The Impact of Sample Compaction Temperatures on the Characteristics of Bituminous Concrete

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Abstract. The compaction of bituminous layers is the operation that determines the asphalt mixtures to reduce their air voids until the desired density is obtained, at the suitable temperature and with specific equipment, in order to reach the physical-mechanical characteristics designed in well-controlled laboratory conditions. The realization of these objectives can be slightly altered by a number of factors which can intervene during the construction, such as: temperatures in the technological process (production, transportation, laying and compaction), weather conditions (atmospheric temperature, wind, humidity, transport distance), type of compactor (certain types of a single device or complex compaction equipment), thickness of the layer, alteration of the mixture during laying, etc. Most of the research concerning the compaction deals with identifying the factors affecting the site compaction and the way they can influence the realization of the designed density, starting from the premise that the reference results offered by the laboratory are those obtained in standardized conditions. The research presented in the paper aims at emphasizing the way different preparation and compaction temperatures influence the physical-mechanical characteristics of a laboratory prepared asphalt concrete. It started from the question of whether these characteristics are significantly influenced by the temperature variation or if they range between “acceptable” tolerances. For clarification, the authors prepared asphalt concrete samples for the wearing course, according to the Romanian technical standards, at different preparation and compaction temperatures, in laboratory-controlled conditions. The determined physical-mechanical characteristics were: density, voids, water absorption, Marshall stability, water sensitivity, dynamic flow and rigidity. The results obtained confirm that, for most of the determined characteristics, the temperatures used significantly influence the values obtained. Also, the paper presents a comparative study between the results obtained in the mentioned conditions in the case of three different bitumen dosages, which are 4.8; 5.2 and 5.7% binder by the weight of the asphalt mix. It was found that the variation of the binder content introduces an additional altering factor as to the preparation and compaction temperature.

1. Introduction
The compaction of the bituminous layers is the main technological operation leading to stability and resistance in the monolith layer. The results depend on all the influence factors during the technological flow (strictness in choosing the materials, designing the dosage and observing it on site, adaptation and maintaining the working temperatures depending on local conditions, choosing the compaction equipment depending on the type, thickness, workability of the asphalt mixture to be compacted, etc.). Otherwise, even with adequate compactors on site, there is the possibility of realizing road layers with inappropriate densities (too high values of air voids, over 5…7%, depending on the type of layer, affecting the mechanical characteristics, too low values of air voids, under 2%, affecting the roughness).
The determination of the compaction conditions on site is based on the interpretation of the results obtained in the laboratory. The correlation between the two types of characteristics is essential, as specified by the French guide for compacting hot asphalt mixtures [1]. The example offered implies two “graves-bitume” with a significantly different behavior in the laboratory (GM 4 reaching air voids of 9% after 50 gyrations, while GB 4 reaches the same air voids after 100 gyrations), for which the compaction needs to be adapted depending on these characteristics. On the other hand, it is shown that for 50/70 bitumen, the laying temperatures must be 135…155°C (spreading) and 105°C (at the end of the compaction). Regardless of the binder type, the difference between the temperature at the end of mixing and the temperature at the end of the compaction must be about 60°C.

In the laboratory, things seem simpler at first sight, as the working conditions are under strict control, but here too, errors may appear in certain situations that can perturb significantly the results obtained. For example, following the authors’ own findings, to be verified in a different research, the increase by about 2 °C of the testing temperature leads to a decrease of the stiffness modulus by 15…20 % and a reduction of the maximum load in the indirect tension test by 10…15 %.

There are different researches concerning the influence of working temperatures on a certain characteristic of the asphalt mixtures. For example, in the doctoral thesis [2] the conclusion is that the compaction temperature of plates used in the determination of rutting did not influence the depth of the rut resulted from laboratory testing and a correlation between the two characteristics could not be established. Instead, the author raised the question of the compacting modality of plates 50 mm and 100 mm thick, the thickest being, seemingly, less stressed by the compaction energy than the thinnest ones.

