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INFLUENCE OF F-T SYNTHETIC WAX ON ASPHALT CONCRETE PERMANENT DEFORMATION

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The paper presents the results of the study of the effect of a Fischer-Tropsch (F-T) synthetic wax on the resistance to permanent deformation of the AC 11S asphalt concrete. The synthetic wax was dosed at 1.5%, 2.5% and 3.5% by weight of bitumen 35/50. The compaction temperatures were 115ºC, 130ºC and 145ºC. The criteria adopted for measuring the resistance to permanent deformation included the following parameters: stiffness modulus at 2, 10 and 20ºC, permanent deformation (RTS), fatigue life determined using the indirect tensile fatigue test (ITFT) and resistance to rutting (WTSAIR, PRDAIR). The test results confirmed the positive influence of F-T synthetic wax on enhancing the permanent deformation resistance of asphalt concrete placed at lower compaction temperatures compared to that of standard asphalt concrete compacted at 140ºC.

Keywords: asphalt concrete, F-T synthetic wax, permanent deformation, stiffness modulus, resistance to rutting, fatigue

1. INTRODUCTION

Permanent deformation (rutting) is one of the most dangerous types of damage to bitumen pavements [1]. Numerous tests performed to find the ways of limiting the occurrence of rutting have been focused on bitumen modification [2, 3]. One of the modifying additions to be used for that purpose is an F-T (Fischer Tropsch) synthetic wax [4, 5].

The tests described in this paper were conducted on the AC 11 S bituminous mixture for pavements under traffic load category KR4, manufactured to WT 2 – 2010 technical requirements and PN EN 13108-1.

The aggregate composition included 55% of gabbro rock fraction. A dolomite mix 0/4 and granite fractured sand were used to increase fraction contents. Bitumen 35/50 (5.2%) was the binder. Optimal grading curve has been done by means of authorial computer programme using particle packing method [19].

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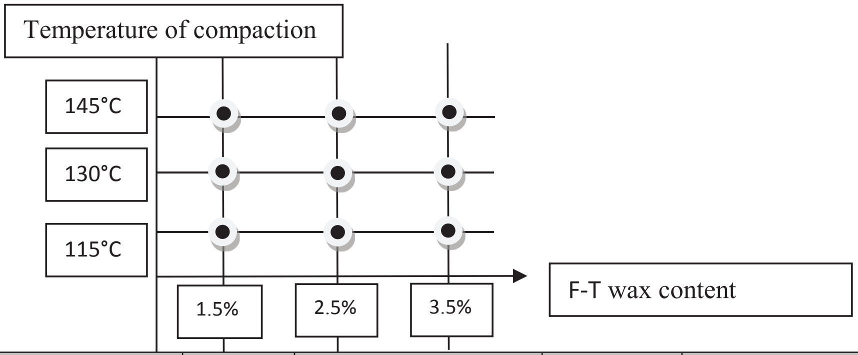
The objective of the tests was to evaluate the influence of the F-T synthetic wax on such parameters as asphalt concrete stiffness modulus at a temperature of 2ºC, 10ºC and 20ºC, permanent deformation (RTS), fatigue life determined using the ITFT method, and potential to rutting. The testing programme was the basis for the optimisation process and identification of asphalt concrete properties most advantageous in terms of F-T wax amount and compaction temperature.

The temperature range of the tests was set at 115ºC to 145ºC with a 15ºC step change. As the lowest value in the temperature range denotes the initiation of F-T wax crystallization process in the bitumen, the resistance of the asphalt concrete against permanent deformation at low compaction temperatures had to be measured. The highest value in the temperature range, i.e., 145ºC is the recommended compaction temperature for asphalt concrete with bitumen 35/50. The results of tests conducted on asphalt concrete with F-T wax at this temperature allow evaluation of the bitumen liquidation on compaction and on mechanical parameters of the asphalt concrete.

All the parameters of the asphalt concrete (dependent variables) were evaluated based on the 3 (compaction temperature levels) x 3 (levels of modification with the F-T wax) factorial composite design. The design of the experiment consisted of two factors:

- temperature of compaction (three levels: 115ºC, 130ºC, 145ºC),
- amount of the modifier, F-T wax (three levels 1.5%, 2.5%, 3.5%).

To unify the character of the asphalt concrete changes, a second-degree polynomial was used [6]. The schematic of the design is presented in Figure 1.



Factor	Unit	lowest value	center	highest value
F-T wax	[%]	1.5	2.5	3.5
temperature	[ºC]	115	130	145

Fig. 1. Design of the experiment

The decision about such a design, with the characteristic densification of test points at the centre of the experiment domain was connected with the optimization study of

F-T wax impact on rheological properties of bitumen, and resulted from the experience of similar analyses carried out for modifiers reducing the viscosity of bitumen [7, 8]. The optimization results for the amount of modifier used in bitumen 35/50 indicated that the interval of 2.5% -3% was the best compromise between the increase in the F-T wax modified binder stiffness and its feasible increase in brittleness at low temperatures. Therefore, the design was strengthened with such modification variants.

2. ASPHALT CONCRETE STIFFNESS MODULUS AT TEMPERATURES OF 2°C, 10°C AND 20°C

The primary goal of the analysis of how the amount of the F-T synthetic wax and compaction temperature affect the changes in the stiffness modulus of AC 11 S at temperatures of 2°C, 10°C and 20°C (E2, E10 and E20) was to build a regression mathematical model (response surface). The domain of experiment determined the boundary conditions. The choice of the model to describe the variation of E2, E10 and E20 was the first step followed by the significance estimation of the fit parameters of the regression model.

