Double Coating of Full Depth Reclamation Materials

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ABSTRACT

Full Depth Reclamation (FDR) and Cold In-Place Recycling (CIR) are popular rehabilitation techniques for flexible pavement. Both techniques can be done with the addition of asphalt emulsion or foamed bitumen as a stabilizer. In most cases, those two techniques to add bitumen are considered equivalent, even if the way they give cohesion to the mix is different.

A research project was undertaken to verify the possibility of using both asphalt emulsion and foamed bitumen on FDR materials to have better mechanical characteristics since it's believed that asphalt emulsion gives a good coating, and foamed asphalt does not coat as well but serves as a binding agent.

FDR mixes were prepared in the laboratory with and without asphalt emulsion and foamed bitumen. Different addition processes were tested in order to find the optimum mix design procedure. Moisture susceptibility tests (Marshall tests and indirect tension tests) and complex modulus tests were performed on the different mixes, and it was shown that the use of both binders can give you a mix with better performance. This paper presents the mix design, the test program and the results of this study.

Keywords: Cold Asphalt, Emulsions, Foam

1 INTRODUCTION

Different techniques of cold in-place recycling have been developed over the years answering to a growing need for re-use of Reclaimed Asphalt Pavement (RAP) coming from roads rehabilitation, i.e. cold in-place recycling (CIR) and full depth reclamation (FDR). This allowed to save materials, but also to the reduction of the emissions, mainly due to the decrease of the production temperature [1]. Cold recycling refers mainly to two types of technologies: cold recycling mix with bitumen emulsion or foamed bitumen. Both techniques, now fully consolidated in practice, have been the subject of numerous studies, reviews [2] and improvements over the years. Very few information is available in the literature and in practice on the joint use of the two techniques. For this reason, this study aims to start a research to get the benefits of both technologies applied to the production of the full depth reclamation mixes. Therefore, at first it focuses on determining the ideal sequence for the production, while the second step deals with the determination of an optimal recipe by varying each of the components involved: emulsion, bitumen and grading curve. The use of the double coating by combining two different emulsions or emulsion and foam is compared with the use of individual technology: emulsion and foam.

2 BACKGROUND

2.1 Foam cold recycled mixes

Foamed bitumen is today one of the most convenient techniques for the rehabilitation and reinforcement of pavements. The foam is obtained by blowing a small percentage of water inside an expansion chamber containing bitumen at temperature of 170-180°C. The expansion reaction that ensues makes bitumen have the consistency of foam, with an increase in volume of 20-30 times. The technology of the foam began to take hold in the 1960s and 1970s [3,4,5] using virgin aggregates. Subsequently it has been integrated in the projects for the reinforcement of existing pavements, thus with the use of milled material [6,7]. Many studies followed to improve this type of application taking into account the most suitable type of curing [8,9] and refining the mix design [2,10].

2.2 Emulsion cold recycled mixes

The use of emulsion in cold recycling processes provides a durable binding action with the RAP material. Standard bitumen emulsion contain normally from 40% to 75% bitumen, 0,1% to 2,5 % emulsifier and water, from 25% to 60%, depending on the peculiar kind of emulsion and the required viscosity [11].

In the last 20 years, efforts have been employed on the emulsion-based technologies for road construction and repair, as well as significant improvements were achieved over the emulsion system [11] as for example the addition of polymers to increase the performance of the final mixes [12]. The curing of those materials has also been studied by many authors [9,2,13].

2.3 Comparison of the foam and emulsion cold recycled techniques

As mentioned previously, both techniques represent a valid solution for pavements reconstruction and reinforcement, but only with a comparison between the two it is possible to highlight the pros and cons of each procedure and understand better the objective of the present paper.

The first thing to note is the different nature of the dispersion of the binder in the two types of mix. Indeed, the emulsion acts as a lubricant during the compaction phase and, before its breaking, the binder is able to completely cover coarse and fine aggregates [14]. In the case of foam mix, foamed bitumen covers mainly the fine aggregates. The difference is also visually, in fact, in the case of emulsion the binder distribution is more homogenous into the material, instead for foamed bitumen black spots appear.