It is unanimously recognized that the asphalt mixture, due to the binder incorporated, shows a rheological behavior, the response of the bituminous layer to external stress being different depending on the temperature, frequency and duration of the respective solicitation. In these conditions, the maintenance of a good correlation between the research laboratory conditions and the laying and finally operation conditions is fundamental for the success of the works. Nevertheless, it can be seen that the modern compaction equipment can offer information on the rate of compaction reached in the bituminous layer, the technologist being able to take the decision of increasing the number of passes over the designed one in order to improve this characteristic.

The present research aims at determining whether, in laboratory conditions, the results obtained for the current tests, stipulated by the Romanian technical norms, are altered significantly by the mixing temperature of the asphalt mixture and the temperature of sample compaction.

2. Particularities of the studied asphalt mixture
The authors considered an asphalt concrete for the wearing course, with a 0-16 aggregate skeleton, the crushed aggregates coming from a diabase quarry (2.812 g/cm³ bulk density, minimum 98% level of compaction and 0.22% water absorption) and the 50/70 bitumen (MOL). The gradation of the aggregate skeleton is represented on a Federal Highway Administration (FHWA) 0.45 Power Graph (figure 1) and ranging in the grading area specified by the Romanian standards for this type of asphalt concrete (figure 2) [3-5].
Figure 1. Gradation curve of the aggregate skeleton on an FHWA 0.45 Power Graph

Figure 2. Gradation curve of the aggregate skeleton depending on the limitations of the Romanian technical standards

It is concluded that the aggregate skeleton has a dense grading, close to the 0.45 power line, leading to the conclusion from the beginning that the remaining air voids in the asphalt mixture will be relatively reduced. On the other hand, the characteristics of the used aggregates (leading to a high total percentage of sands) did not allow a significant correction of the gradation curve in its lower part.

Three binder contents (4.8; 5.2 and 5.7% by weight of the asphalt mixture) were used in this research. The mixing temperature was 160°C and the compaction temperatures 120 and 100°C, respectively. The compaction of the samples was realized with the gyratory compactor (80 or 205 gyrations) and with the Marshall equipment (2x50 blows).

3. Results and discussions
3.1. Variation of the density and the air voids
The results obtained for the maximum density ($\rho_{\text{max}}$), the bulk density ($\rho_{\text{mb}}$) and the air voids ($V_a$) on specimens prepared with the gyratory compactor and the Marshall equipment, for the above mentioned dosages and mixing and compaction temperatures, are presented in table 1 (for a 4.8% binder content), table 2 (for a 5.2% binder content) and table 3 (for a 5.7% binder content).
Table 1. The bulk density and the air voids for a 4.8% binder content

| Mixing temperature/ Compaction temperature, °C | \( \rho_{\text{max}} \), g/cm\(^3\) | Compaction with the gyratory compactor, at: | Compaction with the Marshall equipment |
|-----------------------------------------------|---------------------------------|---------------------------------|---------------------------------|
|                                              | 50 gyrations | 80 gyrations | 205 gyrations | 50 gyrations | 80 gyrations | 205 gyrations |
| 160/140                                      | 2.449       | 4.7          | 2.476        | 3.7          | 2.489        | 3.1          | 2.476       | 3.7          |
| 160/100                                      | 2.372       | 7.7          | 2.429        | 5.5          | 2.460        | 4.2          | 2.422       | 57.          |
| 160/80                                       | 2.318       | 9.8          | 2.363        | 8.1          | 2.394        | 6.8          | 2.337       | 8.0          |
| 140/120                                      | 2.402       | 6.5          | 2.424        | 5.7          | 2.474        | 3.7          | 2.418       | 5.7          |
| 120/120                                      | 2.408       | 6.3          | 2.414        | 6.0          | 2.487        | 3.2          | 2.388       | 7.1          |
| 120/100                                      | 2.366       | 7.9          | 2.407        | 6.3          | 2.459        | 4.3          | 2.396       | 6.7          |