The result of the goodness of fit of the model for the mechanical characteristics distribution of AC 11 S is presented in Table 1-4.

Table 1

Summarized statistics – goodness of fit tests of the AC 11 S with F-T wax model for E2, E10 and E20 (values of test temperature 2°C, 10°C, 20°C)

Response Surface for Variable E2: E2	
Response Mean	19346
Root MSE	1031.946898
R-Square	0.76
Coefficient of Variation	5.3342
Response Surface for Variable E10: E10	
Response Mean	13632
Root MSE	1383.381567
R-Square	0.71
Coefficient of Variation	10.1477
Response Surface for Variable E20: E20	
Response Mean	8011.520833
Root MSE	564.453897
R-Square	0.77
Coefficient of Variation	7.0455

Table 2

Detailed results of polynomial degree fit of the AC 11 S with F-T wax mathematical model for E2 (test temperature 2ºC)

Regression	Type I Sum of Squares	R-Square	F-Value	Pr > F
Linear	24960717	0.5471	11.72	0.0024
Quadratic	7113636	0.2159	3.34	0.0474
Crossproduct	2896222	0.0135	2.72	0.1301
Total Model	34970574	0.776	6.57	0.0059

Table 3

Detailed results of polynomial degree fit of the AC 11 S with F-T wax mathematical model for E10 (test temperature 10ºC)

Regression	Type I Sum of Squares	R-Square	F-Value	Pr > F
Linear	39274368	0.5844	10.26	0.0038
Quadratic	6875930	0.1309	1.80	0.0515
Total Model	48072097	0.7153	5.02	0.0146

Table 4

Detailed results of polynomial degree fit of the AC 11 S with F-T wax mathematical model for E20 (measurement temperature 20ºC)

Regression	Type I Sum of Squares	R-Squares	F-Value	Pr > F
Linear	14275042	0.6662	22.40	0.0002
Quadratic	1993355	0.0930	3.13	0.0881
Crossproduct	1974006	0.0921	6.20	0.0320
Total Model	18242403	0.8513	11.45	0.0007

The results of the analysis indicate that the square function model was the best fit for the AC 11 S stiffness modulus characteristic, regardless of the test temperature. The correlation coefficient took a range of values from 0.71-0.77. This means that the character of changes of the AC 11 S stiffness modulus of elasticity was assigned in a similar manner.

Figure 2 presents a graphical interpretation of the response surface of stiffness modulus variation for E2 (test temperature 2ºC) of the asphalt concrete in relation to the amount of F-T synthetic wax (L_V, %) and temperature of compaction (TEMP, ºC). The results of the fit parameters estimation for the developed model are presented in Table 5.

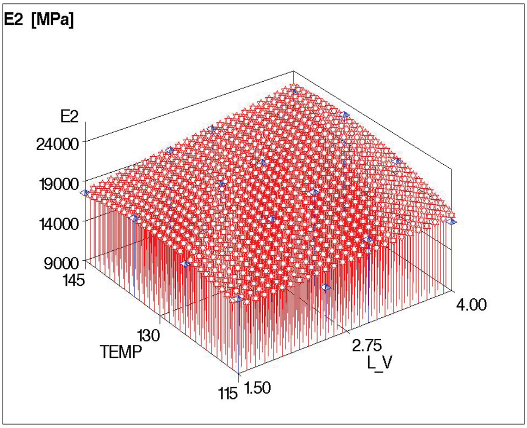


Fig. 2. The effect of the F-T wax (L_V) and the temperature of compaction (TEMP) on the response surface for E2 [MPa] of AC 11 S

Table 5

The results of the model parameters fit estimation (L_V and TEMP) for E2 of AC 11 S and the evaluation of their significance

Parameter	Estimation	Standard Error	Value of t	Pr > |t|
Intercept	-88258	44404	-1.99	0.0749
TEMP	1678.256090	674.844233	2.49	0.0322
L_V	-4773.629701	3838.791720	-1.24	0.2420
TEMP*TEMP	-6.645625	2.579867	-2.58	0.0276
L_V*TEMP	42.217179	25.599452	1.65	0.1301
L_V*L_V	72.527778	343.982299	0.21	0.8372

The results of the analysis confirm a significant impact of the compaction temperature factor (TEMP) and its non-linear course on the stiffness modulus of the asphalt concrete for E2. The variance analysis did not indicate a significant influence of the F-T wax amount on the stiffness modulus of elasticity. Then, the temperature of compaction factor will affect the behaviour of AC 11 S asphalt concrete. As for the presence of the F-T synthetic wax, the concentration level of other crystals did not significantly increase the stiffness of the asphalt concrete, which positively affects its resistance to thermally induced cracking.

Figure 3 presents the graphical interpretation of the response surface of changes in the stiffness modulus E10 (test temperature 10°C) of AC 11 S against the amount of the F-T synthetic wax (L_V, %) and the compaction temperature (TEMP, °C). The estimation results for the fit parameters for the developed model are presented in Table 6.

