ISSN 1330-3651
UDC/UDK 691.16:620.1

INFLUENCE OF SLAG, FLY ASH AND SILICA FUME ON THE MECHANICAL AND PHYSICAL PROPERTIES OF ASPHALT

Miroslav Mikoč, Dalibor Marković

Preliminary notes

The paper examines the impact of waste materials: slag, fly ash and silica fume on the physical and mechanical properties of asphalt. Natural aggregate fractions from 4-8 mm and 8-11 mm in asphalt were substituted with blast furnace slag while mineral filler was substituted with fly ash and silica fume. Physical and mechanical properties of thus prepared samples were tested according to Standard HRN EN 12697.

Keywords: *asphalt, fly ash, silica fume, slag*

Utjecaj šljake, elektrofiltarskog pepela I amorfne SiO_2 prašine na fizikalno-mehanička svojstva asfalta

Prethodno priopćenje

U radu je istražen utjecaj otpadnih materijala: šljake, elektrofiltarskog pepela i amorfne SiO_2 prašine na fizikalno-mehanička svojstva asfalta. Prirodne frakcije agregata od 4-8 mm i 8-11 mm u asfaltu zamijenjene su frakcijama šljake, a punilo, kameno brašno zamijenjeno je elektrofiltarskim pepelom i amorfnom SiO_2 prašinom. Fizikalno-mehanička svojstva tako pripremljenih uzoraka asfalta ispitana su prema normi HRN EN 12697.

Ključne riječi: *amorfna SiO_2 prašina, asfalt, elektrofiltarski pepeo, šljaka*

1 Introduction
Uvod

As the volume of waste and by-product materials generated in our society and the cost of disposal continue to increase, there is increased pressure and incentive to recover and recycle these materials for use in secondary application. Because the construction of pavements requires large volumes of materials, highway agencies have become participants in these recycling efforts. Out of the various waste, the by-products of iron and steel making industries, blast furnace and steel slag can be considered sensible alternative sources of aggregate for asphalt mixture production. These secondary aggregates have similar physical properties to the conventional, primary aggregate and can be processed, crushed and screened into practical size for easy batching into both surfacing and base asphalt materials.

Blast furnace slag is made up primarily of silicates and alumosilicates of calcium and magnesium together with other compounds of sulphur, iron, manganese and other trace elements [1]. Approximately 90 % of the produced slag is air-cooled, rough surface texture and of relatively high porosity which enables it to connect well with the bituminous binder [2], because asphalt mixtures with slag have excellent resistance to the action of water and traffic.

Steel slag is an industrial by-product of the steel making process. Steel slag consists primarily of calcium silicates together with oxides and compounds of iron, manganese, alumina and other trace elements. Steel slag is denser and stronger than blast furnace slag and delivers high resistance to abrasion and polishing under traffic when used in asphalt surface layers [1, 3, 4]. However, steel slag does have the potential to undergo volumetric expansion in the presence of water due to the reaction of oxides of calcium and magnesium in the steel slag with water. Expansion problems can be avoided by subjecting steel slag to a long period of natural weathering in exposed stockpiles for at least a year. It is used as a secondary aggregate [5].

The most significant difference between steel slag and most natural aggregates is its high particle density, which is the consequence of the presence of iron compounds in the slag. Therefore asphalt mixtures produced using steel slag aggregates will display higher density values and generally greater stability and stiffness values compared to conventional, primary aggregate material [6]. The use of blast furnace slag fine aggregate together with steel slag coarse aggregate can compensate for the high particle density of steel slag.

2 Materials
Materijali

For the preparation of asphalt mixture were used: crushed sand, fraction of 0-2 mm, density 2,88 g/cm^3, and natural stone aggregates, fraction of 2-4 mm, 4-8 mm, density 2,88 g/cm^3 and fraction of 8-11 mm, density of 2,92 g/cm^3 from the quarry "Fukinac".

As a filler was used stone flour from the quarry "Sirač", density 2,85 g/cm^3. Stone flour was ground or crushed stone material grain size to 0,71 mm.

The results of sieve analysis of natural aggregates and mineral filler for making asphalt are shown in Tab. 1, and presented by diagrams in Fig. 1.

The quality of some fraction of aggregates was assessed by calculating modulus of grain fineness, by determining the share of oversize, undersize and scrubby grains in each fraction of aggregate.