Table 2. The bulk density and the air voids for a 5.2% binder content

| Mixing temperature/ Compaction temperature, °C | \( \rho_{\text{max}} \), g/cm\(^3\) | Compaction with the gyratory compactor, at: | Compaction with the Marshall equipment |
|-----------------------------------------------|---------------------------------|---------------------------------|---------------------------------|
|                                              | 50 gyrations | 80 gyrations | 205 gyrations | 50 gyrations | 80 gyrations | 205 gyrations |
| 160/140                                      | 2.468       | 3.5          | 2.480        | 3.0          | 2.500        | 2.2          | 2.497       | 2.4          |
| 160/100                                      | 2.397       | 6.3          | 2.422        | 5.3          | 2.468        | 3.5          | 3.392       | 6.5          |
| 160/80                                       | 2.334       | 8.8          | 2.375        | 7.2          | 2.406        | 5.9          | 2.356       | 7.9          |
| 140/120                                      | 2.413       | 5.7          | 2.431        | 5.0          | 2.485        | 2.8          | 2.437       | 4.7          |
| 120/120                                      | 2.404       | 6.0          | 2.423        | 5.3          | 2.477        | 3.2          | 2.434       | 4.8          |
| 120/100                                      | 2.389       | 6.6          | 2.409        | 5.8          | 2.473        | 3.3          | 2.379       | 7.0          |

Table 3. The bulk density and the air voids for a 5.7% binder content

| Mixing temperature/ Compaction temperature, °C | \( \rho_{\text{max}} \), g/cm\(^3\) | Compaction with the gyratory compactor, at: | Compaction with the Marshall equipment |
|-----------------------------------------------|---------------------------------|---------------------------------|---------------------------------|
|                                              | 50 gyrations | 80 gyrations | 205 gyrations | 50 gyrations | 80 gyrations | 205 gyrations |
| 160/140                                      | 2.481       | 2.3          | 2.487        | 2.0          | 2.506        | 1.3          | 2.489       | 2.0          |
| 160/100                                      | 2.418       | 4.8          | 2.437        | 4.0          | 2.485        | 1.6          | 2.425       | 4.1          |
| 160/80                                       | 2.367       | 6.8          | 2.390        | 5.9          | 2.429        | 2.1          | 2.383       | 6.1          |
| 140/120                                      | 2.448       | 3.6          | 2.453        | 3.4          | 2.497        | 4.3          | 2.445       | 3.7          |
| 120/120                                      | 2.438       | 4.0          | 2.441        | 3.8          | 2.493        | 1.8          | 2.453       | 3.5          |
| 120/100                                      | 2.407       | 5.2          | 2.432        | 4.2          | 2.490        | 1.9          | 2.437       | 4.0          |

The interpretation of the results, even with small inconsistencies, can lead to the following remarks:

- the bulk density of the samples increases (and, implicitly, the air voids decrease) when the compaction energy increases from 80 to 205 gyrations, regardless of the binder content. However, the increases in bulk density between the limits of the compaction energy taken into consideration are higher when the binder content is lower (between an average of about 80 kg/m\(^3\) for the 4.8% bitumen content and an average of about 60 kg/m\(^3\) for the 5.7% bitumen content).

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content). In addition, the increases in density are more reduced if the compaction temperature is lower (from about 30 kg/m³ for a 140°C compaction temperature, up to 70…90 kg/m³ in the case of a compaction temperature of 80-100°C). These findings certify the fact that, even in laboratory conditions, it is difficult to obtain an adequate compaction when the compaction temperature is lower;

- the mixing temperature has lesser importance in obtaining a high level of compaction, in relation to the compaction temperature. The claim is supported by the results obtained for the samples compacted at 100°C or 120°C and at different mixing temperatures, regardless of the binder content;

- the conclusion that the densities obtained on samples compacted with the Marshall equipment are comparable to those obtained with the gyratory compactor for 70-100 gyrations can be extrapolated. It supports the idea to compare the results of the tests performed on Marshall samples (stability and flow index) with those obtained through compaction with the gyratory compactor at 80 or 100 gyrations (stiffness, dynamic flow, etc.);

- the increase of the binder content leads to the decrease of the air voids under 2%, which induces the conclusion that the considered asphalt mixture is inappropriate, according to certain technical norms (for example, the Canadian ones [6]). These stipulate air voids of minimum 11.0% at 10 gyrations and minimum 2.0% at 200 gyrations, with the performance tests for the mix design at air voids of 4-7 % for 80-100 gyrations).

