FINAL TECHNICAL REPORT

PARAMIX

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ACRONYM: PARAMIX

TITLE: "ROAD PAVEMENT REHABILITATION TECHNIQUES USING ENHANCED ASPHALT MIXTURES"

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2. EXECUTIVE PUBLISHABLE SUMMARY

There is a clear conscience amongst administrators and builders that investments on road network should increasingly be focused on rehabilitation (maintenance) rather than in building new roads. One of the most important matters in road rehabilitation is the pavement, in such a way that it determines its quality. Bearing in mind these facts, together with the obvious environmental and budget constraints, new rehabilitation and reconstruction techniques of road pavements with minimal resources consumption as those proposed in this project, should be considered as an opportunity and a clear option versus building of new roads.

Pavement recycling is probably the best choice for road maintenance since it provides very important savings compared to conventional options. It also reduces environmental impact, diminishes the use of hydrocarbon binders based on petrol and minimises the need of transport during the building process. The economical gains will surely revert in an increase of safety in the overall road network as more roads can be rehabilitated for the same investment.

Within this project, two pavement asphalt rehabilitation techniques are considered: cold recycling *in situ* and hot recycling in plant. The former consists in rehabilitating the pavement in site. The different processes take place at the same time and are done by the same machine (the milling material is mixed together with the binder while being laid out).The latter consists in producing the recycled asphalt in plant. The milling material is actually carried away to the plant where it is treated before working with it again.

After a three year life project, the following tasks have been carried out:

Analysis and characterisation of milling material and new mixtures.

> Milling material has been obtained from the different layers of pavements and has been sent to the different laboratories. The laboratories have done different testing on these materials as well as on a conventional material belonging to a hot recycling plant.
>
> Laboratories have developed new design criteria (conventional and non conventional tests) to optimise the characterisation of the mixtures.

Development of new asphalt emulsions and bitumens.

> The laboratories have designed several bitumen binders and emulsions to be used in both recycling techniques under study.

Development of structural analysis code for asphalt.

> New software codes have been used and are still being developed (beyond project's original scope) considering the damage and cracking energy of the pavement (homologous to concrete codes). Until now, the existing software for pavement design didn't include this parameters.

Development of new machinery and lay out procedures.

> Hot in plant recycling machinery has been strongly improved following two ideas: machines improvements to have better work and economical conditions and developing a new process to increase the quantity and quality of recycled material.
>
> Machinery for cold recycling has improved by means of first-time design of a variable size of the milling-mixing chamber and drum speed, and an improved heating system.

Rehabilitation of experimental tracks.

> In Spain, a project has been written down considering the different actions to be taken in this road. There are a total of 11 sub-tracks (11 different actions concerning hot and cold recycling techniques as well as conventional reinforcement).
>
> In Sweden, Swedish conventional emulsions have been tested after being designed in Spanish and Belgian laboratories, to perform three experimental tracks.

Evaluation of rehabilitated tracks.

> Required works to evaluate both rehabilitated tracks have been defined as well as those specific actions necessary to calibrate the robustness of the numerical code.

Dissemination and exploitation plan.

> Both scientific and technical outputs of the project will be disseminated and exploited in accordance to a plan elaborated by the Consortium.

3. OBJECTIVES OF THE PROJECT

Current methods for rehabilitation and reconstruction of asphalt pavements in roads are based in two very different techniques world-wide. The first method basically transports the milled pavement to a hot asphalt mixing plant where the milling material is added in relatively small percentage amounts (10-35%) to asphalt mixtures made with *fresh* raw materials. The second technique provides an *in situ* cold treatment of the old asphalt materials. This is obtained by mixing the milled asphalt with small amounts of binder and, sometimes, fresh aggregates. These mixtures improve the final quality of the rehabilitated pavement.

Both existing hot and cold road rehabilitation techniques have severe drawbacks. This project deals with improving these techniques, so that a rehabilitation process with minimal resources consumption, which is essential from social, financial and environmental points of view, can become a competitive and a qualitative pavement rehabilitation procedure. The final aim of the research is that making recycled asphalt mixtures with minimal environmental impact be an alternative to traditional pavement maintenance techniques based on asphalt mixtures produced with a high percentage amount of fresh raw materials and develop a non-linear computational model for predicting cracking and damage in the asphalt pavement under cyclic loading.

The technical-scientific objectives of this project are the following:

- Research and development of new binders for both hot and cold recycling techniques.

  It has been evaluated the effect on the binder for both hot and cold *in situ* recycling of the following things: rejuvenating agents, thermoplastic elastomers and penetration grade of bitumen employed.

  As binders for hot mixture recycling concerns, both reological tests to determine the stiffness of the binders in a large range of temperatures and frequencies and mechanical tests over the mixtures (fatigue, Marshall, indirect tensile) to test the binders have been carried out.
- Research and development of new design criteria to characterise both hot and cold recycled mixtures.

  Proposal of new test procedures to design recycled mixtures. The effect of different compaction techniques has been studied to obtain a better correlation among the properties of the mixtures in laboratory and in field. To evaluate these properties, two kinds of tests have been used: conventional ones, such as Marshall, compression, fatigue bending test, etc, and the non conventional ones, such as indirect tensile test and direct tensile test.
- Developments of a non-linear computational (finite element based) model for predicting cracking and damage in the asphalt pavement under cyclic loading.

  New software codes are being developed considering the damage and cracking energy of the pavement (homologous to concrete codes). Until now, the existing software for pavement design didn't include this parameters.
- Research and development of machinery components concerning both techniques.

  Improvements in the design of the RAD (recycling oven of the asphalt plant) and increasing the amount of recycled material for hot recycling techniques and the effect on the compaction by varying the position of the heating elements as well as developing a new process based on the screening and separation of the milled material, and the effect of changing the grading curve of the milled material as concerns cold recycling techniques are some of the main points to be studied.
- Proposal of recommendations and rules summarising the experience from the new pavement rehabilitation and analysis methods and the evaluation of the overall cost-efficiency of the process on prototype road sections built and tested within the project.

  New design criteria and control procedures to characterise the mixtures.

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SUMMARY OF THE RESULTS

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Following what is described in Annex 1 of the contract, *"Description of the Work"*, during the three year life of the project, these were the workpackages to be completed:

WP1: Specification of relevant numerical, experimental and administrative data.
- *T1.1: Specification of numerical methods for structural analysis.*
- *T1.2: Specification of experimental tests.*
- *T1.3: Definition of validation strategy.*
- *T1.4: Specification of the management structure, dissemination strategy and initial exploitation plan.*

WP2: Analysis and characterisation of the milling material and the new mixtures.
- *T2.1: Analysis and classification of the milling material.*
- *T2.2: Design, production and characterisation of the new asphalt mixtures.*

WP3: Development of new asphalt emulsions and bitumen for the recycling process.
- *T3.1: Development of new asphalt emulsions and bitumen.*
- *T3.2: Analysis of the mixing process.*

WP4: Development of structural analysis code for asphalt pavement.
- *T4.1: Development of constitutive and numerical models.*
- *T4.2: Integration of structural analysis code.*
- *T4.3: Experimental testing of existing pavement.*
- *T4.4: Calibration of the simulation code using experimental tests.*

WP5: Development of improved components and lay out procedures.
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WP9: Dissemination and exploitation plan.
- *T9.1: Dissemination plan.*
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WP10: Project management.
- *T10.1: Project management.*

During the three year life project the technical progress made in the different fields of the project can be summarised in the following results:

MATERIALS

4.1. DEVELOPMENT OF IMPROVED BINDERS FOR HOT IN-PLANT RECYCLING TECHNIQUES

The amount of reclaimed asphalt employed in hot recycling processes, depends mainly on plant limitations, on mixtures design and their final requirements. The fresh binder used will clearly contribute to the final mixture performance. In that sense, the development of binders for hot recycling performed within PARAMIX Project has taken into account the relevance of structural strength and fatigue behaviour in order to improve them so that the life period of pavements can be increased.

Related to hot recycling processes, it is important to take into account that both, a detailed study of the old pavement and the mixture as well as an evaluation of the new fresh binders in the final mixture has to be performed. Therefore, several factors have been evaluated in order to develop and adapt these new binders to the final mixture:

- The gradation of the milled material once the bitumen has been recovered
- The binder content of the milled materials.
- The characteristics of the aged bitumen.
- The characteristics that are looked for in the binder and in the final mixture as well.

Two different types of mixtures have been evaluated. A *semi dense* mixture, S-20, has been considered since this kind of mixture is less influenced by binder and gradation variations and it is quite often used as intermediate layer. It was proposed within the Consortium, the evaluation of this grading also considering a High Modulus polymer modified binder in order to obtain a High Modulus Mixture and its intrinsic benefits (better structural capacity). The second type is a *SMA* mixture, which can be more problematic in adjusting its gradation with milled material. Nevertheless, it has been also considered within the Project as an improvement of hot recycling techniques, the replacement of this mixture also as wearing course.

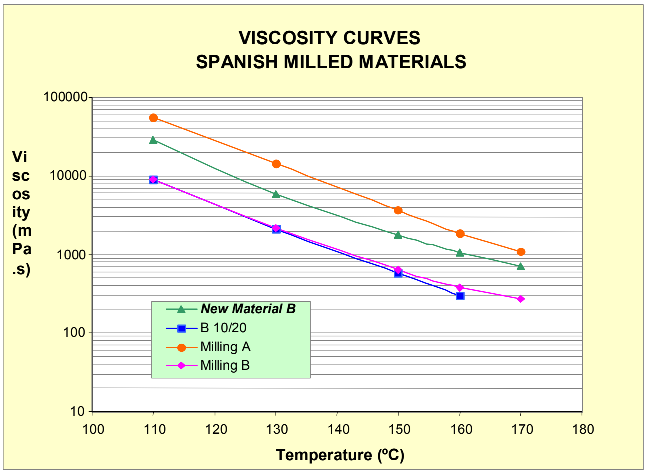
Therefore the first step in this development started with the full characterisation of the millings to be used in the evaluation of binders and mixtures since depending on their characteristics, the new binders and mixtures should be adjusted. Five different milled materials corresponding to different layers of the road were received and characterised for the development of PARAMIX project. Although the five samples of millings were characterised, only two of them have been employed in the development of binders for hot recycling.

- Material B was selected to be employed in the evaluation of S-20 mixture. During the initial characterisation of this material huge differences were obtained mainly in penetration and R&B values of the recovered binder as well as the dispersion of these values when the results of two more laboratories are considered (UPC, BRRC, CEPSA) pointing out one of the main problems of a milled material: unhomogeneity. The first sample of this material was discarded and a new one was prepared by COPCISA, that was used for the development of the project.
- Material A has been the milling considered for SMA mixture study since it came from an upper layer and the aggregates fulfilled the requirements needed to be used in a wearing course.

The binders obtained from these millings have been empirically characterised and the binder content determined.

The viscosity curves of the recovered binders were also determined since it is important to consider that two different binders are expected to be mixed to obtain the final recycled binder. In that case, the aged bitumen will be the less heated although it is the most viscous while the new binder will have a lower viscosity together with a higher heating temperature. Such high differences in viscosity can lead, in some cases, to a mixing problem of these two binders if they are not taken into account and mainly if the temperature in the hot mix plant is not exhaustively controlled could negatively influence the behaviour of the final mixture.

The following Figure 1 represents the curves obtained for binder A and binder B. Two more bitumens are included, B10/20 and B 50/70, only for comparison.



- Figure 1: Viscosity curves of recovered binders -

In order to check if binder A was a polymer modified bitumen, the polymer dispersion has been determined by means of Fluorescence Microscopy in the two recovered binders, the one from material A and also from material B. It was possible to distinguish very small light "yellow" spots (polymer particles) in material A specimens while no yellow points were pictured in case of binder B. The polymer modification of binder A can also explain its higher viscosity.

A large series of binders was developed by CEPSA taking into account the agreements made within PARAMIX partners to evaluate both mixtures. The percentages of RAP used to obtain the final mixes vary depending on the type of mixture. RAP contents of 30% and 50% have been considered for S-20 mixes, whereas the RAP percentages have been reduced to 10% and 30% in case of SMA mixture. As already exposed, milling A would be used for SMA in the upper layer and milling B for S-20 mixes.

The development of the binders has been performed considering the characteristics of the milled materials and also the characteristics of the planned final binder:

- In case of SMA mixture, the final binder has been fixed as a PMB 50/70-60.
- B35/50 in case of S-20 mix. As already mentioned, it has been considered the development of a polymer modified bitumen that allows obtaining a final High Modulus Recycled Mixture from which is expected a better structural strength and fatigue behaviour in the replaced mixture.

Since two different RAP contents for each kind of mixture, either S-20 or SMA, are considered, the new binder has been fully adapted in order to obtain equivalent penetration grades and polymer modification independently from the RAP percentage and therefore making them comparable.

It has been tried within this project to evaluate the influence of the *Renewing agents*, considering S-20 and SMA mixtures and the *polymer modification*, in this case only S-20 mixture has been studied since for the former mix, polymer modification was already a requirement. Firstly, the binders prepared were firstly empirically characterized being verified that they fulfilled the requirements established for them.

In case of ***SMA mixture***, a pre-selection of binders was made by CEPSA PROAS before sending them to BRRC based on the following tests:

- Marshall test
- *"Aged" Marshall*: This test has been performed in order to evaluate the influence of ageing on the final mix. Marshall test has been done after conditioning the test specimens at 80ºC during 8 days.
- Retained compressive resistance test
- Passive adhesivity

The stability figures obtained with these binders did not show clear differences among the three renewing agent contents, 0%, 10% and 20%. It can only be observed that the deformation decreases when increasing the agent content and therefore, the stiffness of the mix, defined as the ratio stability/deformation, increases with the amount of agent. This behaviour could be, perhaps, explained at this stage as a consequence of the following two reasons:

- Binders with renewing agents could age more than binders without these products, or
- Renewing agents can ease the mixing of the old and new binders in the final mix. In that way, the final binder would be harder than in the other cases (with no renewing agents or with less amount of them). Consequently, harder bitumen in the mix would contribute to obtain a stiffer final mix.

The binders were rheologically characterised by BRRC in order to be able to try to better differentiate among their behaviours. The binders finally employed in the Experimental Tracks did not contain renewing agents since no clear positive contribution was possible to asses from the rheological and mixture evaluation (BRRC & UPC).

Considering ***S-20 mixture***, it has been also tried to pre-evaluate the contribution of the renewing agents (0%, 10% and 20%) to the final mixes by means of Marshall and Indirect Tensile Tests before performing further characterisation. This later was only performed taking into account only one content of r. agents since no remarkable influence was observed by Marshall test. Therefore, a modification to the test was introduced in order to harden it and to obtain a better differentiation among them and that was: Half of the test specimens were kept at 5ºC for 6 hours and tested afterwards at this temperature. The remaining half were kept in water at 60ºC during 24 h, next they were conditioned at 5ºC for 6 hours and immediately tested at this last temperature (wet conditions). Nevertheless, no meaningful differences among the binders evaluated were observed and it was decided to characterise them rheologically trying to more easily distinguish their behaviours.

Finally and as a result of the study, no renewing agents were employed neither for SMA nor for S-20 mixtures since no positive contribution to the recycled mixture performance was detected at laboratory level. Taking into account that the recycling of a High Modulus Mixture using a high modulus polymer binder is one of the main innovations of this stage and that, at the laboratory the results obtained were really promising, it was decided by the Consortium to carry out the Experimental Tracks also with this kind of binder (besides the pure bitumen as reference). Anyway, the contribution to the pavement performance (E. Tracks) can not be confirmed within a short time and therefore it will be necessary to follow up the evolution of the Tracks done in order to reach a definite conclusion.

4.2. DEVELOPMENT OF IMPROVED EMULSIONS FOR COLD IN-SITU RECYCLING TECHNIQUES

Cold in-situ recycling technique gives the opportunity of recycling 100% of the old pavement that is probably its main advantage as well as its environmentally friendly behaviour. Cold recycling requires the use of flux oil free bitumen emulsions and therefore there will not be any kind of emissions to the environment.

It has been tried, within PARAMIX project, to solve or at least to improve through the emulsion behaviour, some of the drawbacks that the present cold recycling techniques can have. The main targets of this stage can be summed up as follows:

(a) The development of an emulsion formula capable of giving a coated surface of the milled material over 90%. The coated surface should be kept during mixture, handling and compaction processes.

(b) The emulsion or emulsions should allow an appropriate breaking period verified in the laboratory so that, the mixing is easily performed on the road.

(c) It was also expected that the behaviour of such emulsion did not change when reducing the water added during the pre-coating step. It is also expected that this amount of water can be diminished if the percentage of emulsion is simultaneously increased.

Five different milled materials were received to be considered and studied for the development of PARAMIX. Among them, the material identified as (A+B+C+D), was the milling used for the development of bitumen emulsions for cold recycling process. This material was chosen as representative of the most difficult situation that would happen within the Experimental Tracks. An emulsion formula adapted to this awkward material could be more easily fitted to any modification during the E. Tracks. It is important to mention that this material did not contain granular bases. The milling was characterised by determining its grading, the binder content and the binder characteristics, although this later is not so important in cold recycling processes since a real mixture of the old and new binders is not expected to happen.

The main constituents of a bituminous emulsion on which is possible to act, to modify or to adapt in order to fulfil the above mentioned requirements are the binder and aqueous phases.

The effect on the binder phase of the products indicated below have been evaluated during the development process of the emulsions:

(a) Rejuvenating agents or recycling agents (also called renewing agents). Two different contents have been considered in the study, 10% and 20%.

(b) Thermoplastic elastomers and

(c) The penetration grade of the bitumen employed: B 90, B 150 and B 250.

Traditionally, a bitumen of 150 pen with or without renewing agents is the one employed as the binder phase of a recycling emulsion and therefore, as a challenge within the Project, it has been decided to verify the effect of lower penetration grades and the effect of the polymer modified binder phase as well. It is expected from both of them a positive contribution to the improvement of the *strength* and the *fatigue behaviours* of the final mix. Anyway and as a consequence of the characteristics of a cold recycled mixture and in order to verify it, it will be necessary to follow up the evolution of the final pavement.

Water, emulsifier and acid form the *aqueous phase*. Among these materials, the main effect and contribution are obtained through the emulsifier behaviour. Therefore, nine different emulsifiers have been evaluated during the initial stage of PARAMIX Project. All these emulsifiers have been used varying both the percentages employed and the pH of the aqueous phases prepared.

The nature and behaviour of each of the emulsifiers evaluated, affect the final contribution of the emulsion in relation to the following aspects:

- Coating
- Breaking
- Cohesion increase
- Necessity of water addition

The work was firstly focused on the emulsifier selection and in order to performs it, a fixed binder phase was considered. The first pre-selection of emulsifiers was based on the coating test (over 90%) and passive adhesivity (over 75%).

Once concluded the preliminary evaluation of emulsions and emulsifiers, and before continuing the assessment of additional factors, it was planned to choose only an emulsifier. A minimum retained compressive resistance of 75% was established as pre-selection criterion. Through the study described up to this point, only a conventional 150/200 penetration grade bitumen has been employed with the emulsifiers mentioned. The bitumen was fixed in order to avoid more variables that could influence the emulsifier selection process. A fixed content of added emulsion, 3%, was considered. In that way, it was tried to determine the best emulsion behaviour based on the emulsifier influence. This evaluation allowed us to pass from a total number of 9 to firstly 4 and finally to only 1 emulsifier, therefore it can be assessed that the final behaviour of a cold recycled mixture can be improved by means of the emulsifier employed in the slow setting emulsion.

Once the emulsifier variable was fixed, the binder was the next aspect to be judged. The following binders were evaluated at the laboratory from the point of view of the emulsion quality and also pre-evaluating their behaviour in the recycled mixture:

1. Conventional binder 150 penetration grade
2. Conventional binder 90 penetration grade
3. Conventional binder 250 penetration grade
4. Conventional binder 150 penetration grade containing 10% of renewing agents
5. Conventional binder 150 penetration grade containing 20% of renewing agents
6. Polymer modified binder 90 penetration grade
7. Polymer modified binder 150 penetration grade
8. Polymer modified binder 90 penetration grade containing 10% of renewing agents
9. Polymer modified binder 90 penetration grade containing 20% of renewing agents

At this stage, the first step done was focused on the evaluation of the influence of the bitumen penetration grade in order to select only two from the three ones considered. In that sense, three bitumens coming from the same origin were used to produce emulsions, 1, 2 and 3. The next step supposed the verification of the effect of renewing or regenerating agents on the emulsion behaviour in the final recycled mixture. Consequently, two different regenerating agent contents were checked, 10% and 20% (4 y 5) considering only one of the penetration grades (150). Finally, the influence of the elastomeric modification was evaluated as well together with the renewing agents (6, 7, 8 y 9).   In that case both variables were taking into account since the use of polymer modified emulsions for cold recycling is quite new and therefore further experience is needed.

The pre-selection criterion used during this stage of the development process has been the minimum retained compressive resistance fixed in 75%. The following aspects have been taken into account when evaluating the results obtained from the former test:

- Absolute values of Resistance in dry conditions
- Absolute values of Resistance after being conditioned in water
- Retained Compressive Resistance
- Handling of the mixture

The first two data are directly determined when performing the test and employed to calculate the third property. The handling of the mixture was observed when preparing the specimens.

The initial evaluation of the influence of the penetration grade led us to the election of the two lowest grades, 150 and 90. Higher values (absolute values) of resistances before and after water conditioning were obtained for the two mentioned penetration grades together with better results for retained compressive resistance, although in the three cases the minimum requirement of 75% of retained resistance was achieved.

Related to the handling of the mixtures, no problem was detected during the manufacture of the test specimens and, approximately, the three emulsions showed the same behaviour.

Belonging to the next step and in order to evaluate the effect of the *renewing agents* on the emulsion behaviour, two different contents were taken into account, 10% and 20%. At this point, only pure bitumen and also a fixed penetration grade were considered to check the former influence. The one chosen was bitumen 150 penetration since this was the intermediate penetration grade included in the study and therefore could be considered as representative of the lowest and the highest grades.

Similarly to what had been done within the previous step (influence of the penetration grade), the retained compressive resistance has been the criterion considered for controlling and evaluating the emulsions prepared from the binders with rejuvenating agents. The data got from the study showed that no remarkable contribution from these agents was observed although all the emulsions studied gave higher retained resistance than the established selection criterion, 75%. Nevertheless, the binder with 10% of agents was kept as an option in the study since no clear influence, in favour or against, was detected from the evaluation. The percentage of 20% clearly influenced in a negative sense the properties of the final cold recycled mixture reducing both the individual values of resistances before and after water immersion and the final retained compressive resistance.

The following decisions had been made up to this point of the study:

- Continue this development using conventional bitumens with 90 and 150 penetration grades
- Consider two percentages of renewing agents: 0% and 10%.

Finally, the last variable that has been taken into account has been the influence of polymer modification of the binder. The polymer modification considered within the Project has been based on the elastomeric modification.

Based on this, the modified bitumens tested in this stage belong to the penetration grades chosen and they have also been produced with no and 10% of renewing agents.

The selection criterion was again kept the same (75% minimum of retained compressive resistance). Finally, only four emulsions were chosen as the best options to be further assessed by UPC in cold in-situ recycling processes:

- PMB ~ 90 penetration without renewing agents,
- Conventional bitumen ~ 150 penetration without renewing agents,
- Conventional bitumen ~ 150 penetration with renewing agents,
- Conventional bitumen ~ 90 penetration without renewing agents.

Among these four emulsions, only three of them have been chosen, from the laboratory point of view to employ them in the experimental tracks accordingly to the best results obtained from the whole mixture study carried out by UPC (the above described development has been performed only with Spanish millings):

- PMB ~ 90 penetration without renewing agents,
- Conventional bitumen ~ 150 penetration with renewing agents,
- Conventional bitumen ~ 90 penetration without renewing agents

Therefore and as a consequence of the study carried out, it can be said that by means of the emulsifier employed to produce the slow setting emulsion for recycling, it can be improved the final cold recycled mixture behaviour. Nevertheless, and although a positive contribution to the strength and fatigue behaviour of the mixture would be expected from the slightly harder bitumen and the polymer modified ones it has not been clearly observed in the laboratory study. In that sense it has to be taken into account that the percentages of emulsion for cold recycling are around 3% what is, probably, not enough to definitely show “high” differences among the emulsions used.

DESIGN OF MIXTURES

4.3. MIX DESIGN PROCEDURE FOR HOT BITUMINOUS MIXTURES WITH RECLAIMED ASPHALT

BRRC had already developed a mix design procedure for hot mix asphalts, based on a combined analytical/experimental approach. The different phases of BRRC's mix design procedure are shown schematically in figure 1.

