1. Introduction

Hot mix asphalt (HMA) is a mixture of minerals (stone chips, sand and stone dust) and asphalt binder produced by hot process at temperatures ranging from 135 °C to 170 °C. Asphalt mix must meet certain requirements to ensure stable and enduring surfacing: must be resistant to traffic activities and climatic factors, the occurrence of deformation and have an appropriate acceptability and roughness in case of a final layer of pavement. In order that the asphalt mix meets all of these requirements, it must be properly manufactured and installed, as well as have adequate physico-mechanical properties.

The required physico-mechanical properties of asphalt mixtures are achieved by the process of compaction. Compaction is the process of using external forces to reduce the volume of air voids in the HMA mix. Squeezing the air out of the mix, it takes up less space and its spatial mass is thus increased, i.e. density (Roberts et al. 1996).

The goal of compacting asphalt mix is to produce a smooth, stable and durable asphalt pavement.

HMA compaction is influenced by several factors; some related to the environment, some determined by mix and structural design (Sivilevičius et al. 2011; Vislavičius, Sivilevičius 2013) and some by contractor during construction.

The big influence on the compaction of asphalt mixtures and their properties has the temperature of asphalt mixture. The temperature of asphalt mixture affects viscosity of bitumen and achievement of the maximum density of asphalt mixture. This paper describes a laboratory study on the effects of different installation temperatures on the physico-mechanical properties of specimens of asphalt mixtures: stability, Marshall Quotient (stiffness), density, voids and voids filled with asphalt. By regression analysis of the test results the correlation of certain properties of asphalt mix and compaction temperatures was established. For all the models observed, the coefficients of determination are very high and indicate very solid links. The obtained research results indicate a pronounced effect of compaction temperature on each tested property of asphalt mix.

Keywords: compaction temperature, hot mix asphalt (HMA), laboratory tests, Marshall Quotient, volumetric properties.
is maximized, both in laboratory and field. Six laboratory mixes using three binder grades and two aggregate gradations, as well as five field mixes were used in the study. It appeared that aggregate type, angularity, and gradation had a greater effect on the energy required for compaction than did the compaction temperature. Stas et al. (2007) reported about results of laboratory investigation of the influence of gradation types, compaction temperatures, and immersion times on the durability of asphalt concrete mixtures, using dolomite aggregates. Results clearly showed that both compaction temperatures and immersion times greatly affect the durability of these mixes.

Lee et al. (2008a, 2008b) researched the compaction temperature of crumb rubber modifier (CRM) asphalt mixes. A laboratory investigation was carried out on the volumetric properties of CRM mixes. A total of 128 specimens were manufactured using the Superpave gyratory compactor (SGC) and the Marshall compactor at various compaction temperatures (116 °C, 135 °C, 154 °C, and 173 °C). The results from this study indicated that the compaction temperatures significantly affected the volumetric properties of the CRM mixes, regardless of the compaction methods.

West et al. (2010) reported about research to identify and develop a reliable and accurate procedure for determining the mixing and compaction temperatures applicable for both modified and unmodified asphalt binders in hot-mix asphalt (HMA). Saedi (2012) researched assessment of compaction temperatures on HMA properties for two mixes: binder layer and top coat layer. Six compaction temperatures ranged between 85–160 °C. Results showed that density of both mixes increased with increasing compaction temperature and the highest density occurred over the temperature of 145 °C.

Li et al. (2013) investigated effect of temperature and loading frequency on dynamic modulus and phase angle of three asphalt mixes for different gradations and binders. Results indicated that the dynamic modulus of asphalt mixes decreases with either an increase in temperature or a decrease in loading frequency and relative shift with decreasing load frequencies becoming less and less.

Park and Kim (2013) reported about study of determination the compaction time at which desired temperature is achieved. Compaction temperature profiles were predicted using simulation program and results were compared with results of temperature profiles measured “in situ” during compaction.

With the temperature of asphalt mixture, the maximum density of the asphalt layer is affected by HMA properties, thickness, and stiffness of the substrate temperatures to which asphalt layer is deposited, air temperature, wind speed, humidity and solar radiation (Mieczkowski 2010). The same author also points to the great influence of wind speed on the compaction process in relation to the outside temperature.