The results obtained show that an adequate density (implicitly the air voids stipulated by standards) can be obtained in the laboratory even at reduced compaction temperatures, by increasing the compaction energy. The discussion remains open whether the optimum relation between these influencing factors can be exactly determined without a too important decrease in the air voids. On the other hand, the compaction of samples at a high temperature (over 140°C) can lead to reduced air voids even at a number of gyrations lower than 80.

It is to be noted that the Romanian standard concerning the design of asphalt mixtures [4] stipulates a maximum of 5% air voids at 80 gyrations and a 5.7% minimum binder content for such asphalt mixtures. These conditions do not concord totally with those previously presented and can lead to producing asphalt mixtures with too much bitumen.

3.2. Water sensitivity
The water sensitivity (ITSR – indirect tensile strength ratio) was determined according to method A in the European standard in force [7], on cylindrical specimens prepared with the gyratory compactor, while the Marshall samples respected the already known mixing and testing conditions. ITSR was calculated as the ratio of the indirect tensile strength of water conditioned (wet) samples to that of unconditioned (dry) specimens. The data concerning the characteristics of the samples are presented in tables 1-3, and the results for water sensitivity, stability, flow index and water absorption for the three binder contents are presented in tables 4-6.
### Table 4. The water sensitivity and the Marshall results for a 4.8% bitumen content

| Mixing temperature/Compaction temperature, °C | Water sensitivity | Determinations on Marshall samples |
|---------------------------------------------|-------------------|-----------------------------------|
|                                            | Maximum load (Wet, kN) | Stability, kN | Flow index, mm | Water absorption, % |
|                                            | Dry, kN             | (%)        |                | (%)              |
| 160/140                                    | 8.33 | 8.58 | 93 | 11.75 | 3.5 | 0.45 |
| 160/100                                    | 6.23 | 7.06 | 88 | 8.34 | 4.7 | 1.73 |
| 160/80                                     | 5.91 | 6.43 | 92 | 5.88 | 5.1 | 3.14 |
| 140/120                                    | 7.51 | 8.27 | 91 | 8.93 | 3.3 | 0.68 |
| 120/120                                    | 6.73 | 6.96 | 94 | 7.06 | 3.7 | 1.32 |
| 120/100                                    | 5.81 | 6.08 | 93 | 7.64 | 4.2 | 2.44 |

### Table 5. The water sensitivity and the Marshall results for a 5.2% bitumen content

| Mixing temperature/Compaction temperature, °C | Water sensitivity | Determinations on Marshall samples |
|---------------------------------------------|-------------------|-----------------------------------|
|                                            | Maximum load (Wet, kN) | Stability, kN | Flow index, mm | Water absorption, % |
|                                            | Dry, kN             | (%)        |                | (%)              |
| 160/140                                    | 7.81 | 8.02 | 96 | 12.00 | 4.0 | 0.40 |
| 160/100                                    | 6.07 | 6.28 | 96 | 9.22 | 4.2 | 1.56 |
| 160/80                                     | 5.90 | 6.05 | 97 | 6.48 | 4.7 | 2.78 |
| 140/120                                    | 7.23 | 7.43 | 95 | 8.17 | 3.2 | 0.85 |
| 120/120                                    | 6.88 | 7.00 | 95 | 8.80 | 3.3 | 0.96 |
| 120/100                                    | 5.96 | 6.21 | 94 | 5.96 | 3.4 | 1.47 |