Phase 1 consists of the characterisation of the properties of the constituent materials. Phase 2 is the analytical mix design phase, which uses the material properties as input and outputs a mix composition. In phase 3, experimental tests are performed to verify if the analytically designed mixture meets the specifications. If this is not the case, either new materials are selected or the composition of the materials is adapted.

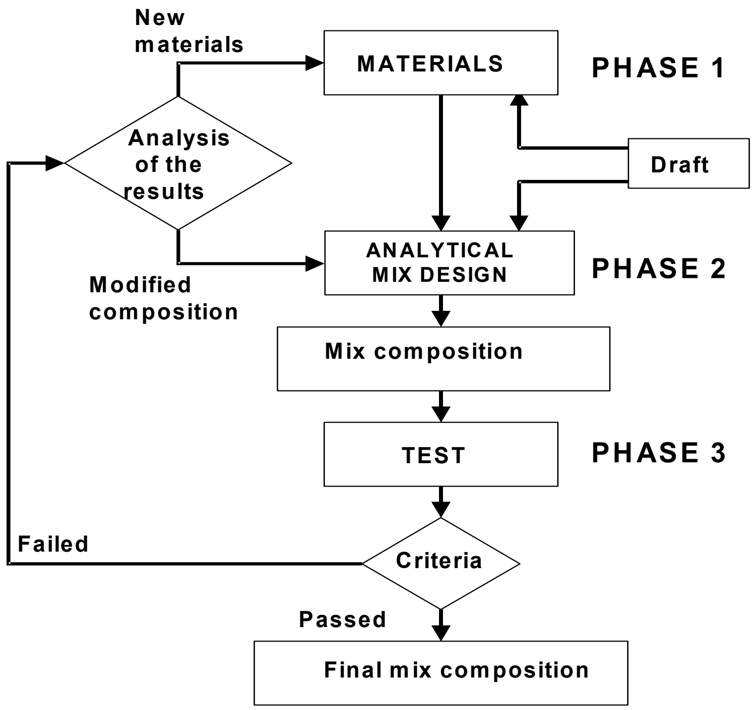


Figure 1: BRRC's hot mix design procedure

Phase 2 is very important, since a good analytical mix design reduces the number of laboratory tests in phase 3. BRRC follows a volumetric approach to make the analytical mix design, because the volumetric composition determines the performance characteristics of the mixture. The calculations have been implemented in a Windows-program called PradoWin, which is widely used in Belgium and abroad. This software was conceived in such a way that it can be applied in any country, because it takes account of the nature of the constituent materials, which can be very different from country to country, and because local specifications can be easily introduced by the user.

The Paramix project allowed BRRC to extend the mix design procedure for mixtures with reclaimed asphalt and to verify the validity of this approach by performance testing on the mixtures in the laboratory on one hand and by testing and monitoring of the mix behaviour on the test tracks on the other hand.

In the extended mix design procedure, the reclaimed asphalt is considered as a separate component, characterized by the grading of the granular material, the binder content and the properties of the binder in the reclaimed asphalt. The grading of the granular material of the reclaimed asphalt makes it possible to compute the grading of the asphalt mix for any given percentage of reclaimed asphalt. Knowing the binder content of the reclaimed asphalt, the percentage of new binder that needs to be added to obtain a given percentage of binder in the final mix can be calculated. Finally, it is also possible to calculate the properties of the binder in the hot mix, based on the properties of the old binder from the reclaimed asphalt, the new binder and the percentage of each in the final mix.

The mix design procedure for mixes with RA was introduced in the PradoWin-software.

This extended mix design procedure was applied for the design of the hot mix asphalts of the Paramix project, according to the Spanish specifications:

- SMA with 10 % and 30 % of reclaimed asphalt (with milled material A)
- S-20 with 30 % and 50 % of reclaimed asphalt (with milled material B)
- MAM (high modulus mix) with 30 % and 50 % of reclaimed asphalt (with milled material B)

The three phases of the procedure are briefly described as follows:

Phase 1: Characterization of the constituent materials

The first step in the design of the hot mixes with reclaimed asphalt was to determine the characteristics of all the constituent materials, the new materials as well as the two types of reclaimed asphalt. The following tests were performed [*]:

- New filler: density, void content, grading
- New coarse and fine aggregate: grading
- Reclaimed asphalt: grading and binder content after recovery, basic characteristics of the recovered binder (penetration at 25 °C and Ring & Ball temperature) for both materials A and B

Because of the importance of consistent input data for the hot mix design, the results were compared with results obtained by UPC and CEPSA. This comparison revealed large differences in the characteristics of the milling material. The source of these differences was found to be the heterogeneity of the reclaimed asphalt. For the milling material A, the problem was solved after homogenising the milled material in the laboratory of UPC and redistributing this material to the other laboratories. For the milling material B, the problem was more difficult to solve because the heterogeneity followed from the fact that the layer, from which the material was milled, had been subjected to different local repairs during its lifetime, leading to a very large heterogeneity in the binder characteristics. To solve this problem, a new batch of milling material coming from a different section had to be provided by COPCISA. This new material was received and homogenised by UPC. It was separated in three fractions as follows:

- 67.9 % passing through sieve of 8 mm;
- 39.4 % passing through sieve of 4 mm.

The three fractions were sent separately to the other two labs. From this point on, the homogeneity of the milling material B could be controlled in a better way and the three labs managed to obtain repeatable results.

[*] For the tests on the new binders: see result nr. 4

Phase 2: Analytical design of the hot asphalt mixtures

Starting from the characteristics of the constituent materials, BRRC made the analytical mix designs according to the Spanish specifications. The grading curves for both percentages of reclaimed asphalt within the same type of mix were adjusted to be as close as possible. The main results of a PradoWin mix design are the composition by mass of the different constituent materials and the volumetric composition of the mixture. The composition by mass can be seen as the formula for preparing the mixture, while the volumetric composition is important in view of the mechanical performance of the mixture.

Phase 3: Laboratory tests for optimising the mix design

Especially the percentage of air voids in the mixture plays a dominant role in the mechanical performance and has to be carefully controlled. Therefore, the analytical mix design was verified by measuring the void percentage of specimens compacted according to the Marshall method.

A comparison of the Marshall procedures between Spain and Belgium revealed an important difference in the test conditions: for the S-20 mixture, the Spanish procedure prescribes 75 blows to compact the cores, whereas in Belgium, only 50 blows are used. For the SMA mixtures, both countries apply 50 blows. PradoWin was developed to calculate the void percentage for Marshall compacted specimens using 50 blows. The prescribed void percentages in the Spanish specifications on the other hand refer to specimens compacted with 75 blows. This explains why, for the case of the S-20 mixtures, the void percentage calculated with PradoWin was systematically higher than the experimental void percentage. This systematic discrepancy was taken into account in the final PradoWin study, by designing for a higher void percentage.

Based on the results of the laboratory tests, the analytical mix designs in phase 2 were optimized by tuning the composition.

These mix designs were further used for the performance related laboratory tests made by UPC and BRRC and for the test tracks (see results about performance testing and rheological characterization). All of this provided confirmation of the validity of the hot mix design procedure.

4.4. RHEOLOGICAL CHARACTERISTICS OF NEW BINDERS AND THEIR COMBINATION WITH BINDER FROM RECLAIMED ASPHALT

The binder in reclaimed asphalt is very stiff as a result of long term ageing. When mixing the reclaimed asphalt with new materials and a new binder, the old and new binder form a binder mix, with rheological characteristics that are a combination of the characteristics of the two components. For hot mix asphalts with a high percentage of reclaimed asphalt, the selection of the new binder should be based on the characteristics of the old binder, the binder content of the reclaimed asphalt and the percentage of reclaimed asphalt in the mixture. An important result of the Paramix project is that rheological characterization of the binder make is possible to select binders for bituminous mixtures with a high rutting resistance.

In a first step, a series of candidate new binders were selected in order to obtain a binder mix within a given PEN class (30/50). In a second step, these binders were subjected to more extensive rheological tests at BRRC, including the evaluation of the sensitivity to rutting and to ageing. This allowed to narrow the selection of the new binders to a smaller number, which were then used for the performance related laboratory tests on the asphalt mixtures. In a third step, the set of binders selected for one asphalt mix (the S-20 mix), were mixed in the laboratory with old binder recovered from the reclaimed asphalt. The old binder and the binder mixes were also subjected to rheological testing. This allowed to derive binder indicators for rutting and to investigate how the rutting susceptibility of the binder mix depends on the rheological characteristics of the new and old binder. The fourth and last step consisted of the comparison of the characteristics of the binder mix prepared in the laboratory with the characteristics of the binder mix extracted from the test tracks. The conclusions drawn in these four steps are now summarized.

<u>Step 1: First selection of candidate new binders</u>

A first set of candidate new binders, was selected by CEPSA. One of the selection criteria to make this choice was the following rule of binder mixtures:

$$\log(PEN(binder \quad mix)) = \frac{a}{100}.\log(PEN(old \quad binder)) + (1-\frac{a}{100}).\log(PEN(new \quad binder))$$

where a is the percentage of old binder in the binder mix.

PEN is the penetration of the binder (at 25 °C, after 5 sec, for a needle of 100 g). It is a conventional binder characteristic that is used for grading binders.

This rule makes it possible to determine which PEN grade the new binder should have in order to achieve a given PEN for the binder mix. The new binders were selected, so that the combination with the old binder gave a binder mix with PEN between 30 and 50. The validity of this rule was confirmed by PEN measurements on the new binders, the old binders extracted from the reclaimed asphalt and laboratory made mixes of both.

The following binders were proposed by CEPSA-PROAS :

1. Binders for SMA mixtures
    1. PmB without renewing agents for the mixtures with 10 % RAP
    2. PmB with 10 % renewing agents for the mixtures with 10 % RAP
    3. PmB without renewing agents for the mixtures with 30 % RAP
    4. PmB with 10 % renewing agents for the mixtures with 30 % RAP
    5. PmB with 20 % renewing agents for the mixtures with 30 % RAP

2. Binders for S-20 mixtures
    1. B80/100 without renewing agents for the mixtures with 30 % RAP
    2. B80/100 with 10 % of renewing agents for the mixtures with 30 % RAP
    3. B80/100 with 20 % of renewing agents for the mixtures with 30 % RAP
    4. PmB without renewing agents for the mixtures with 30 % RAP
    5. PmB with 10 % of renewing agents for the mixtures with 30 % RAP
    6. PmB with 20 % of renewing agents for the mixtures with 30 % RAP
    7. B150/200 without renewing agents for the mixtures with 50 % RAP
    8. B150/200 with 10 % of renewing agents for the mixtures with 50 % RAP
    9. B150/200 with 20 % of renewing agents for the mixtures with 50 % RAP
    10. PmB without renewing agents for the mixtures with 50 % RAP
    11. PmB with 10 % of renewing agents for the mixtures with 50 % RAP
    12. PmB with 20 % of renewing agents for the mixtures with 50 % RAP

<u>Step 2: Rheological characterisation of the new binders</u>

1. Binders for SMA mixtures

The rheological characterisation comprised the measurement of the stiffness modulus and phase angle of each binder by means of a dynamic rheometer (Metravib). The measurements were performed in a large range of temperatures and frequencies: from –20 to 60°C and from 0.01 to 50 Hz. Two specimens were tested per binder. Binders 3 and 4 were also tested before and after long term ageing (with RCAT), to evaluate the sensitivity to ageing.

The main conclusions from these tests were the following:

- The PmB's showed a very good performance with respect to ageing. A stiffness increase with a factor of less then 2.5 was observed after long term ageing (pure binders typically show an increase with a factor 6 or more).
- The difference in rheological behaviour between the binders with and without renewing agents was small, for the aged binders as well as for the unaged binders.

As the rheological tests were unable to discriminate between binders with and without renewing agents, it was decided in agreement with UPC and CEPSA to continue the tests on the asphalt mixtures with the binders with and without renewing agents. Only the binder with 20 % renewing agents (binder 5) was not withheld for further testing. This binder was equivalent to binder 4 in the low temperature range, but softer at the high temperature range and thus more susceptible to rutting.

2. Binders for S-20 mixtures

Because of the large number of binders selected in step 1 for this mixture, the rheological tests were limited to the temperatures of -6 °C, 22 °C and 52 °C. These temperatures are the most relevant with regard to the performance of the binders in asphalt pavements.

The main conclusions from these tests were:

- The PmB's have more favourable rheological characteristics than the pure binder: they behave more stiff at high temperature, while they are softer at low temperature.
- The effect of the renewing agents could not be observed in the rheological tests.

It was decided in agreement with UPC and CEPSA to continue the laboratory testing of the asphalt mixtures with binders 1, 4, 7, 10 and 12. This would allow to investigate whether the difference in rheological characteristics between pure binders and PmB's is also reflected in the asphalt mix behaviour. Also, these binders were supposed to have a low rutting susceptibility (see step 3 also) The PmB with 20 % renewing agents (binder 12) was also selected for further testing within asphalt mixtures, to investigate if there was a possible effect of the renewing agents on the asphalt performance.

<u>Step 3: Rheological tests on new binders, old binder recovered from reclaimed asphalt and mixtures of new and old binders</u>

Rutting resistance is one of the most important asphalt properties and the selection of the new binders on the basis of the PEN (see step 1) does not guarantee that the rutting resistance or resistance to permanent deformation of the binder mix will be good. Therefore, this step was taken to investigate how the rutting resistance of the mix depends on the rutting resistance of the new and old binder. This will allow to improve the selection of new binders for hot mix asphalts with reclaimed asphalt, by taking also the rutting resistance into consideration.

The four new binders used in this step were binders 1, 4, 7 and 10 of the S-20 mix, this mix type is the most susceptible to rutting. Two binder indicators for rutting resistance were considered:

1. <u>G/sinδ (@ T=52 °C and ω= 10 rad/sec) - SHRP indicator for rutting</u>*

The complex modulus G* and loss angle δ were measured by DSR (Dynamic Shear Rheometer) at a fixed temperature of 52 °C, which is relevant for asphalt rutting.
The following conclusions could be drawn:

- The logarithmic rule of mixtures, which is also used for the prediction of the PEN, gives equally good results for G*.
- The PmB's appeared to be only slightly better than the pure binders, but it is known that the SHRP parameter underestimates the rutting susceptibility of PmB's.
- The mixtures with 50% of old binder revealed a higher G*/sinδ, both for the pure binders as for the PmB's.

2. ZSV (@ T=52 °C and f= 0.001 Hz) – Candidate European indicator for rutting

A frequency sweep at a fixed temperature down to very low frequencies, also by DSR, allows for the estimation of the so-called zero shear viscosity (ZSV), which has been proposed as an indicator for the contribution of the binder to asphalt rutting in Europe.

The following conclusions could be drawn:

- The logarithmic rule of mixtures overestimates the ZSV for the mixes with PmB's. This was explained as follows: the polymer phase is diluted by mixing the PmB with the old binder, in this case a binder without polymer modification. The polymer phase thus loses its effectiveness at small loading frequencies (or high temperatures), to a larger extent than predicted by the law of mixtures.
- The difference between the pure binders and the PmB's is far more important when the ZSV is considered instead of the SHRP indicator.
- The binder data also predict a better rutting resistance for the mixtures with 50 % RAP than for the 30 % RAP mixtures.

The results of this step were also used in the interpretation of the rutting tests that were made on the asphalt mixtures.

Step 4: Comparison with rheological characteristics of the binder mix recovered from the test tracks

When the binder mix is extracted from the pavement, the new binder has also been submitted to short term ageing due to fabrication and laying of the test tracks. This was not the case for the laboratory prepared binder mixes. This and other possible effects related to the plant production and the realization of the test tracks made it necessary to perform also a set of rheological tests on binder extracted from the test tracks. This was only done for the S-20 mixes with the pure binders.

The following conclusions were drawn from this step:

Comparison of the results on the laboratory mixes with the mixes recovered from the test tracks showed a good agreement for the mix with 50 % RAP, but for the mix with 30 % RAP (extracted form test track 7), the binder was harder than predicted by the laboratory tests. This was confirmed by all rheological data: PEN, R&B, G*, sinδ and ZSV.

This shows that it is possible to make predictions of the binder behaviour in asphalt tracks in the design phase. These predictions make it possible to select binders with a good resistance to rutting. However, within a given class of performance, it is not possible to make accurate predictions of which binder will show the best rutting resistance in the asphalt mix. Probably, there are several factors causing this uncertainty: ageing of the new binder during production and laying of the tracks, variability in the properties of the RAP and variability in the asphalt mix due to production and laying. A more precise estimation of the uncertainty on the rheological properties of the binders in the test tracks would be interesting, but this would require a large amount of statistical data that could not be gathered in the context of this project.

4.5. PERFORMANCE CHARACTERISTICS OF HOT BITUMINOUS MIXTURES WITH A HIGH PERCENTAGE OF RECLAIMED ASPHALT

The use of reclaimed asphalt in hot bituminous mixtures can only be enhanced if it is shown that the performance related characteristics of the mixtures are good. BRRC considered two important characteristics, that could be affected by the use of high percentages of reclaimed asphalt: compactability and rutting susceptibility. Within the Paramix project it could be demonstrated that it is possible to design and produce hot bituminous mixtures with a good compactibility and with a high resistance to rutting.

The following mixtures were subjected to these performance related tests:
SMA mixtures:

- 10 % RA A, with Pmb without renewing agents
- 10 % RA A, with Pmb with 10 % renewing agents
- 30 % RA A, with Pmb without renewing agents
- 30 % RA A, with Pmb with 10 % renewing agents

S-20 mixtures:

- 30 % RA B, with B80/100 binder without renewing agents
- 30 % RA B, with Pmb without renewing agents
- 50 % RA B, with B150/200 binder without renewing agents
- 50 % RA B, with Pmb without renewing agents
- 50 % RA B, with Pmb with 20 % renewing agents

Compactability

Compactability of the mixtures was investigated with two methods: Marshall compaction and gyratory compaction. Marshall compaction is still used in many countries to predict the void content in the mixture. It consists of compacting the mixture in a mould by means of a series of successive hammer blows. Gyratory compaction is considered as a better test to predict the behaviour under compaction and the air void content on site. This method consists of kneading the mixture in a mould by applying a pressure, while the mould is tilted and performing rotations (called gyrations).

Table 1 shows the prediction of the air voids with BRRC's PradoWin mix design software, the void percentage at 100 gyrations in the gyratory compactor and the void percentage from the Marshall tests for the case of the SMA mixtures.

***Table 1**: Comparison of air voids*

	SMA-10% RA		SMA-30% RA	
Binder	Pmb without renewing agents	Pmb with renewing agents	Pmb without renewing agents	Pmb with renewing agents
PradoWin calculation	**10.6%**		**11.0%**	
Gyratory tests at 100 gyrations (on 3 samples)				
mean	**8.3%**	**9.9%**	**11.2%**	**10.5%**
St. dev.	1.3%	0.9%	0.9%	0.6%
Marshall tests, using 50 blows (on 2 samples)				
mean	**7.9%**	**7.5%**	**8.7%**	**10.0%**
s.d.	1.9%	0%	0.6%	0.9%

This study shows that the voids of the gyratory compacted specimens are very close to the voids predicted with the design software Prado-Win. The differences with the voids for the Marshall compacted samples was larger. This could be explained by crushing of the aggregates taking place during Marshall compaction.

The mixtures with 10 % RA and 30 % RA were initially designed for the same air void content (10.6 %, according to the PradoWin calculations). Based on the results of the Marshall tests performed at UPC, UPC proposed to decrease the binder content for the 30 % RA mix (5.5 % instead of 5.7 %). With this decreased binder content, the PradoWin software predicts a void content of 0.4 % higher. Both gyratory tests and Marshall tests also produced a higher void content in the 30 % RA mixtures, but the difference between the experimental data is higher than the predicted 0.4 %.

Table 2 shows the results for the S20 mixtures. The Marshall compaction was only performed on the mixtures with the pure binders, since Marshall compaction is not significantly sensitive to the binder type.

***Table 2**: Comparison of air voids*

	S20-30% RA		S20-50% RA		
Binder	B80/100 without renewing agents	Pmb without renewing agents	B150/200 without renewing agents	Pmb without renewing agents	Pmb with renewing agents
PradoWin calculation	**6.35%**		**6.4%**		
Gyratory tests at 60 gyrations (4 samples)					
average	**7.2%**	**7.6%**	**6.8%**	**6.6%**	**6.4%**
s.d.	0.7%	0.8%	0.8%	0.6%	0.5%
Marshall tests, using 75 blows (4 samples)					
average	**5.2%**		**4.7%**		
s.d.	0.2%		0.4%		

The void content is slightly higher for the mixtures with 30 % RA than for 50 % RA. The voids obtained from gyratory tests are very close to the values calculated by Prado-Win. They show very little difference between the mixtures with a same percentage of RA and a different binder. Also here the differences between the calculated air voids and the void contents of Marshall compacted samples were higher, also as a result of crushing of aggregate during Marshall compaction.

Gyratory tests were also performed on material extracted from the test tracks. Although the number of tests is limited, it is seen that the material from the test tracks has a slightly higher percentage of air voids. This could be explained by slight differences in the grading curves of the plant produced mixes compared to the laboratory prepared mixes.

The main conclusion from the compactability tests is that none of the mixtures showed any problem of compactability. A good agreement was obtained between the calculated air void contents by the Prado-Win design software and the air voids of the gyratory compacted specimens. Similar air void contents can be obtained to those of mixes without reclaimed asphalt.

Rutting susceptibility

This was investigated by means of the wheel tracking test, made with a large size device according to prEN 12697-22, at a temperature of 50 °C. Two plates were tested per mix. The average curves are plotted in figure 3 for the SMA-mixes and in figure 4 for the S20-mixes.

The following conclusions were drawn for the SMA-mixes:

- The SMA-mixes perform well in the wheel tracking test. According to the future European and present Belgian standards, they belong to the best category for rutting resistance. This can be attributed to the stable stony skeleton and the relatively high percentage of air voids.
- The difference in percentage of RA and the difference between the binders with and without renewing agents seem to have no impact on the ranking of the test results. This is explained by the fact that the mix gradings and binder content of the mixtures with and without RA were the same and that all new binders were selected to obtain a similar rheological behaviour when mixed with the old binder from the RA.
- The SMA-mix with 10 % RA without renewing agents showed the lowest rutting resistance. However, this was not reflected in the binder stiffness measurements at high temperatures as this binder showed the highest binder stiffness value (about 50 % higher than that of the other binders). Consequently, small differences in binder performance to rutting are not always reflected in the mix rutting performance.

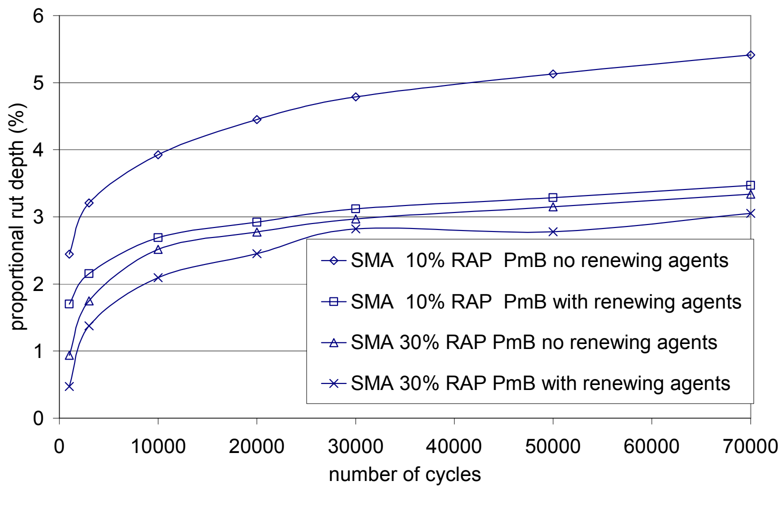


Figure 3: Wheel tracking tests on SMA-mixes

For the S20-mixtures, the following conclusions were made:

- The S20-mixes also perform very well in rutting. According to the present Belgian classification, they also belong to the best category.
- As for the SMA-mixes, there is no impact of the percentage of RA on the rutting results. The PmB's do not improve the results of the test, when compared to the pure binders. There are two possible explanations for this. First of all, the aggregate skeleton itself is very stable and resistant to rutting; variations in the binder properties have less influence for such mixes. Secondly, the rheological characteristics of the binders were not significantly different and the wheel tracking test was not sensitive enough to reflect the differences. We note also that the test temperature of 50 °C and the test frequency of 1 Hz are not optimal for discriminating PmB's and pure binders of the same grade, as PmB's improve the rutting resistance especially at high temperatures and low frequencies. It is probable that at higher temperatures and very low traffic speed, the PmB's will perform better than the pure binders.
- The mix with the renewing agent performed not significantly different than the comparable mix without renewing agent.

