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Foamed Bitumen in Half-Warm Asphalt: A Laboratory Study

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Abstract: Techniques to reduce production temperatures of asphalt have become popular. In warm techniques, mixing temperatures are reduced to around 120-130°C; while in semi- or half-warm techniques, asphalt mixing temperatures are below 100°C. In cold paving technology, asphalt is produced at ambient temperature. In the last two techniques, the aggregates still contain considerable amounts of moisture. Moreover, in these techniques the presence of water is required to some extent. Of course, the savings in energy and emissions are considerably large, when there is no need to fully dry all the materials. In 2006, Nynas and the Belgian Road Research Centre started a project to evaluate the performance of hot versus warm and semi-warm produced asphalts. In the half-warm technique, foamed bitumen, wet aggregates, and a mixing temperature of 90°C were used. This publication focuses on the laboratory evaluation of the foam technique. Several parameters were varied, including the moisture content of the aggregates at mixing, the time lag between mixing and compaction of the asphalt, the influence of adding active filler, and the effect of foaming the binder versus just adding hot bitumen to the mixture. The evolution of the mechanical properties after compaction was also followed as a function of time.

***Key words**: Curing; Foamed bitumen; Half-warm; Reduction of production temperature.*

Introduction

Foamed bitumen has been applied a lot, for example, in road base stabilization and in place cold recycling [1]. In these techniques the foam is used with aggregate material at ambient conditions. When compared to unbound base layers, this use of foamed bitumen gives a clear improvement. On the other hand, when compared to hot mix asphalt, cold mix asphalt with foamed bitumen has inferior performance and cannot be used for wearing courses intended for high traffic.

To improve the performance of the foaming technique and to extend its use, a number of special techniques were developed. Most of these techniques use higher aggregate temperatures, typically up to 80-100°C. Under these conditions, foamed bitumen (at 140-160°C) is added to the aggregates. The equilibrium temperature of the mixture, after mixing, is commonly around 80-95°C. In these techniques, referred to as semi- or half-warm techniques, the aggregates still contain some moisture and the production temperature is below 100°C [1-7].

In this paper the focus is on half-warm mixes produced in the laboratory. The following parameters were varied and evaluated: the initial moisture content of the mix, the time between mixing and compaction, the use of bitumen as such or as foam, and the need for active filler. In this respect, two types of active filler were evaluated. Mechanical properties of the prepared mixes were also investigated with a special attention to possible effects on curing. Since the compacted mixtures prepared with foamed bitumen contain a certain amount of moisture, it is believed that a curing period is necessary to allow further drying of the compacted samples and to reach the final performance of the mix. In addition, the presence of active filler can also have an impact on the curing. Performance properties like indirect tensile strength and indirect tensile strength ratio were followed as a function of curing time.

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Experimental

Materials and Mix Design

A Belgian mix, AB-4C, according to the standard specifications SB250-v2.1 was used. This is dense asphalt concrete for top layers, AC 0/10 according to the European standards. The PradoWin software of BRRC [8] was used for the mix design. With the characteristics of the different constituents as input data, this software predicts the volumetric composition and void content of the mix for a given mix composition. Table 1 shows the dry mix composition. The binder is Nyfoam 50, which also fits a paving grade bitumen 50/70 (acc. to EN12591), added in 5.84 % by mass in the mix (6.2 % by mass on the aggregate mass). If active filler was used, 1% of the standard filler was replaced by 1% of active filler.

Laboratory Production of Foamed Asphalt

Compared to hot mix asphalt, the production of half-warm foamed mixes requires additional steps and extra parameters need to be taken into account:

- The bitumen needs to be foamed. In this study, a Wirtgen laboratory foam unit was used. The optimum water content of the foam needs to be determined, based on a compromise between expansion ratio and collapse time of the foam. The procedure is explained in reference [9]. For the laboratory study described in this paper, the water content of the foam was

Table 1. Composition of the Reference Mix AC 0/10 (Dry Aggregates).

Type	Component	Density (g/cm^3)	Volume (%)	Mass (%)
Filler	Duras II	2,61	7,7	7,4
Stone	Porphyry 4/6.3	2,71	19,9	20,0
Stone	Porphyry 2/4	2,71	22,4	22,5
Stone	Porphyry 6.3/10	2,71	16,6	16,7
Sand	Porphyry 0/2	2,72	25,1	25,3
Sand	Round sand	2,62	8,4	8,1

Fig. 1. Wirtgen Laboratory Foam Unit, Together with the Asphalt Mixer.

fixed at 3% and this parameter was kept as a constant through this study.