### Table 6. The water sensitivity and the Marshall results for a 5.7% bitumen content

| Mixing temperature/Compaction temperature, °C | Water sensitivity | Determinations on Marshall samples |
|---------------------------------------------|-------------------|-----------------------------------|
|                                            | Maximum load (Wet, kN) | Stability, kN | Flow index, mm | Water absorption, % |
|                                            | Dry, kN             | (%)        |                | (%)              |
| 160/140                                    | 6.32 | 6.56 | 94 | 11.3 | 3.8 | 0.43 |
| 160/100                                    | 5.72 | 6.02 | 93 | 9.64 | 4.6 | 1.05 |
| 160/80                                     | 5.44 | 5.74 | 94 | 6.23 | 6.2 | 1.89 |
| 140/120                                    | 5.81 | 6.13 | 92 | 9.41 | 4.1 | 0.77 |
| 120/120                                    | 5.93 | 6.21 | 95 | 7.87 | 4.8 | 0.92 |
| 120/100                                    | 5.67 | 5.90 | 94 | 6.75 | 5.8 | 1.14 |

Apart from the influence of the mixing and compaction temperature on the characteristics obtained, it was aimed to determine a correlation between the maximum load in the indirect tension test and the Marshall stability of the specimens.

The results obtained lead to the following conclusions:

- concerning the water sensitivity, it was found that the maximum load in the indirect tension test (both for conditioned and unconditioned samples) increases with the reduction of the binder content, while the ITSR varies in more narrow limits. However, for the smallest binder content a more significant increase of water sensitivity correlated to higher air voids in samples at 50 gyrations is noted;
- the water sensitivity presents significantly higher values than the 80% limit values for all binder contents. It can be correlated to the bitumen adhesiveness to the respective aggregates (over 90%). That means that in case of an adequate adhesiveness, the variation of the bitumen content between reduced limits does not influence the water sensitivity in a significant way;

- the value of the Marshall stability seems to be significantly influenced by the mixing and compaction conditions and the results obtained present inconsistencies, it is very clear that the stability decreases with the alteration of the conditions in which the samples are prepared;

- a clear consistency between the value of the maximum load in the indirect tension test and the value of the Marshall stability could not be established;

- the flow index is relatively little influenced by the temperatures, providing that these do not decrease under 100°C and the bitumen content is reduced (in relation to the limit imposed by the Romanian standards);

- the value of the water absorption can be correlated to the value of the air voids but, inexplicably, it kept extremely reduced values.

The previous analysis opens the discussion on the utility of the Marshall tests (kept in the Romanian standard [4] as efficiency test in determining the optimum bitumen content in asphalt mixtures), or whether it would be more useful to introduce determinations recommended by the Superpave methodology (as for example the cracking test used in the USA [8]).

3.2. Stiffness and dynamic flow
The dynamic characteristics stipulated by the Romanian technical norms [4] were determined according to the European standards in force [9, 10] for the conditions presented above. The results obtained are presented in tables 7-9, for the three binder contents used and for two different compaction energies (80 and 205 gyrations).

**Table 7.** The stiffness and dynamic flow for a 4.8% bitumen content.

| Mixing temperature/ Compaction temperature, °C | Stiffness, MPa | Dynamic flow: | Stiffness, MPa | Dynamic flow: |
|-----------------------------------------------|----------------|---------------|----------------|---------------|
|                                               | 80 gyrations   | 205 gyrations | Deformatio, µm/m | Creep rate (f_c), µm/m/cycle | Deformation, µm/m | f_c, µm/m/cycle |
| 160/140                                       | 5 746          | 6 420         | 16 534         | 0.644         | 7 884         | 0.187         |
| 160/100                                       | 4 768          | 5 312         | 15 235         | 0.494         | 13 469        | 0.344         |
| 160/80                                        | 3 892          | 4 004         | 19 855         | 0.724         | 17 336        | 0.636         |
| 140/120                                       | 4 606          | 5 124         | 12 728         | 0.308         | 10 767        | 0.268         |
| 120/120                                       | 4 331          | 4 857         | 17 334         | 0.491         | 14 295        | 0.337         |
| 120/100                                       | 4 136          | 4 426         | 17 885         | 0.514         | 15 148        | 0.378         |
Table 8. The stiffness and dynamic flow for a 5.2% bitumen content