Some factors have a direct impact on the speed of the layer cooling, and thus on the efficiency of its compaction. Time available between the recommended temperature for depositing asphalt layer and termination compaction temperature is short, especially for rolling thin asphalt layers. Experience has shown that the rolling of the asphalt layer no longer has any effect on its density at a temperature of 85 °C (Babić, Horvat 1984). About quality assurance during construction of asphalt pavement reported Beainy et al. (2012). The intelligent asphalt compaction analyzer (IACA) was used to estimate asphalt pavement density during construction and thereby to determine overall quality of compaction.

Some countries, with installation requirements for the minimum temperature of asphalt mixture, recommend the minimum temperature of the substrate to which the layer related to thickness of the pavement layer is deposited. Thus, the authors (Roberts et al. 1996) gave approximate values of temperature for the compaction of bituminous mixtures that are commonly used in the United States. According to the Guidelines on Minimum Roadway Placement Temperatures of 2006, the stringent compaction requirements have been defined in relation to time (compaction during the day or night) and min substrate temperatures. In this way, most of the factors that affect the process of compaction and the realization of the required properties of asphalt mixtures are taken into account, and the performers were given precise instructions. Furthermore, certain technical regulations define the values of compaction temperatures of asphalt mixtures, depending on the properties of a binder (bitumen). Thus, the compaction temperature recommended in the current procedures for Superpave asphalt mixtures (the Asphalt Institute) is determined as the range of temperatures where an un-aged asphalt binder has the viscosity of 0.28±0.03 Pa·s (Lee et al. 2008a). In the Polish asphalt standard PN-S-96025:2000 [Roadways and Airport – Asphalt Pavements – Requirements] (in Polish) with usual climatic parameters (rainfall, ambient temperature) there is a requirement related to the wind speed up to 16 m/s (Mieczkowski 2007).

The current technical regulations in the Republic of Croatia (General Technical Conditions for Roadwork of 2001) for the installation of asphalt mixtures do not define in detail different factors that affect compaction. Mentioned regulations define the min temperature for installing asphalt mix depending on the applied bitumen, from 135 °C to 145 °C, and the lowest ambient temperature during the installation of asphalt mixtures. According to the technical regulations, asphalt mix is placed only under favourable weather conditions, while the installation of asphalt mix in the rain and on a wet surface is not permitted. When laying the wear layer, the floor and air temperature must be higher than 10 °C, and at installation of the bonding and supporting layer higher than +5 °C. For wind effects, intensity conditions are not set, but instead a supervising engineer is enabled to cease making asphalt layer on the basis of assessment of weather conditions and at temperatures that are higher than the minimum prescribed if there is reasonable doubt that under
such conditions asphalt mix will not be properly installed. The Croatian technical regulations (2001) define the protection of asphalt mix during transportation to the place of installation and the maximum transportation time of mixtures (max 2 hours).

The two most critical procedures during which the change in temperature of asphalt mixture is the largest refer to the transportation of HMA mix from the base to the construction site and to the procedure of installing asphalt mixture. The process of transportation is considered critical because, in addition to the price, it also affects the quality of asphalt mixture, and the installation is critical because it affects the quality of the embedded layer (Roberts et al. 1996). In both of the aforementioned procedures, temperature changes in the asphalt mix mostly reflect the physico-mechanical properties of asphalt mixture and directly affect the layer compaction.

The aim of the researches described in this paper was to determine the effect of different installation temperatures on the physico-mechanical properties of asphalt mixture specimens (under laboratory conditions) as well as to establish their dependence correlation.

2. Materials and test program

The aim of the laboratory tests was to determine the effect of temperature variability of asphalt mixture intended for performance of the Asphalt Concrete AC 8 surf 50/70 wear layer on the achieved physical and mechanical or physico-mechanical properties of specimens. The designed asphalt mix was made of constant gradation and share of paving bitumen, of variable compaction temperature in the range of 120–170 °C and of equal compaction energy.