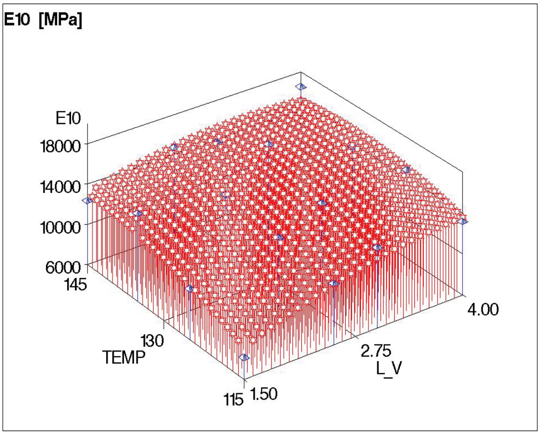


Fig. 3. The effect of the F-T wax amount (L_V) and the compaction temperature (TEMP) on the response surface for E10 [MPa] of AC 11 S

Table 6

The estimation results of model (L_V and TEMP) parameters for characteristic E10 of AC 11 S and the estimation of their significance

Parameter	Estimation	Standard Error	Value of t	Pr > |t|
Intercept	64.111828	28.180866	2.28	0.0462
TEMP	-88258	44404	-1.99	0.0749
L_V	1678.256090	674.844233	2.49	0.0322
TEMP*TEMP	-4773.629701	3838.791720	-1.24	0.2420
L_V*TEMP	-6.645625	2.579867	-2.58	0.0276
L_V*L_V	42.217179	25.599452	1.65	0.1301

The results of the analysis indicate a relatively significant effect of the linear course of the compaction temperature (TEMP) and a highly significant effect of the F-T synthetic wax amount (L_V) on the stiffness modulus of AC 11 S at a temperature of 10°C. Additionally, the effect of interaction between those two parameters emerged. Thus, at the temperature of 10 ° C, the properties of asphalt concrete will also depend on the magnitude of void space compression (as at the temperature of 2°C). There is, then, the effect of synergy of the F-T wax crystalline phase level and the temperature of compaction, which affect the stiffness modulus of AC 11 S at the temperature of 10 °C.

Figure 4 presents a graphical interpretation of the response surface of changes in the stiffness modulus E20 (test temperature 20°C) of AC 11 S against the amount of the F-T synthetic wax (L_V, %) and the compaction temperature (TEMP, °C). The estimation results for the fit parameters for the developed model are presented in Table 7.

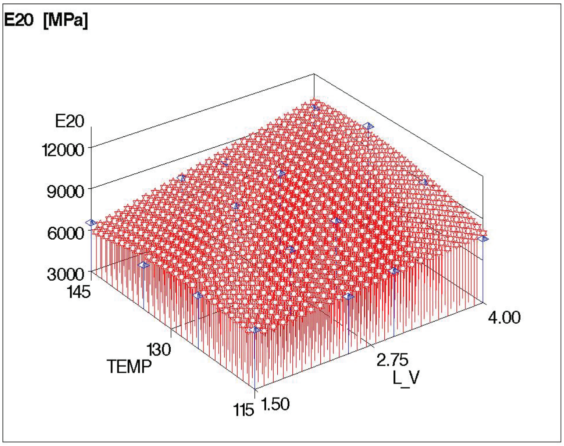


Fig. 4. The effect of the F-T wax amount (L_V) and the compaction temperature (TEMP) on the response surface for E20 [MPa] of AC 11 S

Table 7

The estimation results of model (L_V and TEMP) parameters for characteristic E20 of AC 11 S and the estimation of their significance

Parameter	Estimation	Standard Error	Value of t	Pr > |t|
Intercept	-44219	24288	-1.82	0.0987
TEMP	841.022628	369.126026	2.28	0.0459
L_V	-3402.679274	2099.740744	-1.62	0.1362
TEMP*TEMP	-3.526458	1.411135	-2.50	0.0315
L_V*TEMP	34.853590	14.002378	2.49	0.0320
L_V*L_V	-20.027778	188.151299	-0.11	0.9173

The analysis of the results collated in Table 7 primarily indicates the significant impact of the temperature of compaction (TEMP) on the stiffness modulus of asphalt concrete AC 11 S. No direct impact of the F-T synthetic wax (L_V) concentration on the stiffness modulus was observed in the developed model for the temperature of 20°C (p-value > 0.05). However, as was the case with the stiffness modulus at the test temperature of 10°C, the effect of interaction between those two parameters occurred. We can state that the interaction between the compaction temperature and the amount of the F-T synthetic wax has a highly significant effect on the E20 variation. The impact of significance of this fit element of the model (L_V*TEMP) was confirmed in the previous studies of stiffness modulus of asphalt concrete at the temperatures of 2°C and 10°C. This fact can be related to different dynamics of bitumen and F-T wax viscosity variation during the investigations of the stiffness modulus of asphalt concrete AC 11

S. As a result, the presence of the constant phase of F-T wax crystalline forms in combination with the process of asphalt concrete compaction acts jointly on its stiffness modulus at mean test temperatures (here: 2°C do 20 °C).

3. PERMANENT DEFORMATION (RTS) OF ASPHALT CONCRETE AT TEMPERATURE OF 50°C

The investigation of RTS [17] in relation to the amount of F-T wax (L_V) and the temperature of compaction (TEMP) of AC 11 S was based on a regression mathematical model. The domain of the experiment set the boundary conditions. The first step of the experiment was devoted to determining the adequacy of the model for describing the variation of RTS. In the second step, the significance of the parameters used in the developed regression response surface was estimated. The results of the analysis of the model fit for the RTS characteristic of asphalt concrete are presented in Tables 8 and 9.