- Secondly, to be able to add the correct amount of binder to the mixture, a relation between foaming time and bitumen amount needed to be established before starting the asphalt mixing process. By adjusting the foaming time, the desired amount of binder could then be added to the asphalt mix.
- As the foam unit that used in this study is suited for foaming larger quantities of bitumen, it was unpractical to prepare the mix in small quantities. The quantity prepared in one batch in the laboratory was 40 *kg* of asphalt. This means that from one batch, a large number of test specimens could be compacted in the gyratory compactor. Consequently, when comparing specimens, the time between mixing and compaction is an additional parameter.
- Finally, in these tests the aggregates were wet, and extra tests were needed to control their water content.

The foamed asphalt mixes were prepared using a Guedu asphalt mixer. The foamed bitumen was directly transferred from the foaming unit into the asphalt mixer. To control the moisture content of the aggregates, a special procedure was followed: first, all aggregates were completely dried; then calculated water content was added to the mixture of stone and sand fractions; and subsequently this mixture was stored at 90°C for 12 *hrs*. During storage at 90°C, the aggregates were kept in a closed container but with a small hole to avoid pressure build-up. This procedure was followed to allow the water to be absorbed inside the pores of the aggregate material, which corresponds better to field conditions. After these 12 *hrs*, the water content was again verified (by weighing), and was, if needed, corrected to the desired amount. Then the damp aggregates and sand were transferred to the asphalt mixer. Foam was added and mixed for 2 *mins*. Afterwards, the dry filler combined with active filler, if desired, was added to mix continuously for another 3 *mins*. In Fig. 1 the bitumen foaming equipment and the asphalt mixer are shown. Both equipments are mobile so the foam can be directly injected into the asphalt mixer.

Test Methods

Before compaction, the water content of the loose mixture was evaluated by measuring the weight loss during storage for 12 *hrs* at 110°C. This time interval should be sufficiently long to dry the mixture. The water content of compacted cores was evaluated by following the weight loss after storage at controlled conditions of humidity and temperature (15°C and a relative humidity of 40-55%). Finally, the compacted cores were considered as completely dry after stored for about 10 weeks.

To evaluate compactability, the gyratory compactor was used according to the European standard (EN 12697-31). The mix preparation procedure followed EN 12697-35. According to this standard, the reference temperature (temperature at which compaction starts) of the hot mix asphalt type AC 0/10 is 150 °C (case of a bitumen B 50/70).

The water sensitivity of the mix was investigated by means of the indirect tensile strength (ITS) test (EN 12697-23), before and after conditioning in water according to EN 12697-12. Six cores are needed to perform the water sensitivity test. Three cores are subjected to the ITS test without conditioning. The other three cores are conditioned according to EN 12697-12, before being subjected to the ITS test. The ITS ratio (ITSR) after and before conditioning is a measure for the water sensitivity of the mix and indirectly for the adhesion between binder and aggregate. As water sensitivity is very dependent on the degree of compaction, the tests were performed on cores with a low degree of compaction to simulate the worst case in field situations. In this study, the gyratory cores used for indirect tensile testing were compacted to 25 gyrations, because field trials with warm mix techniques by using wax modified binders or zeolites showed that compaction to 25 gyrations was representative for the lowest degree of compaction in the field. This will be verified for the half-warm foam technique once the field sections are constructed.

ITS and ITSR were followed as a function of curing time. This curing was simulated by storing the samples in a climatic chamber at temperature of 15°C and relative humidity of 40-55%. These conditions are chosen as close as possible to the average outside conditions in order to prevent the impact of artifacts.

Results

Compactability

For the two warm techniques using waxes and zeolites studied in this project, the compactibility could be established with the gyratory compactor [10, 11]. For these warm techniques, every

Table 2. Overview of Test Cases and Test Runs Preparing for Reference and Foamed Asphalt.

Asphalt Batch	Use of Foam	Use of an Active Filler	Moisture Content Aggregates (in % of the Aggregate Mass)
Ref. Mix at 150°C	No	None	Dry
Ref. Mix at 90°C	No	None	Dry
*Case 1-batch 1	Yes	1% Filler A	2.5
Case 1-batch 2	Yes	1% Filler A	2.5
Case 1-batch 3	Yes	1% Filler A	2.5
Case 1-batch 4	Yes	1% Filler A	2.5
Case 2	Yes	None	2.5
Case 3	No	1% Filler A	2.5
Case 4	No	1% Filler B	2.5
Case 5	Yes	1% Filler B	2.5
Case 6	Yes	1% Filler A	1.0

*Case 1-batch 1 differs from batches 2, 3 and 4 in the storing conditions of the loose mix before compaction.

sample compacted in the gyratory compactor was mixed in a separate batch using a small volume asphalt mixer. For the foam technique however, this was not possible, as explained in the experimental section. When a batch of foam mix was made, a large number of asphalt cores were compacted from this batch with increasing time intervals between mixing and compacting. Overviews of the respective cases for foamed mixes with respective varied parameters are given in Table 2. The differences between the various batches of case 1 are explained below.