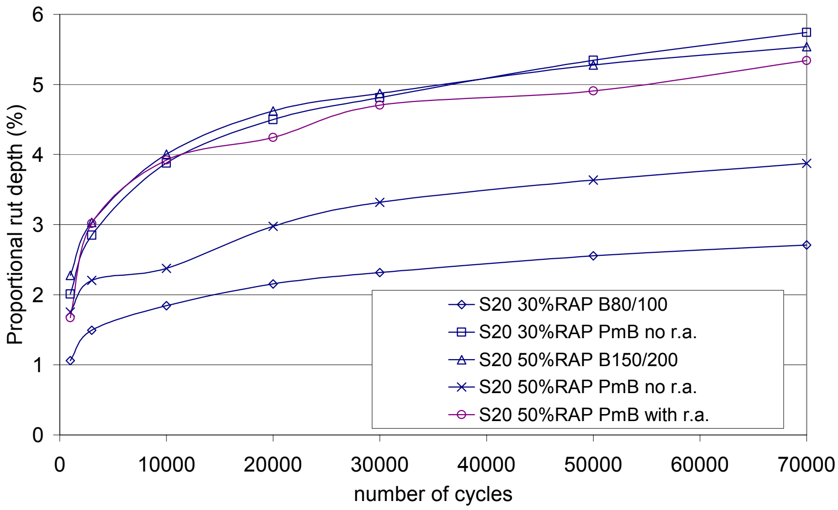


Figure 4: Wheel tracking tests on S20-mixes

The main conclusion from the wheel tracking tests is that all mixes showed an excellent resistance to rutting. Hence this study shows that it is possible to design mixes with high percentages of re-use that are very resistant to rutting. This is a positive result, taking into account the fact that the binder in such mixes consists of hard old binder on one hand and new soft binder on the other hand, which are only mixed very shortly during production of the hot mix.

4.6. DESIGN METHODOLOGY FOR COLD RECYCLED MIXTURES WITH EMULSION

In situ recycled mixtures with emulsion

The cold recycling process of a bituminous pavement lies, basically, in crushing and grinding the existing pavement by means of a milling machine and coating the resultant material (composed by particles smaller than 25-40mm but with a few presence of sand and powder) with a thin binder covering by adding a little quantity of water (0-3%) and a bituminous emulsion (2-4%). The coating process it usually takes place inside de milling drum or inside an especial mixer placed inside the milling machine. Then, the mixture is extended again and finally compacted. During the compaction process the binder particles are joined giving cohesion to the milled material. The cohesion is, then, the most important property to consider in this kind of mixtures, replacing the stability or the rutting resistance, which are the parameters considered in the conventional mixtures design.

Starting from this point it has been developed a testing procedure based in the determination of the mixture cohesion by means of the indirect tensile test.

Independently of the test used, the design and the characterization of a laboratory mixture must be carried out with a sample with the same density and composition as the mixture manufactured in the field. This have always been an important problem in the cold recycled mixtures characterization because it is never known which will be the density obtained in the field, and usually, the specimens manufactured in the laboratory with other procedures have a higher density than the field cores.

The method proposed is based on an especial specimen manufacture procedure which allows to obtain similar mechanical characteristics and densities between laboratory and field mixtures. It also allows to obtain the optimum percentages of water and emulsion to be added to the mixture, starting from the cohesion determined by means of indirect tensile test at 5ºC. The construction of the experimental tracks and the laboratory searching has confirmed that the procedure proposed is adequate to establish quality values as well as minimum strength and density values to demand to the mixtures.

DESIGN METHODOLOGY FOR COLD RECYCLED MIXTURES WITH EMULSION

The methodology proposed is based on the determination of the emulsion content to be used in the mixtures, starting from its indirect tensile dry resistance at 5ºC and from its retained strength after one day immersion in water at 60ºC. The method includes the specimen manufacture process, their curing, breaking and design process, and also, the design criteria.

SPECIMEN MANUFACTURE

Two procedures have been developed for the specimen manufacture, one, using a press for the manufacturing of the specimens by applying a static compaction, the other, compacting with the gyratory machine. The first method easies the expulsion of the coating fluids, allowing the compaction through a consolidation effect. The second compaction process is due to a batching compression effect, having the moulds two splits for the expulsion of the water. It is important to point out that if it is used an impact compaction process, like Marshall compaction, the fluids like coating water or emulsion fluids absorb the compaction energy and they interfere in the compaction process. In that last case, the compaction at the laboratory is lower than the one obtained at the field.

Static compaction

The static compaction consists on manufacturing a cylindrical specimen of 101.6 mm of diameter and 5-6 cm of height, by pouring the material into a metallic mould of 101.6 mm of diameter. A compaction load is applied by a piston, with a deformation speed of 1.27 mm/min until the compaction load achieves 60 kN, which must be held up during 2 minutes. The densities and resistances obtained in the specimens manufactured using this method in the laboratory, are similar to the field cores, as it will be exposed further on.

Gyratory compaction

The gyratory compaction consists on applying 300 revolutions with a gyratory compactor. The pressure must be of 0.6 MPa and the angle of 1.25º. The specimens obtained, again with a 101.6

mm diameter and a 5-6 cm of height, have also similar densities and resistance to the cores extracted from the field.

Curing process

Once the specimens are manufactured by using one of the methods explained above, they are removed from the moulds and they are brought about to an accelerated curing process, which takes place inside an oven at 60ºC during 3 days.

Once the specimens are cured and before their testing, it is determined their density by the immersion in water method.

<u>Testing process</u>

Dry test (conditioning of the specimen)

Once the specimens are cured, they are introduced in a chamber which temperature can be controlled. The specimens are inside the chamber at 5ºC during at least 4 hours in order that they reach the temperature homogeneously.

Testing after immersion (conditioning of the specimen)

In this case, the specimen will be introduced in water at 60ºC during 24 hours. Then, they will be air dried during 8-12 hours before putting them inside the temperature controlled chamber. As in the previous case they will rest in the chamber a minimum of 4 hours at 5ºC. Finally, they will be tested.

Specimen testing

For their testing, each specimen is placed on the testing devices (bars), verifying the alignment of the bars in order that the load shall be applied in the vertical diametric plane of the specimen. During the testing process, the load displacement speed (50.8 mm/min as Marshall speed test) must remain constant until the breaking of the laboratory sample. Both the load and the displacement are registered, and the indirect tensile strength or resistance is calculated by means of the following expression:

$$R_{TI} = (2 \cdot P) / (\pi \cdot h \cdot d)$$

where,
R_{TI}, is the indirect tensile strength (in $N.mm^{-2}$, MPa),
P, is the breaking load (in N),
h, is the height of the specimen (in mm) and,
d, is the specimen diameter (in mm)

It is recommended to carry out the test in a chamber which temperature can be controlled in order to maintain it constant the temperature during all the testing process. Nevertheless, if that is not possible, the test can be carried out in a conventional press, taking care that the time passed between the moment the specimen is taken of the chamber until its testing, shall be as shortest as possible.

<u>Design methodology</u>

The cold recycled mixtures design methodology is based on the indirect tensile test. First of all, it is determined the optimum humidity percentage of compaction of the milled material by means of Modified Proctor Test, which is a reference value for the compaction fluids (water plus emulsion). Starting from this value, the water and the emulsion contents are modified in order to obtain a proper coating and a high cohesion of the mixture. That way, it is determined the coating quality evolution and the indirect tensile strength evolution for different emulsion and water contents. The number of specimen tested for each emulsion and water content, and for each testing condition is of 3 specimen.

Checking proposed methodology

The control and pursuit of the experimental tracks have allowed the validation of the design methodology proposed, comparing the results obtained in the specimens manufactured at the laboratory to the results obtained testing the cores extracted from the different cold actions performed in the experimental tracks, Table 1.

MIX	D (g/cm3)	Rc (MPa)	Dc (mm)
ECL-2	2.192	1.61	1.22
ECL-2-m	2.28	1.36	0.95
ECL-2-r	2.263	2.22	1.11

Table 1: Experimental tracks cores results.

The mechanical strengths obtained in the cores extracted from the recycled layer will depend, in an important way, on the execution and service conditions (environmental conditions, draining, traffic, structural section, etc.). However, considering other works carried out, it have been checked that if the maturing process (removing of the water coming from the breaking of the emulsion) is adequate, in about 18 months the cores achieve a similar strength to the specimen cured at the lab, Figure 1.

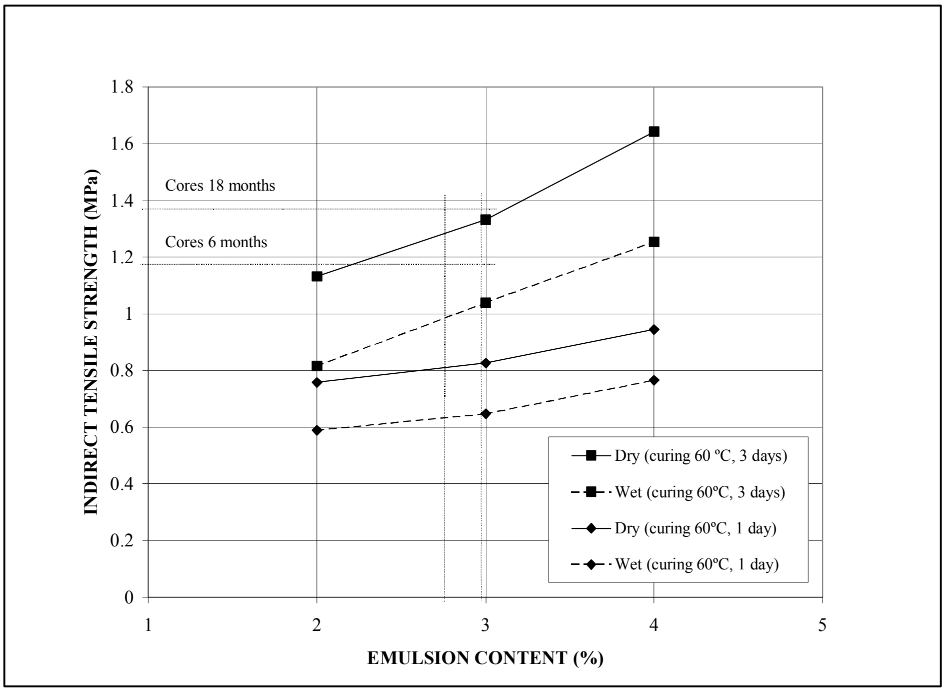


Figure 1: Indirect tensile resistance under different compositions, curing and testing conditions.

Design criteria

Although nowadays it is been studied the possibility to establish a design criteria depending on the quality obtained in the mixture, (establishing different classes or categories for cold recycling mixtures), with the studies carried out up till now it can be fixed some minimum values for the indirect tensile strength, which must be achieved in the laboratory for any class of mixture.

To sum up, the emulsion content to use will be the one which allows to achieve a minimum indirect tensile strength of 1.0 MPa. The test will be carried out at 5 ºC, determined on a specimen manufactured by static or gyratory compaction, after an accelerated curing process of 3 days in an oven at 60ºC. The minimum resistencia conservada (after water immersion during 1 day at 60ºC) is of 75%.

4.7. DESIGN METHODOLOGY FOR HOT RECYCLED MIXTURES

Hot recycled mixtures have the handicap that the adding of a big amount of RA implies an important diminution of the mixtures fatigue resistance and also their resistance to thermic stresses.

The milled material has always two characteristics: a high stiffness and an ageing of its binder. That is the reason why the recycled mixtures are manufactured with soft binders or binders with renewing agents, in order to achieve a more ductile binder which gives a better fatigue performance to the recycled mixture.

So, in this project, taking in account these facts, fatigue has been considered as the most important property of the hot recycled mixtures. It have been determined, first of all, the fatigue laws of the different recycled mixtures used in the experimental tracks to be compared to the conventional mixtures fatigue laws. The results have shown, as it will be pointed out further on, that if the added new binder and the mixture composition are adequate, it can be obtained recycled mixtures with a good fatigue performance, similar to the conventional ones.

As it is known, fatigue test implies long, expensive and laborious procedures that are difficult to be used as a base methodology for the design or control of the recycled mixture. These tests require especial dynamic presses which are rarely found in the conventional laboratories. That is the reason why one of the objectives followed in this project, satisfactory achieved, has been the analysis of the correlation between the mixtures fatigue behaviour and its response to a static direct tensile test in which three properties are determined: breaking resistance, deformation modulus and its final breaking deformation. This has allowed us to develop, as it is explained further on, an easy methodology for the design and characterization of these mixtures which can be also used for the conventional mixes.

Finally, for the analysis of the asphalt recycled mixtures manufactured and extended on the experimental tracks, it has been used the indirect tensile test, which has allowed to establish a new quality criteria that can be used for both recycled and conventional mixes, and which can also be included in the European Union EC Marking procedures for mixtures quality control.

Two procedures for manufacturing and testing specimens are going to be presented with the same methodology. The procedure based on BTD test was the first one that was developed and it is the easiest to manufacture the specimens. The procedure based on CTD test, permits a better application and control of the tensile stresses. Design techniques and design criteria of both procedures are presented together as they are part of the same methodology.

BTD test specimen manufacturing

The specimens are manufactured and compacted in the Marshall compactor, using two especial bases which allow to pull of the mixture and to apply a tensile stress to it.
The bases and the compaction procedure are shown in figure 2. The only difference with regard to Marshall conventional method is that the compaction process consists on applying only 50 blows in one face. With this number of blows the density obtained at the laboratory is similar to the one achieved at the field and it is only a one face compaction because the specimen is shortest and basically we are interested in the compaction of the upper part of the specimen.

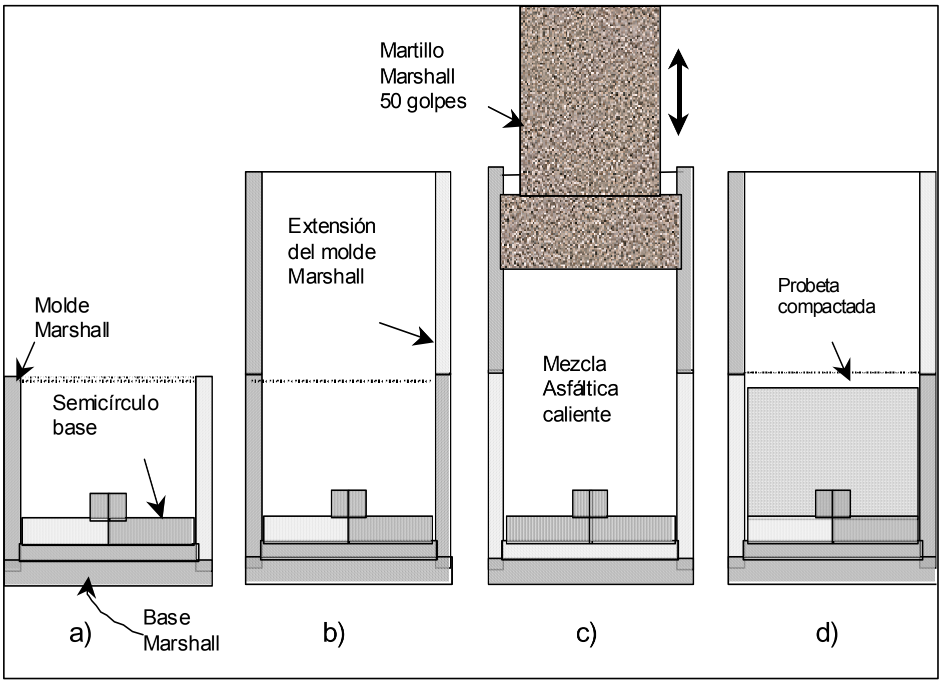


Figure 2: BTD test specimen manufacturing.

Breaking of the specimen.

The bases of the specimen are fastened to two especial jaws of the press. The deformation speed applied is 1 mm/min and the temperature is 20ºC.
During the test, the curve stress-strain is registered obtaining a curve similar to the one drawn in figure 3.

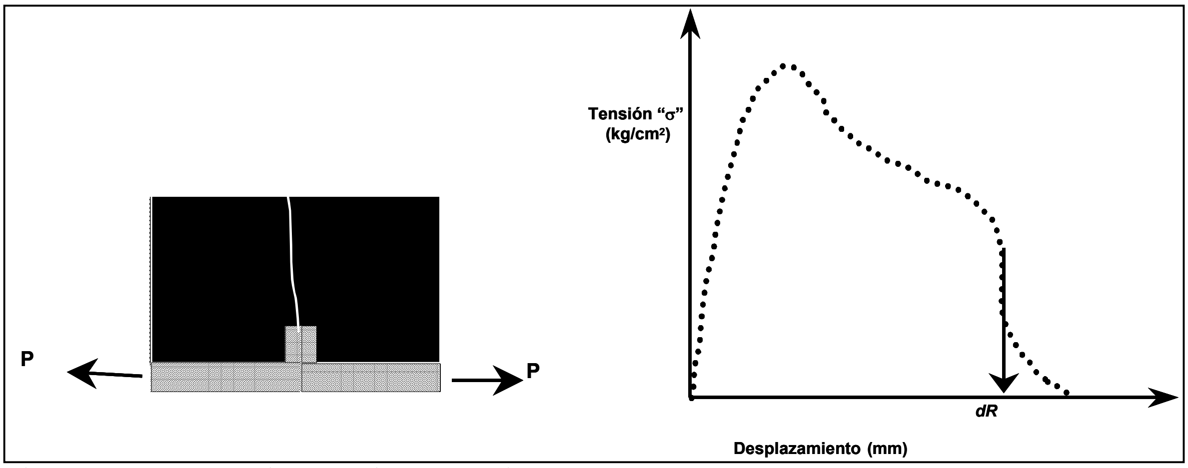


Figure 3: BTD test: scheme and stress-strain curve.

The tensile is calculated dividing the load applied by the area of the specimen section which is just above the joint of the two bases.

CTD test specimen manufacture

The specimen tested in CTD test is prismatic. Its dimensions are 5 cm x 5 cm x 15 cm, and it has and indent made with a saw in its central fibre in order to reduce this section and to force the rupture in this fibre. The prismatic specimen is obtained by sawing a bigger specimen of 30 cm x 30 cm x 5 cm, which compaction is described in the NLT-173/84 spanish standards.

Breaking of the specimen.

For the specimen testing, two metallic gripping devices are stuck to each base. They allow to subject the specimen to the press and to test it applying a tensile load. A constant speed deformation of 0.1 mm/min is applied and the testing temperature is 20ºC.

The sticking process of the metallic devices to the specimen bases is carried out by means of an especial system which assure the linearity and normality of the loads applied to the specimen.

As for the BTD test, during the testing process the stress-unitary strain curve is registered by means of two extensometers placed in the area where the fracture is expected. They register the unitary deformation. This testing procedure allows a better control of the applied stresses and the deformations obtained, and it has been used, basically, in the study of the recycled mixtures.

Design procedure

BTD and CTD tensile tests can be used to study the effect of the RAP content in the mixtures, the influence of using different types and binder percentages, the grading of the mixture and the effect of the rest of its components. For each variable, different specimens will be manufactured changing the value of the parameter considered. The curves obtained after the testing process will allow to select the mixture according to the design characteristics.

Result checking

The procedures proposed have been validate with later studies. First of all analysing, by means of the breaking curves, the effect of the RAP content and the use of soft binders or binders with renewing agents, figure 4. After, it has been checked the correlation between the parameters determined with CTD test and the fatigue mixtures behaviour.

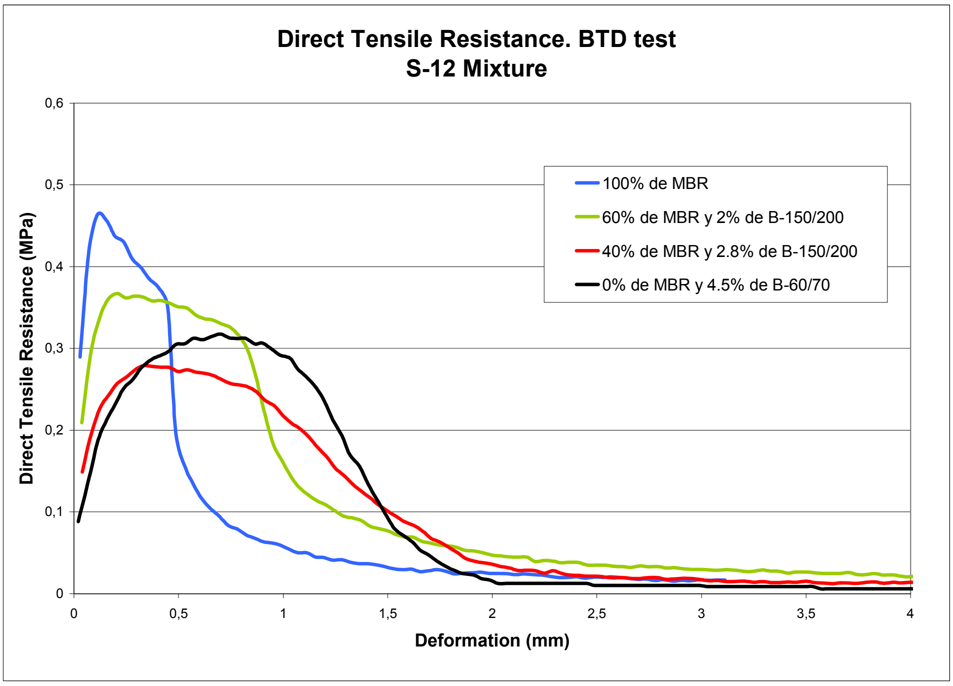


Figure 4: BTD test of mixtures with different RAP contents.

In figure 4, it can be observed that the mixtures manufactured with a high RAP percentage and a little new binder quantity have a fragile fracture, whereas, the higher the binder with renewing agents quantity is added and the lower the amount of RAP, the closer the performance to a conventional mixture is. It is important to point out that all the mixtures tested have the same binder percentage, which is about a 4.5% on 100% of dry aggregates.

In Figures 5 and 6 are shown the following correlations obtained: the correlation between the deformation at maximum strength (CTD static mode) and the final fatigue deformation of the mixture, and, the correlation between the stiffness modulus (CTD test) and the dynamic modulus of the mixture determined by the three point bending fatigue test.

The laboratory tests have revealed that the fatigue breaking deformation and the dynamic modulus of the mixtures are the variables which command the fatigue failure of the mixtures, Figure 7. With these three figures it can be obtained the fatigue life of the mixtures starting from the CTD test, because knowing the breaking deformation and the static stiffness modulus, it can be determined the fatigue deformation and the dynamic modulus of the mixtures by using the graphics of Figures 5 and 6. Then, using the graphic of Figure 7, it can be obtained the fatigue life value of the mixture depending on the deformation that will suffer the mixture in the pavement.

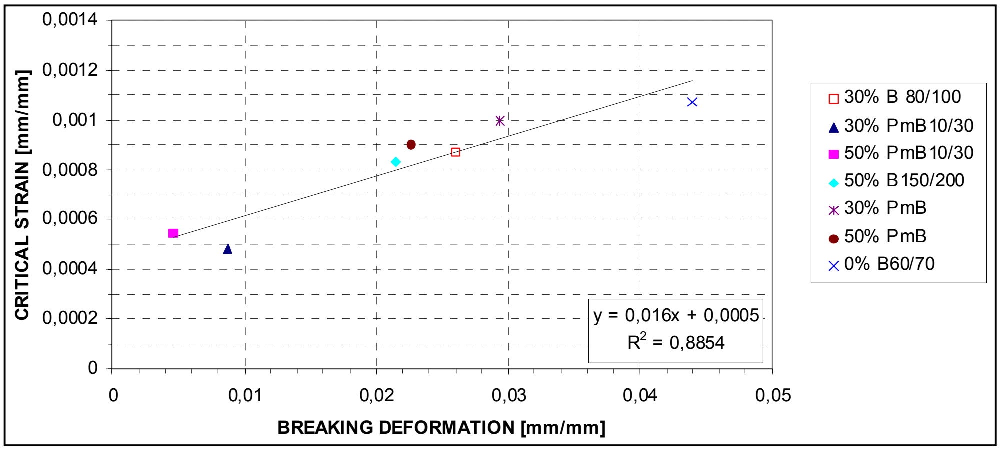


Figure 5: Breaking deformation and critical strain correlation.