As demonstrated by recent studies [15], given the same curing time, foam specimens have higher dynamic modulus than the specimens with emulsions, probably due to the less moisture content. Bitumen emulsion and foamed bitumen for cold recycling show both a similar averages in the results of tensile strength [16,17]. On the other side, it should not be neglected that the bitumen grade and RAP content affect ITS results [18]. Regarding fatigue properties, it has been proven [19] that for low stress levels foamed mixes give higher performance, but on higher stress levels longer fatigue life is registered for emulsion mixes. In addition, the rupture that occurs in emulsion mix is a plastic fracture, while foam mix exhibits brittle fracture. Another important performance to take into account in order to achieve long life pavement is the permanent deformation. For both it depends on the curing time and rut depth decreases with increasing time [20]. The rutting resistance tested after the same amount of days is superior for emulsion mixes than for foam mixes.

3 STUDY OBJECTIVES

The main objective of this study is to design FDR materials that have all the benefits of emulsion and foam mixes. The first phase of the research is presented in this paper and was aimed to set a mix design procedure and prove the effectiveness of emulsion-foam and emulsion-emulsion double coating and compared them with simple coating of foam mix and emulsion mix. The focus will be on the results comparison of Marshall Stability, Indirect Tensile Strength resistance and moisture sensitivity.

4 METHODOLOGY

4.1 Materials

The samples of FDR tested in this study were prepared in the laboratory using RAP, virgin aggregates, foamed bitumen, bituminous emulsion, Portland cement and water. The Reclaimed Asphalt Pavement (RAP) used in the laboratory study was obtained from a stockpile in the Montreal area, had a maximum size of 14 mm and contained around 6.38 percent of binder measured in accordance with ASTM D6307-10[21]. The RAP was homogenized and separated to ensure that all mixes have a similar gradation. The virgin aggregate was a MG20 which is the 0 mm to 20 mm aggregate normally used in Quebec as a base material for highways. The gradations of the FDR mix gradation in accordance with Technical Guidelines 2 [22] is shown in Figure 1. The FDR mixtures tested in this study were made of 50 percent of RAP and 50 percent of virgin aggregate (MG20). For the mixtures with emulsion, two different types of binders were used. A Cationic Slow-Setting with soft bitumen emulsion (CSS-1S) for the first coating and a Cationic Slow-Setting with Polymer bitumen emulsion (CSS1P) for the second coating were employed. The base bitumen content of the emulsions was 65.2% and 61.6% respectively. For emulsified cold recycled mixtures, 1.0% cement was used (by dry mass of mix). The emulsion mixtures used a pre-mix water method. The pre-mix optimum water content was 6.5% for the weight of the total dry mass including cement. The percentage of bitumen emulsion and optimum water content matched field levels in order to represent the FDR mixtures placed in the field. Foam was produced with a Writgen laboratory foaming machine showed in Figure 2. Foamed bitumen was produced by injecting water and air into hot bitumen under varying pressure, using PG 58-28 bitumen, 3.25% of water content was used to produce the required foaming characteristics, which gives an expansion ratio of 15 and the half-life of 12s at 170°C.

4.2 Mix Design Procedure

In order to prove the workability of the double coating mix emulsion/foam, four series of tests were carried out, which matches with four types of mixes: an emulsion bitumen mix, a foamed bitumen mix, an emulsion/emulsion double coating mix and finally an emulsion/foam double coating mix. The first three being used as the comparison to the fourth mix. The addition of the aggregates to the different binders (Foam and Emulsion) in the mix design has been divided into two parts. For each mix 10 replicates were compacted to test the Marshall Stability and Indirect Tensile Strength (ITS) resistance.

4.2.1 Single and double coating emulsion mixtures

Simple coating emulsion mix design was done in according to MTQ’s method LC 26-002 [23]. The pre-mix optimum water content was 6.5% for the weight of the total dry mass including cement. Pre-mix water has several advantages, including higher levels of RAP and virgin aggregate coating, better lubrication of the mixture during compaction, and accelerating the reaction of cement hydration [17]. Cement and water are added in right proportions, and the whole is mixed during one minute. Then, emulsion bitumen CSS-1S is poured and mixed with the aggregates one more minute.

Double coating emulsion follows approximately the same process although there are two phases in the mixing process. First, half of aggregates are mixed with all water and cement during one minute. Then, half of the emulsion bitumen CSS-1S is poured and mixed during 1 minute again. Carrying out the second coating needs to let the first emulsion break. After first emulsion breaks, the second half of the aggregates and bitumen emulsion CSS-1P can be added and mixed during one minute.