After evaluation of the first batch, case 1-batch 1 in Table 2 was observed that the compaction levels of cores prepared from the same asphalt batch, decreased with the increase of the time between mixing and compaction. During this time, the loose asphalt was just left in the partly covered asphalt mixer at 90° C, and immediately before taking a sample, the mixer was run for a few minutes. The variation in compaction was attributed to an evaporation of moisture from the mixer. Because of this observation, the storing conditions for the loose asphalt were slightly modified for the later test runs: the first samples (compacted up to 2 *hrs* after mixing) were taken directly from the asphalt mixer, while samples intended for compaction at a later stage were all taken from the mixer within 1*hr* after mixing, and subsequently stored in separate cans at 90°C. This procedure was used so that all weights could be recorded carefully and followed for each individual specimen.

In Fig. 2, densities obtained after 25 gyrations are shown as a function of time between mixing and compacting. This density is calculated from the sample weight and the dimensions after 25 gyrations. The first two tests in this figure refer to the density of the reference mix (without foaming) at compaction temperatures of 150 and 90°C, respectively. In the reference cases, all components were fully dried and the mixing temperature was approximately 15°C higher than the compaction temperature. The minimum and maximum densities of the reference case which compacted at 150°C are indicated by two straight lines. The densities reported in Fig. 2 are average values of at least two consecutive tests, and the times reported are median times. The error bars represent the standard deviation between the different repeats.

From Figs. 2-4, it is clear that there are time effects in the compactability of the asphalt cores. Cores that are compacted more quickly after mixing have a higher density than cores compacted after longer times. This observation is important for the preparation of test samples. This is of course an extra parameter that needs to be taken into account. However the repeatability of the tests is not very high. This is most likely related to differences in the evaporation of water prior to the compaction test, even if the loose mix was stored under similar conditions.

For this type of mix, when it is used in a reference situation which refers to asphalt production in the standard hot mix mode, the

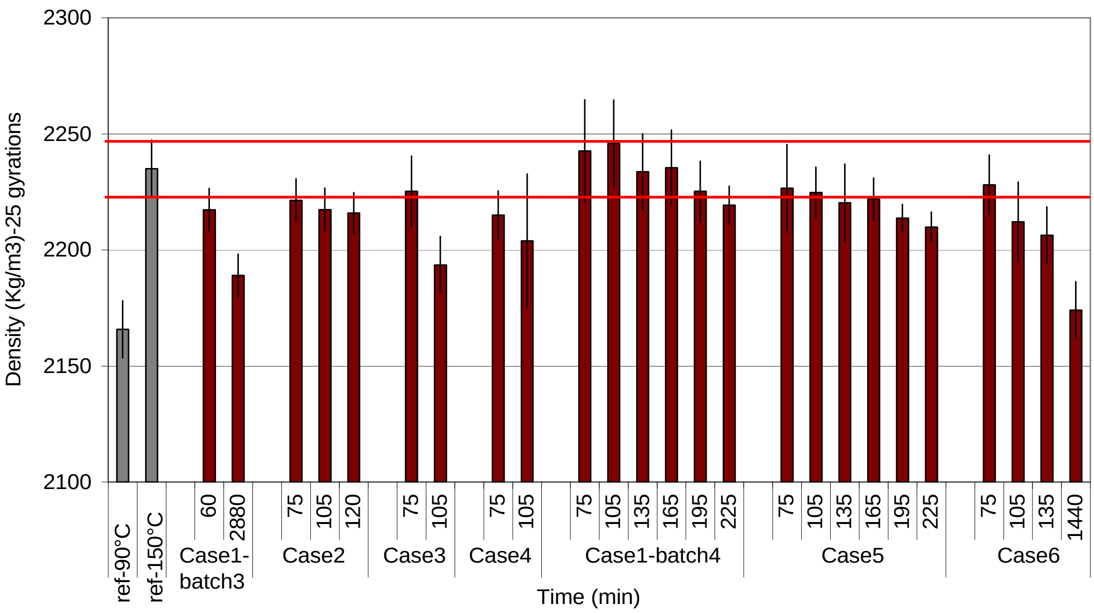

Fig. 2. Densities Recorded after 25 Gyrations, the Time Referring to the Time the Mix Stored at 90°C between Preparation and Compaction.