Physico-mechanical properties of specimens of asphalt mixture AC8 surf 50/70 were tested according to the Croatian standard HRN EN 13108-1:2007 Bituminous mixtures – Material specifications – Part 1: Asphalt Concrete (in Croat) (EN 13108-1:2006). Mineral mixture (Fig. 1) consisted of stone fraction 0/2 mm, 2/4 mm and 4/8 mm of a volcanic origin (Vetovo quarry), stone dust of category label KB-I (Veličanka quarry). Sampling of used mineral fractions for testing was done at the landfill of stone aggregates in the asphalt plant. For each fraction used, three samples each weighing 5 kg (3×5 kg for a single fraction) were sampled. As a result, the average gradation was determined which was obtained from the three samples for each stone fraction (Fig. 1). Paving bitumen 50/70 was used as the binder, of standard density properties pb = 1.016 g/cm³, the softening point PK = 49.9 °C and penetration PEN = 51.7 1/10 mm. This type of bitumen is widely used in asphalt mixes in Croatia. The determination of the optimal share of bitumen was performed using the Marshall’s method whereby it was adopted a constant gradation (Fig. 2) of mineral mixture. Share of bitumen was changed in the range from 4.9% to 6.1% (five series) of the total weight of the asphalt mix. The optimal share of bitumen was adopted in the proportion of 5.5%.

2.1. Design of composition of asphalt mixture

The following asphalt mixtures of an equal composition with different compaction temperatures are designed for the purposes of the planned tests:

- Mixture 170, compaction temperature 170 °C,
- Mixture 160, compaction temperature 160 °C,
- Mixture 150, compaction temperature 150 °C,
- Mixture 140, compaction temperature 140 °C,
- Mixture 130, compaction temperature 130 °C,
- Mixture 120, compaction temperature 120 °C.

Gradation of the stone mixture is determined according to HRN EN 12697-2:2003 Bituminous Mixtures – Test Methods for Asphalt Produced by Hot Process – Part 2: Determination of Particle Size Distribution (in Croat) and the soluble proportion of paving bitumen according to HRN EN 12697-1:2003 Bituminous Mixtures – Test Methods for Asphalt Produced by Hot Mix – Part 1: The Soluble Share of Binder. Fig. 1 shows the gradation of stone fractions and filler used to produce asphalt mixtures.

The gradation of the designed asphalt mixture with limited curves is defined by the standard HRN EN 13108-1:2007 (Fig. 2). The default composition of stone mixture in its composition contains 3% of mineral filler, 35% of fraction 0/2 mm, 21% of fraction 2/4 mm and 41% of fraction 4/8 mm from the overall mass of mineral mixture.

2.2. Production of specimens of asphalt mixtures

For each group of asphalt mixtures, three specimens were made according to the standard procedure of compaction on the rammer with a falling hammer. The appearance of the
asphalt specimen is shown in Fig. 3. The temperature of asphalt mixtures ranges from 120°C to 170°C. Average temperature of mixing was 5°C higher than compaction temperature. After cooling to room temperature, the following physico-mechanical properties are determined on the specimens:

– density of asphalt specimens (EN 12697-6:2003 Bituminous Mixtures – Test Methods for Asphalt Produced by Hot Process – Part 6: Determination of Bulk Density of Asphalt Specimens);
– density of asphalt mixture (EN 12697-5:2003 Bituminous Mixtures – Test Methods for Asphalt Produced by Hot Process – Part 5: Determination of Bulk Density of Asphalt Mixtures);
– air voids content (EN 12697-8:2003 Bituminous Mixtures – Test Methods for Asphalt Produced by Hot Process – Part 8: Determination of Voids in Asphalt Specimens);
– voids in mineral aggregate (HRN EN 12697-8:2003 Bituminous Mixtures – Test Methods for Hot Mix Asphalt – Part 8: Determination of Void Characteristics of Bituminous Specimens (EN 12697-8:2003));
– voids filled with asphalt (HRN EN 12697-8:2003 Bituminous Mixtures – Test Methods for Hot Mix Asphalt – Part 8: Determination of Void Characteristics of Bituminous Specimens (EN 12697-8:2003));
– stability/flow/Marshall Quotient (HRN EN 12697-34:2004 Bituminous Mixtures – Test Methods for Asphalt Produced by Hot Process. Marshall Test).