Modulus of grain fineness was calculated according to expression (1):

$$MF = \frac{\sum_{0,09}^{D} p_o}{100}, \tag{1}$$

where:
MF – modulus of grain fineness

***Table 1** Particle size distribution: of crushed sand, fraction from 0-2 mm, crushed stone aggregate, fractions from 2-4 mm, 4-8 mm , 8-11 mm and mineral filler*
***Tablica 1.** Granulometrijski sastavi: drobljenog pijeska, frakcije od 0-2 mm, kamene sitneži frakcija od 2-4 mm, 4-8 mm, 8-11 mm i kamenog brašna*

Percent passing Cumulative passing/mass %	Sieve size/mm									
	0,09	0,25	0,71	2	4	8	11,2	16	22,4	31,5
	Sand fraction, 0-2 mm									
Passing	5,4	12,6	27,1	50,5	3,8	0,6	0,0	0,0	0,0	0,0
Cumulative	5,4	18,0	45,1	95,6	99,4	100	100	100	100	100
	Natural aggregate fraction, 2-4 mm									
Passing	1,2	1,2	1,3	15,4	74,3	6,6	0,0	0,0	0,0	0,0
Cumulative	1,2	2,4	3,7	19,1	93,4	100	100	100	100	100
	Natural aggregate fraction, 4-8 mm									
Passing	0,7	0,3	0,1	0,2	8,4	84,7	5,5	0,0	0,0	0,0
Cumulative	0,7	1,0	1,1	1,4	9,7	94,5	100	100	100	100
	Natural aggregate fraction, 8-11 mm									
Passing	0,4	0,3	0,5	1,0	1,4	17,3	68,1	11,1	0,0	0,0
Cumulative	0,4	0,7	1,2	2,1	3,5	20,8	88,9	100	100	100
	Mineral filler									
Passing	94,9	4,5	0,3	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Cumulative	94,9	99,4	99,8	100	100	100	100	100	100	100

***Table 2** Modulus of grain fineness, mass shares of undersize, oversize and scrubby grains for fraction of aggregate from 0-2 mm, 2-4 mm, 4-8 mm and 8-11 mm*
***Tablica 2.** Moduli finoće zrnatosti, maseni udjeli nadmjernih, podmjernih i trošnih zrna za frakcija agregata od 0-2 mm, 2-4 mm, 4-8 mm i 8-11mm*

Property	Standard	Fraction 0-2 mm	Fraction 2-4 mm	Fraction 4-8 mm	Fraction 8-11 mm
Modulus of grain fineness, *MF*	HRN U.E4.014	2,36	3,74	3,96	3,96
Scrubby grains/mass %	HRN B.B8.036	5,36	1,22	0,72	0,39
Undersize grains/mass %	HRN U.E4.014	0,00	19,11	9,74	20,77
Oversize grains/mass %	HRN U.E4.014	4,37	6,57	5,54	11,09

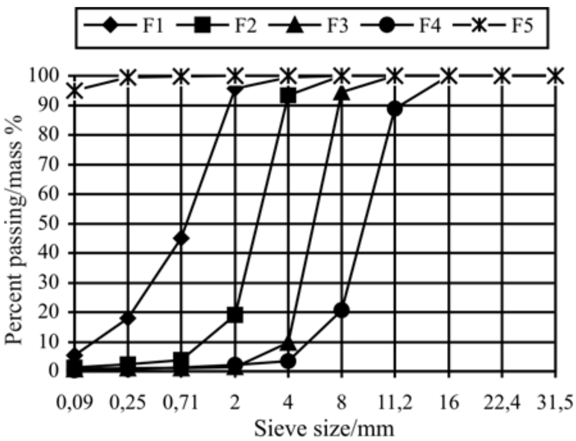

***Figure 1** Diagrams of particle size distribution: of crushed sand, fraction from 0-2 mm, (F_1) crushed natural stone aggregates, fractions from 2-4 mm, (F_2), 4-8 mm, (F_3), 8-11 mm, (F_4) and mineral filler (F_5)*
***Slika 1** Dijagrami granulometrijskog sastava: drobljenog pijeska, frakcija 0-2 mm, (F_1), kamene sitneži: frakcija 2-4 mm, (F_2), frakcija 4-8 mm, (F_3), frakcija 8-11mm, (F_4) i frakcije kamenog brašna (F_5)*

p_o – percent of the rest on sieves, g
D – maximum aggregate size, mm.