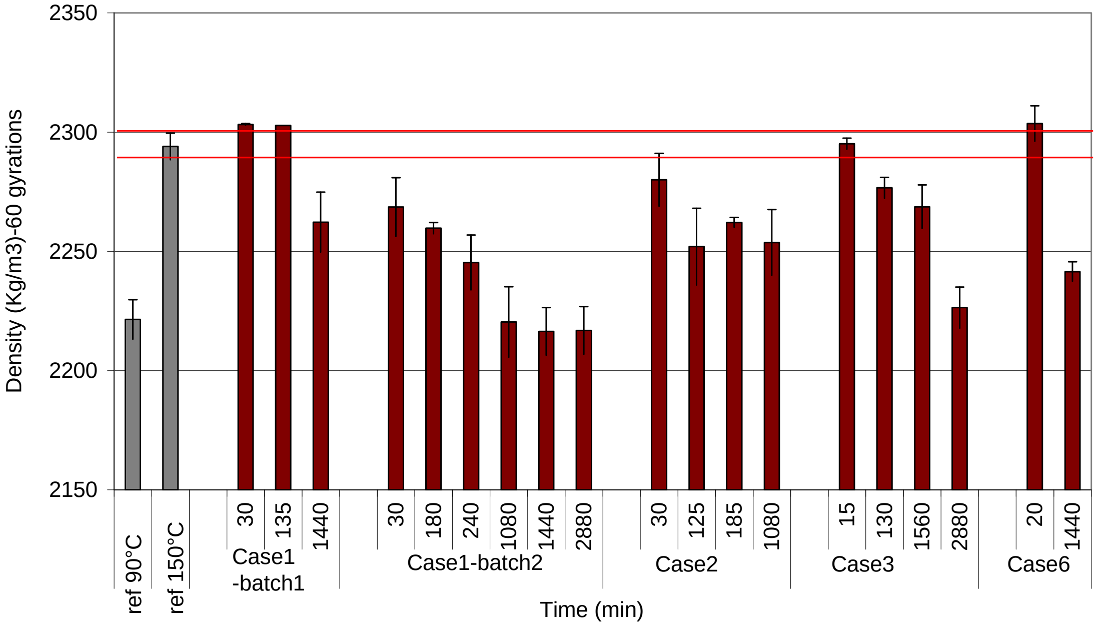

Fig. 3. Densities Recorded after 60 Gyrations, the Time Referring to the Time the Mix Stored at 90°C after Preparation and before Compaction.

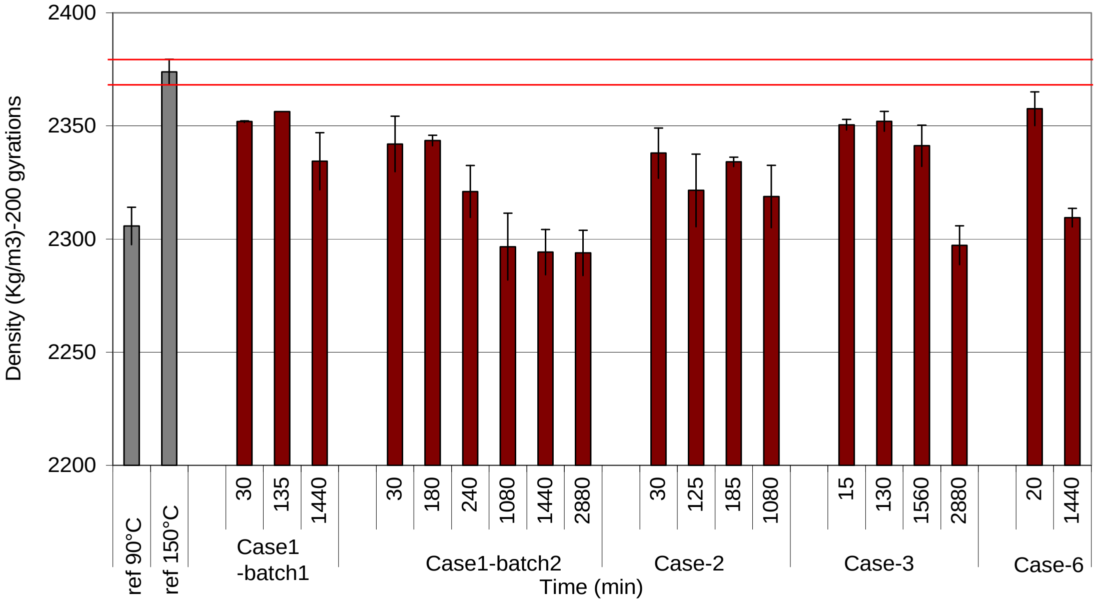

Fig. 4. Densities Recorded after 200 Gyrations, the Time Referring to the Time the Mix Stored at 90°C after Preparation and before Compaction.

authors already have some insight in the relation between the compaction level in field tests and the number of gyrations needed in a laboratory test. Under these conditions, densities obtained after 200 gyrations characterize as over-compacted situation (the void contents of these cores are only about 1%). Densities obtained after 60 gyrations are representative for a normal/good compaction level on site, and densities obtained after 25 gyrations for those places in a field test describe as a very low or worst compaction level. In Figs. 3 and 4 the densities at 60 and 200 gyrations are also plotted.