Table 8

Summary results of the model fit for RTS of AC 11 S

Response Surface for Variable RTS: RTS [%]	
RMSE	0.289316
R-square	83.48%
Coefficient of Variation	21.45567

Table 9

Detailed results of polynomial degree fit for RTS of AC 11 S

Regression	**SS**	**MS**	**F**	**Pr > F**
Linear	2.323617	0.464723	6.488589	0.00614
Quadratic	1.918112	0.959056	13.39059	0.001485
Crossproduct	0.096695	0.048348	0.675042	0.53089

The results of the analysis indicate that the square function model was the best fit for the RTS total change estimation. The value of the correlation coefficient was $R^2=0.76$, which confirmed a high degree of fit of the model function with the deformation variation (RTS) in the entire domain determined by the amount of the F-T synthetic wax in AC 11 S and its temperature of compaction.

Figure 5 presents a graphical interpretation of the response surface for the RTS variable of AC 11 S at the temperature of 50 °C in relation to the amount of the F-T synthetic wax (L_V, %) and the temperature of compaction (TEMP, °C). The results of the estimation of the developed model parameters are presented in Table 10.

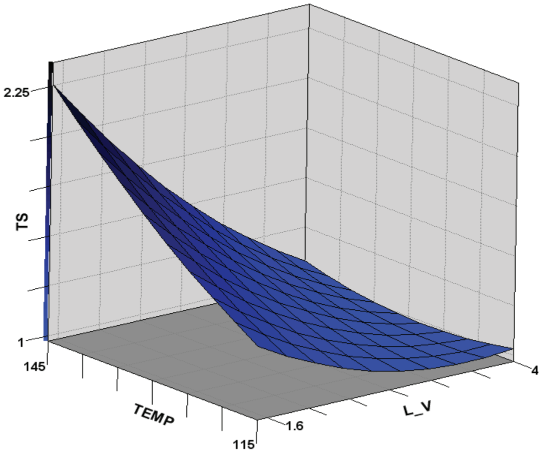


Fig. 5. The response surface for RTS [%] of AC 11 S against the amount of F-T wax (L_V) in asphalt concrete and the temperature of compaction (TEMP)

Table 10

The results of the estimation of the parameters of model (L_V and TEMP) for RTS of asphalt concrete AC 11 S and estimation of their significance

Parameter	Estimation	Standard Error	Value of t	Pr > |t|
L_V	1.335684	1.335684	18.64916	0.001517
TEMP	0.582428	0.582428	8.132016	0.017201
L_V*L_V	0.074939	0.074939	1.046318	0.330464
L_V*TEMP	0.30881	0.30881	4.311683	0.06458
TEMP*TEMP	0.021756	0.021756	0.303766	0.59363

The analysis results show that there is a significant impact of both factors on the level of accumulated permanent deformation (RTS) of asphalt concrete. The effect of the temperature factor (TEMP) proved to be smaller than that of the F-T wax amount (p-value = 0.017). The significant influence of the non-linear parameter L_V in the model indicates that the F-T wax concentration in asphalt concrete, unlike the TEMP factor, has a dynamic effect. We can state that the amount of F-T wax in asphalt concrete 35/50 reduces non-linearly the level of total deformation of asphalt concrete and contributes to the increase in its resistance to this type of deformation [18]. Temperature affects the total deformation of asphalt concrete RTS proportionally to its increase. Increasing the temperature of compaction (TEMP) in interaction with an increased amount of modifier (L_V) at about 145ºC causes a statistically significant increase in the susceptibility of asphalt concrete to permanent deformation. This effect is probably connected with improper compaction of asphalt concrete and reduction in friction level at the aggregate interfacial transition zone. It is thus necessary to reduce the compaction energy amount to obtain optimal level of void spaces for the asphalt concrete with non-modified bitumen compacted at temperatures recommended in WT-2/2010.

4. FATIGUE LIFE OF ASPHALT CONCRETE, DETERMINED USING THE IT-FT METHOD

The evaluation of AC 11 S asphalt concrete fatigue process using the IT-FL method supplements the investigation of the effect of F-T wax on the deformation of asphalt concrete. In the light of regulations currently in force [10, 11] no fatigue criteria are available for surface courses of bitumen pavements. As the properly produced surface course with retained interlayer bond is subjected to compressive stresses, its fatigue life should tend to infinity. The range of tensile stresses occurs in the binder course at the depth from 8 to 12 cm [12].

To evaluate how the amount of F-T wax affects the fatigue life of the investigated asphalt concrete mixture, the controlled stress mode was employed in accordance with PN-EN 12697-24, Annex E [13] in the indirect tensile fatigue tests (IT-FT). The significant element of the investigation was introducing such a stress that will induce strain amplitude higher than 50με. In this range of compressive stress, fast cracking initiation in asphalt concrete can be expected [14, 15, 16]. The compressive stress used in the tests was 700 kPa. The tests ended when the asphalt concrete specimens shifted vertically by 5 mm or its stiffness modulus dropped by 50% after 30,000 loading cycles at a frequency of 1 Hz.