Modulus of grain fineness for each fraction of aggregates, mass shares of oversize, undersize and scrubby grains are shown in Tab. 2.

Beside the modulus of grain fineness, the quality of the individual fractions of aggregate determines the mass share of oversize and undersize grains. Limitations of mass share of pollution are:

- fraction of aggregate should not contain more than 10 % oversize grain
- fraction of aggregate should not contain more than 15 % undersize grain.

From Tab. 2 and Fig. 1 can be seen that the fraction of 8-11 mm has a higher mass share of oversize and undersize grain of the prescribed limits, and a fraction of 2-4 mm larger mass share undersize grain.

The bitumen used in this research was pure bitumen with penetration degrees of 50 to 70 obtained from the Pančevo refinery.

The physical and mechanical properties of the bitumen used in this study are shown in Tab. 3.

***Table 3** Physical and mechanical properties of bitumen used in asphalt mixtures*
***Tablica 3.** Fizikalno-mehanička svojstva korištenog bitumena za asfaltne mješavine*

Specific gravity at 25 °C/g/cm^3	1,01
Softening point/°C	49,5
Ductility at 25 °C/cm	>150
Wax number, mass %	2,5
Mass loss after warming at 163 °C/mass %	0,1
Breakpoint by Fraass/°C	–17
Breakpoint by Fraass after warming/°C	–11
Degree of penetration at 25 °C/0,1 mm	70
Penetration index	–0,5
Insoluble compounds in HCl/mass %	0,1
Reduction of penetration after warming/%	30

Air-cooled steel slag from the steel production in Split was used as a replacement of natural aggregates in the preparation of bituminous mixture.

Modulus of grain fineness, mass shares of oversize, undersize and scrubby grains for fraction of aggregates

Table 4 *Modulus of grain fineness, mass shares of oversize, undersize and scrubby grains for fraction of aggregates from 4-8 mm, and 8-11 mm*
Tablica 4. *Moduli finoće zrnatosti, maseni udjeli trošnih zrna i maseni udjeli nadmjernih i podmjernih zrna frakcija šljake od 4-8 mm i 8-11mm*

Property	Standard	Slag fraction 4-8 mm	Slag fraction 8-11 mm
Modulus of grain fineness, *MF*	HRN U.E4.014	3,93	3,97
Scrubby grains/mass%	HRN B.B8.036	1,13	0,42
Undersize grains/mass%	HRN U.E4.014	18,14	21,81
Oversize grains/mass%	HRN U.E4.014	2,61	0,00

Table 5 *Particle size distribution of slag "Split" fractions of 4-8 mm, 8-11 mm, fly ash and silica fume*
Tablica 5. *Granulometrijski sastavi korištenih frakcija šljake "Split" od 4-8 mm, i od 8-11 mm, letećeg pepela i amorfne SiO_2 prašine*

Percent passing and cumulative passing/mass %	Sieve size/mm									
	0,09	0,25	0,71	2	4	8	11,2	16	22,4	31,5
	Slag fraction, 4-8 mm									
Passing	1,1	0,4	0,2	0,4	16,0	79,3	2,6	0,0	0,0	0,0
Cumulative	1,1	1,5	1,8	2,2	18,1	97,4	100	100	100	100
	Slag fraction, 8-11 mm									
Passing	0,4	0,2	0,1	0,1	0,2	20,7	78,2	0,0	0,0	0,0
Cumulative	0,4	0,7	0,8	0,9	1,1	21,8	100	100	100	100
	Fly ash									
Passing	59,8	32,1	7,5	0,6	0,0	0,0	0,0	0,0	0,0	0,0
Cumulative	59,8	91,9	99,4	100	100	100	100	100	100	100
	Silica fume									
Passing	58,0	24,1	15,8	2,2	0,0	0,0	0,0	0,0	0,0	0,0
Cumulative	58,0	82,0	97,8	100	100	100	100	100	100	100

from 4-8 mm. and 8-11 mm. are shown in Tab. 4.

The results of sieve analysis of the slag "Split" fractions from 4-8 mm and 8-11 mm are shown in Tab. 5 and presented by diagrams in Fig. 2.