From Figs.2-4, the following observations can be made:

- There is clearly a time effect in the degree of compaction obtained. The degree of compaction is generally higher for cores prepared after short times and decreases when the mix is

Table 3. Binder Contents of Samples Taken from Various Test Runs.

Asphalt Batch	% Bitumen	Asphalt Batch	% Bitumen
Case 1-batch 1	6.4	Case 3	6.2
“ 6.0		“	6.1
Case 1-batch 2	6.0	Case 4	6.2
“	6.1	Case 1-batch 4	6.1
Case 2	6.0	Case 5	6.2
“ 6.6			

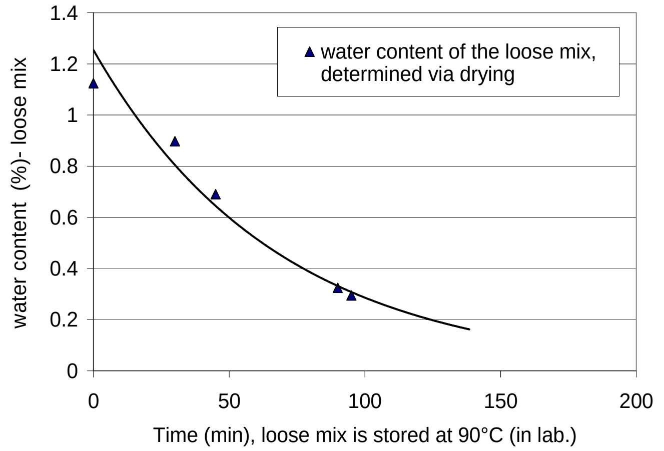

Fig. 5. Water Content of the Loose Mixture versus Time the Mixture Stored at 90°C for Case 2. (The Initial Water Content at the Time the Asphalt Mixing Process Started was 2.5%).

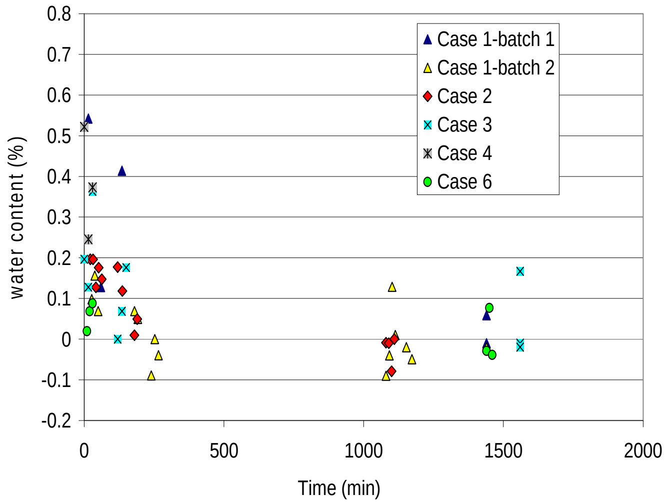

Fig. 6. Water Content Determined from Compacted Cores versus the Time between Mixing and Compacting the Core.

stored before compacting it. At short times, the compaction of the mixes with foamed bitumen is always better than the compaction of the reference mix at 90°C. After 1 day storage or longer, the degree of compaction is either still somewhat better or very close to the one obtained for the reference mix at 90°C. Time effects are also presented in those cases where the bitumen was not foamed (case 3 and 4).

- There is also an influence of the number of gyrations on the relative (compared to the reference cases) degree of compaction obtained: At 25 gyrations, the degree of compaction of the reference mix at 150°C can be reached using the foamed asphalt when the time between mixing and compaction is short. It seems that this compaction level can be reached up to 2 to 3 *hrs* after mixing. But, as this time window is established for laboratory tests, it will probably differ for large scale samples. At 60 gyrations, the degree of compaction of the reference mix at 150°C is reached in most cases; while at 200 gyrations, the compaction level of the reference mix at 150°C is no longer reached using the foam technique.
- In compaction tests, the variability between test runs is large, even if all investigated variants and storing conditions of the loose mix are kept the same. Therefore, it was not possible to determine the effect of some additional parameters on the compactability. These include; adding the binder as such or using foam, replacing 1% filler fraction with 1% of active filler, or changing the initial water content of the wet aggregates from 2.5 to 1%.