3. Results and discussion

Table 1 shows the achieved results of physico-mechanical properties of asphalt specimens. Shown values are the average values of the three tested specimens. The boundary conditions of the air voids content are defined in the range from 3.0% to 6.0% and voids filled with asphalt in the range 65%–83%.

The obtained results of laboratory tests clearly show that, due to the growth of temperature of installing of asphalt mixture, it comes to the growth of stability, reduced flow, and higher density of asphalt specimens and lower air voids content as well as better filling of the voids with the paving bitumen. Lower temperatures of installing of asphalt mixture result in the appearance of reduced values of the degree of compaction of the embedded layer. In continuation, by regression analysis of the test results, correlations of individual properties will be established and the shape and strength of these links will be determined.

3.1. Dependence of compaction temperature and Marshall Quotient of the mixture

Fig. 4 shows the dependence of Marshall Quotient of asphalt specimens at different compaction temperatures. Marshall Quotient (or stiffness) is the ability of a material to resist the flow, and is defined as the ratio of Marshall Stability and flow. It is noticed that stiffness increases with increase of compaction temperature. Stiffness is directly proportional to Marshall Stability and inversely proportional to Marshall flow. By applying the obtained values of Marshall Quotient of asphalt mix ($ST$) and compaction temperatures ($T$), a linear relationship between the values is established and the link model is analysed:

$$ ST = aT + b. \quad (1) $$

![Fig. 4. Relationship between compaction temperature and Marshall Quotient](image)

Table 1. Physico-mechanical properties of asphalt specimens

| Compaction temperature, °C | Stability, kN | Flow, mm | Marshall Quotient, kN/mm | 1) Asphalt specimen density, kg/m³ | 2) Asphalt mixture density, kg/m³ | 3) Air voids content, % (v/v) | 3) Voids in mineral aggregate, % (v/v) | 3) Voids filled with asphalt, % (v/v) |
|---------------------------|---------------|----------|--------------------------|----------------------------------|-------------------------------|---------------------------------|----------------------------------|-------------------------------|
| 120                       | 9.8           | 3.3      | 3.0                      | 2400                             | 2598                          | 7.6                             | 20.6                             | 62.9                           |
| 130                       | 9.6           | 2.6      | 3.7                      | 2424                             | 2598                          | 6.7                             | 19.8                             | 66.1                           |
| 140                       | 10.4          | 2.5      | 4.2                      | 2443                             | 2598                          | 6.0                             | 19.1                             | 68.8                           |
| 150                       | 10.7          | 2.5      | 4.2                      | 2446                             | 2598                          | 5.8                             | 19.0                             | 69.3                           |
| 160                       | 11.8          | 2.5      | 4.8                      | 2457                             | 2598                          | 5.4                             | 18.7                             | 70.9                           |
| 170                       | 12.5          | 2.4      | 5.3                      | 2470                             | 2598                          | 4.9                             | 18.3                             | 73.0                           |

Note: according to 1) HRN EN 12697-5:2003; 2) HRN EN 12697-6:2003; 3) HRN EN 12697-8:2003.
A linear relationship between the Marshall Quotient of asphalt mix and compaction temperatures is very solid, and the coefficient of determination is very high: $R^2 = 0.959$. That means that a large amount of data is mathematically described by the selected model. From the mathematical records, it is clear that in the tested temperature range 120–170 °C every increase of compaction temperature of 10 °C results in the average higher Marshall Quotient of asphalt specimens in the amount of 11.2%.

### 3.2. Dependence of compaction temperature and Marshall Stability of the specimens

It is noticed that Marshall Stability increases with the increase of compaction temperature. Marshall Stability increases with the increase of compaction temperature due to the more adhesive forces caused by the decrease in the viscosity of the asphalt concrete to reach good workability and compaction condition. Fig. 5 shows the dependence of Marshall Stability of asphalt specimens compacted at six different temperatures.