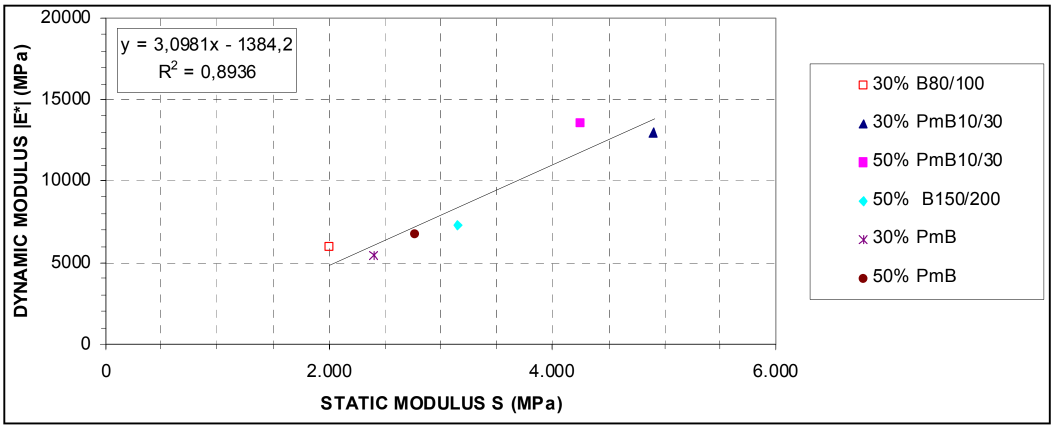


Figure 6: Static modulus and dynamic modulus correlation.

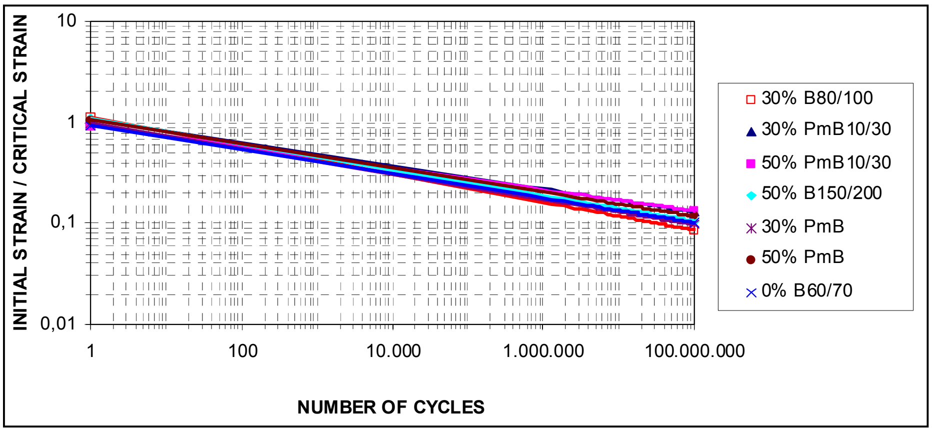


Figure 7: Fatigue curves. Deformation in the inferior fibre of the specimen.

For the same stress, as higher the modulus and the breaking deformation are, better will be its response.

Following these criteria, the following step, in which we are in this moment, is to fix the minimum modulus and deformation values of the mixtures for the CTD test.

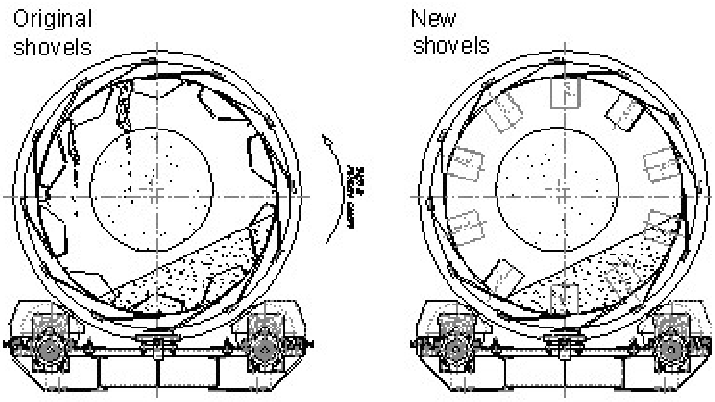
MANUFACTURING SYSTEMS

4.8. DESIGN OF MACHINES AND COMPONENTS FOR HOT IN-PLANT RECYCLED ASPHALT MIXTURES MANUFACTURING.

The developments on machines design concerned:

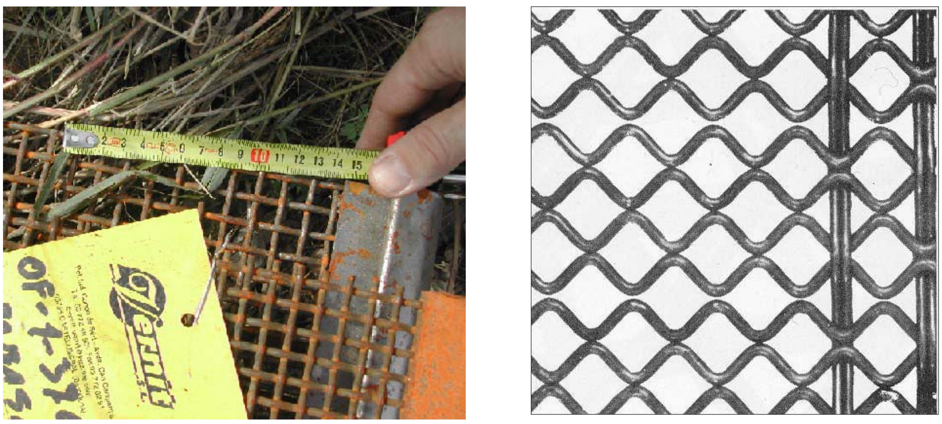
- Design improvement of the RAP drum dryer (RAD).
- Evaluation of the screening system for the milled material.
- Design of the “Combined Recycling” feeding line on the hot asphalt plant.

The design of the RAP drum dryer has been improved in the flame chamber. It contains new shovels that mix the milled material without lift it during the rotation of the cylinder.
This system aims mainly to avoid sticking and obstruction problems of cavities, having a “self-cleaning” effect by the flow of grains. It should also improve the quality of the heated RAP, with less aging of the bitumen because the reduction of the flame exposition. Important benefits are expected for maintenance costs and burning quality.



The screening system for the milled material has been studied and tested, considering a vibrating screen. The main parameters that have been analysed are:
- The mesh dimensions for the nets to obtain the required granulometry (0-5 and 5-20 mm).
- The surfaces of the nets to obtain the required production capacity (expressed in tons/h/m2).

The nets used have meshes of precise dimensions, to let the material of defined granulometry pass. The kinds of nets commonly used are:
a) standard nets
d) anti-clogging nets, called “Arpa” (made with a corrugated wire)(see the picture below).



On the left standard net, on the right “Arpa” net.

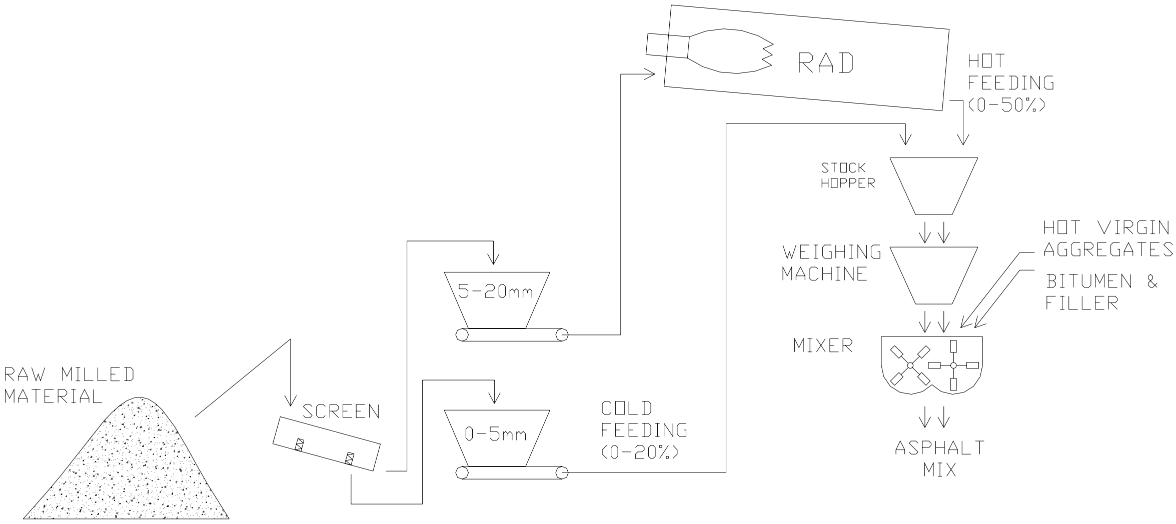
An experimental "Combined Recycling" feeding line has been realized on an existing hot recycling asphalt plant (RAD) in Italy. This supplementary line allows introducing in the mixer the cold and fining milled material without pass trough the dryer.

4.9. NEW MANUFACTURING PROCESS FOR HOT IN-PLNAT CRECYLCED ASPHALT MIXTURES MANUFACTUTRING: "COMBINED HOT & COLD RECYLCING" PROCESS

A new process, called "Combined cold & hot Recycling", has been invented, with a study of its postulation, expected performances and application requirements.

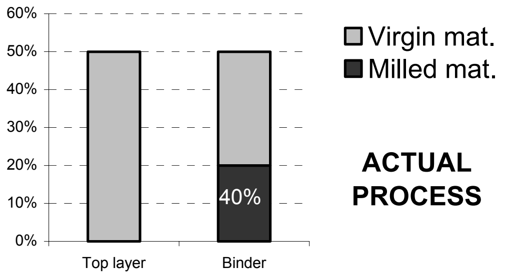
This new process has been considered because an observation on the quality of the milled material (reclaimed asphalt): the different bitumen content between the finest and the bigger part. The finest part contains a higher amount of bitumen, which with the filler and the sand creates most of the problems during the heating process in the drum dryer and in the filter (problems due to the sticking attitude of this binder).

The new process consists in a preventive screening of the milled material, with separation of fine and big grains (respectively 0-5 mm and 5-20 mm). These materials are inserted into the hot asphalt mix following two different ways: the 0-5 is cold-added in small amount (up to 20%) into top layer mixes, the 5-20 is heated and added in bigger amount (up to 60%) into binder mixtures.
The cold and hot inserts can be done also at the same time, utilising a plant configuration as schemed below.

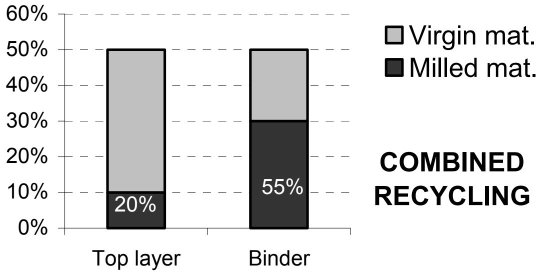


The main advantage of this new process is the increasing of the **total** recycling amount of the asphalt plant by the introduction of the milled material in the top layer mixes. It also allows to increase the recycling rate in some specific hot asphalt receipts.

In a raw summarisation, the annual average production of an asphalt plant consists in 50% top layer (0-15 mm) and 50% binder (0-30 mm). Many EU countries (like Italy and Germany) produce a bigger amount of top layer because they have mainly maintenance of existing roads, with a lot of reclaimed asphalt to recycle.
Actually the recycling in the top layer is not extensively considered and the recycling rate in the other mixes is about 40%. The "Combined Recycling" process would increase up to 85% the amount of milled material recycled by the asphalt plant, with performances as showed below.



0% + 20% = **20%** **TOTAL RECYCLING**



10% + 27% = **37%** **TOTAL RECYCLING**

4.10. *IMPROVED COMPONENTS FOR THE MILLING AND MIXING PROCESS:* DEVELOPMENT OF AN IMPROVED MILLING AND MIXING DRUM TOGETHER WITH A LARGER MIXING CHAMBER TO IMPROVE THE MIXING QUALITY AND INFLUENCE THE GRAIN SIZE OF THE RECYCLED MATERIAL.

The grading and mixing degree could possibly be improved by theoretically and practically changing the forward speed of the recycling machine, by changing the arrangement of the cutting tools on the milling drum and by changing the volume and exit area of the milling and mixing chamber on the recycling machine. It was decided to carry out these changes on an existing recycling machine of type 2200 CR, which were then tested on various milling and recycling jobs. The theoretical aspects and practical results are discussed in the deliverable report, titled "D.5.1. Study of and improvements to components that affect the grading of the milled material and the degree of mixing with the added binding agents". The enhanced milling drum together with the newly designed milling and mixing chamber were tested on a job site in Rumania. It should be noted that the practical aspects contained in this report are part of WP 6.1. They have however been included in this report in order to follow a logical sequence of the results.

4.11. *IMPROVED COMPONENTS FOR THE MACHINERY AND LAY OUT METHODS FOR IN-SITU COLD RECYCLING:* DEVELOPMENT OF A MORE EFFICIENT HEATING SYSTEM.

The coverage of the added binding agent, being the bitumen emulsion, on the milled material that is being recycled in-place could be improved by warming up the material. Even if the material temperature were only increased to 30 °C, the advantage would be in the cold regions and / or the cooler periods of the year, such as spring and autumn. The various heating methods were analysed in form of a literature study, which led to the decision to develop the existing in-place pre-heating machine. These newly designed in-place pre-heating machines were then extensively tested on various in-place hot recycling jobs. In addition, a small practical test was carried out with a modified pre-compaction screed. All these theoretical studies and practical tests are discussed in the deliverable report, titled "D.5.2. Study of and improvements to components that affect the mixing and lay-down quality." Again, it should be noted that the practical aspects contained in this report are part of WP 6.1. They have however been included in this report to follow a logical sequence of the results.

NUMERICAL SIMULATION

4.12. MATHEMATICAL FORMULATION AND CALIBRATION OF THE VISCOELASTIC MODEL

4.13. MATHEMATICAL FORMULATION AND CALIBRATION OF THE VISCO-DAMAGE MODEL

4.14. MATHEMATICAL FORMULATION AND CALIBRATION OF THE VISCOPLASTIC MODEL ACCORDING TO EXPERIMENTAL TESTS

4.15. APPLICATION OF THE VISCOPLASTIC MODEL TO SIMULATE THE REAL PAVEMENT'S RESPONSE UNDER DYNAMIC LOAD

4.16. FATIGUE FORMULATION TO SIMULATE THE MATERIAL'S DAMAGE UNDER CYCLIC LOADS

Mainly, CIMNE has been centred in the development of a constitutive model to simulate numerically the behaviour of the asphaltic pavements in service by means of the finite elements method. These constituent developments has been classified and incorporated to three fundamental tasks and then it will be mentioned with more detail.

The starting points of the CIMNE software were:

1. **A finite element method** (FEM) software program for non linear structural analysis. Originally had several non-linear constitutive models, but not appropriated for the asphaltic pavements application.

2. **A pre/post-processing software environment**. This program is under continuous development and has facilities for optimal generations of data for finite element analysis including a general interactive geometric modeler, a three dimensional (3D) mesh generator.

I. Introduction

During the project development the CIMNE have been worked in the in the viscoelastic, damage, viscoplastic and fatigue constitutive models, that will be detailed in later sections, after this introduction. Also, during this period the Civil Engineering specialization thesis has been concluded, (José M. González. “A viscousplastic model for the stress-strain characterization of asphaltic materials”. Advised by J. Miquel and S. Oller. Civil Engineering School - UPC. July 2003 (written in Spanish)).

This study it is centred on the rheological behaviour of the asphaltic mixtures samples under several load speed (see

Figure 1). In this thesis have been verify a laboratory test using the viscous-plastic models. Good results have been obtained whose comparison can it turns in Figure 2.

Also the numerical models here developed have been applied to the real rehabilitated pavement (see

Figure 3), and this numerical capability has been compared with the experimental results obtained by other partner in the real rehabilitated roads.

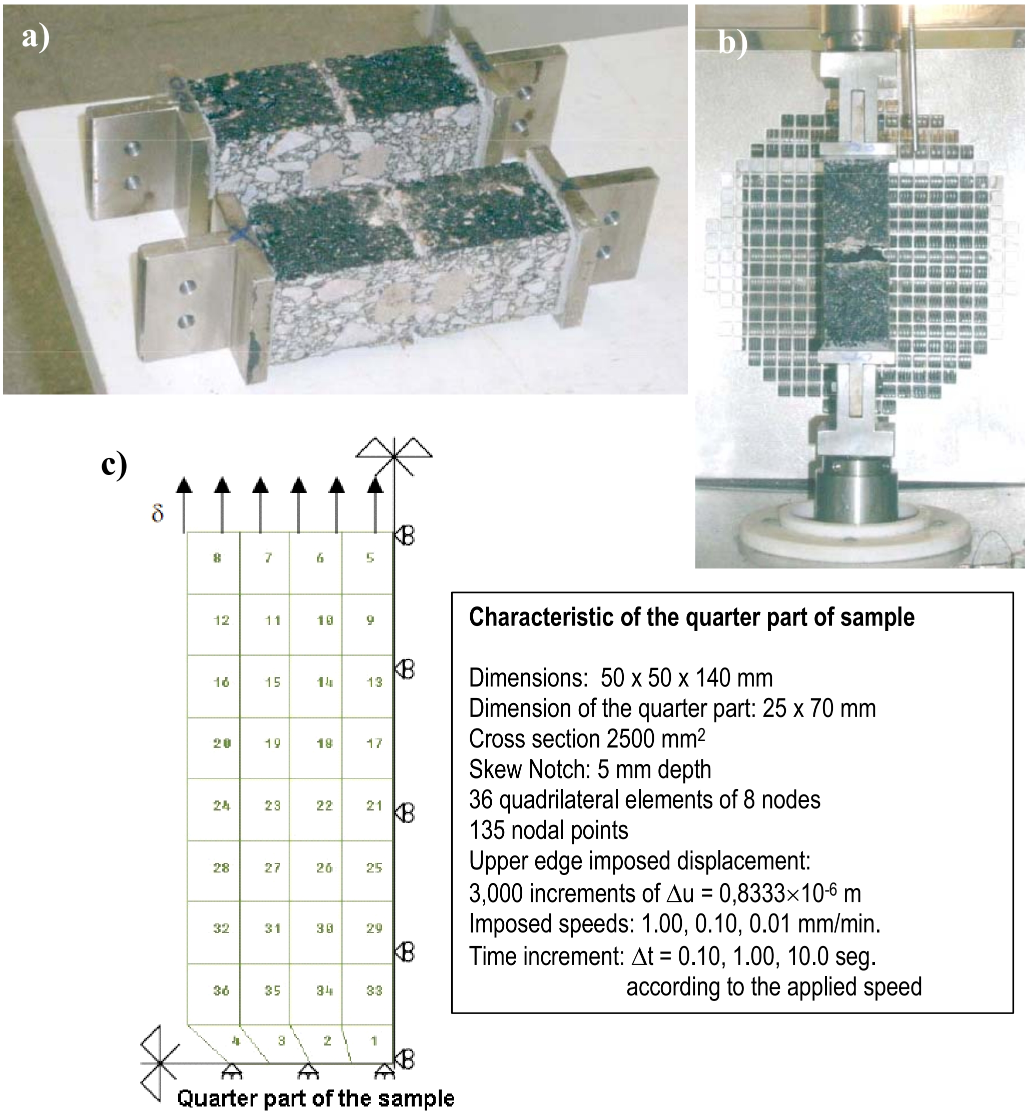


Figure 1.- Asphaltic mixed sample: a) Laboratory sample. b) Sampled under tension test. c) Finite element mesh and test characteristic.

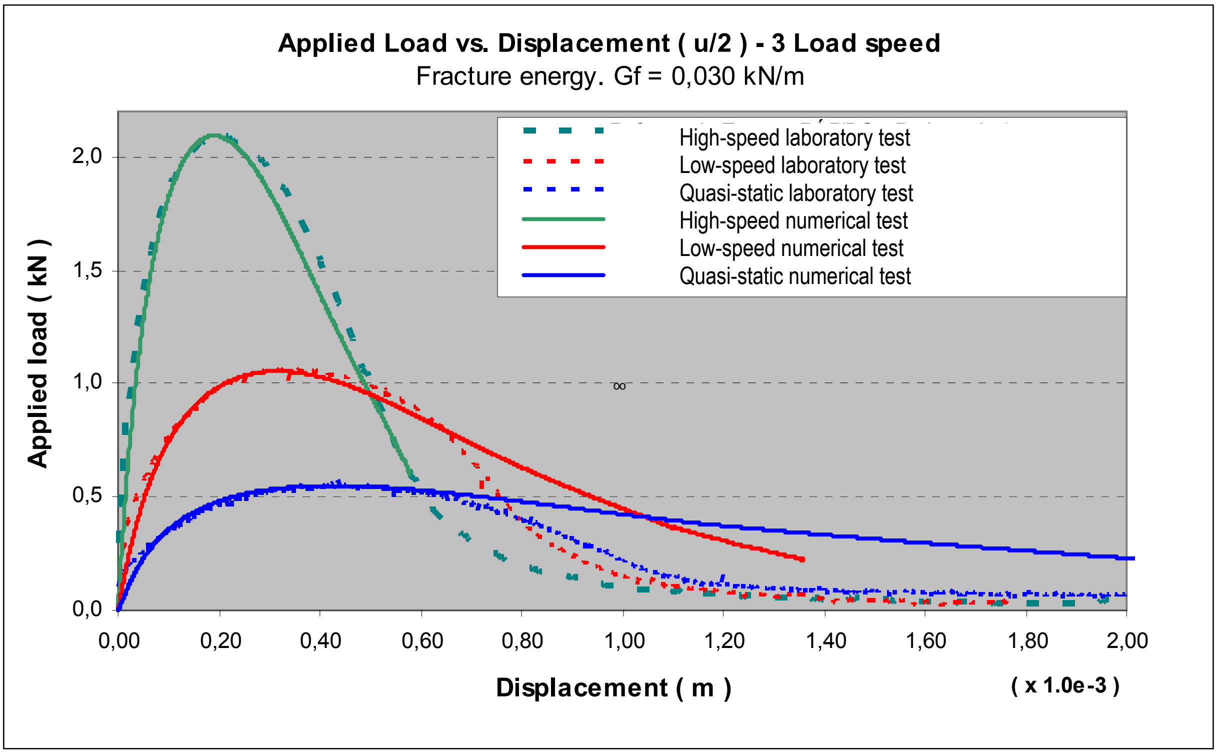


Figure 2 – Simple tension test results. Numerical vs. experimental results obtained for the sample showed in Figure 1.

Finite element MODELIZATION

Longitudinal pavement section & gauges location for cold recycled track 6

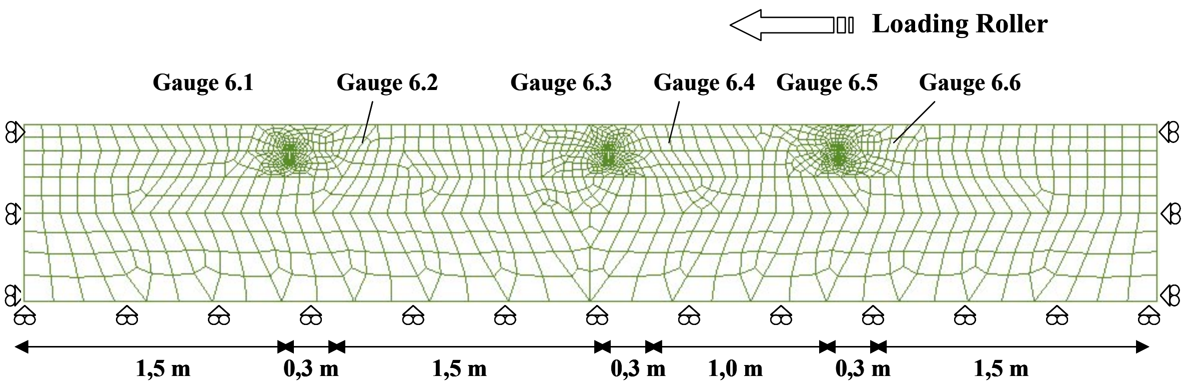


Figure 3 – Finite element discretization for the longitudinal cross section of the pavement.

II. Description of the CIMNE work carried out in the WP4 and WP7 work packages.

The present report shows a description of the activity carried out by the CIMNE as leader of the tasks 4.1, 4.2, 4.4 and 7.3, corresponding to the constitutive models and finite element simulation of the rehabilitated pavement.

These three tasks (T4.1, T4.2 and T4.4, see deliverable 4.1) belonging to the Work Package 4, driving by CIMNE, have been concluded satisfactorily in the elapsed time indicated in the proposal of the project.
Initially we had intended to simulate the behaviour of the pavement by means of a viscoelastic formulation with damage. This formulation began giving good results, but at then didn't have the capacity to adjust the loss of strength of the material for different speeds of application of loads.

This model limitation was solved with a new viscoplastic formulation, which has been able to obtain good results.
Overcome the problems of adjustment of the non-linear models formulated, these models are correctly running in the finite elements program developed by CIMNE.

Regarding to the 7.3 task of the Work Package 7, leading by CIMNE, we will present a brief description of the activity carried out by the CIMNE. Basically, CIMNE has been developed a special model to simulate the fatigue process. This formulation, compatible with the viscoplastic model formulated in the WP 4, allows evaluating the life of a pavement subjected to the cyclic type of load. The developments reached in the fatigue life prediction are basics, but the carried out tests show a great future for this procedure that has been transported from the metals and adapted to the pavements.