Variation in Binder Content

To add accurate amounts of binder when preparing foamed asphalt mixtures, more elaborate procedures were considered and the binder contents for some of the cores were measured. Results are shown in Table 3. The binder contents were measured from gyratory compacted cores (about 1 *kg*) according to EN-12697-1. From Table 3, it is clear that the average binder content is close to the target binder content of 6.2%. But the variation between individual cores of one asphalt batch is rather high according to EN 12697-1, where the repeatability limit, r, should be of the order of 0.3 %. It is not clear yet why this variation is so high. But this observation can certainly have an effect on the repeatability of test results made with individual cores.

Water content

It was shown above that the time interval between mixing and compacting the sample has a considerable effect on the density obtained in gyratory tests. As we expect that these changes are related to changes in the water content of the mix, this water content was followed as a function of time. The procedure is described in the experimental section, and data are represented in Fig. 5. It is clear that the moisture content of the mix decreases rapidly with time. The water content of the first samples, taken directly after mixing, has already decreased to 1.2%, even if the initial water content of the aggregate fraction was 2.5%.

Moisture contents of compacted cores were also determined by measuring the weight changes that between the moment of compaction and after two months at ambient temperature. These values are shown in Fig. 6. They show the same trend, but the values are smaller; obviously since there is also water evaporating during compaction, which is not taken into account. Secondly it is possible that these data underestimate the real water content, because it is assumed that the cores are completely dry after 2 months. But Fig. 6 also reveals, especially at short times, large differences between the various cases and batches and these variations may explain the large variability that was observed in the compaction tests.

Fig. 7 illustrates more in detail of the loss of moisture of gyratory compacted cores in the days following compaction under conditions of controlled temperature and humidity. In this test the cores were stored in a climatic chamber at temperature of 25°C and relative humidity of 30 to 40 %. To recalculate the water content at the moment of compaction, it is assumed that the core is dry after 35 days. Core 1 was compacted 12 *mins* after mixing, while cores 8, 9, and 10 were compacted after a longer period. This is seen in the initial water content, which is lower for the three last specimens.

Table 4. Effect of Foaming on the Results of the Water Sensitivity Tests Which Carried Out 10 Days (±1) after Compaction.

	With 1% Filler A			With 1 % Filler B	
	Foamed	Foamed	Unfoamed	Foamed	Unfoamed
	Case 1-batch 3	Case 1-batch 4	Case 3	Case 5	Case 4
Voids (%)	7.2	6.1	7.3	5.9	7.1
ITSR (%)	52	67	43	71	61

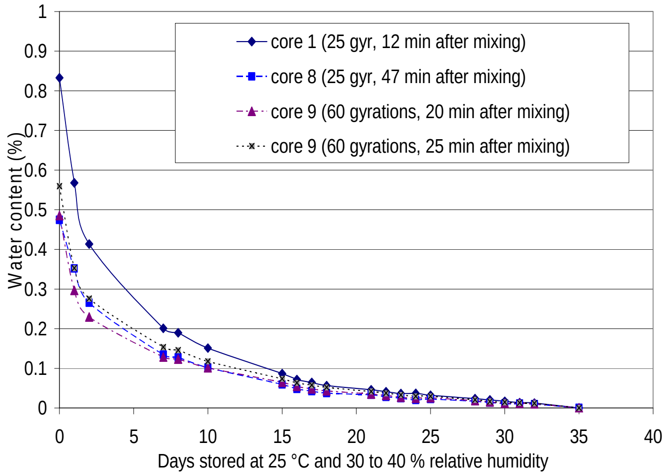

Fig. 7. Evolution of the Water Content of Cores Prepared Using Foamed Bitumen and Wet Aggregates (Cores from Case 1-batch 3).

Table 5. Effect of Active Filler on the Results of the Water Sensitivity Tests Which Carried Out 30 Days (±2) after Compaction.

	No Active Filler	With 1% Filler A	With 1 % Filler B
	Case 2	Case 1-batch 4	Case 5
Voids (%)	6.9	6.5	5.9
ITSR (%)	56	72	81

Water Sensitivity

ITSR was used to investigate the water sensitivity which is described in the experimental section. Since the water content of compacted samples changes in the period after compaction (see Fig. 7), it was expected that this would have an impact on the results of the water sensitivity test. Therefore, the curing time (time between compaction and testing) is indicated for all the tests reported. And since, as described in the compaction tests, the level of compaction is dependent on the time interval between mixing and compaction, this time interval was also kept constant as much as possible.