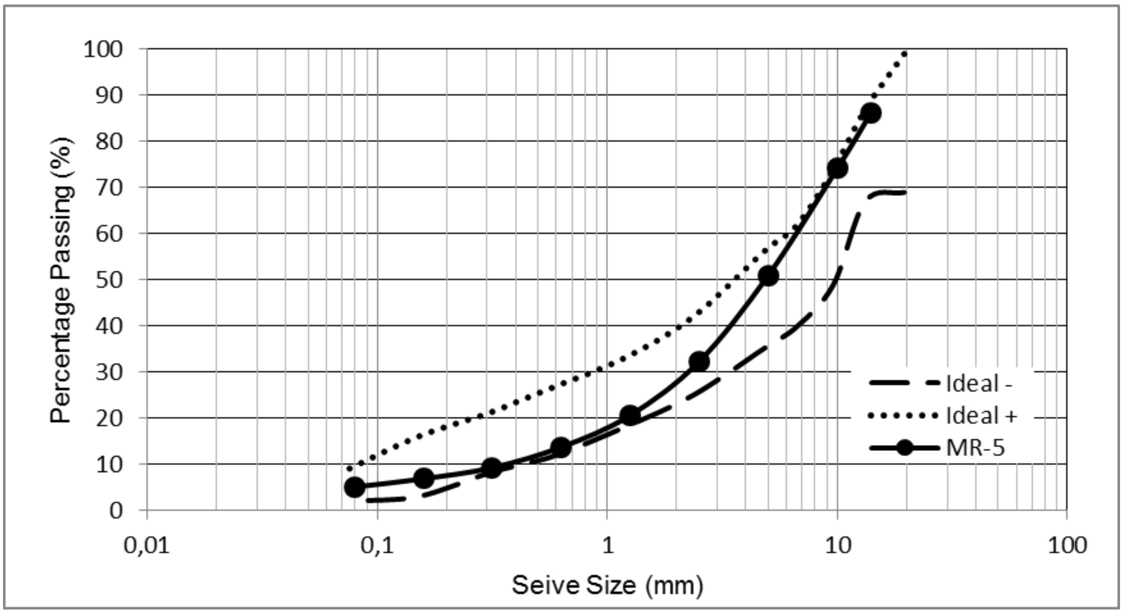

Figure 1: Particle size distribution of the Full Depth Reclamation (MR-5) mix.

Figure 2: Writgen laboratory foaming machine at École de Technological Supérieure.

4.2.2 Double coating Foam and Emulsion

Double coating with emulsion and foamed bitumen follows the same process although there are two phases of mixing process. First half of the aggregates were mixed with half percentage of water and required percentage of CSS-1P emulsion, and mixed about 1 minute, then as soon as emulsion break the mix was added to the second half of aggregates in the mixing machine. Then second half of water and 1% of cement were poured and according to the mix design, the required amount of foam was added.

Each sample was compacted to 13 percent ±1 percent air voids (According to LC 26-003, [24]) with the Marshall compactor with 50 blows on each face and cured 24 hours at room temperature in their mould and 24 hours out of them at 38°C. And, the curing was done without humidity control with the relative humidity in the lab being at around 50%.

5 RESULTS AND ANALYSIS

5.1 Marshall Stability Test

Marshall Stability and flow can be used to relatively evaluate different mixes and the effects of conditioning such as with water of each mix[25]. After curing it is placed in the Marshall Stability testing machine at ambient temperature and loaded at a constant rate of deformation of 51 mm per minute until it failure (Figure 3). The load that causes failure of the specimen is taken as Marshall Stability, which is corrected according on the height of the sample tested.

Figure 3: Marshall Stability test setup with Marshall Hammer, Compacted bricks, Marshall Testing (Left to Right)

Marshall Stability results for the four formulations in dry and wet conditions are illustrated in Figure 4. According to MTQ's method LC 26-002 [23] standard, a minimum Marshall Stability is 8 kN required, which was exceeded by all mixtures. As expected, Marshall Stability of the fourth formulation, the double coating emulsion/emulsion and foam/emulsion are the highest, although the gain of stability was not much compared with the simple coating. It was also observed that no gain of stability for the saturated specimens of all the formulations.