As a replacement for natural filler were used the Tuzla thermal power plant fly ash, density 2,04 g/cm^3 and silica fume "Elkem" produced in Norway.

Particle size distribution of fly ash and silica fume are shown in Tab. 5 and presented by a diagram in Fig. 2.

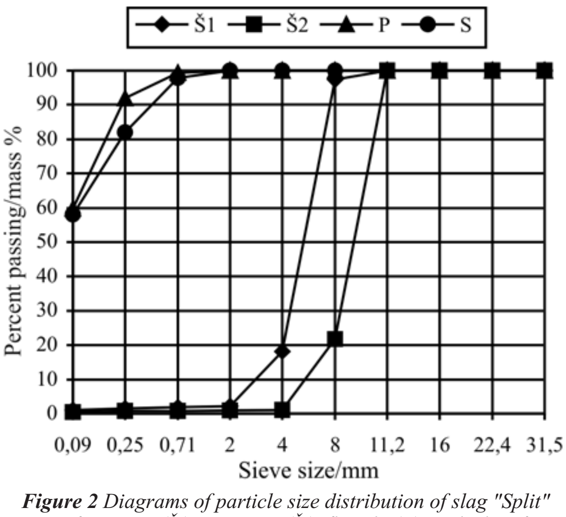

Figure 2 *Diagrams of particle size distribution of slag "Split" fractions of 4-8 mm, ($Š_1$), 8-11 mm, ($Š_2$), fly ash, (P), and silica fume (S)*
Slika 2. *Dijagrami granulometrijskih sastava: šljake "Split" frakcije 4-8 mm, ($Š_1$), 8-11 mm, ($Š_2$), letećeg pepela (P) i amorfne SiO_2 prašine (S)*

The chemical compositions of the slag, fly ash and silica fume are shown in Tab. 6.

Table 6 *Chemical composition of the blast furnace slag, fly ash and silica fume*
Tablica 6. *Kemijske analize korištene šljake, letećeg pepela i amorfne SiO_2 prašine*

Components	Slag/ mass %	Silica fume/ mass %	Fly ash/ mass %
CaO	31,52	2,55	5,29
SiO_2	14,24	91,50	55,80
Al_2O_3	7,40	1,75	19,20
Fe_2O_3	25,74	-	8,85
MgO	7,42	1,00	2,88
MnO	3,80	-	-
SO_3	0,44	-	-
Na_2O	0,13	0,85	2,00
K_2O	0,08	0,70	0,26
LOI	4,71	1,60	5,60
Total	95,48	99,85	99,88
Density/g/cm^3	3,41	2,21	1,91
Blaine/m^2/kg	569,20	11334,00	2930,00

3 Asphalt samples' composition designing
Projektiranje sastava asfaltnih uzoraka

Asphalt mixtures were designed according to the "General technical conditions" for work on roads, [7] that prescribe the minimum requirements for the quality of ingredients used in obtained asphalt. From the proposed minimum and maximum quantities that determine the asphalt mixture the share of bitumen in the asphalt sample $C_{B(AU)}$ was first calculated according to expression (2) and the expression of (3) percentage of bitumen in asphalt mix.

$$C_{B(AU)} = \frac{ISP \cdot C_{Š(AU)}}{100 - ISP}, \quad (2)$$

where:
$C_{B(AU)}$ – share of bitumen in the asphalt sample, vol. %
ISP – share of voids in aggregates filled with bitumen, vol. %

***Table** 7 Border values of particle size distribution for asphalt mixtures AB-11s*
***Tablica** 7. Granične granulometrijske krivulje za asfaltne mješavine AB-11s*

Sieve size/mm	0,09	0,25	0,71	2,0	4,0	8,0	11,2	16,0	22,4	31,5
Lower border curve	3	8	16	31	49	75	97	100	100	100
Upper border curve	11	18	30	48	65	87	100	100	100	100

$C_{\check{S}(AU)}$ – share of voids in the asphalt sample, vol. %.

$$B_{(\text{mass }\%)} = \frac{\rho_B}{\left[\dfrac{1-\dfrac{C_{\check{S}(KM)}}{100}}{C_{B(AU)}} - \dfrac{1}{100} + \dfrac{\rho_B}{100\cdot\rho_{KM}}\right]} \quad (3)$$

where:
$B_{(\text{mass }\%)}$ – mass of bitumen, kg
ρ_B – density of bitumen, kg/m^3
ρ_{KM} – density of stone materials, kg/m^3
$C_{\check{S}(KM)}$ – share of void in stone materials, vol. %.