It is expected that foaming the bitumen improves the aggregate coating while compared to just adding the binder. If this is the case, it would be reflected in the water sensitivity. Therefore a mix produced with foamed bitumen was compared to the same mix which prepared in identical conditions but without foaming the bitumen. This is shown in Table 4 for two active filler types; 1 % of filler A and filler B. The table shows two sets of data for the mix with 1 % of filler A using foamed bitumen, which gives an idea of the reproducibility (same case, but different batches).

From these limited data, the first observation is that the repeatability is poor: comparing case1-batch 3 versus case 1-batch 4 ITSR differs by 15 %. But also the void content differs by more than 1%. In fact, the "poor" repeatability of the ITSR values is related to the "poor" repeatability of the compaction at 25 gyrations. But still, in Table 4, there is an improvement in the water sensitivity by foaming the binder in both cases. The ITSR increases with foaming from 43 to 52%, when considering the first set of results. Also in the case of filler B, foaming the binder has a positive effect on the water sensitivity, when comparing specimens compacted with the same compaction energy. The results may also indicate a difference between both types of active fillers: especially for the unfoamed mixes; the mix with filler A may be somewhat more sensitive to water conditioning, 43% versus 61%.

The effect of active filler is further evaluated in Table 5: tests made without filler additive are compared to tests made with 1 % of active filler A and B, respectively. For the interpretation of the results, it should be noted that the tests made in Table 5 were performed after 30 days (±2) of "curing" compared to 10 days for the data presented in Table 4. In the remainder of this paragraph, it will be shown that the ITSR increases within this time frame. Table 5 indicates that the water sensitivity is improved when using active filler.

To investigate the effect of curing of compacted samples, series of water sensitivity tests were made after various periods of curing with additive of active filler A (case 1-test 4) and active filler B (case 5). From the results plotted in Fig. 8, we can clearly conclude that the ITSR increases with curing time. It is not clear from these data if the values reached their maximum after a period of two months. Additional measurements after longer curing periods would be necessary to determine the maximum level that can be achieved.

Small differences are noticed between the case with active filler A or B. On average, the results appear to be slightly better for the case with filler B. But as there is also a difference in void content between both series as well as a slight difference in binder content, it is not possible to conclude that the type of filler is the parameter that makes the difference.

Finally, Fig. 9 shows the effect of the initial water content of the aggregates (case 1-batch 4 versus case 6). For the case with 1% water content, the tests were made after 3 curing intervals; 10 days, one month, and 2 months. But, due to the large variation in void contents between the various curing times, it was not possible to asses the decrease in initial water content of the aggregates.

Conclusions

In general, compared to the laboratory production and testing standard of hot mix asphalt, the production and testing of foamed mixes are more elaborate with more parameters to be taken into account:

- To have the desired bitumen percentage in the mixture, a relation between foaming time and bitumen amount needs to be established for the foam unit;

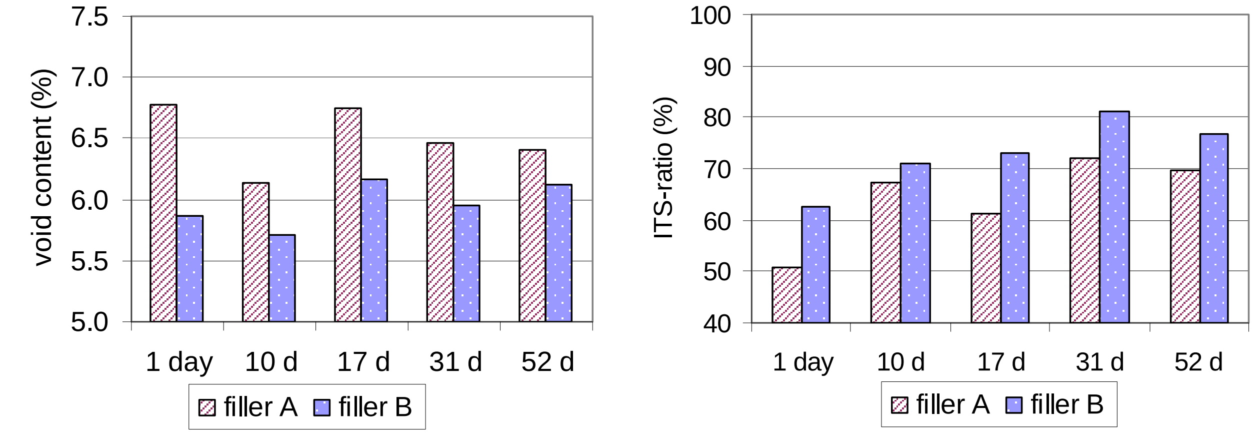

Fig. 8. Effect of Curing Period (in Days) on the Water Sensitivity Test Results for Two Types of Active Filler.