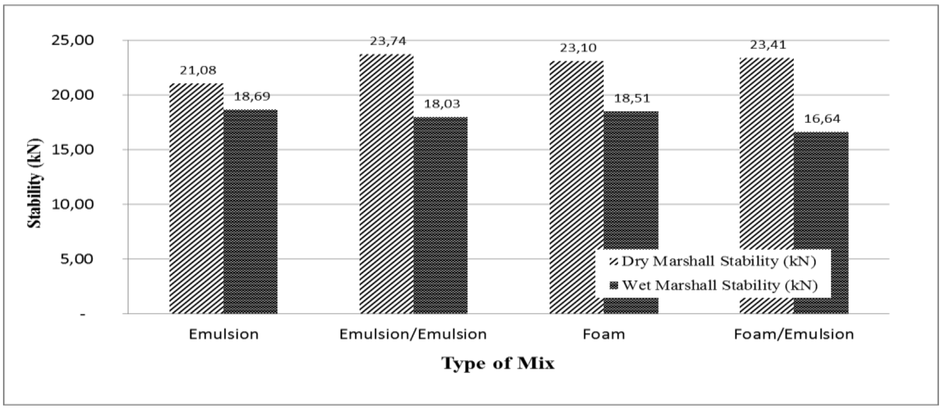

Figure 4: Marshall Stability FDR materials treated with different bituminous mixes.

Marshall Moisture sensitivity results were not up to the mark. Figure 5 shows higher stability loss for the double coating mixes. Simple emulsion mix has the lowest stability loss (11.35%) because of great coat provided by the emulsion. The two other formulations using foamed bitumen have quite high moisture sensitivity which is due to their low coating quality because of foamed bitumen which agglomerates mainly the fines. However, it would have been expected that double foam/emulsion coating mix to reach lower moisture sensitivity than simple foam mix.

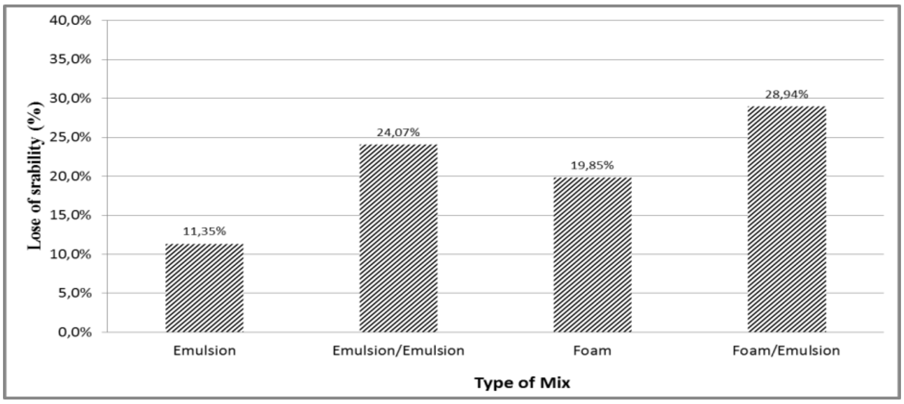

Figure 5: Marshall Loss stability of FDR Materials

5.2 **Indirect Tensile Strength test**

The stripping resistance of bitumen mixtures is evaluated by the decrease in the loss of the ITS according to AASHTO T283[26] (Figure 6). The ITS test has been done at ambient temperature. The recorded maximum compressive strength is divided by appropriate geometrical factors to obtain the ITS using the following equation 1 [26].

$$ITS = \frac{2000 \times P}{\pi \times H \times D} \tag{1}$$

Where,

ITS : Indirect Tensile Strength (kPa);
P : Maximum load (N);
D : Diameter of the specimen (mm); and
H : Average height of the specimen (mm).

Moisture susceptibility of the compacted specimens is evaluated by Tensile Strength Ratio (TSR) which is calculated by dividing the average conditioned ITS result by the average unconditioned dry ITS result [25]. For example, Wirtgen [28] gives a standards for FDR between 250 kPa and 600 kPa for ITS resistance and 0,8 and 1,0 for TSR ratio.

Dry and wet ITS tests results are illustrated in Figure 7. Every formulation obtained satisfactory values, between 250kPa and 600kPa. As in Marshall Stability, there is not a considerably increasing of stability between the simples and doubles coatings. The double coating emulsion/foam and the foam mix gave good results. Simple coating foam mix is very similar to the latter.