The results of the analysis indicate a very close level of tests errors. The highest error level was recorded for asphalt concrete AC 11 S compacted at the low temperature of 115°C and when the amount of F-T wax was the smallest, i.e., 1.5%. The dispersion of the results is related to high bitumen stiffness and the differentiation in the number of voids in the asphalt concrete. For all but one of the specimens there were no outliners at the variation coefficient of up to 20%. The asphalt concrete at the compaction temperature of 115°C and F-T wax content of 1.5% had the stiffness modulus drop below 50%, between 1900th and 2200th loading cycle. In the remaining cases the asphalt concrete had the stiffness modulus drop below 50% after 30,000th loading cycle.

To visualise the course of changes in the stiffness modulus of AC 11 S in terms of the fatigue life for strains higher than 50με, the results of representative individual spectra are shown in Figure 6.

On the basis of data in Figure 6 we can state that low temperature of asphalt concrete compaction in interaction with small amount of F-T wax affected the compaction quality. In that case the initiation of cracking progresses the most quickly. The comparison of asphalt concrete compacted at 145 °C and 1.5% content of F-T wax with that compacted at 125°C and 2.5% content of the modifier shows comparable results for the stiffness modulus drop. This confirms the fact that optimisation for bitumen 35/50 with an addition of 2.5% of F–T synthetic wax helps to reduce the compaction temperature by 25°C compared to conventional asphalt concrete. In addition, at the comparable fatigue life, higher resistance to permanent deformation was achieved for AC 11 S with F-T wax modified bitumen than for non-modified bitumen compacted in accordance with the relevant standard.

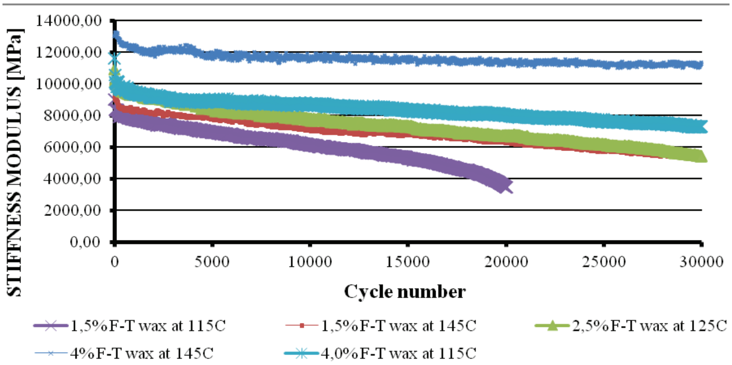


Fig. 6. Influence of F-T wax on the change in stiffness modulus of AC 11 S under cyclic loading

The influence of F-T wax and the temperature of compaction on the global evaluation of mean results of AC 11 S stiffness modulus testing using the IT-FT method as well as the test error assay are presented in Figure 7.

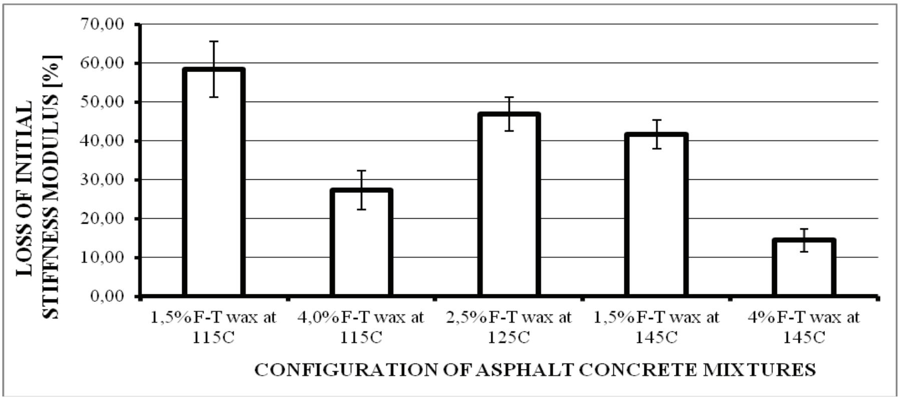


Fig. 7. Amount of F-T synthetic wax and temperature of compaction versus stiffness modulus of AC 11 S under cyclic load (ITFT)

The results of analysis indicate that the dynamics of fatigue cracking initiation in AC 11 S asphalt concrete is significantly affected by the amount of F-T synthetic wax, the increase in which reduces the drop in the stiffness modulus value. Therefore, for the same loads lower strain values will be obtained and the cracking initiation dynamics will be reduced. In any case, an increase in F-T wax concentration from 1.5% to 4% caused the drop in stiffness of AC 11 S of about 50%. This change in the stiffness modulus of the asphalt concrete was obtained when the temperature of compaction was 145°C and the modifier content was 4.0%. A slight reduction in the stiffness modulus indicates a higher resistance of AC 11 S asphalt concrete to fatigue cracking in the range of up to 30,000 loading cycles may be connected with the character of over-densification of asphalt concrete and the low content of voids. However, in the case of the resistance to permanent deformation under conditions specified above, the asphalt concrete becomes highly susceptible to cyclic loading effect in the rutting tests. Thus the best solution, in relation to the reference asphalt concrete, is the application of F-T synthetic wax in the amount of up to 2.5-3% at the lower compaction temperature of about 25°C. In this case, an increase in AC 11 S resistance to permanent deformation may reach 40% compared with the reference asphalt concrete at the comparable level of resistance to cyclic loading effect in the range of up to 30,000 loading cycles.