By applying the obtained values of Marshall Stability of asphalt specimens ($S$) and compaction temperatures ($T$) a square function relationship between the values is established and the link model is analysed:

$$S = aT^2 - bT + c.$$  \hspace{1cm} (2)

A square function relationship between the Marshall Stability of asphalt specimens and compaction temperatures is very solid, and the coefficient of determination is very high: $R^2 = 0.974$ in projected area.

### 3.3. Dependence of compaction temperature and mixture density

The asphalt specimen density is defined as the ratio of mass and volume of asphalt specimen prepared in a Marshall rammer. As results show, density of asphalt specimens increases with increased compaction temperature. This is the result of asphalt binder viscosity due to temperature increase and, subsequently, the aggregates location beside each other is denser. Fig. 6 shows the dependence of density of asphalt specimens ($D$) and compaction temperatures ($T$). And in this correlation, a linear model connection is selected (Formulae (3)) although other observed models (exponential, logarithmic, polynomial) pointed to a strong link and resulted in high coefficients of determination.

$$D = aT + b.$$ \hspace{1cm} (3)

Linear relationship between the density of asphalt mix and compaction temperature is in this case very strong, and the coefficient of determination is very high: $R^2 = 0.953$.

### 3.4. Dependence of compaction temperature and proportion of air voids content of asphalt specimens

The proportion of air voids content in asphalt specimens is defined as the ratio of the density of asphalt specimens and asphalt mix. The higher compaction temperature results in the decreasing air voids content. The decrease in percent air voids with the increase in compaction temperature is due to lubricating effect of asphalt concrete keeping viscosity of the binder suitable for compaction. Air voids have a significant effect on the resistance of asphalt mixtures to different distresses including rutting, fatigue cracking, moisture damage and low temperature cracking.

The correlation between the proportion of air voids content of asphalt specimens ($SV$) and compaction temperature ($T$) is shown in Fig. 7. The two mathematical models were analysed:

$$SV = aT + b;$$ \hspace{1cm} (4)

$$SV = aT^b.$$ \hspace{1cm} (5)

Regression analysis examined both of the proposed models, and the analysis has shown that most of the obtained results were accurately displayed by the model.
This model has been chosen for the interpretation of the test results of the dependence of air voids content and compaction temperature. The coefficient of determination in this model amounts to $R^2 = 0.981$.

The increase in compaction temperature of asphalt mix results in a lower air voids content in asphalt specimens.

### 3.5. Dependence of compaction temperature and voids filled with asphalt in asphalt specimens

The compaction of asphalt mixture at lower temperatures leads to an increased air voids content in asphalt specimens. Higher volume of air voids content at the same proportion of bitumen leads to the insufficient filling of voids with asphalt. Dependence of compaction temperature ($T$) and voids filled with asphalt in asphalt specimens ($VB$) is shown in Fig. 8. The correlation between compaction temperature and voids filled with asphalt in asphalt specimens is observed by the model:

$$VB = aT + b.$$  \hfill (6)

The link between voids filled with asphalt in asphalt specimens and compaction temperature is in this case very strong, and the coefficient of determination very high: $R^2 = 0.956$. The mathematical model shows that at the tested temperature range 120–170 °C, every increase of compaction temperature of 10 °C results in a low share of voids of asphalt specimens in the amount of 2.44%.

In Table 2 the correlation is visible between the properties of asphalt mix and compaction temperature and the forms and strengths of links for all the obtained results.

#### 4. Conclusions

1. The paper describes the laboratory tests of physico-mechanical properties of asphalt mixture. The tested asphalt mix had a constant gradation, and a constant share of the paving bitumen (5.5%). The specimens were made at six different temperatures in the range 120–170 °C with equal compaction energy. Average temperature of mixing was 5 °C higher than compaction temperature.

2. The following properties of asphalt mixtures were tested: Marshall Stability, Marshall Quotient (stiffness), density, air voids content, and the filling of voids with asphalt, with the aim of establishing the size of the impact of different compaction temperatures on properties of asphalt mixtures.