The UPC and COPCISA have developed experimental studies "in-situ" on a new highway pavement subjected to static and dynamic loads. The CIMNE has reproduced part of these static tests that coming from extracted samples of the highway (see deliverable 7.1), obtaining good numeric results as those that are shown in the mentioned deliverable. The results of fatigue in pavement that we have obtained are basics and they consist on the simple verification of the numerical behaviour of the constitutive model and it will begin to be applied in the future, thanks to the knowledge acquired in this project.

The numerical cyclic results will be compared with those experimental studies obtained by the UPC. Starting from our model with the calibration made from the laboratory values we try to validate our formulation according to real pavement's behaviour.

4.17. CONSTITUTIVE MODEL FOR NON-LINEAR MODELLING OF ASPHALT CONCRETE.

IN THIS PART OF THE PROJECT A VISCO-ELASTIC MATERIAL MODEL HAS BEEN FORMULATED AND IMPLEMENTED INTO THE FE PROGRAM ABAQUS. THIS MATERIAL MODE IS USED FOR SIMULATION OF THE VISCOUS RESPONSE OF THE ASPHALT CONCRETE

4.18. STRUCTURAL MODELLING TECHNIQUES FOR NUMERICAL SIMULATION OF THE RESPONSE OF ROAD STRUCTURES WHEN SUBJECTED TO TRAFFIC LOADS.

DIFFERENT TECHNIQUES FOR DESCRIBING THE GEOMETRIC DESCRIPTION OF THE ROAD STRUCTURE IN THE FE PROGRAM ARE EVALUATED E.G. 2D AXI-SYMMETRIC OR FULL 3D REPRESENTATION.

4.19. IMPLEMENTATION OF SUB ROUTINES FOR INCORPORATION OF TEMPERATURE DISTRIBUTION WITH EMPHASIS ON THE ASPHALT LAYER IN THE ROAD STRUCTURE.

THE TEMPERATURE IN ASPHALT CONCRETE LAYER IS ONE OF THE MOST IMPORTANT FACTOR FOR ESTIMATION OF THE SERVICE LIFE FOR THE ROAD STRUCTURE IN COURTIERS WITH LARGE TEMPERATURE DIFFERENCES BETWEEN COLD AND HOT SEASONS.

4.20. IMPLEMENTATION OF THE RESULTS OBTAINED IN 1-3 ABOVE INTO THE ROAD DESIGN SOFTWARE VÄGFEM.

THIS SOFTWARE IS DEVELOPED IN COOPERATION BETWEEN CHALMERS AND THE SWEDISH NATIONAL ROAD ADMINISTRATION WESTERN REGION.

Computer software development for road design including recycled asphalt concrete materials.

The development of software for road design in which recycled asphalt concrete is utilized has strong resemblance with the procedure of creating general road design software. This is due to the fact that if a methodical approach is taken in the process of describing the structure (structural models) and the materials (constitutive models) the difference between using virgin material versus recycled material can be taken care of in the two models described above. The different phases that has been included within the different work packages outlined in the PARAMIX-project concerning the development of a road design software including recycled asphalt material are as listed below.

- Structural modelling of a road structure

The first and the most essential step is the selection of method to build the new design software on. In this case the selection was made based on the fundamental needs for software that should be used in design procedures i.e. reliability and proven usefulness. In this case the Finite Elmont Method was the obvious choose based on its versatility and that it is used in several application from aerospace to biomechanical applications. Modelling of road structures was performed and literature surveys were also conducted at this stage to evaluate how the geometrical models within the FEM environment should be describe i.e. if 2D would be sufficient or if full 3D representation was needed. The conclusion of this research is that in order to be able to simulate deterioration processes such cracks in the asphalt material a full 3D representation is needed. The 3D representation also makes it possible to include essential boundary conditions such as slopes and other physical limitation of the structure in the lateral direction.

Main achievement: Choice of modeling technique and base for the design software to be built on.

- Material models for recycled asphalt

As stated above the material models that are going to be used in a road design software has to be able to describe the rheological behaviour of asphalt. This means finding a mathematical formulation that can mimic it behaviour when subjected to different types of loads. The material test performed at UPC and test presented in international journals clearly indicates a viscous behaviour. Based on this knowledge a visco-elastic material model was formulated and finally implemented in the general-purpose finite element program ABAQUS. The chosen material model can be calibrated by the use of the material tests suggested by the PARAMIX-partner UPC but also by test data from another type of test called frequency sweep test. The second method mentioned is used in Sweden by research institutes as well as in the new AASHTO 2002 design guide that was handled over to Federal Highway Administration (FHWA) earlier this year.

The road mechanics research team at Chalmers University of Technology have also performed research in the field of simulation of environmental loads, such as temperature, in order to simulate the temperature distribution in a road structure at a given point in time. This is of immense importance for design of new roads or when planning maintenance tasks under Nordic conditions since the behaviour of the asphalt concrete placed on top of the structure is very temperature sensitive. The research performed within these areas are presented in the Ph.D. thesis[i] that was presented by Johan Olsson at the department of Structural Mechanics at Chalmers University of Technology in May 2003.

Main achievement: New material model for asphalt implemented.

▪ Material models for unbound materials

During the first months of the third and last year of the PARAMIX project Dr. Johan Olsson has been working with the implementation of analysis of constitutive models for unbound road structure materials. The research has been focused on a non-linear elastic model, which also has been used in the US design code for this purpose. The non-linear response has been treated as one of the main issues to be dealt with in the designing of the new federal design code for road structures developed in the US which was handed over to the Federal Highway Administration (FHWA) earlier this year by the AASHTO 2002 design team. It has been proven in the literature that the response of the unbound road materials is clearly non-linear when subjected to loads. This feature is included in the structural model described above through the use of a non-linear elastic material model that has been implemented into ABAQUS in order to better model the behaviour of the road structure.

Main achievement: A material model for unbound material implemented.

▪ Implementation of the method into real road design

In order to make the introduction of the FEM into real pavement design procedures an educational program has been started within the Swedish National Road Administration Western Region. This educational program is ongoing and Chalmers is taking part in the project. During November 2003 and January 2004 Dr. Johan Olsson has attended these meeting in form of lecturer and as technical expert answering questions regarding finite element method based design tools. Attending these meeting has been as selected group of consultants and representatives from Swedish construction industry. The intension is to let them use the finite element method parallel to the existing approved method on ongoing project and through process get them used to new design tool and eventually if everything works out replace the existing design procedures with new ones. Dr. Olsson has also participated in educational program aimed at the geotechnical department of Swedish National Road Administration Western Region and has during the last year during April through May 2003 lectured in the subject of finite element analysis in geotechnical application. This program also serves the purpose of integrating finite element analysis in the other department to get the method widely accepted in the civil engineering application of interest for the Swedish National Road Administration.

During the last year Chalmers has been involved in the development of a new Swedish road design software. The project was initiated by the Swedish National Road Administration Western Region and is a cooperation between Chalmers and Volvo IT. The product is called VÄGFEM and is a road design tool based on FEM. A first version of the program is currently beta tested by a selected number of Swedish construction companies and consultants. Development of VÄGFEM has made it possible to implement results achieved by the Chalmers research team into a future road design software that are being implemented in the construction industry.

Main achievement: Initial implementation of the method in the construction industry.

EXPERIMENTAL TRACKS CONSTRUCTION

4.21. CONSTRUCTION PROJECT CONCERNING TO THE SPANISH EXPERIMENTAL TRACKS

GISA, as a Catalan public works management company in Spain, has contributed to the general objectives of the project sharing its experience in the management, technical assistance and coordination of the road reinforcement works promoted by the Catalan Ministry of Town and Country Planning and Public Works. It has adopted the role of supplying all the administrative and legal tools as well as the technical knowledge that has concluded with the choice and management of the reinforcement project that has helped to the development of the project. According to this, it can be stated that the main objectives of GISA as a partner of the consortium have been accomplished in the scheduled period.

The accomplished objectives during the 36 months of the contract may be summarised as follows:

- Administrative management and technical coordination of the drawing-up of the project: "Reinforcement and other works. Road C-58 from Terrassa to Castellbell i el Vilar, from kilometre 23+370 to kilometre 28+406. ", keyword RB-00092.1, that includes 11 experimental sub-tracks.

- Administrative management and technical coordination of the works related to the mentioned project.

- Support to experimental testing of rehabilitated pavement tracks, including extractions of cores and study of pavement deflection.

COPCISA, as a general construction company, has carried out the works of construction of the 11 experimental tracks in Spain.

COPCISA also provided the manpower and material assistance for the collection of milled materials to perform the preliminary design of mixtures. At the end of the construction period, COPCISA provided the assistance in terms of machinery and road surveillance to perform the auscultation campaigns on the Spanish experimental tracks.

The experience has allowed to compare the relative advantages of the three basic recycling techniques: ordinary fresh asphalt reinforcement, hot in-plant recycling and reinforcement, and cold in-situ recycling plus top finishing reinforcement.

The cost analysis of the experimental tracks construction, gives some clues to the general approach to a rehabilitation project on a section of road.

It must be pointed out some of the general results:

- Cold in-situ recycling techniques have shown a good behaviour under heavy traffic condition. The only major constraint seem to be sections where great shear efforts by traffic are expected, specially in the transversal sense of the traffic flow (crescents).
- Hot in plant recycling has been performed successfully being in all cases beyond Spanish standards: RAP has been used on top layers and on micro mixtures; percentages of RAP are above Spanish constraints.
- Cold recycling feasibility is bond not only to traffic intensity or environmental weather conditions, but rather to a combination of them. This extends its suitability to heavy traffic roads sections with rather straight shape, provided that good weather periods can be used for the construction.
- Cost study versus technical warranty of the future behaviour of the mixtures can be matched in case of an intense study of important sections of road to be rehabilitated, where the cost of these preliminary studies can be mortgaged.

In all cases, it must be pointed out that the evaluation period is very short in terms of a road life-cycle, but laboratory tests performed in the PARAMIX project (both regarding mechanical properties and fatigue behaviour) allow to be daring and optimistic on the feasibility of these techniques.

AUSCULTATION

4.22. NEW PARAMETERS TO CORRECT RELATIVE MOISTURE EFFECT ON CENTRAL MEASURED DEFLECTION WHEN COMPARING SEVERAL DATA AUSCULTATION.

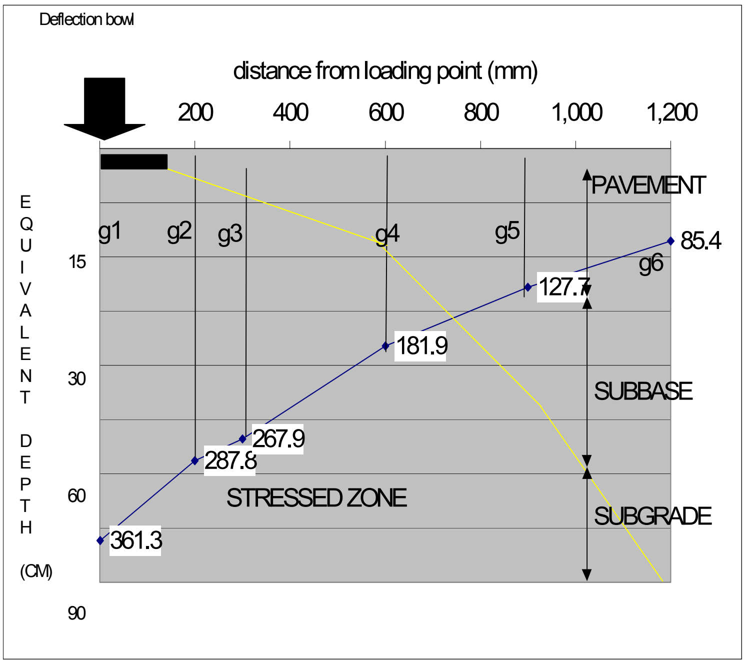
1. STRUCTURAL EVALUATION

LGAI has carried out a complete road structural evaluation before and after the recycling actions were performed on the experimental tracks, located in C-58 road (near Terrassa City).
Structural study has also consisted of the installation of 12 gauges, 6 on hot recycled and 6 on cold recycled tracks. The aim was to measure horizontal strains on the lower surface of the recycled layer and use them to calibrate CIMNE's pavement behaviour model.

INTRODUCTION

Paramix project has twenty-two 300 meters long test sites. All the tracks have a different recycling solution.

The experimental site located in Spain has 2 lanes, the right lane goes from Terrassa to Vacarises(RL) and the left one goes from Vacarisses to Terassa(LL). In the next page we can see the main traits of the recycled actions designed in Spain (Table nº1).



It has been carried out a structural evaluation, using NDT tests (Non Destructive Tests) and core extractions, to know layer mechanical parameters and thickness, before and after the recycling process. On February and December of 2003, horizontal strains were measured under the compacting machine and the FWD load by the 12 gauges installed in track nº6 of the left lane (cold recycling) and in track nº7 of the right lane (hot recycling). Collected data had been used to calibrate the pavement behaviour model and to estimate dynamic layer modulus.

NDT technology is probably the best way to estimate road structural bearing capability because of, each compression layer can be estimated. The secret lies on measure surface deflections at several distances from the load applied point. As we can see in this picture above, the central deflection comes from all road structure because all layers are stressed. But if we pay attention to deflections measured at some distances from the load plate, we can see that as far we measure that deflections as smaller is the stressed zone underneath each measuring point, and therefore, as smaller is the measured deflection. The measured deflection comes form all layers located underneath the equivalent depth that is equal to distance from the load plate to the measuring geophon. For example, d1 is the total structure deflection and d3 is the deflection coming from 300 mm of equivalent depth to the bottom layer so, if we subtract d3 from d1 the compression of the first 300mm of road structure can be estimated. This can be assumed by transforming the multi-layer system into a one-layer system following the equivalent thickness and Boussinesq theory (Odemark method). So, we can consider a homogenous and isotropic material and say that the equivalent depth is equal to the geophon position distance. In other words, by collecting NDT data we are able to estimate the stiffness of each road layer (layer modulus and compression parameters).

TRACK Nº	LANE	THICK. (cm).	ACTION	BINDER OR EMULSIÓN
1	R	10	COLD	ECL-2(V1)
1	L	10	COLD	ECL-2(V2)
2	R	10	CONVENTIONAL	B-60/70
2	L	10	CONVENTIONAL	B-60/70
3	R	15	HOT 30% RAP	HIGH MODULUS BIND.
3	L	15	HOT 30% RAP	HIGH MODULUS BIND.
4	R	15	HOT 30% RAP	HIGH MODULUS BIND.
4	L	15	HOT 30% RAP	HIGH MODULUS BIND.
5	R	15	HOT 50% RAP	B-150/200
7		10	HOT 30% RAP	B-80/100
8	R	5	CONVENTIONAL	B-60/70
8	L	5	CONVENTIONAL	B-60/70
9	R	10	COLD	ECL-2-m
		10	HOT 50% RAP	B-150/200
9	L	15	COLD	ECL-2
10	R	3	SURF. 30%RAP	
10	L	3	SURF. 10%RAP	
11	R	15	COLD	ECL-2-r

Table nº1 Recycling actions in Spain

1.1. TESTS AND WORKS CARRIED OUT FOR ROAD EVALUATION

- **Core extraction**

We have obtained road cores before and after the road rehabilitation.

Before road rehabilitation, the test site structure estimated by extracting about a hundred of cores was as follows:

A 4 cm of reinforcement wearing course (layer A).
A 5.5 cm of reinforcement base course (layer B).
A 4 cm of old wearing course (layer C).
A 9 cm of old base course (layer D).

Layer A and B, are the overlays used to improve the old surface layer irregularities and increase pavement structural capacity. During core extraction, low bearing capacity of C layer was exposed. There was no way to take out a complete core because it was like an unbound material. Underneath the asphalt layers, we have a 15 cm thickness of muddy sand and gravel as road base and a slate stone (Licorella) as subgrade.

After the recycling works the new structure became as follows:

-A 5 cm of reinforcement wearing course (layer A').
-A 10/15 cm of hot or cold recyclied base course (layer B').
-A 4 cm of old wearing course (layer C).
-A 9 cm of old base course (layer D).

- -**<u>Non Destructive Tests (NDT)</u>**

Non destructive tests had been performed to measure the road structural capability. We have used a Falling Weight Deflectometer and a Lacroix-05 deflectograf for measuring deflections. The strctural evaluation is going to be focused on FWD data, collected each 10 meters, taking also into account Lacroix-05 data, collected each 5 meters.
Measurements performed employing the FWD and Lacroix had been compared. Both devices had measured, more or less, the same deflection (dFWD=dLacroix) due to the high pavement structure stiffness (correlation between both devices depend on road stiffness).

-NDT test had been performed with the Falling Weight Deflectometer as follows:

-C-58 road had been tested two times before recycling actions. Tests are called in chronological order, BR0(07/06/02) and BR(19/09/02) (wearing old layer,A).
-Gauges position had been tested before recycling actions (wearing old layer, A).
-Milled surface had been tested at each hot recycled track before recycling actions (layer C).
-Gauges position had been tested after recycling actions (New recycled pavement layer,A2).
-Recycled pavement, had been tested after the recycling action (New recycled pavement layer,A2).
-Wearing layer had been tested 3 times after recycling the action which are called AR1(24/04/03), AR2(27/05/03) and AR3(10/12/03)(all three were performed above the new wearing layer, A’).

-NDT test had been performed with the as Lacroix-05 deflectograf as follows:

-C-58 road had been tested one time before recycling.
-Recycled pavement had been tested after the recycling action, the 05/2003 and the 12/2003 (New recycled pavement layer, A’).

Main FWD test traits are:
Plate radius: 150 mm
Geophons distance: 0/g1 200/g2 300/g3 600/g4 900/g5 1200/g6 (distance from load plate/geophone)
Applied load: about 65 KN.
Load pulse: 35 □sec (moving axle at 60 km/h)
Temperature measurement: Air, pavement surface and 5 cm deep pavement layer
Deflections measured each 10 meters

Main Lacroix test traits are:
The vehicle measures deflections at 3 km/h.
Deflections are measured each 5 meters. The applied dynamic load is 65 Kn and the contact pressure is about 919 Mpa.

Main FWD and Lacroix results traits are:
Layer modulus: Layer modulus are estimated by backalculation process following Boussinesq and equivalent thickness theory and are adjusted to 20ºC of temperature and 65 KN of applied load. It had been used the AASTHO equation for modulus temperature adjustments.
Deflection data: Deflections are adjusted at 20ºC of temperature and 65 KN of applied load.

1.2 ROAD BEARING CAPABILITY EVALUATION:

The aim of collecting NDT data is to evaluate the increase of pavement layers bearing capability due to the recycled actions performed at the experimental tracks. We have analysed collected data by using two different methods. The first one estimates the pavement layers bearing capability and the second one the total road structure strenght.

The first one is the backcalculation technique. It's an iterative process that try to fit the calculated deflections with the measured one, by changing the layer modulus and taking into account parameters as poisson ratio, layer thickness and pavement temperature. Due to the local minimus to be sure that we have found the right solution, a direct calculation is a must. Therefore, to reach this goal central deflection and data collected with horizontal gauge, installed on track number 7, had been used as the objective of the forward calculation to adjust the layer modulus.

The second one takes into account just the central deflection. First of all, to compare both situations (the bearing capability before and after pavement recycling), the central deflection must be corrected because of the influence that moisture has on granular layers. Spanish standard try to corrected by calculating a parameter, ch, that depends on how rainy has been the last month and a half but when we are trying to check small gaps, a more accurate parameter, that reflects local moisture variation, is going to be used.
As has been explained, the farthest geophone measures displacements coming from the bottom part of the stressed area caused by the dynamic load. So if we compare subgrade displacements with several moisture conditions we can adjust them to the highest moisture content (*Chi=d6(wmax)/d6(wi),* where *d6(wmax)* is the deflection with the highest moisture contents and *i* is data collect date, measured at 1200 mm from the load point.). We assume that any deflection increase is due to the damage caused by the trucks that had ran through the test sites between the measurements dates.

All two methods are based on the elastic theory. It is supposed that the road structure is made of a homogeneous and isotropic material. So, Boussinesq equations and the equivalent thickness method can be applied. On the other hand, we have corrected moisture effect when the bearing capability has been analysed by the second method. We didn't used any moisture correction when back calculated the layer modulus.

For road bearing analysis, we had used BR, AR1 and AR3 data.

1.2.1 BACKCALCULATION METHOD ANALYSIS

Pavement layers capability before and after recycling actions is now shown in the following layer modulus table (E1 is the pavement modulus).

Layer modulus had been corrected to 20ªC of temperature following the AASTHO formula.

Left lane	19/09/02	24/04/03	10/12/03
	BR	AR1	AR3
modulos Mpa	**E1**	**E1**	**E1**
Track 1	**3731**	**2203**	**3534**
Track 2	**4537**	**4268**	**5584**
Track 3	**2928**	**4421**	**6191**
Track 4	**3258**	**6175**	**6295**
Track 5	**3456**	**3704**	
Track 6	**3583**	**3749**	
Track 7	**4670**	**4805**	
Track 8	**5393**	**3785**	**5315**
Track 9	**5120**	**2819**	**3285**
Track 10	**4838**	**4192**	**4640**
Track 11	**2713**	**4230**	
average	**4021**	**4032**	**4979**

Table 2. Left ad right lane layer modulus. Average track values.

Rightlane	**BR**	**AR1**	**AR3**
modulos Mpa	E1	E1	E1
Track 1	**4536**	**2165**	**3470**
Track 2	**3771**	**5157**	**6220**
Track 3	**3356**	**4109**	**6347**
Track 4	**3216**	**3588**	**6489**
Track 5	**3135**	**5299**	**7332**
Track 6	**3972**	**5818**	
Track 7	**3915**	**4731**	**4883**
Track 8	**4566**	**4118**	**6066**
Track 9	**3211**	**2760**	**5038**
TRAMOS 10	**4569**	**4252**	**4708**
TRAMOS 11	**3145**	**4107**	**4600**
average	**3763**	**4191**	**5716**

As has been explained before, the back calculation method consists of fitting calculated deflections with measured. This goal is carried out by a iterative process. That means that one has to know how far is the real deflection bowl from the calculated one because the method does not always provides reliable results. In our case, the fit of all calculated deflection bowl is quite good ($R^2 < 1$).

Road evaluation performed before and after recycling works show, right now, that cold recycling process has arrived to different level of performance depending on the track. Hot recycled has increased pavement layer capability in all tracks were it has been performed. We can see how bearing capability increases when hot recycling pavement had been used as base layer. On the other hand, we can notice how cold recycled tracks have a low structural capability during the first month but in 12 months of live, they have reach similar values to original ones, and therefore why don't suppose that they are going to continue increasing during some more time. So, under a structural point of view it seems that recycling techniques can improve right now, road lives.

Another thing that we have to take into account is that cold material is much more flexible than hot ones. That means that it can have a better behaviour in the future, lasting more than the hot one. We have to know the long-term hot and cold behaviour to conclude which has been the final road structural improvement.

Cold tracks have reached a dynamic layer modulus, caused by a 65 kN load, about 3430 Mpa (cold tracks average), and hot about 6340 Mpa. The conventional reinforcement had reach a value about 6046 Mpa.

To be sure that the estimated dynamic modulus are closed to real one we have compared them with the Instant Resilient Modulus calculated by UPC at the road laboratory. As we can see in the next figure we have found a good fit between them.

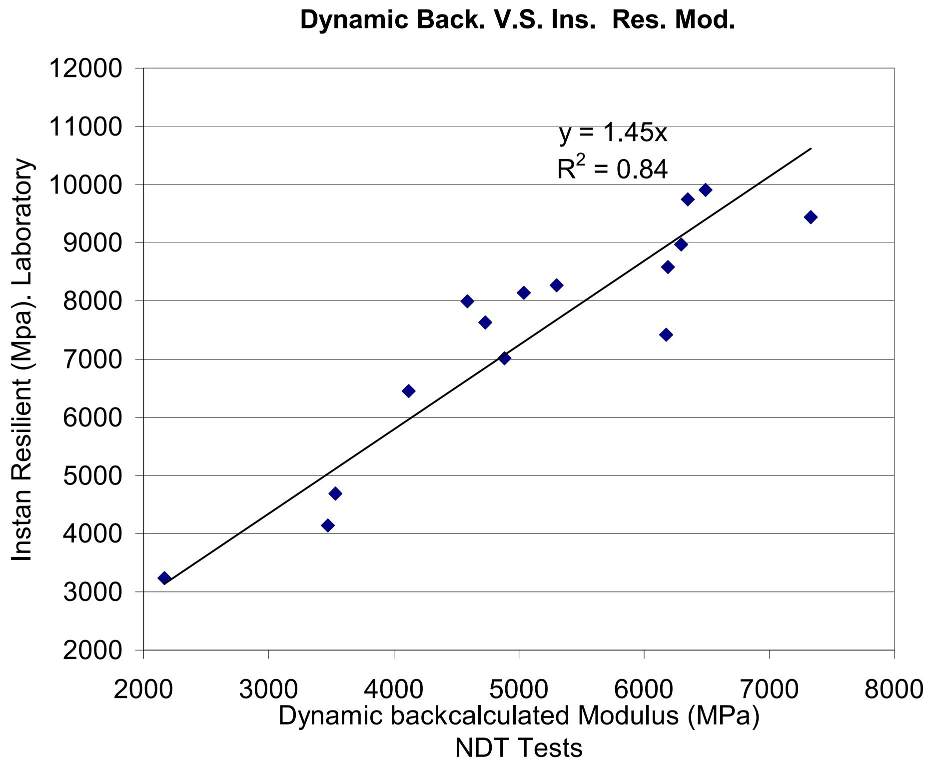


Figure nº 1**.** Relationship between Dynamic Back calculated Modulus and Instant Resilient Modulus calculated at road laboratory with core tests.