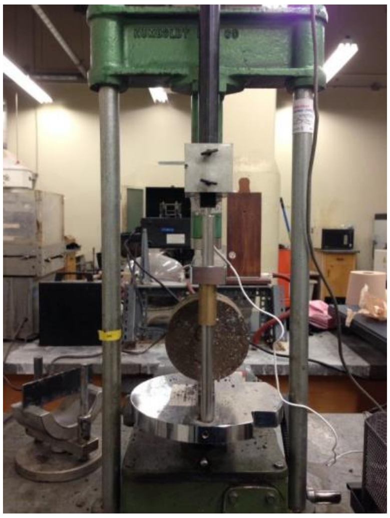

Figure 6: Indirect Tensile Strength Test loading

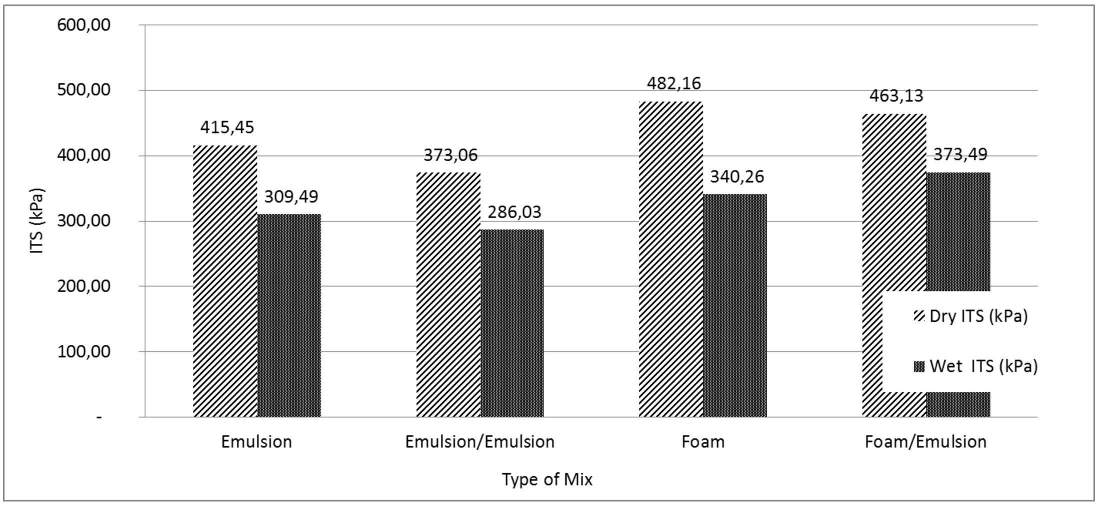

Figure 7: Tensile strength for FDR Materials treated with different bituminous mixes

The ITS moisture sensitivity gives more comprehensible results. As expected, double coating mixes gives better results, where the foam/emulsion reached the higher value. It is important for the new double coating mix to respect the Wirtgen standard criterion because moisture sensitivity is the most important characteristic focused in this research. As it is shown in Figure 8, the foam/emulsion mixes reached a value of 81% TSR. It indicates a good and appropriated coating of aggregates and proves the effectiveness of the formulation used for the double coating.

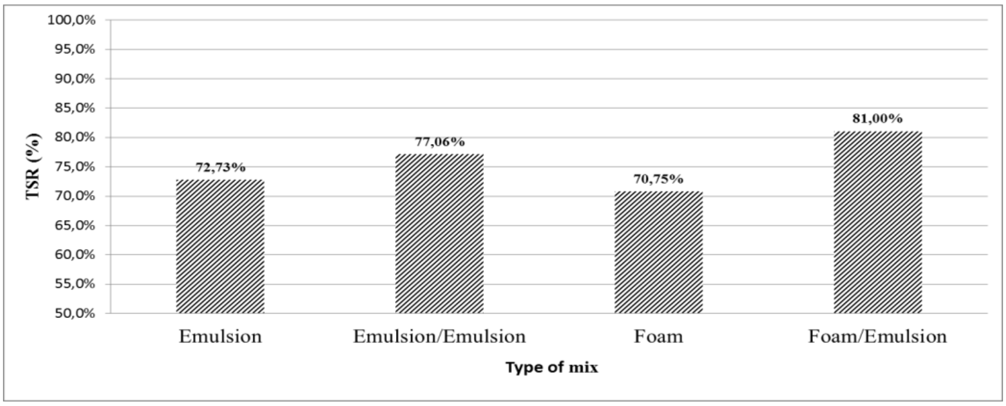

Figure 8: Tensile strength ratio of the FDR materials

5.3 An approach to optimize the double coating mix design procedure

As showed before, the double coating of foam/emulsion shows a satisfactory value of ITS moisture sensitivity. Aiming to increase this value and to determine the optimal mixing procedure for the double coating, three parameters were tested:

- The order of the aggregate sizes addition during the mixing phase. The FDR material was divided in: coarse parts, from 5 mm to 14 mm, and fines parts, from 0 mm until 2,5 mm. Two combinations were tested using: 1) the coarse aggregates in the first part of the mix and the fines in the second, 2) the fine aggregates in the first part of the mix and the coarse grains in the second;

- The type of binder for the first and second coatings. The following binders were used: emulsion and foamed bitumen;

- Rupture time: it was used a time span of 1 and 2 minutes.