3. It was found that the density, Marshall Stability and Marshall Quotient values of asphalt mixes increase with increase of compaction temperatures, also percent of voids filled with asphalt, while percent of air voids decrease with increase of compaction temperatures at optimum bitumen contents.

4. By regression analysis of the test results, the correlation of certain properties of asphalt mixture and compaction temperatures has been established. For all the models observed, the coefficients of determination are very high and indicate very strong links from 0.953 to 0.981. A strong relation between various parameters of Marshall specimens and compaction temperature was found:

- due to the growth of compaction temperature of asphalt mixture (120–170 °C) the Marshall Quotient of asphalt specimens increases even for 76.67%;
- an increase in compaction temperature of asphalt mix results in higher densities of asphalt specimens to 2.92%, which ultimately leads to achieving a higher degree of compaction of the asphalt layer;
- lower installation temperature results in the appearance of a larger air voids content (to 55.10%) at the same invested compaction energy;
- higher compaction temperature (170 °C) results in better voids filled with asphalt compared to asphalt specimens compacted at lower temperatures (120 °C) even for 16.06%;
- the defined bordering conditions of air voids content in the range from 3.0% to 6.0% and voids filled with asphalt in the range 65–83% indicate that the asphalt specimens compacted at lower temperatures (120–130 °C) are not satisfactory in terms of the requested air voids content;

#### Table 2. Correlations of properties of asphalt mixtures and compaction temperatures

| Mixture property         | Comaption temperature | Link form | Coefficients     | Determination coefficient, $R^2$ |
|--------------------------|-----------------------|-----------|------------------|---------------------------------|
| Marshall Quotient (ST)   | ($T$)                 | $ST = aT^2 + b$ | $a$ = 0.0423, $b$ = 0.0000 | 0.9590 |
| Marshall Stability (S)   | ($T$)                 | $S = aT^2 + bT + c$ | $a$ = 0.0010, $b$ = 0.0000, $c$ = 0.0000 | 0.9741 |
| Density (D)              | ($T$)                 | $D = aT + b$ | $a$ = 0.0000, $b$ = 0.0000 | 0.9530 |
| Air voids content (SV)   | ($T$)                 | $SV = aT^b$ | $a$ = 0.0000, $b$ = 0.0000 | 0.9550 |
| Voids filled with asphalt (VB) | ($T$)             | $VB = aT + b$ | $a$ = 0.0000, $b$ = 0.0000 | 0.9590 |
asphalt specimen compacted at a temperature of 120 °C is not even adequate in terms of voids filled with asphalt.

5. From the study results obtained (also according to numerous previous research in the world) it is obvious that there is a large impact of compaction temperature on the physico-mechanical properties, and consequently on the installation of asphalt mixture at the construction site. It is very important for appropriate asphalt mixture to clearly define factors and rules (for constructors) that affect the compaction temperature and the realization of the required properties of mixtures.

6. In comparison with the technical regulations of other countries, which clearly define different factors that affect the compaction of asphalt mixtures, in the (still valid) Croatian Technical Regulations (General Technical Conditions for Roadwork of 2001) certain shortcomings and ambiguities exist.

7. Considering that the development of satisfactory technical conditions is the first step towards the successful delivery of hot mix asphalt, in Croatia in 2012 the new Technical Regulations Elaboration of Technical Characteristics and Requirements for Construction Products for Asphalt Mixtures Production and Asphalt Pavement Layers were proposed. In the new Technical Regulations preventive measures are aimed at sustainability of the optimal conditions during the installation of asphalt mixtures. Thus, these Regulations impose restriction for the maximum transportation time of 2 hours or 120 km distance from the installation site. The maximum installation temperatures of asphalt mixture are defined, while the lowest installation temperatures are partly prescribed. Also, the prohibition of performing asphalt works in the wind (although intensity has not been defined) and rainfall has been introduced.

8. The goal of compacting of asphalt mixtures is to obtain stable and constant layer (surfacing) resistant to traffic and climatic factors and the occurrence of deformation. Understanding the impact of various factors on the compaction of asphalt mixtures is an important step in achieving this goal.

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