1.2.2 STRUCTURAL CAPABILITY ANALYSYS WITH CENTRAL DEFLECTION

Total road structure analysis by means of measured central deflection.

Now, we are going to take it into account the central deflection and correct the moisture effect on it. The aim is to define a new method to correct central deflection as they were measured in the worst moisture condition (the more wet). In our case the subgrade was more wet in AR1 auscultation than in the other dates. That can be checked by the subgrade layer modulus and also by d6 deflections.
In the next table we can see the corrected deflections coming from the total road structure. The moisture correction had been calculated as follows- Corrected deflection = *Chi* * Measured deflection.

Average *Chi*	1.35	1.00	1.24
Right lane	BR	AR1	AR3
Track 1	44	48	41
Track 2	34	28	25
Track 3	56	39	34
Track 4	39	30	28
Track 5	43	27	25
Track 7	40	26	25
Track 8	36	25	27
Track 9	46	36	26
Track 10	42	29	31
Track 11	44	26	23
Average	42	31	29

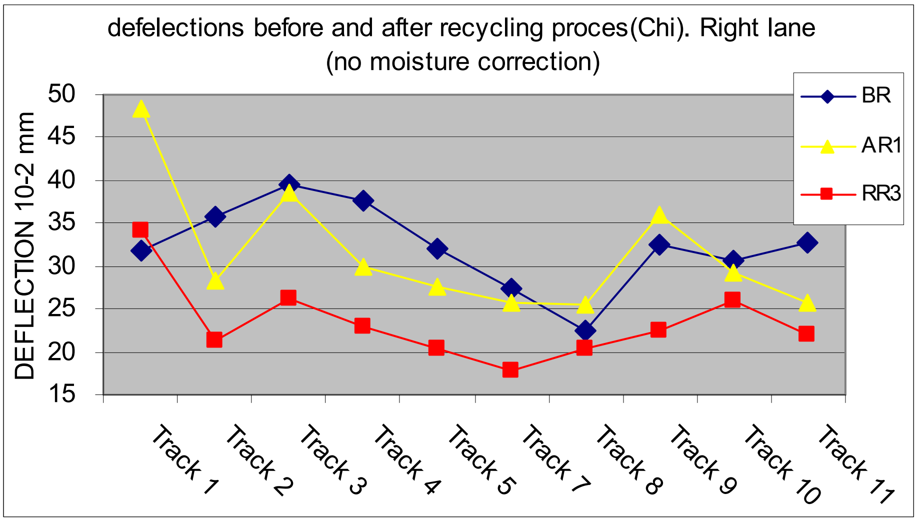
Average *Chi*	1.26	1.03	1.24
Left lane	BR	AR1	AR3
Track 1	40	44	38
Track 2	47	28	27
Track 3	43	26	26
Track 4	57	27	24
Track 6	33	28	
Track 8	31	32	26
Track 9	38	32	32
Track 10	35	26	30
Average	41	30	29

Table nº3. Deflections corrected

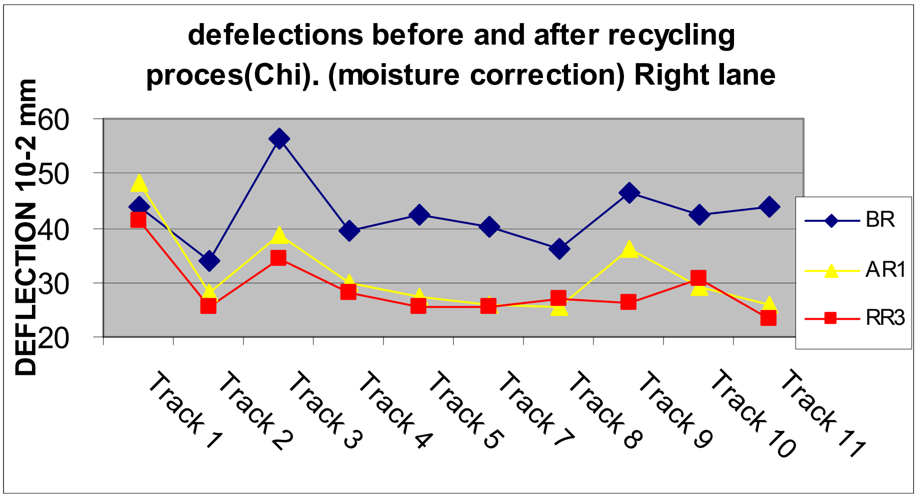
In all the tracks the central deflection had diminished after the rehabilitation actions.

Taking into account the layer modulus we are analysing the pavement layer but with the central deflections we are estimating the total road structure strength. By means of the second one, small gaps are more difficult to catch, but comparing the two methods we can see how, more or less, they agree. The lack we have to solve, if we want to correct the total moisture effect, is that we should know which deflection should be expected with the worst wet conditions on granular layers. Now we are correcting data taking into account the more wet deflections of the performed tests (AR, BR1 and BR3), but we don't know if AR is the wettest situation of the subgrade.

In the next figures we can see deflections without correcting the moisture effect and correcting it. We can see how, when correcting it results have more sense than without doing it.



Deflections non corrected to the wettest situation of the right lane (Figure nº2).



Deflections non-corrected to the wettest situation of the right lane (Figure nº3).

REHABILITATION GUIDELINES

4.23. PROPOSAL OF REHABILITATION METHODOLOGY AND RULES

A. Recommendations and improvements in the design, production and reliability analysis of rehabilitated asphalt pavements using cold recycled asphalt mixtures

1. MIXTURE DESIGN

1.1 Characterisation of the milled material

In order to be able to optimally develop and adapt the emulsions that are going to be used in cold recycling process, it is necessary to carry out the following tests:

- Grading of the milled material without having extracted the old binder. This will be the material directly used in the cold recycling process. It should be taken into account that excessively large sizes of the milling will negatively influence the final behaviour of the recycled mixture. Therefore, besides the grading of RA is a needed input for cold recycling, it can also be considered as a tool that can help to know the operation conditions of the milling machine and to adjust them, whenever possible. Also the specific surface of the milled material can be taken into account to better adapt the percentage of emulsion to be used.
- Characterisation of the old binder; considering mainly the binder content, its penetration and softening point (R&B).

1.2 Selection of the emulsion

The emulsion selection should be done by evaluating the emulsion behaviour together with the milled material and therefore, it is necessary to verify at the same time, the minimum percentage of added water needed as well as the percentage of emulsion required. Only in that way, it will be possible to evaluate the following:

- Aggregates coating test: a minimum of 90% of covered surfaces should be required (test procedure described in Deliverable 1).

- Active adhesivity: a minimum of 75% of covered surfaces should be required (test procedure described in Deliverable 1)
- Passive adhesivity: a minimum of 75% of covered surfaces should be required (test procedure described in Deliverable 1)
- Workability

Once, an estimation of the behaviour of the cold recycled mixture has been performed through the above mentioned tests, a further evaluation and optimisation of the cold mixture should be done in order to definitely establish the formula as well as the final behaviour of the mixture:

- Retained compressive strength test: minimum values of retained strength of 75% should be required.
- Indirect Tensile Test

1.3 Dosage of the mixture

The cold recycled mixtures design methodology is based on the indirect tensile test. First of all, it is determined the optimum moisture content of compaction of the milled material by means of Modified Proctor Test, which is a reference value for the compaction fluids (water plus emulsion). Starting from this value, the water and the emulsion contents are modified in order to obtain a proper coating and a high cohesion of the mixture. That way, it is determined the coating quality evolution and the indirect tensile strength evolution for different emulsion and water contents. The minimum number of specimen tested for each emulsion and water content, and for each testing condition is of 3 specimen

Specimen manufacture

Two procedures have been developed for the specimen manufacture, one, using a press for the manufacturing of the specimens by applying a static compaction, and the other, compacting with the gyratory machine.

Static compaction

The static compaction consists on manufacturing a cylindrical specimen of 101.6 mm of diameter and 5-6 cm of height, by pouring the material into a metallic mould of 101.6 mm of diameter. A compaction load is applied by a piston, with a deformation speed of 1.27 mm/min until the compaction load achieves 60 kN, which must be held up during 2 minutes.

Gyratory compaction

The gyratory compaction consists on applying 300 revolutions with a gyratory compactor. The pressure must be of 0.6 MPa and the angle of 1.25º. The specimens obtained, again with a 101.6 mm diameter and a 5-6 cm of height, have also similar densities and resistance to the cores extracted from the field.

The Swedish practise developed is to use 150 mm perforated molds, a pressure of MPa and an angle of 2º. The number of revolutions is limited to 35. The perforated moulds allow water to be released during the compaction process.

Curing process

Once the specimens are manufactured by using one of the methods explained above, they are removed from the moulds and they are brought about to an accelerated curing process, which takes place inside an oven at 60ºC during 3 days.

The Swedish practise is to cure in room temperature for one week and in a ventilated oven (40ºC) for one week.

Testing process

Dry test (conditioning of the specimen)
Once the specimens are cured, they are introduced in a chamber where temperature can be controlled. The specimens are inside the chamber at 5ºC during at least 4 hours in order that they reach the temperature homogeneously.

Testing after immersion (conditioning of the specimen)
In this case, the specimen will be introduced in water at 60ºC during 24 hours. Then, they will be air dried during 8-12 hours before placing them inside the temperature controlled chamber. As in the previous case they will rest in the chamber a minimum of 4 hours at 5ºC. Finally, they will be tested.

During the testing process, the load displacement speed (50.8 mm/min as Marshall speed test) must remain constant until the breaking of the laboratory sample. Both the load and the displacement are registered, and the indirect tensile strength or resistance is calculated by means of the following expression:

$$R_{TI} = (2 \, . \, P) / (\square \, . \, h \, . \, d)$$

where,
R_{TI}, is the indirect tensile strength (in $N.mm^{-2}$, MPa),
P, is the breaking load (in N),
h, is the height of the specimen (in mm) and,
d, is the specimen diameter (in mm)

Design criteria

The emulsion content to be used will be the one which allows to achieve a minimum indirect tensile strength of 1.0 MPa. The test will be carried out at 5 ºC, determined on a specimen manufactured by static or gyratory compaction, after an accelerated curing process of 3 days in an oven at 60ºC. The minimum retained resistance (after water immersion during 1 day at 60ºC) is of 75%.

2. PRODUCTION

2.1 Enhanced milling drum and mixing chamber

The grading and mixing degree can be improved by changing the forward speed of the recycling machine, by changing the arrangement of the cutting tools on the milling drum and by changing the volume and exit area of the milling and mixing chamber on the recycling machine.

The improvements are :

- Extra „Paddles“ for improved mixing and transportation of the material being recycled
- Changed cutting tool arrangement
- Changing the internal shape of the milling and mixing chamber

The results are :

- approx. 60 % increase in advance speed
- improved grading
- improved material flow

2.2 Warming-up the material

A new heater system has been developed.

The new and old heater system of the Wirtgen HM 4500 was compared and tested.

The improvements are:

- new heater panels with combination of IR and fresh air heating

The results are :

- reduction in smoke emission
- 33 % saving in gas consumption
- improve binder coverage and compactability.

3. COMPACTION

The main recommendation one should consider when facing both cold recycling lay down and compaction of the mixture is to control the evolution of the mixture nuclear densities as long as the rollers pass properly over the mixture till the densities stabilize and get their maximum level.
The improvement is the new generation screed with vibration plates and tamper bar fitted on the Wirtgen 2200 CR .
The result are fewer roller passes after pre-compaction by the high compaction screed.

4. STRUCTURAL CONTRIBUTION

4.1 Deflection analysis

This chapter is going to be focused on cold recycling recommendations to evaluate the structural contribution due to the rehabilitation actions.

4.1.1. Structural evaluation of cold recycled tracks

The structural evaluation can be done by using NDT tests with a Falling Weight Deflectometer and by extracting road cores.

a) Tests and works carried out for road evaluation

Road Coring.
To obtain a representative number of road cores to know pavement layer thickness before and after the recycling actions. This information is being used as an input for back calculation methods.

Deflections measurements

To measure road deflections under 65 kN dynamic load with a FWD. Deflections have to be measured before and after the road rehabilitation. This data is going to be used for structural analysis.

As we are talking about cold recycling, tests after the recycling works must be done at least twice, after six and twelve months from the end of the rehabilitation works.

It is very important to know the moisture content of the granular layers, because it can cause variations on the measured deflections. To reach this goal, piezometers should be installed on road structure.

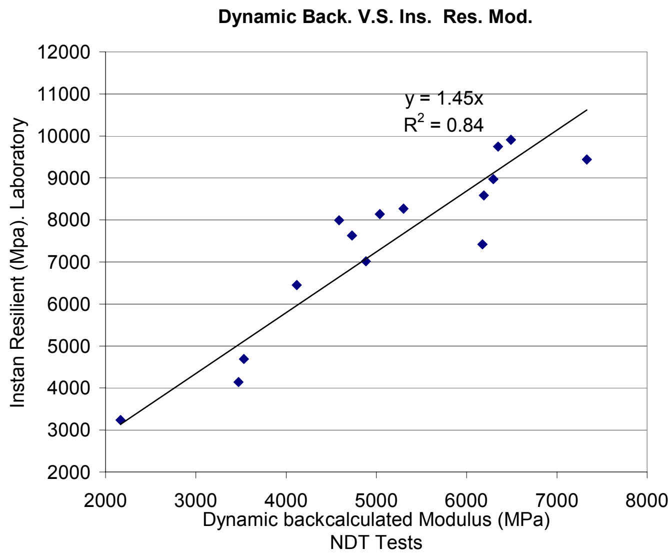
b) Road bearing capability evaluation

The structural evaluation has to be done through the central deflection and through back calculation methods.

b.1) Back calculation method

To estimate the dynamic modulus of pavement layers, deflections had to be analysed by using back calculations methods. As it consists on an iterative process, horizontal strains data measured by means of horizontal gauges installed underneath the recycled pavement layer, must be collected to perform forward calculations for mechanical parameters adjust purposes.

On the other hand, laboratory tests (Instant Resilient Modulus) had to be performed on road cores to compare laboratory and analytical results (Dynamic Modulus of Pavement Layer). An example can be seen in the figure below.



b.2) Central deflection method

To check the variation of the total road structure strength, a central deflection analysis have to be done taking into account collected deflections before and after the road rehabilitation.

First of all, to compare both situations (the bearing capability before and after pavement recycling), the central deflection must be corrected because off the influence that moisture content has on granular layers.

A parameter that reflects local moisture variation has to be used. On the FWD, the farthest geophone measures displacements coming from the bottom part of the stressed area, caused by the dynamic load (coming from the subgrade). So if we compare in the same test point some subgrade displacements measured at different test date with several moisture conditions we can adjust them to the highest moisture content by calculating Chi parameter;

Chi = d6(wmax) / d6(wi) , where *d6(wmax)* is the farthest deflection with the highest moisture contents and *i* is data collect date, measured at 1200 mm from the load point)

And correcting the measured deflection;

Corrected deflection = Chi* measured deflection

With Chi we can corrected deflections measured at a dry day.

4.1.2. Conclusions

Dynamic modulus

We are expecting dynamic modulus of the cold recycling pavement layer to be about half of the dynamic modulus of conventional pavement layer. Cold material used to double its strength during the first year of live.

Dynamic modulus is not a long-term pavement behaviour parameter, so we cannot conclude about which is going to be its behaviour in the future. Because it is more flexible the cold pavement than conventional pavement, cold one could last more time due to its flexibility.

Deflections

Cold actions had diminished the total road structure deflection.

When we are comparing deflections before and after the rehabilitation works we have to correct the moisture effect on measured deflection.

4.2 Mechanical analysis

Numerical methods research partners propose a new methodology to analyse pavement's behaviour under static and dynamic loads, based on the constitutive models developed.

- This methodology consists in a software code that calculates the material's response under different loads, using as input the **geometry** of the multi-layered structure and **mechanical parameters** obtained from simple laboratory tests, like elastic Young modulus, Poisson ratio or yield stress for each material involved in the calculation process.

This constitutive values can be obtained from bibliographic references as well, for well known materials like granular layers, or applied loads like roller or pneumatic compactor.

- This constitutive parameters are used in the developed model based in the Finite Element Method, available for the end-users.

- The structural code offers as output the stress – strain distribution along de pavement structure, the deflections in the surface, the plastic strains in the pavement and the possibility of damage in the material, as well as the critical points in stresses or damage.

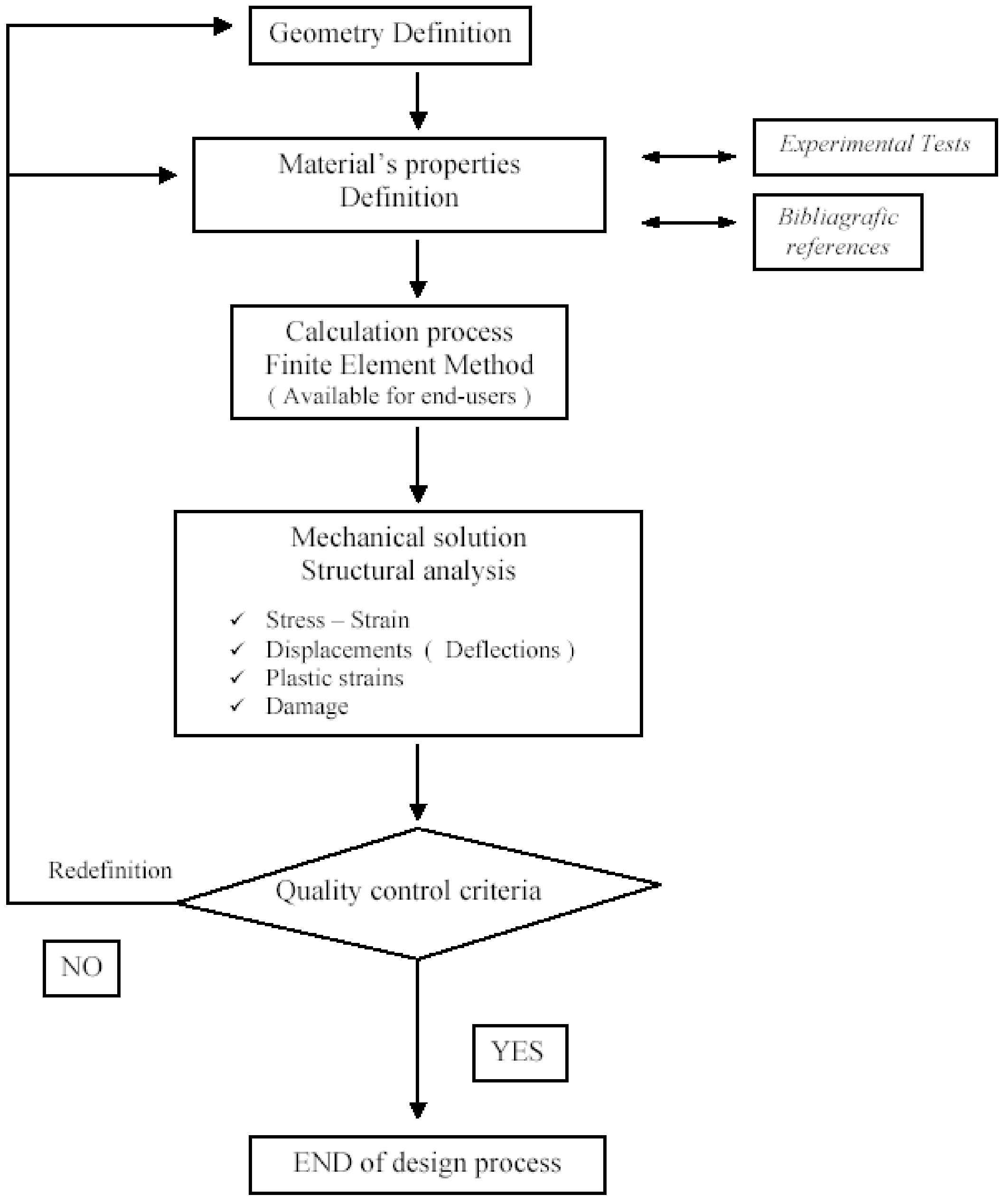
- That leads us to a mechanical solution the user can study to take conclusions about the pavement's behaviour. Once we have the simulation of the pavement's behaviour the end-user can apply some quality control criteria to evaluate the response obtained, so as to change the material, its properties, or the geometry, layers' thickness and so on.

- According to these quality criteria the user can stop the design method if the quality parameters are acceptable, or repeat the design with the changes in the geometry or the material's properties.

- This methodology can be used as many times as necessary until an acceptable solution is reached.

Methodology and rules for asphalt pavements' rehabilitation in road tracks

(CIMNE)



B. Recommendations and improvements in the design, production and reliability analysis of rehabilitated asphalt pavements using hot recycled asphalt mixtures

1. MIXTURE DESIGN

1.1 Characterisation of the milled material

The characterization of the milling material is a crucial step to determine if the milling material is useful for hot bituminous mixes. The following characteristics are important:

- Detection of tar in RA. Severe limits are imposed in certain European countries, because of environmental and health reasons. In case tar is present, further use in hot bituminous mixes is excluded in these countries. Therefore, this is a first necessary check to be performed.
- Grading curve of the RA: this is an interesting information in order to prevent of having very large RA sizes. It can be considered also as a tool that can help to know the operation conditions of the milling machine and to adjust them, if possible.
- Grading curve of the RA once the binder extraction has been done: this is crucial for the later design of the mix. Also, the grading curve of the "clean" RA, is predominant for the type of mixes that can be produced with a given RA, especially in the case of use of high percentages of RA.
- Characteristics of the old binder present in the RA: content, penetration, Ring&Ball temperature and detection of modification by polymers.

1.2 Selection of the new binder and new granular materials

The selection of the new binder should be based in the first place on the pen-rule of mixes of binders. For roads where high performance is required, special attention should go to the determination of the temperature susceptibility of the binder. For this purpose use is made of rheological measurements on the binders. The high temperature properties are determined by measurements by the dynamic shear rheometer at high temperature with determination of the parameters $G^*/\sin\delta$ or the zero shear viscosity are the most adequate parameters to be used as predictors for the rutting resistance of the binders. Together with the low temperature stiffness and the behaviour upon ageing, adequate binders have to be selected.

1.3 Dosage of the mixture

For the design of bituminous mixes with reclaimed asphalt the following mix design procedure can be followed. An analytical mix design is made by means of BRRC's software Prado-Win. This phase requires that most of the characteristics about the reclaimed asphalt and the new materials gathered in steps 1 and 2 are introduced as input in the software. The analytical design makes it possible to get a good estimate of the design of the bituminous mix. It limits the number of trials to be made in the laboratory and hence is very time-saving and gains personnel. Fine tuning of the mix can subsequently be done as a result of simple laboratory tests, such as gyratory testing or Marshall testing, by which the void content in the mix can be determined. Gyratory compaction of the mix is further recommended to check the compactibility of the mix.

1.4 Performance testing

In case of heavy traffic roads, or when high performance is required, further performance testing is required on the mix prior to production and laying. Various performance characteristics can be checked, depending on the application and on the requirements that are found important for the road under construction:

- Resistance to rutting: use can be made of the European (pre)standard prEN12697-22 , such as the large test device to determine the resistance to permanent deformation of the designed mix
- Resistance to fatigue
- Moisture sensitivity , stiffness and others

As a general recommendation, the bituminous recycled mixture should be controlled by the same kind of tests required to the same type of bituminous mixture and fulfil, at least, the same requirements established for the bituminous mixture.

BTD and CTD tensile tests can be used to study the effect of the RAP content in the mixtures, the influence of using different types and percentages of binder, the grading of the mixture and the effect of the rest of the mixture components. For each variable, different specimens will be manufactured changing the value of the parameter considered. The curves obtained after the testing process will allow to select the mixture according to the design characteristics.