5. RESISTANCE OF ASPHALT CONCRETE TO RUTTING

The result for the resistance to rutting was determined for two measurements with difference of not more than 8% for all the possible changes of factors. Thanks to low dispersion of factors, its evaluation in the form of a mathematical model was conducted for two replications. Another stage of the analysis was devoted to the process of finding the model that would fit. The preliminary analysis of the model adequacy for characteristic WTS_{AIR} of asphalt concrete in relation to the investigated independent variables (L_V, TEMP) is presented in Table 11.

Table 11

Summarised statistics of the model fit for WTS_{AIR} of AC 11 S

Response Surface for Variable WTS_{AIR}: WTS_{AIR}[mm/1000 cykli]	
RMSE	0.024
R-square	82.97%
Coefficient of Variation	7.42399

For this class type of experiment, the most rational, considering the number of degrees of freedom (number of combinations of independent variables), is the classical type I response surface. The linear model fit is characterised by the coefficient of determination $R^2 = 0.83$. The value of “Lack of fit” parameter if greater than the critical value (p-value = 0.07), which indicates the significance of the model applied. Therefore the description of variation of WTS_{AIR}, depending on the amount of F-T wax F-T (L_V) and the temperature of compaction (TEMP) of AC 11 S indicates a very good fit of the model.

A graphical interpretation of the response surface of the variation of rut increment WTS_{AIR} at the test temperature of 60°C related to the amount of F-T synthetic wax (L_V, %) and the temperature of compaction (TEMP, °C) is presented in Figure 8. The results of the model parameters estimation for WTS_{AIR} are collated in Table12.

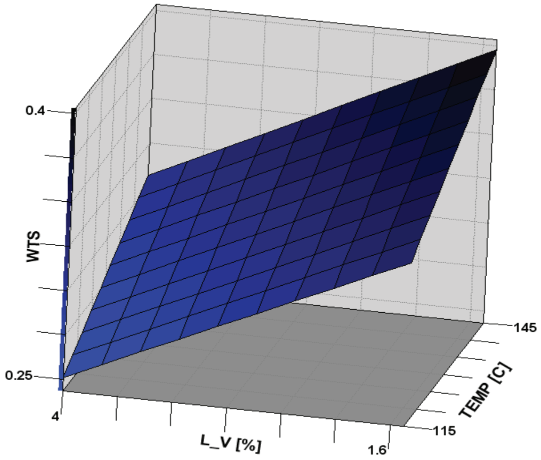


Fig. 8. Effect of the F-T wax amount (L_V) and the temperature of compaction (TEMP) on the response surface for WTS_{AIR} [mm/1000 cycles] of AC 11 S

Table 12

Results of the model parameters estimation (L_V and TEMP) for WTS_{AIR}

Parameter	Estimation	Standard Error	Value of t	Pr > |t|
TEMP	0.06375	0.016877	3.77726	0.00921
L_V	-0.09625	0.016877	-5.70292	0.001257
L_V*TEMP	-0.00375	0.016877	-0.22219	0.831535

The analysis of the characteristics obtained indicates that factors, the amount of F-T wax and the range of the compaction temperature, had a significant effect on WTS_{AIR} variable of AC 11 S asphalt concrete. The synergy effect proved to be statistically insignificant. The lack of interaction is connected with the transition of bitumen 35/50 modified with F-T synthetic wax into the state close to the Newtonian liquid. The stiffness during the rutting test at 60ºC was caused by the F-T wax crystals. The temperature of compaction affects the quality of the asphalt concrete, expressed as a viscosity level of the binder and the resistance of its compaction in the constant volume. The effect of compaction temperature of AC 11 S remains independent of the amount of the F-T synthetic wax that affects the level of WTS_{AIR} parameter. Generally, the bitumen 35/50-crystalline phase of F-T wax ratio will determine the velocity of deformation and the progressing structural damage to the asphalt concrete. With high quality of the model fit, we can state that the effect of F-T wax affects constantly and proportionally the decrease in the level of velocity of accumulation of permanent strain of the asphalt concrete AC 11 S represented by WTS_{AIR} parameter.

Another parameter that was evaluated to determine the resistance to deformation was the characteristic of the rut increment PRDAIR of the asphalt concrete according to recommendations in WT-2 2010 [11]. Two samples were assayed of each factor combination (L_V, TEMP) of the experiment domain, the results of which varied within 6%. The fit estimation of the model is presented in Table 13.

Table 13

Summarised statistics of the model fit for PRD_{AIR} of AC 11 S

Response Surface for Variable PRD: PRD [%]	
RMSE	0.613
R-square	98.17%
Coefficient of Variation	5.01

For this class type of experiment, the most rational, like in the case of WTS_{AIR}, is the classical type I response surface. The linear model fit is characterised by the coefficient of determination $R^2 = 0.98$. The value of “Lack of fit” parameter if greater than the critical value (p-value = 0.387), which indicates the significance of the model applied. Therefore the description of variation of WTS_{AIR}, depending on the amount of F-T wax F-T (L_V) and the temperature of compaction (TEMP) of AC 11 S indicates a very good fit of the model applied.

A graphical interpretation of the response surface of the variation of rut depth PRD_{AIR} at the test temperature of 60ºC for asphalt concrete related to the amount of F-T synthetic wax (L_V, %) and the temperature of compaction (TEMP, ºC) is presented in Figure 9. The results of the developed model parameters estimation are collated in Table 14.

