some potential might be identified with fly-ashes or activated mineral dust particles (back filler, or fines from aggregate or cement production);
  - Some countries reported the use of additives such as foaming agents, adhesion promoters and/or fly-ashes.
- Typical compositions of cold-recycled bitumen stabilised materials:
  - A geographical variation among European countries was noticed, with Central European countries commonly using bituminous binder combined with relatively high contents of hydraulic binder (≈ 3 – 5 %), Northern countries using only bituminous binders in form of foamed bitumen and Southern countries using just

bitumen emulsion or emulsion combined with low content of hydraulic binders (≤ 1 %).

- Laboratory test procedures applied for assessed traditional and/or updated mix designs:
  - Modified Proctor compaction is often used for estimation of the optimum water content;
  - Test procedures for investigation of optimum binder content and its effect on cold recycled mix differ considerably among countries, namely with reference to compaction methods, curing procedures and testing conditions and quality characteristics. Nevertheless, the most promising methods seem to be the following:
    - Compaction methods: Static pressure and gyratory compaction, with a need for adjusting and further harmonizing compaction energy;
    - Curing procedures: 7 days / 14 days at room conditions for early to medium ages, and 21 days at room conditions (for later ages) or 3 days at 50ºC as an accelerated curing procedure. This nevertheless applicable only for cold recycled mixes with ≤1 % cement;
    - Testing conditions and quality characteristics: Moisture sensitivity tests (for effect of water impact evaluation), indirect tensile strength tests or compressive strength test (for strength assessment), and repeated indirect tensile tests (as a functional test for stiffness assessment – further assessed mainly in WP2).

Taking into account these initial conclusions, experimental studies were initiated in order to assess the identified aspects for further research. The main results obtain up to the present were presented in the previous chapter. Additionally – not presented in this report – comparability studies have been done for assessment of bituminous binder origin to clarify the importance of the bitumen or emulsion source on the final mix qualities.

# 6 Acknowledgement

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