BTD test specimen manufacture

The specimens are manufactured and compacted in the Marshall compactor, using two especial bases which allow to pull of the mixture and to apply a tensile stress to it.

Breaking of the specimen.

The bases of the specimen are fastened to two especial jaws of the press. The deformation speed applied is 1 mm/min and the temperature is of 20ºC.
During the test, the curve stress-strain is registered obtaining a similar curve to the one drawn in figure 1.

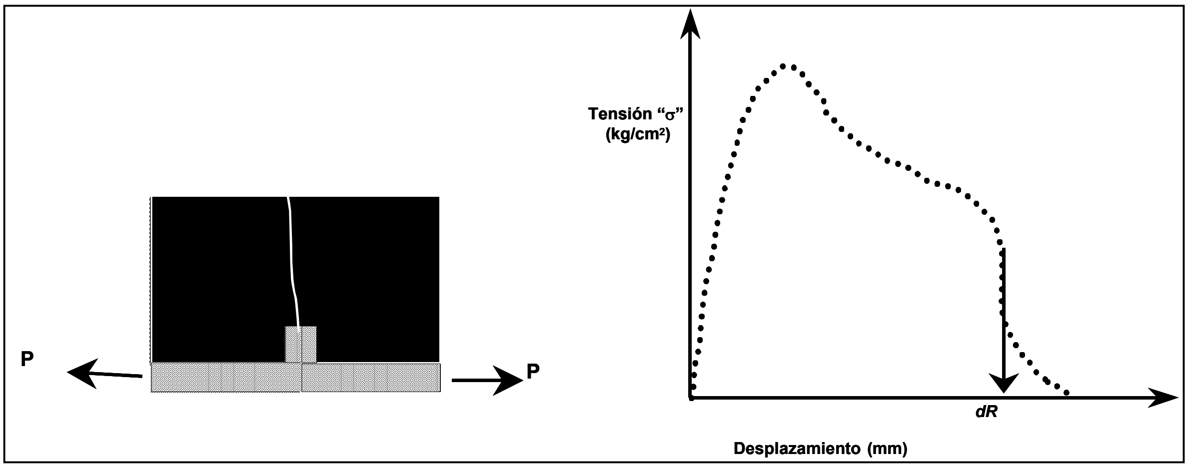


Figure 1: BTD test, scheme and stress-strain curve.

CTD test specimen manufacture

The specimen tested in CTD test is prismatic. Its dimensions are 5 cm x 5 cm x 15 cm, and it has and indent made with a saw in its central fibre in order to reduce this section and to force the rupture in this fibre.

Breaking of the specimen.

For the specimen testing, two metallic gripping devices are stuck to each base. They allow to subject the specimen to the press and to test it by applying a tensile load, Figure 2. A constant speed deformation of 0.1 mm/min is applied and the testing temperature is 20ºC.

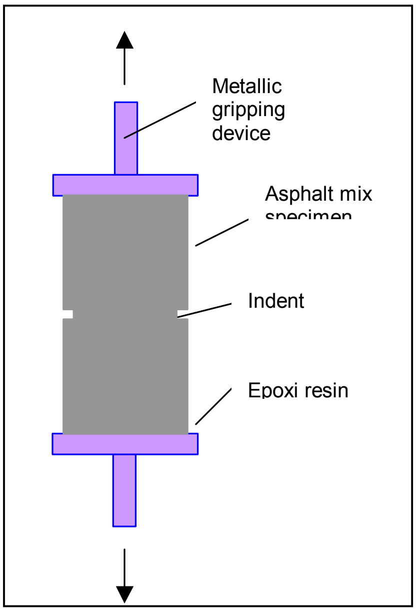


Figure 2: Direct Tensile Test scheme.

As for the BTD test, during the testing process the *stress-unitary strain* curve is registered by means of two extensometers placed in the area where the fracture is expected. They register a unitary deformation. This testing procedure allows a better control of the applied stresses and the deformations obtained, and it has been used, basically, in the study of the recycled mixtures.

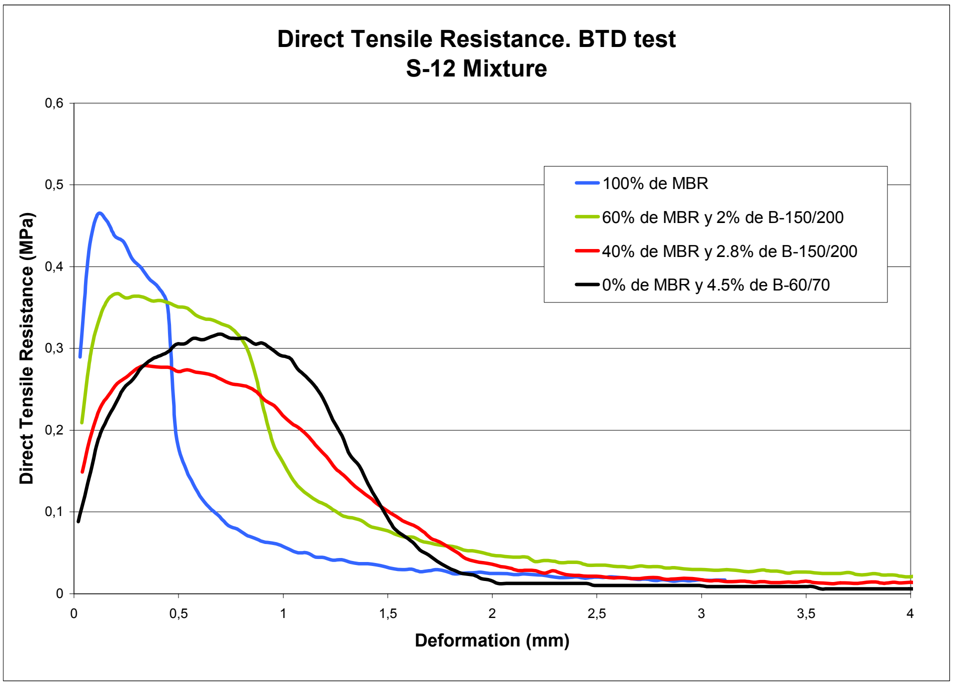


Figure 3: BTD test of mixtures with different RAP contents.

In Figure 3, it can be observed that the mixtures manufactured with a high RAP percentage and a little new binder quantity have a fragile fracture, whereas, the higher the binder with renewing agents quantity is added and the lower the amount of RAP, the closer the performance to a conventional mixture.

2. PRODUCTION

2.1 New recycling process

To increase the quantity and the quality of the total recycling amount of asphalt plant is necessary to introduce milled material in the top layer mixes and to increase the recycling rate in some specific hot asphalt receipts; it is possible with the new process called "Combined cold & hot Recycling".

The process consists in a preventive screening of milled material (reclaimed asphalt), with separation of fine and big grain ("sand" 0-5 mm and "gravel" 5-20 mm). Then these materials are inserted into the hot asphalt mix following two different ways: the "sand" is cold-added in small amount (up to 20%) into top layer mixes, the "gravel" is heated and added in bigger amount (up to 60%) into binder mixture.

The cold and hot inserts can be done also at the same time into binder mixtures (10% 0-5 mm, 45% 5-20 mm) utilizing a plant configuration as schemed below
The process requires some new machines and modifications in the asphalt plant layout.

1. RAP screen
   - It must have at least two nets with 8 mm and 25 mm openings.
   - A crusher has to work the material >20 mm.
2. Double feeding line
   - Two separate pre-feeders have to contain the 0-5 and the 5-20 selections.

- Meanwhile the hot feeding line goes through the heater, the cold one goes by a belt into a separate hopper over the RAP weigh machine.

3. Storage areas
   - In addition to the milled material one, another storage areas have to be disposed for 0-5 and 5-20 mm selections.
   - The 0-5 stock area will be better covered to avoid rain moisture.

2.2 Improvements in machine design

The design of the RAP drum dryer has been improved in the flame chamber with a new typology of shovels. They mix the milled material and make it flow without lift it during the rotation of the cylinder with reduction of material's falling particles.
The new drier increase the quality of the heated milled material, with less ageing of the bitumen and less polluting gases and vapors obtained by reduction of the flame exposition.

The screening system for the milled material has been studied and tested, considering a vibrating screen. To assure an efficient screening, without clogging and excessive flowing, meshes on the nets must be larger than the material to screen.
To screen milled material with a granulometry of 5 mm, avoiding clogging, the meshes must be 7,5 mm (+50%) using "arpa" nets (made with a corrugated wire).

3. COMPACTION

The main recommendation one should consider when facing both hot recycling lay down and compaction of the mixture is to control the nuclear mixture evolution densities as long as the rollers pass properly over the mixture till the densities stabilize and get their maximum level.

Special attention should be given when dealing with High Modulus Mixtures. In this case the binder production temperatures must be over 180ºC. Otherwise, when producing hot recycled mixtures with high percentages of RA (30% or more) the final mixture temperature do not reach the 160-170ºC required range to success when laying down and compactioning the mixture.

4. STRUCTURAL CONTRIBUTION

4.1 Deflection analysis

This chapter is going to be focused on hot recycling recommendations to evaluate the structural contribution due to the rehabilitation actions.

4.1.1 Structural evaluation of hot recycled tracks

The structural evaluation can be done by using NDT tests with a Falling Weight Deflectometer and by extracting road cores.

a) Road Coring

To obtain a representative number of road cores to know pavement layer thickness before and after the recycling actions. This information is going to be used as an input for back calculation methods.

b) Deflections measurements

To measure road deflections under 65 Kn dynamic load with a FWD. Deflections had to be measured before and after the road rehabilitation. This data is going to be used for structural analysis.

Tests after the recycling works must be done at least twice, after six and twelve months from the end of the rehabilitation works.

Its very important to know the moisture conditions of the granular layers, because it can cause variations on the measured deflections. To reach this goal, piezometers should be installed on road structure.

4.1.2 Road bearing capability evaluation

The structural evaluation has to be done through the central deflection and through back calculation methods.

a) Back calculation method

To estimate the dynamic modulus of pavement layers, deflections had to be analysed by using back calculations methods. As it consists on an iterative process, horizontal strains data measured by means of horizontal gauges installed underneath the recycled pavement layer, must be collected to perform forward calculations for mechanical parameters adjust purposes.

On the other hand, laboratory tests (Instant Resilient Modulus) had to be performed on road cores to compare laboratory and analytical results (Dynamic Modulus of Pavement Layer).

b) Central deflection method

To check the variation of the total road structure strength, a central deflection analysis had to be done taking into account collected deflections before and after the road rehabilitation.

First of all, to compare both situations (the bearing capability before and after pavement recycling), the central deflection must be corrected because of the influence that moisture has on granular layers.
A parameter that reflects local moisture variation has to be used. On the FWD, the farthest geophone measures displacements coming from the bottom part of the stressed area, caused by the dynamic load (coming from the subgrade). So if we compare in the same test point some subgrade displacements measured at different test date with several moisture conditions we can adjust them to the highest moisture content by calculating Chi parameter;

Chi = d6(wmax) / d6(wi) , where *d6(wmax)* is the farthest deflection with the highest moisture contents and *i* is data collect date, measured at 1200 mm from the load point)

And correcting the measured deflection;

Corrected deflection = Chi* measured deflection

With Chi we can correct deflections measured at a dry day.

4.1.3 Conclusions

Dynamic modulus

We have to expect a dynamic modulus of the hot recycling pavement layer more or less equal to the dynamic modulus of conventional pavement layer.

Dynamic modulus is not a lnog-term pavement behaviour parameter, so we cannot conclude about which is giong to be its behaviour in the future.

Deflections

Hot actions had diminished the total road structure deflection.

When we are comparing deflections befote and after the rehabilitation works we have to correct the moisture effect on measured deflection.

4.2 Mechanical analysis

Numerical methods research partners propose a new methodology to analyse pavement's behaviour under static and dynamic loads, based on the constitutive models developed.

- This methodology consists in a software code that calculates the material's response under different loads, using as input the **geometry** of the multi-layered structure and **mechanical parameters** obtained from simple laboratory tests, like elastic Young modulus, Poisson ratio or yield stress for each material involved in the calculation process.

This constitutive values can be obtained from bibliographic references as well, for well known materials like granular layers, or applied loads like roller or pneumatic compactor.

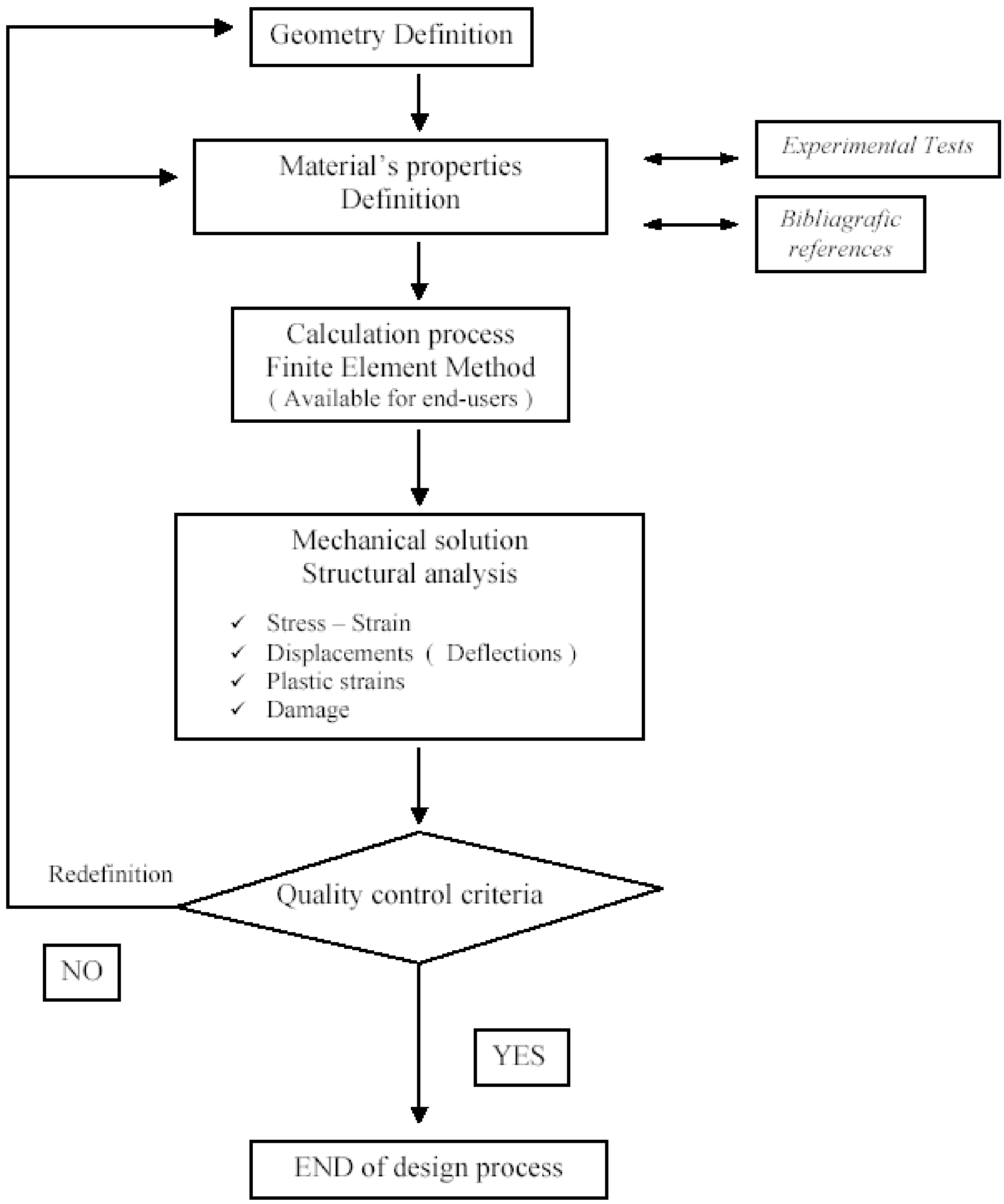
- This constitutive parameters are used in the developed model based in the Finite Element Method, available for the end-users.
- The structural code offers as output the stress – strain distribution along de pavement structure, the deflections in the surface, the plastic strains in the pavement and the possibility of damage in the material, as well as the critical points in stresses or damage.
- That leads us to a mechanical solution the user can study to take conclusions about the pavement's behaviour. Once we have the simulation of the pavement's behaviour the end-user can apply some quality control criteria to evaluate the response obtained, so as to change the material, its properties, or the geometry, layers' thickness and so on.

➢ According to these quality criteria the user can stop the design method if the quality parameters are acceptable, or repeat the design with the changes in the geometry or the material's properties.

➢ This methodology can be used as many times as necessary until an acceptable solution is reached.

Methodology and rules for asphalt pavements' rehabilitation in road tracks

(CIMNE)



5. LIST OF DELIVERABLES

OVERVIEW OF DELIVERABLES			
Deliverable nr.	**Delivery date/ Issue date**	**Output from WP nr.**	**Nature of deliverable and brief description**
D1	Month 4/ 13-11-02	WP1	Report containing specifications of relevant numerical, experimental and administrative data
D2.1	Month 7/ 13-11-02	WP2	Procedure for classification and analysis of milled material
D2.2	Month 19/ 13-11-02	WP2	Characterization of asphalt mixtures
D3	Month 13/ 13-11-02	WP3	New emulsions and bitumens for hot and cold mixtures
D4.1	Month 20/ 13-11-02	WP4	Finite element software incorporating new elastic-plastic-damage model for life cycle analysis of road pavement
D4.2	Month 25/ 20-2-04	WP4	Laboratory and in-situ experimental tests on existing road pavement
D5.1	Month 16/ 1-4-04	WP5	Enhanced machinery for milling process
D5.2	Month 20/ 1-4-04	WP5	Machinery and lay out methods for in-situ cold recycling
D5.3	Month 20/ 1-4-04	WP5	Machinery and lay out methods for in plant recycling
D6.1	Month 25/ 1-4-04	WP6	Rehabilitated tracks using new cold and hot asphalt mixtures
D6.2	Month 25/ 1-4-04	WP6	Rehabilitated tracks using standard reinforcement techniques
D7.1	Month 31/ 20-2-04	WP7	Numerical analysis of the structural behaviour of the rehabilitated pavement
D7.2	Month 31/ 20-2-04	WP7	In-situ experimental tests on the rehabilitated pavement
D7.3	Month 35/ 20-2-04	WP7	Laboratory tests on the quality of the mixtures
D8	Month 37/ 1-4-04	WP8	Methodology and rules for design and rehabilitation of road pavement using new hot and cold recycled asphalt mixtures
D9	Month 37/ 1-4-04	WP9	Dissemination and exploitation plan
D10	Month 37/ 1-4-04	All WP’s	Technical and financial reports

6. COMPARISON OF INITIALLY PLANNED ACTIVITIES AND WORK ACCOMPLISHED.

In *Table 1. Man Power and Progress Follow up* and *Table 3. Work packages bar chart* in chapter 7 a comparison between the planned work and the actual work accomplished is reflected.

Concerning the works referred to the analysis of the milling material, all the milling material coming from the Spanish experimental track has already been completely analysed and classified. However, because it came out that one of the milling materials (milling B) wasn't a ordinary milling aged material, it was decided to send new samples of milling material coming from the reserves of a conventional hot recycling plant and finally these have also been studied.

As concerns the works referred to both characterisation of the new mixtures and development of new asphalt emulsions and bitumen there has not been major deviations in comparison with what was scheduled in *Description of the Work.*

As refers to the development of structural analysis code for asphalt pavements all tasks have been doing well despite the initial delay in the starting date of the Spanish rehabilitation works.

Wirtgen's and Sim's planned activities were the investigation of the evolution of recycling machinery. In Wirtgen's case all components have been researched, developed, manufactured and tested. The pre-heating panel machine has also been transported ant tested in a job-site.

In SIM's case also the RAD drum has been tested at real-scale, and the cold addition technique, not originally planned has been tested in laboratory (obtaining the technical factibility parameters), and tested in different running plants in Spain and Italy.

As a deviation concerning the works that were taking place in Spain it should be stated that because of the high increase of number of sub-tracks to rehabilitate with new cold and hot asphalt mixtures, the rehabilitation with conventional reinforce suffered a decrease.

During the application process for the PARAMIX project, it was expected to carry out only three test tracks. Soon the first general meetings proved that in order to allow room for real test of newly developed mixtures, as well as to make a risk diversification, it was necessary to increase the number of different applications. Only one of the eleven tracks wasn't successfully completed, due to the lack of flexibility on the plant used to manufacture the mixtures, unable to make temperature increases required for high modulus bitumen. Another of the tracks suffered a delay when one of the experimental emulsions had to be manufactured twice. This originated a one month delay in one of the tracks, that suffered from bad weather conditions and was to be repaired.

Collaboration with SIM and a local subcontractor allowed to install and perform test on the new RAD drum device, that were successfully completed.

As major deviations as it was already pointed out just mention that which concerns the rehabilitation works in the Sweden motorway. Following with what was said in our 1st Management Report (27th September 2.001), the election of the Swedish experimental track had been done. There exists already some data, by means of coring and measurements of evenness, rutting and FWD, of this track. Three cold recycling sections were agreed to be done in Sweden during the Köln Meeting (March 2002).

However, underneath layers investigations in this first site selected showed a too coarse unbound material, so a new site was taken into consideration in order to begin works by the beginning of September 2002. Luckily, this initial delay did not interfered in the normal development of the rest of the tasks.

Finally, concerning the enhanced structural analysis code, it is the result of the experimental-numerical validation exercise but up to now it can not be used as a practical daily tool by the end-users partners although the structural analysis code does reproduces both the in-situ and laboratory tests.

7. MANAGEMENT AND CO-ORDINATION ASPECTS

Since the start of the project, there has been taking place a Consortium Meeting every six month period. The Kick-Off Meeting took place in Barcelona, Spain, March 2.001, with the participation of the EC Officer. Six month after, October 2.001, a 2nd meeting took place in Gothenburg, Sweden, following with a 3rd meeting which took place in Köln, Germany, March 2.002 (once we had completed the first year of the project). Following the Mid-term Meeting, in Barcelona, November 2.002, again with the participation of the EC Officer, it came a 4th meeting took place in Verona, Italy, June 2.003. Finally, a 5th final meeting, Barcelona, Spain, March 2.004, took place in order to prepare the Final Meeting, Madrid, Spain, April 2.004.

Between this Consortium Meetings, several other smaller meetings have been taking place (between laboratories, machinery companies…). In the other hand, the Technical Committee has been meeting once a month in order to survey all the works being carried away in the different fields of the project.

As Plans for Use and Dissemination concerns, PARAMIX Project is being involved in the following aspects:

- A web-site has been created on which all Paramix-reports are available. Reference to this site should be made via all partners dissemination channels.
- It would be desirable to organise an international workshop at the end of the project to present the final results of Paramix.
  Training courses for professionals
  Realisation of diffusion seminars of the new recycling techniques
  In order to disseminate the cold in-place and hot in-place recycling technologies Wirtgen held the 1st Cold Recycling days in September 2002. This was visited by over 800 people from within Europe and also from the rest of the world.
- The results of this project will be presented on international conferences and congresses of bituminous mixtures, and technical papers will be publicised in specialised journals both national and international.
  Copcisa, as Co-ordinator of the PARAMIX project, has been involved in the TRA-EFCT project, Cluster 10, giving dissemination of the different activities taking place within the PARAMIX project.
  An abstract was recently introduced by L. De Bock for the conference "WASCON 2003: On the road to sustainability" which took place from 4 to 6 June 2003 in San Sebastian (Spain).
  Another abstract will be introduced for the Eurobitume-conference in Vienna in 2005.
- Dissemination of the results will also be done in important European standardisation committees, such as:
  CEN 227 WG1/TG2 “test methods for bituminous mixtures”: e.g. for the standard procedure for the manufacturing of mixtures with RA in the laboratory.
  CEN 227 WG1 “Bituminous mixtures” in charge of setting up the future European specifications for bituminous mixtures and reclaimed asphalt.
  A. Vanelstraete is member of both committees.
- The results of the Paramix project with the aim to apply higher percentages of RA are of high interest for the road authorities and contractors. Design, production, as well as performance aspects are of large importance.

  Technical Assistance to the Highway Administrations for the study of the working formulas of the cold and hot recycled mixtures. Elaboration of Sheets of Technical Prescriptions to use in the recycled pavement construction. Design of pavements with recycled layers as much in construction as in conservation.

Technical assistance to the manufacturing companies of bituminous mixtures during the process of production and setting in work of the cold and hot recycled mixtures.

In Belgium, the outcome of the Paramix project is directly followed by BRRC's technical committees TC4 "Asphalt roads and bituminous applications" and TC 2 "Environment and recycling". These committees follow and guide BRRC's research projects. Representatives of road authorities, contractors, study groups,… are present in these committees. At the end of the project these groups may decide for the organisation of a BRRC-seminar on the outcome of Paramix in Belgium.