Software program was used to calculate the optimum mass fraction of bitumen and the optimum asphalt mixture. Granulometric composition of the stone material of asphalt mixtures AB-11s must meet the "General technical conditions" of the granulometric border curves shown in Tab. 7.

AB-11s asphalt mixture is a narrow border area granulometric mixture of silica stone composition.

Asphalt sample from the optimal composition of aggregate and bitumen share must meet also the "General technical conditions" of the physical and mechanical properties shown in Tab. 8.

***Table 8** Mechanical and physical characteristics of asphalt mixtures AB-11s*
***Tablica 8.** Fizikalno- mehanička svojstva asfaltnih mješavina AB-11s*

Property	Minimum	Maximum
$C_{\check{S}(AU)}$/vol. %	3,0	6,0
ISP/vol. %	65,0	82,0
Stability/kN	8,0	Not specified
Stiffness/kN/mm^2	2,0	Not specified

Calculations of mass share of the ingredients for the control asphalt sample A, asphalt sample A_1 in which the fraction of aggregates of 4-8 mm. and 8-11 mm. were replaced by blast furnace slag, asphalt sample A_2 at which the filler was replaced with silica fume and asphalt sample A_3 in which the filler was replaced with fly ash are shown in Tab. 9.

4 Preparing samples for testing
Priprema ispitnih uzoraka

4.1 Preparing samples of asphalt mixtures for testing according to Standard HRN EN 12697-35
Priprema uzoraka asfaltnih mješavina za ispitivanje prema normi HRN EN 12697-35

Asphalt mixture samples were prepared at the target control temperature of the bitumen BIT 50/70 which should be 150 °C, for a limited time in order to prevent separation of aggregates. Some fractions of aggregates were first dried to constant mass.

Before using certain fractions of aggregates were placed in a ventilated chamber to control temperature of 150±5 °C and left in the chamber for at least 8 hours. After that, the required mass of individual aggregate fractions was shaken out in a mixing vessel. Bitumen was poured into a metal container, closed and heated at the control temperature of 150±5 °C in a ventilated chamber for 3 to 5 hours. According to the recipe, the necessary mass of bitumen was weighed and then added to the aggregate until all of the aggregate grains were wrapped by the bitumen.

***Table 9** Mass portion of components for control sample of asphalt A, samples A_1, A_2 and A_3*
***Tablica 9.** Proračun masenih udjela sastojaka za kontrolni uzorak asfalta A i uzorke asfalta A_1, A_2 i A_3*

Asphalt components	Sample A Mass		Sample A_1 Mass		Sample A_2 Mass		Sample A_3 Mass	
	%	kg	%	kg	%	kg	%	kg
Sand Fraction 0-2 mm	28,60	8,58	20,47	6,14	25,20	7,56	19,50	5,85
Aggregate Fraction 2-4 mm	13,35	4,01	16,75	5,02	14,94	4,48	20,43	6,13
Aggregate Fraction 4-8 mm	26,70	8,01			26,14	7,84	26,00	7,80
Slag Fraction 4-8 mm			24,20	7,26				
Aggregate Fraction 8-11 mm	20,98	6,29			19,61	5,88	19,50	5,85
Slag Fraction 8-11 mm			24,20	7,26				
Filer	4,89	1,46	7,94	2,38				
Fly ash							8,77	2,63
Silica fume					8,36	2,51		
Bitumen BIT 50/70	5,48	1,64	6,44	1,93	5,75	1,73	5,80	1,74
Total	100	29,99	100	29,99	100	30,00	100	30,00

4.2
Preparing average sample for testing according to Standard HRN EN 12697-28
Priprema prosječnog uzorka za ispitivanje prema normi HRN EN 12697-28

The portion of an average laboratory sample for testing was obtained by repeating the process of mixing and quartering according to standard HRN EN 12697-28.