| Mixing temperature/Compaction temperature, °C | 80 gyrations | 205 gyrations |
|---------------------------------------------|--------------|---------------|
|                                            | 80 gyrations | 205 gyrations |
|                                            | 160/140      | 160/100       | 160/80        | 140/120       | 120/120       | 120/100       |
|                                            | Stiffness, MPa | Dynamic flow: |                          | Stiffness, MPa | Dynamic flow: |                          |
|                                            |              | Deformation, μm/m | f_s, μm/m/cycle |              |                          |                          |
|                                            | 5 270        | 19 221         | 0.663          | 6 035        | 10 313        | 0.208          |
|                                            | 4 167        | 15 212         | 0.626          | 4 480        | 16 626        | 0.686          |
|                                            | 3 588        | 19 472         | 0.779          | 4 089        | 18 763        | 0.747          |
|                                            | 4 684        | 19 874         | 0.683          | 5 480        | 13 450        | 0.326          |
|                                            | 4 368        | 20 288         | 0.756          | 5 206        | 10 654        | 0.254          |
|                                            | 4 127        | 18 670         | 0.760          | 5 077        | 12 373        | 0.272          |

For the studied bitumen contents, situated close to the supposed optimum binder content, the obvious findings are as follows:

- the stiffness of the asphalt mixture decreases with the increase of the binder content and increases by increasing the compaction energy, without maintaining a certain proportionality between these variations;

- by decreasing the sample compaction temperature under 100°C, the stiffness obtained becomes inadequate, being inferior to the value of 4 000 MPa;

- the characteristics linked to the dynamic flow generally observe the same tendencies: the higher the values (even overpassing the admissible values) the lower the compaction temperature and the higher the binder content. Generally, the behavior of the samples is improved by increasing the number of gyrations, without decreasing the deformation and the creep rate proportionally to the number of gyrations;

- the series of results confirm the fact that the best results for stiffness and dynamic flow are obtained by maintaining the compaction temperature around the values stipulated by the technical standards in force (140-150°C).

The authors would like to clarify, through further research, which are the causes of this variability of the results obtained, with no proportional variation of the characteristics in relation to the mixing and compaction temperatures and the compaction energy. However, in the case of the stiffness, it was found that during testing, the temperature too high in the laboratory could alter the temperature in the climate chamber, leading to significant variations in the stiffness modulus.
4. Conclusions

The determinations performed in the laboratory for the conditions mentioned above confirmed the results obtained on site concerning the rate of compaction obtained on asphalt mixtures at low temperatures. At low compaction temperatures, less than 100°C, the increase of the compaction energy in the laboratory allows a decrease in the air voids, without compensating in the end the lack of workability in the asphalt mixture (the remaining air voids exceed the admissible value of 5-6%, even by increasing the binder content). The increased porosity of the specimens compacted at low temperatures leads to mechanic characteristics that are generally inadequate for the Marshall stability and the stiffness and dynamic flow as well.

The mixing temperature seems to have a lesser impact on the physical-mechanical characteristics obtained on samples prepared in the laboratory, in relation to the compaction energy.

In addition, the observation of the standardized testing conditions is essential for obtaining comparable results. It was found that the testing in temperatures that differ by only 1-2°C can influence the results in a significant measure. The authors intend to continue the research in this field to emphasize the impact of the temperature in which the samples are tested on the characteristics of the asphalt mixtures. The intention is to develop and improve the testing method by using software that allows the correction of the stiffness value in relation to the precise temperature of the asphalt mixture in the sample.

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