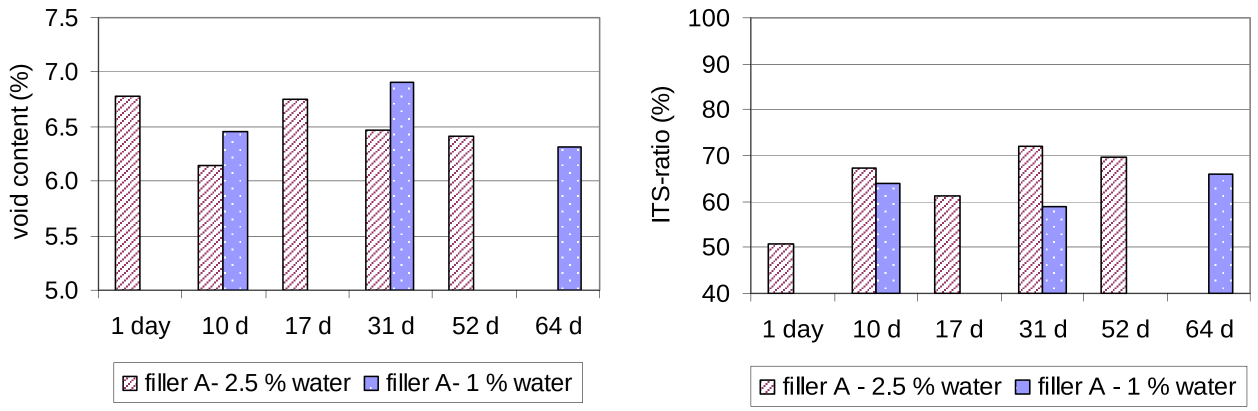

Fig. 9. Effect of Curing Period (in Days) on the Water Sensitivity Test Results for Two Different Water Contents.

- The optimal water content of the foam needs to be determined;
- The aggregate fractions are wet, and their water content needs to be controlled;
- The test results show that after mixing, water evaporates rapidly from the loose mixture. Hence, the time between mixing and compaction is a parameter that needs to be taken into account when preparing these mixes. This also includes that a procedure of how to store the loose mixture before compaction is needed. Moreover, this procedure may have an impact on the obtained test result;
- Since in this study, it was not practical to prepare 1 *kg* asphalt batches, larger amounts, about 40*kg* per batch, were prepared. From such an asphalt batch, a number of small (±1 *kg*) test specimens were compacted and used in the water sensitivity tests. So, the storage time of the loose mix was an inevitable extra parameter;
- And even after compaction of these mixes, there is an effect on curing time. This study clearly demonstrates that after compaction, moisture slowly evaporates from the compacted core. The time interval between compaction and testing can therefore have an influence on the test result. Yet again, the conditions under which the asphalt cores are stored prior to testing can become important; and
- Finally, it was observed that the binder contents between individual cores compacted from the same asphalt batch vary considerably.

Consequently, there are more parameters in foamed mixes while compared to standard hot mix. When known, these parameters can be recorded, but they are difficult to control in general. As combined with the large variation in binder content, it is clear that the variability between test results in foamed mixes is larger that of hot mix.

Regarding the gyratory compaction tests, these tests clearly show the effect of changing the time between mixing and compaction. In addition, these tests also show that at 25 gyrations, the degree of compaction of the reference mix at 150°C can be reached using foamed asphalt with short period time between mixing and compaction. At 60 gyrations, the degree of compaction of the reference mix at 150°C can be reached in most cases; while at 200 gyrations, the compaction level of the reference mix at 150°C is no longer reached. Other parameters, like foaming the bitumen, using active filler, type of active filler, and initial moisture content (1 or 2.5%) were varied, but their effects on gyratory compaction data were small when compared to the variability of the test results. Hence, it was not possible to draw further conclusions.

The water sensitivity tests clearly show the effects of curing. The ITSR increases with the increase of the time between compaction of the asphalt and testing. The ITSR tests also show an improvement on the water sensitivity by using foamed bitumen when compared to by just adding the (non-foamed) bitumen and using active filler. On the other hand, the ITSR tests results did not allow differentiating the type of active filler applied or the initial water content of 2.5 or 1%.

Based on the laboratory investigations of bitumen foaming techniques, we estimate that high quality asphalt mixes could be produced at 90° C in large scale provided that all factors are kept under carefully control. However, to maintain a high quality is very important to have a continuous control program during all production.

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