5
Methods of testing samples
Metode ispitivanja uzoraka

5.1
Determination of the density of asphalt samples according to Standard HRN EN 12697-5
Određivanje gustoće asfaltnih uzoraka prema HRN EN 12697-5

Density of asphalt mixtures was calculated according to expression (4):

$$\rho_{mv} = \frac{m_2 - m_1}{1000 \cdot V_P - \dfrac{m_3 - m_2}{\rho_W}}, \tag{4}$$

where:
ρ_{mv} – density of the asphalt mixture/kg/m^3
m_1 – mass of the empty pycnometer with funnel/g
m_2 – mass of pycnometer with funnel and asphalt sample/g
m_3 – mass of pycnometre with funnel, asphalt sample and liquid/g
V_p – volume of the pycnometer/m^3
ρ_w – density of the liquid at the test temperature/kg/m^3.

First, the mass of the dry pycnometer with the funnel (m_1) was determined. The sample of dry asphalt which was cooled to the temperature of the environment was then added. The mass of the empty pycnometer and sample (m_2) was determined. The pycnometer was then filled with solvent to the maximum of 30 mm below the calibrated mark and then placed in a rotary device in order to separate air bubbles. The pycnometer was then placed in water at temperature of 25±1°C and kept there until the temperature of the sample and the solvent in the pycnometer was equal to the temperature of water. The pycnometer was then taken out of the water, wiped off and its mass was determined again (m_3).

5.2
Determination of soluble binder content according to Standard HRN EN 12697-1
Određivanje topljivog udjela veziva prema normi HRN EN 12697-1

A sample of asphalt from the pycnometer known mass (m_2) was put in the device for sieving on test sieves. Extraction device was put into operation and the sample was treated with toluene in which the asphalt is soluble. After 20 minutes the device stopped sieving, the sieve was removed and the mass remains were separated on individual sieves. Bitumen was dissolved in toluene and only the aggregate particles of 0,09 to 11 mm remained in sieves. Filler particles size below 0,09 mm were separated in a cuvette mass (m_1) on a device for separating. Separated aggregate and filler were then placed in a ventilated chamber and dried at 110±5 °C to constant weight.

After drying the mass of dry aggregate (m_3) and cuvette with filler (m_4) was determined.

The mass of filler (m_5) was calculated from the expression $m_5 = m_4 - m_1$. The mass of dry aggregate (m_3) was added to the mass of filler and then the total mass of aggregate and filler was $m_6 = m_5 + m_3$.

Mass fraction of bitumen was calculated by the expression (5):

$$S = \left(100 - \frac{m_6}{m_2}\right) \cdot 100, \tag{5}$$

where:
S – mass share of bitumen/mass %
m_6 – total mass of aggregate/g
m_2 – mass of asphalt mixture/g.

5.3
Determination of particle size distribution according to Standard HRN EN 12697-2
Određivanje granulometrijskog sastava prema HRN EN 12697-2

Determination of particle size distribution of aggregate in asphalt samples by sieving and weighing was carried out after separation of bitumen. Dried aggregate was placed in the device for sieving. After 30 minutes of sieving the mass of residue on each sieve was determined and the sieve curve was calculated from the expression (6):

$$f_i = 100 - \left(\frac{R_i}{M_l} \cdot 100\right), \tag{6}$$

where:
f_i – cumulative pass through a sieve/mass %
R_i – mass of residue on sieve/g
M_l – total mass of material/g.

In this way the granulometric curves were obtained by testing samples.

5.4
Samples preparation by impact compactor according to Standard EN 12697-30 and determination of the dimensions of asphalt samples according to Standard HRN EN 12697-29
Priprema uzorka udarnim zbijačem prema EN 12697-30 i mjerenje visine uzorka prema HRN EN 12697-29

To prepare the four samples, cylinder form diameter 101,6±0,1 mm and height 63,5±2,5 mm was weighed the mass of 1250 g asphalt mixture for each sample. Four vessels with samples were placed in a ventilated chamber and heated to a temperature of compaction of the bitumen BIT 50/70 of 150 °C.

Before the compaction of the samples the heated mold was filled with asphalt mixture by using a funnel.

Figure 3 *Device for sieving and bitumen separation*
Slika 3. *Uređaj za prosijavanje i odvajanje bitumena*

Figure 4 *Preparation of samples by impact compactor*
Slika 4. *Priprema uzoraka udarnim zbijačem*

After setting the hammer, samples were compacted with fifty blows from both sides (Fig. 4).