Considering the above mentioned parameters, eight different combinations representing eight different procedures for the double coating were carried out. For each combination, 48 samples were compacted with the Marshall hammer (8 Combinations x 2 curing conditions (wet and dry) x 3 ITS Tests). The specimens were compacted to test the dry and wet ITS. Table 1 shows each combination and their results.

Table 1: Different Combinations of the double coating of FDR materials

Combination	Double Coating procedure	Avg. Dry ITS (kPa)	Avg. Wet ITS (kPa)	TSR (%)
1	1 coating: Coarse with foam 2 coating: Fines with emulsion Rupture time: 1 minute	334.66	324.57	97
2	1coating: Coarse with foam 2 coating: Fines with emulsion Rupture time: 2 minutes	283.18	276.29	98
3	1 coating: Fines with foam 2 coating: Coarse with emulsion Rupture time: 1 minute	389.19	329.11	85
4	1 coating: Fines with foam 2 coating: Coarse with emulsion Rupture time: 2 minutes	372.72	278.57	75
5	1 coating: Coarse with emulsion 2 coating: Fines with foam Rupture time: 1 minute	388.03	336.94	87
6	1 coating: Coarse with emulsion 2 coating: Fines with foam Rupture time: 2 minutes	377.08	348.67	92
7	1 coating: Fines with emulsion 2 coating: Coarse with foam Rupture time: 1 minute	378.74	305.41	81
8	1 coating: Fines with emulsion 2 coating: Coarse with foam Rupture time: 2 minutes	427.10	271.92	64

In order to achieve the optimal mixing recipe for the double coating, it is necessary to understand which factors are significant and which are negligible. A variable or factor is any parameter that has, in reality or all likelihood, an influence on the studied phenomenon. The factors are considered as the possible causes of the response. To determine which parameters have a stronger influence on the results a sensitivity analysis was conducted using a multiple regression analysis, i.e. considering all the factors at the same time. When several variables are treated at the same time, they are expressed in different units, and it is thus convenient to convert them to a common scale to proceed with the model implementation. For this reason, the variables were standardized so that the coefficients are not dependent on the measurement unit [29]. The following parameters were investigated:

- x_1= order of the aggregates addition in the procedure (fines or coarse)
- x_2= order of addition of the type of binder in the procedure (emulsion or foam)
- x_3 = time span between the first and the second phase of the mix

A linear model with interactions was developed. In Table 2 are summarized all the coefficients of the model considered for the sensitivity analysis.

Figure 9 represents the distribution of the measurements in the experimental domain investigated. The points highlighted in Figure 9 correspond to the combinations tested and reported in Table 1.

Table 2. Summary of coefficients used in model.

Coefficient notation	Type of coefficient	Coefficient meaning
x_0	Constant factor term	Constant
x_1	Main effects	Order of aggregates
x_2		Order of binders
x_3		Time span
x_{12}	Two-way interaction effects	Order of aggregated/order of binders
x_{13}		Order of aggregates/Time span
x_{23}		Order of aggregates/Time span
x_{123}	Three-way interaction effect	Order of aggregated/order of binders/Time span

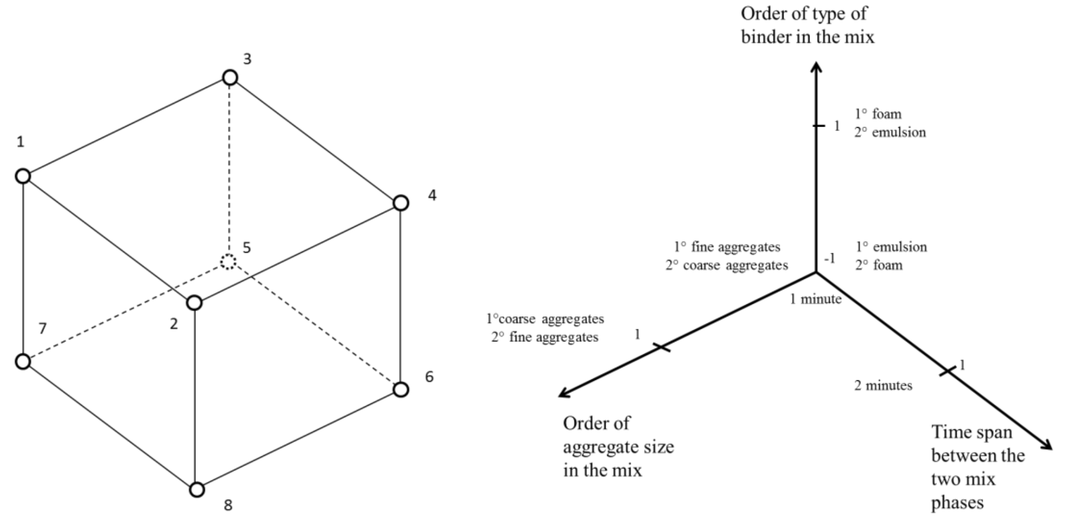

Figure 9 Distribution of measurement points in experimental domain.