In Spain GISA, as a road administrator, has increased its environmental conscience in the last years and has the intention of promoting the recycling techniques to hinder the disposal of road construction waste. After the conclusion of the PARAMIX project, all the results achieved will be taken into consideration in order to apply them in the maximum number of road reinforcements managed by GISA where these techniques are suitable to be used.

GISA, COPCISA and CIMNE presented the Paramix project in the Ministry of Public Works in a meeting on 28th March 2001.

- Dissemination of the results also occurs in different national committees, like the committees for revision of the standard tender specifications or the "CKB"-commission, a committee for improvement of the quality of bituminous mixtures",… Several BRRC-members are present in these committees.

As concerns the design procedure, BRRC's software PRADO is widely used in Belgium and also distributed abroad. The existence and use of this software makes the practical implementation of the design procedure for mixtures with RA easier.

In the following tables please find enclosed the performance of the consortium and the individual partners in trems of dedication to the project:

Table 1. Man Power and Progress Follow-up Table, information about the actual man power allocation is given.

Table 2. Follow-up budget, information about the project budget is given.

Table 3. Work packages bar chart, an updated real time project scheduling against the original plan is reflected.

Finally, *List of contact persons*, an updated list of the contact persons concerning the follow-up of the project of each partner organisation can be found.

8. RESULTS AND CONCLUSIONS

1. DEVELOPMENT OF IMPROVED BINDERS FOR HOT IN-PLANT RECYCLING TECHNIQUES.

2. DEVELOPMENT OF IMPROVED EMULSIONS FOR COLD IN-SITU RECYCLING TECHNIQUES.

The research work carried out within Paramix project related to cold recycling in situ, has been focused on the improvement on the final behaviour of the recycled mixture acting on both phases of the emulsions.

In that sense, it has been verified the possibility of improving the behaviour of the cold recycled mixture through the emulsifier contribution since, on the one hand the pre-coating water needed has been reduced and in the other hand the immediate cohesion and resistance of the mixture increased.

The evaluation of the effect of different binders did not show a clear distinction among the behaviour of different emulsions (with different binders) and only small differences were got, pointing out that only "slight" better properties resulted from the employ of lower penetration grades of bitumen. Similarly, no great improvement of the final behaviour was obtained when polymer modified binders were used and, finally, no differences were got during the laboratory evaluation when the renewing agents were used although, this emulsion showed the best final behaviour in the experimental tracks.

Related to hot recycling, the research performed on binders has been focused on the general improvement of the recycled mixture so that, the life cycle of pavement could be increased. The results obtained by the Consortium show that no definitive contribution has been obtained from using renewing agents referred to pure bitumen. Similarly and contrary to what was expected, the use of polymer modified binders in S-20 mixture did not lead to clear improvement compared to pure bitumen. It has to be taken into account that the amount of "fresh" binders employed in recycling processes (less than the 50% of the total binder) makes difficult the establishment of clear distinction among different binders. In any case, all the binders evaluated performed very well from the ageing, rutting, fatigue and workability points of view at the laboratory and also the ones used in the experimental tracks.

3. MIX DESIGN PROCEDURE FOR HOT BITUMINOUS MIXTURES WITH RECLAIMED ASPHALT

The Paramix project allowed BRRC to extend the mix design procedure for mixtures with reclaimed asphalt and to verify the validity of this approach by performance testing on the mixtures in the laboratory on one hand and by testing and monitoring of the mix behaviour on the test tracks on the other hand.

For mixtures with a high percentage of reclaimed asphalt, it is essential that the characteristics of the reclaimed asphalt are properly taken into account. This is the case for the PradoWin software. Variations in the characteristics of the materials, which are larger for reclaimed asphalt than for new materials, can easily be introduced in the PradoWin database and the effect of these variations on the final mix can thus be evaluated.

In the Paramix project, the reclaimed asphalt was used to prepare new mixtures of the same type. This practice is recommended, because it allows for a higher flexibility in changing the percentage of reclaimed asphalt.

The problems encountered in phase 1 show that it is important to use thoroughly homogenised milled material. When the variability of the characteristics of the milled material is known, PradoWin is again a powerful tool to evaluate the impact of these variations on the final mix characteristics.

4. RHEOLOGICAL CHARACTERISTICS OF NEW BINDERS AND THEIR COMBINATION WITH BINDER FROM RECLAIMED ASPHALT

The procedure followed in this project for selecting the new binders was proved to give good results, as confirmed by the performance related laboratory tests and the observations on the test tracks. Rheological charaterization of the binders make it possible to select binders for bituminous mixtures with a high resistance to rutting. This is an interesting result, because it should be realized that especially for high percentages of re-use, the binder consists of a very hard old binder on one hand and a very soft new binder on the other hand (both are only mixed very shortly at the production process). This study showed also that, within a given class of performance, it is not possible to make accurate predictions of which binder will show the best rutting resistance in the asphalt mix.

5. PERFORMANCE CHARACTERISTICS OF HOT BITUMINOUS MIXTURES WITH A HIGH PERCENTAGE OF RECLAIMED ASPHALT

The main conclusion from the compactability tests is that none of the mixtures showed any problem of compactability. A good agreement was obtained between the calculated air void contents by the Prado-Win design software and the air voids of the gyratory compacted specimens. Similar air void contents can be obtained to those of mixes without reclaimed asphalt.

The main conclusion from the wheel tracking tests is that all mixes showed an excellent resistance to rutting. Hence this study shows that it is possible to design mixes with high percentages of re-use that are very resistant to rutting. This is a positive result, taking into account the fact that the binder in such mixes consists of hard old binder on one hand and new soft binder on the other hand, which are only mixed very shortly during production of the hot mix.

6. DESIGN METHODOLOGY FOR COLD RECYCLED MIXTURES WITH EMULSION

7. DESIGN METHODOLOGY FOR HOT RECYCLED MIXTURES

The interest of the proposed methodology lies in the fact that up to now it wasn't an specific procedure to adapt the conventional mixtures properties to the recycled ones because, although both are bituminous mixtures, their properties, or better, the properties to characterize and to optimise during the design process are different in each case. That has leaded us to develop new test procedures, more adequate to the mixtures characteristics, and to establish new design criteria based on the new parameters considered.

8. NEW RECYCLING PROCESS

9. DESIGN OF MACHINES AND COMPONENTS

Recycling in hot asphalt production is very attractive from many point of view:

- Re-utilisation of milled material instead of dig out virgin material from the environment.
- Avoid to discard the RAP in dumps, with it’s ecological implication.
- Have a good economic advantage utilizing cheaper materials.

The increased amount of recycling of the combined hot & cold process increase these advantages.

The results obtained with the application of these new technologies are very good.

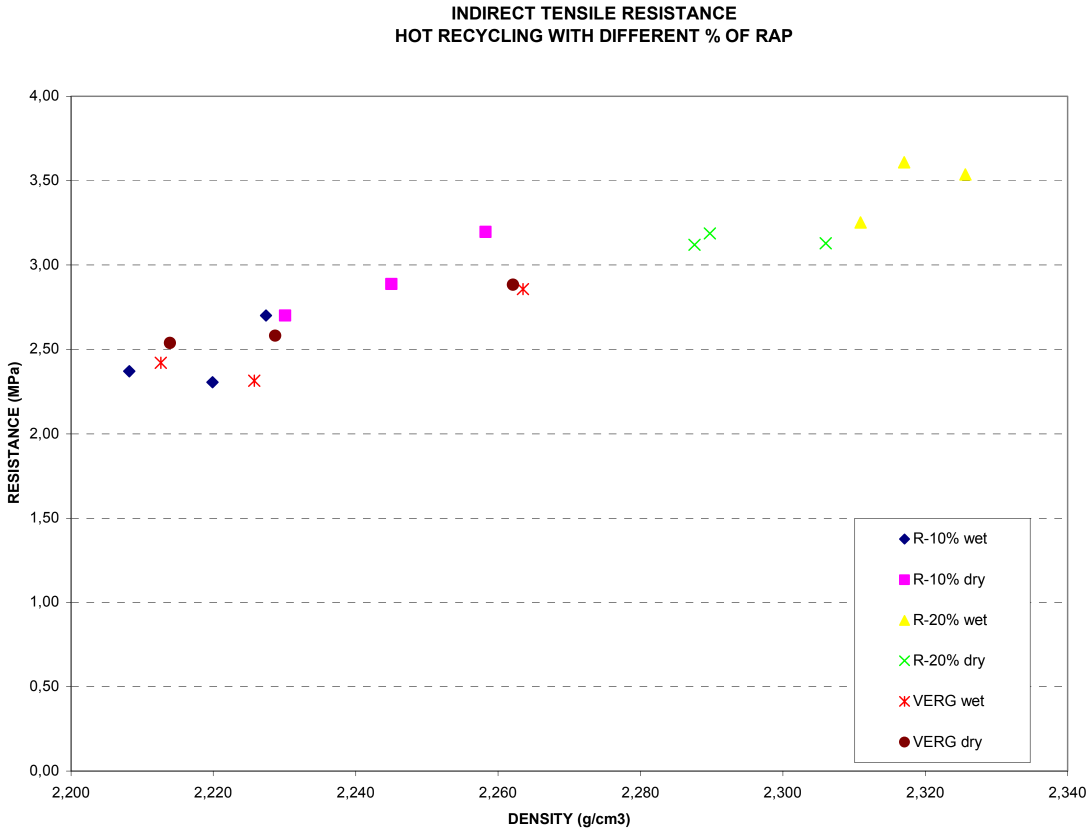
- The new process “Combined cold & hot Recycling” is working for 24 months. The recycling rate is very high: usually 50% in the binder (hot insert) and 20% in the top layer (cold insert). The sticking problems and the maintenance is reduced nearly to zero. The road contractors are satisfied of the asphalt quality.
- The new flame chamber in the RAD dryer has totally eliminated any maintenance intervention (see the photo of the internal part of the cylinder after about 30.000 tons of milled material heated). Now, after about 50.000 tons, it hasn’t been cleaned yet.
- The screening, separation and stock of the fine a big part of the milled material has became a standard process in the plant that utilizes the “Combined Recycling”. There isn’t any problem of accumulation of one of the two parts.

PRODUCT TESTS

SIM has collaborated with UPC to study the mixture in order to see if these new process of making the mixture can help to improve its properties.
The quality of production obtained by hot recycling is known so SIM asked to UPC to carry out a study to observe the property of Marshall samples with different percentage of cold insert recycling:

1. Samples of top layer without RAP:
2. Samples of top layer with 10% of RAP cold added:
3. Samples of top layer with 20% of RAP cold added:

The results of Indirect Tensile Test (UPC), under wet and dry conditions are showed in the graph:



We can see a higher density and higher resistance for the mixture with a higher amount of RAP, 20%, in cold.

COST ANALYSIS

The annual average production of an asphalt plant consists in 50% top layer (0-15 mm) and 50% binder (0-20 mm). Many EU countries (like Italy and Germany) produce a bigger amount of top layer because they have mainly maintenance of existing roads, with a lot of reclaimed asphalt to recycle.

The cost analysis concerning raw materials (combustible and maintenance costs are ignored), with these hypothesis:

- Average year Production = 100.000 ton: 50.000 ton of top layer and 50.000 ton of binder.
- Cost of aggregates = 12 €/ton *
- Cost of bitumen = 200 €/ton *

* Raw average costs in Italy based on last 6 months.

gave these results:

	Saving of bitumen on total production	**Saving of aggregates on total production**	**Saving cost on total production**	**Pay-Back period of recycling components for 100.000 t/year**
Standard plant	0	0	0	-
RAP	17 %	25%	22%	14 month
Combined	30 %	37%	35%	12.5 month

EXPLOITATION OF NEW PROCESS

The convenience of the new process "Combined cold & hot Recycling" and the performance and reliability of the components have been successfully tested.

- The new flame chamber of the RAD dryer has already become a standard design and it gave good results: two RAD are working for one and two years respectively and they haven't needed to be cleaned yet.
- The "Combined cold & hot Recycling" process is now offered by SIM as the most enhanced recycling system on hot asphalt plants. Results and validations obtained in the Paramix project will be used as reference. The prototype plant is also taken as an example to show to the customers.

DISSEMINATION

The new tested process will be divulgated to the market (roads constructions specialized magazines and conferences) and at the same time the new devices will be promoted when the Paramix project will be closed.
Results and validations obtained in the Paramix project will be used as reference.

10. *IMPROVED COMPONENTS FOR THE MILLING AND MIXING PROCESS:* DEVELOPMENT OF AN IMPROVED MILLING AND MIXING DRUM TOGETHER WITH A LARGER MIXING CHAMBER TO IMPROVE THE MIXING QUALITY AND INFLUENCE THE GRAIN SIZE OF THE RECYCLED MATERIAL.

The three goals at the beginning of the project were to establish a relationship between milling machine speed and milling drum speed, to achieve a greater mixing space for the aggregate and binding agent and to achieve a greater depth of cut with the current machine. Unfortunately, the machine that received these components has only been working in concrete and therefore these factors could only be tested and proven to a certain extend. This subject is interesting to many contractors and consultants as it can influence the production and quality of the milled material and also the end product when stabilising. Wirtgen is planning to test these components in the course of 2004 and 2005.

11. *IMPROVED COMPONENTS FOR THE MACHINERY AND LAY OUT METHODS FOR IN-SITU COLD RECYCLING:* DEVELOPMENT OF A MORE EFFICIENT HEATING SYSTEM.

The conclusion that can be drawn out of the literature study, which is described in the deliverable report (Appendix C), serves to explain the decision that was made to develop the new pre-heating system. The actual prototype and consequent pre-heater machines then backed up these theories. The most significant conclusion that can be made is that the heating system with the combination of infra red and fresh air is 40 % more efficient than the heating system with only infra red heating panels. This means that there is a significant reduction in gas consumption and therefore the process costs is reduced.

12. MATHEMATICAL FORMULATION AND CALIBRATION OF THE VISCOELASTIC MODEL

13. MATHEMATICAL FORMULATION AND CALIBRATION OF THE VISCO-DAMAGE MODEL

14. MATHEMATICAL FORMULATION AND CALIBRATION OF THE VISCOPLATIC MODEL ACCORDING TO EXPERIMENTAL TESTS

15. APPLICATION OF THE VISCOPLASTIC MODEL TO SIMULATE THE REAL PAVEMENT'S RESPONSE UNDER DYNAMIC LOAD

16. FATIGUE FORMULATION TO SIMULATE THE MATERIAL'S DAMAGE UNDER CYCLIC LOADS

The CIMNE participation in this project had allowed the development of appropriate constituent models to represent the behaviour of the asphalts materials. Also this constitutive model has been applied to the some real cases that have been studied experimentally by other partners of the project.

The results have been satisfactory, so much in the prediction and evolution of the stresses in the material for different states of the load speed and temperature; likewise as for the prediction of damage and deterioration for fatigue.

As for the fatigue properly, it has been able to transfer this concept characteristic of the metals conceptually to the asphalts. Nevertheless, it is considered important to continue the studies of fatigue in pavements, because this project has opened the doors for future developments.

It is concludes that the CIMNE participation in the project has allowed the development of tools for the mechanical quantification of the pavements behaviour. These tools should continue improving and to make them accessible for the practical use, because at the moment they are at the level verification.

17. CONSTITUTIVE MODEL FOR NON-LINEAR MODELLING OF ASPHALT CONCRETE.

18. STRUCTURAL MODELLING TECHNIQUES FOR NUMERICAL SIMULATION OF THE RESPONSE OF ROAD STRUCTURES WHEN SUBJECTED TO TRAFFIC LOADS.

19. IMPLEMENTATION OF SUB ROUTINES FOR INCORPORATION OF TEMPERATURE DISTRIBUTION WITH EMPHASIS ON THE ASPHALT LAYER IN THE ROAD STRUCTURE.

20. IMPLEMENTATION OF THE RESULTS OBTAINED IN 1-3 ABOVE INTO THE ROAD DESIGN SOFTWARE VÄGFEM.

The results obtained in the project concerning development road design software by Chalmers can be summarised as. The first steps in the process of establish a sound base for the area that we call Road Mechanics has been performed. By this we mean by that is a stable and reliable method has been identified in the Finite Element Method. This is definitely a promising base since it has proven to be stable and reliable in a large number of areas from biomechanics to aerospace applications. By the use of soft ware based in FEM an engineer can perform multi-physics simulation, which is a necessity if realistic simulations of pavement are going to be executed.

In order to be able to use FEM as a useful tool in active pavement design a realistic description of the materials in the structure is essential. This is made through the use of constitutive models also called material models. In the project a visco-elastic material model were chosen for the purpose of simulating the asphalt concrete. The benefit with this material model is that it not only can be calibrated by the material test suggested in the PARAMIX project but also with the material test suggested in the new US federal “2002 Pavement Design Guide” i.e. the frequency test. The material model, given proper material data from test, can be used for both recycled asphalt and virgin material. This also makes it useful in design and evaluation phases of new pavements projects as well as in the case of maintenance projects. User groups targeted is both the pavement engineers at the construction or consultant company as well as the government representative at the local road administration. The later group can use the tool for comparing competitive alternatives, with regard to e.g. service life, in an early stage in the project phase were costs are low for changes.

The investigation concerning the use of 2D or 3D models indicates that in order to fully simulate the impact from traffic and environmental loads (temperature, water …) a full 3D analysis is necessary in the future. Results from the project is going to be directly implemented in a new Swedish road design code called VÄGFEM which is being developed in a cooperation between Chalmers and SNRA Western region. This software is web-based and will be beta tested by a selected number of Swedish consultant firms and by the researchers at the US Federal Highway Administration during 2004.

21. CONSTRUCTION PROJECT CONCERNING TO THE SPANISH EXPERIMENTAL TRACKS

GISA, as a Catalan public works management company in Spain, has contributed to the general objectives of the project sharing its experience in the management, technical assistance and coordination of the road reinforcement works promoted by the Catalan Ministry of Town and Country Planning and Public Works. It has adopted the role of supplying all the administrative and legal tools as well as the technical knowledge that has concluded with the choice and management of the reinforcement project that has helped to accomplish the objectives of the project.

GISA has taken care of all the administrative process in order to allow the construction of the project. The workflow of activities began when the call for the project was received from the Government of Catalonia.

Among some possible projects that GISA was preparing at that moment, COPCISA, UPC and GISA decided the placement, length and thickness of the experimental cold and hot experimental tracks in Spain, in the framework of the project “Reinforcement and other works. Road C-58 from Terrassa to Castellbell i el Vilar, from kilometre 23+370 to kilometre 28+406.”, keyword RB-00092.1, with the characteristics that have been already mentioned.

After the project draft was completed, it was subjected to all the pertinent administrative procedures and was finally approved by the Director General of Roads on 30th April 2002, and then the bidding phase began.

GISA asked the Government of Catalonia to allow COPCISA to carry out the construction of the project, alleging that this project had to be developed in the framework of the PARAMIX European programme, and according to the research and development characteristics of the project. On 7th June 2002 the Government allowed GISA to start the negotiated procedure.

On 15th July 2002 the contract for the construction of the project was signed by GISA and COPCISA.

The works started in September 2002 and finished in January 2003.

In addition, GISA has given support to LGAI to carry out in-situ experimental tests on the rehabilitated pavement tracks. Tests included the in-situ study of pavement deflection and the in-situ evaluation of structural failure of the rehabilitated pavement under static and dynamic loads.

As a future user of the conclusions of PARAMIX project, GISA has followed the development of the proposal for evaluation and design of recycling actuations.

GISA will take an active role in the tasks of dissemination of the technology derived from the project, an will take part in the discussion and agreement on the exploitation plans and marketing actions.

According to this, it can be stated that the main objectives of GISA as a partner of the consortium have been fully accomplished in the scheduled period.

COPCISA has performed 11 test tracks with an overall good behaviour. Little setbacks have existed, mainly originated to the fact of using conventional industrial plants rather to due to the properties of the materials used.

It must be pointed out some of the general results:

- Cold in-situ recycling techniques have shown a good behaviour under heavy traffic condition. The only major constraint seem to be sections where great shear efforts by traffic are expected, specially in the transversal sense of the traffic flow (crescents).
- Hot in plant recycling has been performed successfully being in all cases beyond Spanish standards: RAP has been used on top layers and on micro mixtures; percentages of RAP are above Spanish constraints.
- Cold recycling feasibility is bond not only to traffic intensity or environmental weather conditions, but rather to a combination of them. This extends its suitability to heavy

traffic roads sections with rather straight shape, provided that good weather periods can be used for the construction.

- Cost study versus technical warranty of the future behaviour of the mixtures can be matched in case of an intense study of important sections of road to be rehabilitated, where the cost of these preliminary studies can be mortgaged.

In all cases, it must be pointed out that the evaluation period is very short in terms of a road life-cycle, but laboratory tests performed in the PARAMIX project (both regarding mechanical properties and fatigue behaviour) allow to be daring and optimistic on the feasibility of these techniques.

The cost analysis of the experimental tracks construction, gives some clues to the general approach to a rehabilitation project on a section of road.

The rehabilitation techniques based on asphalt recycling do perfectly match in long-term conservation projects. This is compatible with the general evolution of the market for road conservation, as contracts based on long term concessions, based on giving a warranty on performance parameters rather than contracts based on specific and planned tasks, are more and more expected to be the future. Budget constraints and the accent on environmental friendly management give a wide room to the introduction of the use rehabilitation techniques in road maintenance programs.

The PARAMIX project has given an enough number of data to be confident on the long-term behaviour of roads based on asphalt rehabilitation techniques.

Actual technical constraints to the use of asphalt rehabilitation that exist throughout in national standards seem to have no other reason than the lack of experience and the main menace of this techniques which is the heterogeneity of the old asphalt substrate to be repaired. This can be solved with an intensive previous investigation on both the old asphalt and the materials to be used (bitumens and emulsions). For this reason, it is possible to make proposals to road administrations that go beyond national standards, whereas the size and intensity of study for a specific road are big enough.

In other conditions, actual constraints to the technical capabilities of the reclaimed asphalt rehabilitation techniques seem to be fairly conservative.

The economical gap between standardized rehabilitation with recycled asphalt, and the use of non-standardized solutions can be filled with an intense former study of the materials in the road, since the short term auscultation performed on the Spanish tracks shows that the mechanical behaviour is good.

22. NEW PARAMETERS TO CORRECT RELATIVE MOISTURE EFFECT ON CENTRAL MEASURED DEFLECTION WHEN COMPARING SEVERAL DATA AUSCULTATION.

Results of the road bearing capability analysis show us that the hot recycling actions had a better structural behaviour than cold ones, but we have to wait to see how they behave in the future. We have seen that, due to the emulsion need of water absence to reach nominal strength values, cold tracks increase a lot their structural strength in the first year of live. So, to conclude about the road strength improvement we need to know the long-term behaviour of cold and hot recycled tracks.

On the other hand, we have seen that to do the structural analysis, as we have to compare deflections with several moisture conditions, it is a must to develop a method to correct in-situ granular moisture effect, taking into account the deflection bowl. The *Chi* parameter, used for moisture correction objective, can correct it successfully.

23. PROPOSAL OF REHABILITATION METHODOLOGY AND RULES

The experience accumulated in previous tasks on the development and validation of new asphalt mixture, milling and analysis of the rehabilitated pavement is being used for proposing a methodology for enhanced production of recycled cold and hot asphalt mixtures and pavement rehabilitation techniques. This also includes the definition of the numerical-experimental methodology for assessing the structural behaviour and life cycle of the rehabilitated pavement using the new mixtures.

The proposed methodology includes recommendations on the improvement in the design, production and reliability analysis of rehabilitated asphalt pavements using recycled asphalt mixtures so as to achieve better life performance. The methodology also includes specifications on the experimental testing and numerical experiments required for predicting the behaviour of a rehabilitated road pavement, the design of the new hot and cold recycled mixtures, the machinery and procedures for the rehabilitation process and the evaluation of the impact of organic substances used in the mixtures on health and safety. The methodology and the structural analysis software will be subsequently used as a practical daily tool by the end users for enhanced design, construction and endurance analysis of rehabilitated asphalt pavements with minimums environmental impact.

9. GLOSSARY

- BTD: Direct Tensile Barcelona
- ECL-2: Slow Cathodic Emulsion
- ECL-2-m: Modified Slow Cathodic Emulsion
- ECL-2-r: Slow Cathodic Emulsion with regeneratings
- ETI: Indirect Tensile Test
- FEM: Finite Element Method
- HBM: Hot Bituminous Mixture
- HDBM: Hot Discontinuous Bituminous Mixture
- HMM: High Modulus Mixture
- PMB: Polymer Modified Binders
- RA: Reclaimed Asphalt
- RAP: Reclaimed Asphalt Pavement
- SMA: Stone mastic Asphalt