The result of the analysis indicate a significant impact of both factors, the amount of FT wax and he compaction temperature of AC 11 S, on the rut depth PRD_{AIR} increment expressed in percentage. Alongside the statistically significant impact of the factors investigated (L_V, TEMP) on asphalt concrete, the synergy effect occurred for the independent variables discussed. This indicates that the rut depth is affected by the amount of the F-T wax present in the bitumen 35/50 in combination with the quality of compaction of AC 11 S determined by the compaction temperature. Hence, ensuring the proper process of asphalt concrete compaction can reduce deformation of the asphalt concrete. Also, the deformation depth increment, as in the case of RTS (simplify triaxial compression) [17], shows a strong relation to the asphalt concrete compaction temperature. When the bitumen viscosity level is too low at the compression phase at the constant compaction energy, the content of voids is insufficient. The lack of aggregate interlocking in the asphalt concrete produces an adverse effect. In such a case an excessive amount of F-T wax in combination with high temperature makes the asphalt concrete "flow." The course of the response surface confirms that fact. For the given value of F-T wax, the deformation of asphalt concrete expressed by PRD_{AIR} increases with the compaction temperature increase.

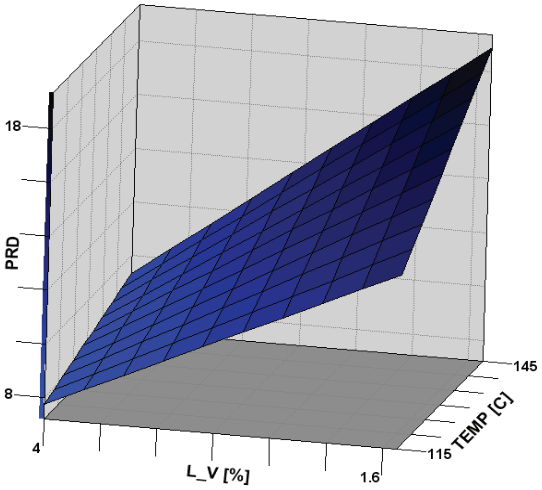


Fig. 9. Effect of the F-T wax amount (L_V) and the temperature of compaction (TEMP) on the response surface for PRD_{AIR} [%] of AC 11 S

Table 14

Results of the parameter estimation of (L_V an TEMP) model for PRDAIR

Parameter	Estimation	Standard Error	Value of t	Pr > |t|
TEMP	3.525	0.433229	8.136572	0.0002
L_V	-8.625	0.433229	-19.9086	0.0001
L_V*TEMP	-2.125	0.433229	-4.90503	0.0027

On the basis of the properties of AC 11 S that are connected with the resistance to permanent deformation, an attempt was made to find predictions for parameters RTS and WTS_{AIR}. The frequency of loading was similar in both tests with the value of about 1.5 Hz. The difference between the test temperature in both tests was 10°C. Both tests were conducted with the side restraint of the asphalt concrete specimens. A regression analysis was used to evaluate the relationship between the parameters.

The noise connected with the outliers was eliminated by eliminating measurements that contained large errors, owing to a high sensitivity of the coefficient of determination R^2. Large errors may cause disturbance in the whole process of finding the trend line model. To carry out an analysis of correlation, all the tests results were used and the results for WTSAIR and RTS were grouped by the compaction temperature level and F-T wax content in the asphalt concrete. For that purpose, t-studentised residuals were used. The test values higher than 2 have to be treated as those that contribute to biased estimation of regression parameters and which destabilise the correlation variance. The distributions of residuals of the explanatory variable WTS_{AIR} are presented in Figure 10.

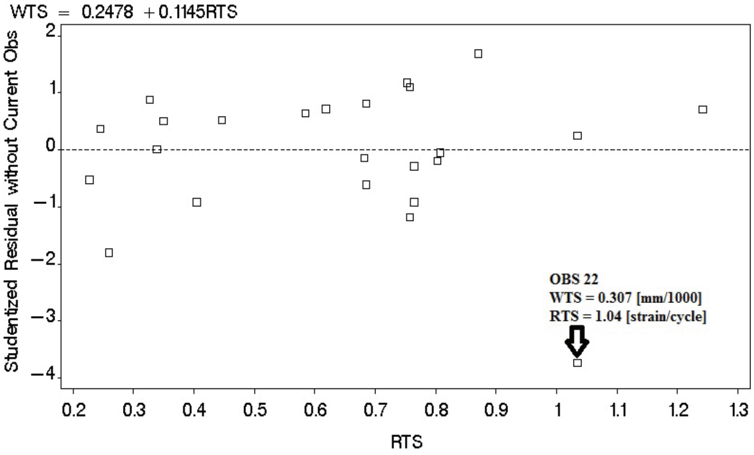


Fig. 10. Values of t-studentised residuals of the explanatory variable (WTS_{AIR}) of AC 11 S

It must be emphasized that observation 22 lies far from the mean value level. The value of the t-studentised residual is greater than 2. Therefore, further in the analysis this observation was eliminated. The ultimate form of the model is shown in Figure 11.

Analysis results presented in Figure 11 indicate that there is a close relationship as for the measurement of the velocity of total irreversible deformation increment in relation to parameters WTS_{AIR} and RTS of AC 11 S. The correlation strength is at a very high level reaching 81%. Owing to information about the AC 11 S deformation velocity, obtained from the dynamic creep tests with the side restraint, it is possible to predict the susceptibility of the asphalt concrete in rutting tests much faster (the duration of the dynamic creep tests with the side restraint was 2 hours).