To calculate the coefficients of the model that describes the phenomenon in the specified validity range, it is possible to use the least square fit algorithm (Equation 2). Dividing the coefficients for the constant term (x_0) allows the relative effects to be obtained (Equation 3):

$$x = (Z'Z)^{-1} \cdot Z'y \tag{2}$$

$$x_i^* = \frac{x_i}{x_0} \tag{3}$$

Where:

y= vector (n x 1) of the observation of the dependent variable (measurements of ITS or TRS)

Z= model matrix (n x (k+1))

x= vector ((k+1) x 1) of unknown coefficients of the model

ε= vector (n x 1) of stochastic errors

Figures 10-12 compares the relative effects obtained from Equation 3. For the dry results the most important parameters are the order of the addition of the aggregates and the order of the binder type. The time span between the two coatings (x_3) is not relevant. The sign of the effect x_1 (aggregates order) is negative, that means that if small aggregates are used in the first mixing phase (first coating) the ITS will increase and vice versa. The sign of the effect x_2 (type of binder) is negative, that means that the best results are obtained using the emulsion during the first coating. The two-way interaction terms are not negligible (x_{12}; x_{13}, x_{23}), that means that the factors have a mutual influence.

Analyzing the results for the dry specimens it is possible to conclude that the optimal procedure to first coat the fine aggregates with emulsion and afterwards coat the coarse aggregates with foam bitumen.

On the other hand, as can be seen in Figure 11, for wet results x_1 is positive which means that using coarse aggregates in the first mixing phase the ITS is higher. The time span between the two coatings (x_3) becomes important for the water resistance and its effect is negative, which means that increasing the rupture time between the coatings the ITS decreases. The order of the type of coating (x_2) is less relevant in this case. The interaction terms are not negligible (x_{12}; x_{13}, x_{23}), that means that the factors have a mutual influence and that the factors are not independent from each other.

Analyzing the results for the wet specimens it is possible to conclude that the optimal procedure is to first coat the coarse grains with the emulsion and afterwards coat the fines with the foam bitumen. Contrary to what happens with the dry specimens, for the wet ones the rupture time is important. Finally, as it can be seen from Figures 10 and 11, treating separately the results, the definition of the optimal recipe is not unique. Indeed, it depends of the type of criterion used (wet or dry ITS).

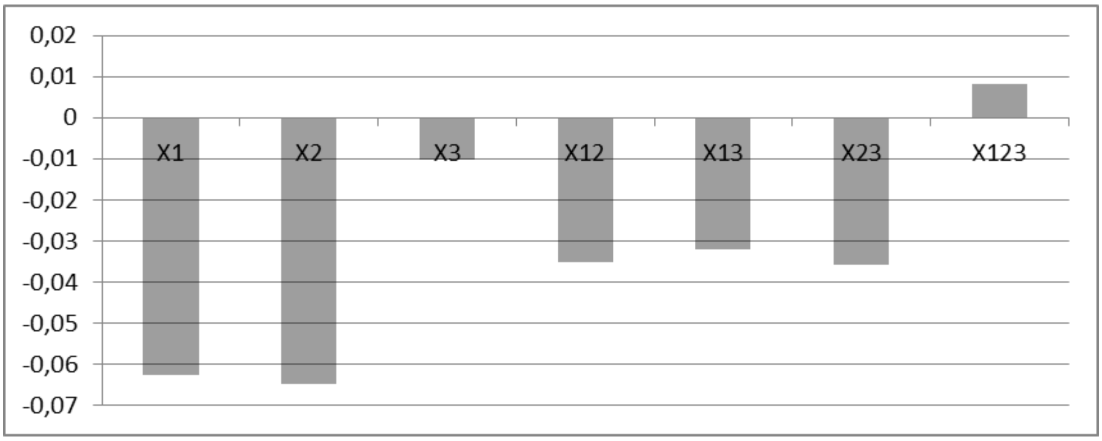

Figure 10: Relative effects in case of ITS dry.

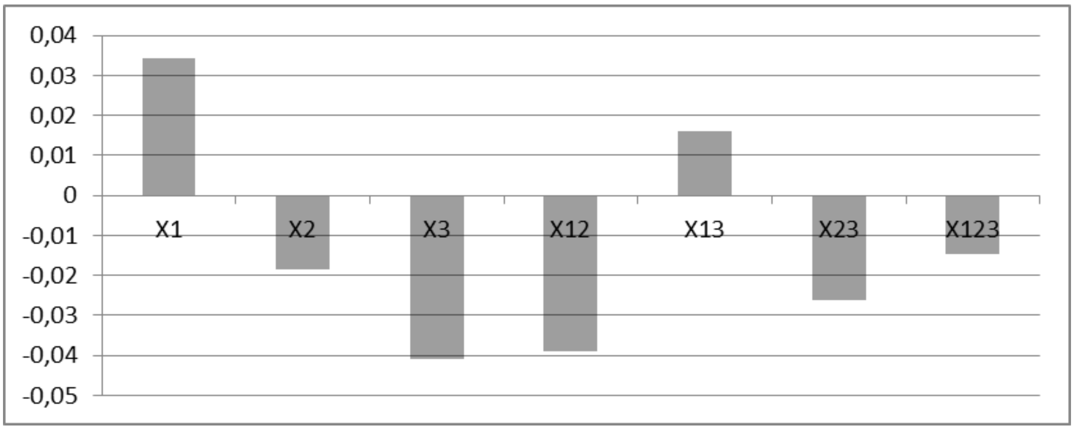

Figure 11: Relative effects in case of ITS wet.

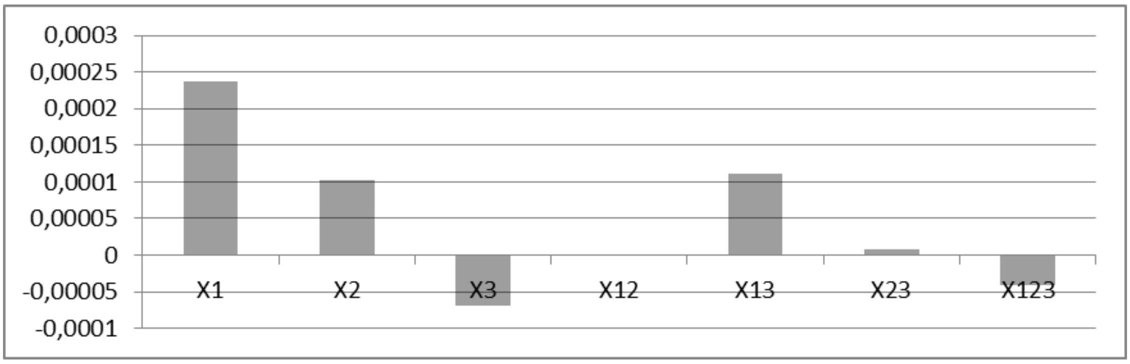

Figure 12: Relative effects for the ratio between the ITS dry and wet.

As shown in the Figure 12, analyzing the results for the ratio between the results characterizing dry and wet specimens, it is possible to conclude that the optimal procedure is to first coat the coarse part with foam and afterwards coat the fines with the emulsion. The appropriate time span between the coatings is 1 minute. In this case the interactions results less significant and could be ignored (with the exception of x_{13}).

6 SUMMARY OF FINDINGS

In this study two-phase mixing method was evaluated in producing the FDR mixes. This new method is mainly based on pre-coating a part of the aggregates with an appropriate amount of optimum binder content. The double emulsion/foam coating mix shows promising results for ITS and Marshall stability test. However some enhancements remain to be made with moisture content.

Adding more bitumen with emulsion or separating coarse and fine aggregates seems to be good solutions to deal with a poor coating. Improving the coating of the aggregates, should result in a less water sensitive asphalt mixture. Moreover, these changes in the formulation and in the production could enhance resistance which is already improved compared to the standard formulations. Nevertheless, additional research efforts have to be employed to achieve higher performances.

The work presented represents a first promising step towards a new type of production for cold mix asphalt. Nevertheless, additional work is needed to verify the results obtained in the laboratory when the mixtures are produced in the plant.

It enables to keep an open-mind on ideas which seem unsuitable at the first sight. This is the case for the two-phase mixing process with coarse aggregates separated which is currently inadequate to cold in place recycling but can be used for central recycling unit. Additional work is needed to test the complex modulus that characterizes the double coated materials, for a possible use in the pavement design.

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