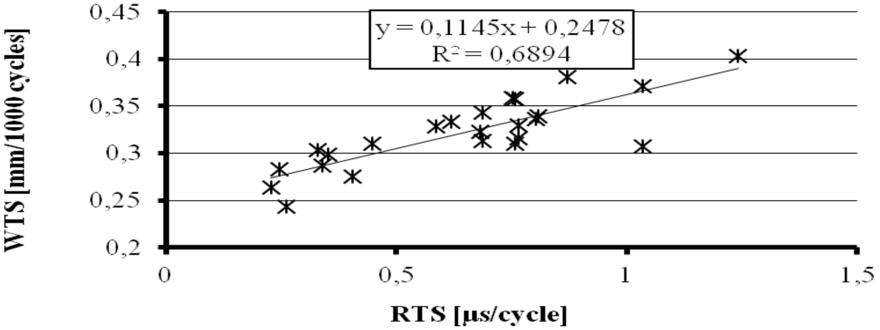


Fig. 11. Correlation of the velocity of deformation according to the rutting test for WTS_{AIR} and according to the dynamic creep tests with a side restraint for RTS of AC 11 S

6. CONCLUSIONS

The investigations of the effect of F-T synthetic wax on the resistance of AC 11S asphalt concrete helped formulate the following conclusions:

- the structuring property of F-T wax present in the bitumen 35/50 significantly contributes to the reduction in the level of AC 11 S strain in the triaxial compression tests (RTS) and rutting tests (WTSAIR, PRDAIR), increasing its resistance to permanent deformation;
- the velocity of stiffness modulus drop, determined during the estimation of the fatigue life according to the ITFT method, for the asphalt concrete with 2.5% of F-T wax compacted at the temperature of 125°C, is comparable with the characteristics of the reference asphalt concrete compacted at 145°C;
- the use of bitumen with an addition of 2.5% F-T wax in the asphalt concrete AC 11 S at the compaction temperature of 125°C leads to the reduction in the level of WTSAIR parameter that characterizes the velocity of permanent deformation by 40% when compared with conventional asphalt concrete, which ensures higher resistance of bitumen pavements to rutting.

References

1. J. Judycki, B. Dołżycki, Analysis of permanent deformation of asphalt pavement on the basis of field and laboratory testing of permanent deformations (in Polish), VIII Konferencja Naukowa Komitetu Inżynierii Lądowej i Wodnej PAN i Komitetu Nauki PZITB, Krynica 2002, Inżynieria komunikacyjna, s. 201-208.
2. J. Piłat, P. Radziszewski, Road materials technology (in Polish). WKŁ, 2009, 509 s.
3. B. Stefańczyk, P. Mieczkowski, Hot mix asphalt - performance and research (in Polish). WKŁ. Warszawa. 2008.
4. M. Kilas M, A. Vaitkus., M. Paliukaitė, Warm Mix Asphaltes Research, Analysis and Evaluation, The 10th International Conference "Modern Building Materials, Structures and Techniques", Vilnius, 2010, pp. 149–155,
5. T. Butz, Warm Mix Asphalt - Technologies, research and Experiences, Sasol Wax GmbH
6. H. Silva H, J.Oliviera, J.Peralta, S. Zoorob, Optimization of warm mix asphalts using different blends of binders and synthetic paraffin wax contents, Construction and Building Materials, 24, pp. 1621-1631, 2010
7. Z. Piasta Z., A. Lenarcik, Methods of statistical multi-criteria optimization, [in] A.Brandt (ed.), Optimization Methods for Material Design of Cement-based Composites, E&FN Spon, London, New York, 45-59, 1998
8. J. Judycki, M. Stienss M, Bituminous mixtures tests coated at low temperature (in Polish), Raport końcowy GDDKiA, 2011
9. M. Duriez, Nouveau traité de materiaux de construction, Bd III,1961.
10. B. Stefańczyk, praca zbiorowa, General Building Engineering (in Polish). Tom I, Arkady, 2005
11. PN EN 13108-1 Road bituminous mixtures (in Polish).
12. WT-2 Technical requirements (in Polish), GDDKiA 2010
13. J. Judycki, Fatigue o asphalt mixes, OULU 1991.
14. S. Lawrence, Effect of Bitumen Flow Improvers on the Compatibility and Stability of Hot Rolled Asphalts, Diplomarbeit an der HAW Hochschule fur angewandte Wissenschaften, Hamburg 2001.
15. M. Zaky, N.H. Mohamed, Comparative study on separation and characterization of high melting point macro- and micro-crystalline waxes, Journal of the Taiwan Institute of Chemical Engineers, 41, 2010.
16. M. Iwański, G. Mazurek, Water and Frost Resistance of Asphalt Concrete Produced in the Warm Technology – 10th International Conference Modern Building Materials, Structures and Techniques in Vilnius, 19-21 May 2010, pp. 200-206.
17. PN EN 12697-25:2005 Bituminous mixtures. Test methods for hot mix asphalt - Part 25: Cyclic compression test (in Polish).
18. W. Grabowski, M. Słowik and M. S. Kuczma, Modelling the creep experimental results for a polymer modified bitumen (in Polish), Archives of Civil Engineering L, 1, 2004, 151-160
19. S. Gopinath, A. Ramachandra murthy, D. Ramya, Nagesh R. Iyer, Optimised mix design for normal strength and high performance concrete using particle packing method, Archives of Civil Engineering, LVII, 4, 2011, 357-371

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