After completion of compaction the samples were cooled to 40 °C and removed from the mold by hydraulic presses.

On each sample were made four measurements of the sample's height and the height was expressed as the mean of four measurements.

5.5
Marshall test
Marshallovo ispitivanje stabilnosti uzoraka prema normi HRN EN 12697-34

Samples were immersed in the bath with water temperature 60 ± 1 ºC and held between 40 and 60 minutes. The samples were then placed on the device for testing the stability of the sample (Fig. 5).

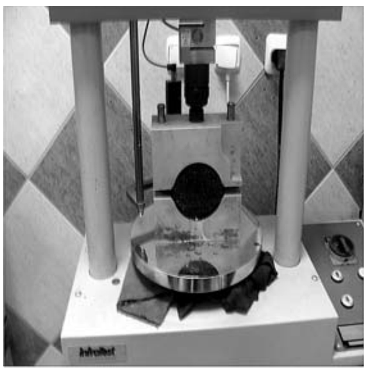

Figure 5 *Marshall press*
Slika 5. *Marshallova preša*

The stability of asphalt samples was determined by the maximum resistance to deformation.

5.6
Determination of the share of voids in the asphalt samples according to Standard HRN EN 12697-8
Određivanje udjela šupljina u asfaltnom uzorku prema normi HRN EN 12697-8

The share of voids in the asphalt sample was obtained from the expression (7):

$$V_{\mathrm{m}} = \frac{\rho_{\mathrm{m}} - \rho_{\mathrm{b}}}{\rho_{\mathrm{m}}} \cdot 100, \qquad (7)$$

where:
V_{m} – share of voids/vol. %
ρ_{m} – density of sample/kg/m^3
ρ_{b} – volume density of sample/kg/m^3.

5.7
Determination of the share of voids in the aggregate filled with bitumen
Određivanje volumnog udjela šupljina u agregatu ispunjenom bitumenom

The share of voids in the aggregate filled with bitumen was obtained from the expression (8):

$$V_{\mathrm{FB}} = \frac{B \cdot \dfrac{\sigma_{\mathrm{b}}}{\sigma_{\mathrm{B}}}}{V_{\mathrm{MA}}} \cdot 100, \qquad (8)$$

where:
V_{FB} – share of voids in the aggregate filled with bitumen/vol. %
B – share of binder in the sample/vol. %
σ_b – volume density of sample/kg/m^3
σ_B – density of binder/kg/m^3
V_{MA} – share of voids in aggregate/vol. %.

Share of voids in the aggregate was obtained from the expression (9):

$$V_{MA} = V_m + B \cdot \frac{\sigma_b}{\sigma_B}, \qquad (9)$$

where:
V_{MA} – share of voids in the aggregate/vol. %
V_m – share of voids in the sample/vol. %
B – share of binder in the sample/vol. %
σ_b – volume density of sample/kg/m^3
σ_B – density of binder (bitumen)/kg/m^3.

6 Results and discussion
Rezultati i rasprava

The obtained results of investigations of physical and mechanical properties of asphalt-prepared samples are shown in Tab. 10, and presented by diagrams in Figs 6-11.

The sample of asphalt A_1 in which the aggregate fraction was replaced with slag and samples A_2 and A_3 in which the filler was replaced with silica fume and fly ash had greater stability than the control sample A. Sample A_2 in which the filler was replaced with silica fume had the highest stability, 15,3 kN compared with the control sample A stability of 11,1 kN.

Sample A_1 in which the fraction of aggregates was replaced with slag had the highest density of 2713 kg/m^3 compared with the control sample A density of 2619 kg/m^3. Sample A_2 in which the filler was replaced with silica fume and sample A_3 in which the filler was replaced with fly ash had lower density 2528 kg/m^3 and 2510 kg/m^3 compared with the control sample A density of 2619 kg/m^3.

The largest proportion of voids in the aggregate which were filled with bitumen was also found in sample A_1, 77,6 % compared with the control sample A, whose fulfillment was 75 %.

Sample A_1 had the highest density of stone mixture, 3066 kg/m^3 in comparison to the control sample of 2883 kg/m^3.

The sample A_3 had the largest share of the required bitumen, 8,77 %, compared to the control sample of 5,4 %.

The results of sieve analysis of asphalt samples A, A_1, A_2 and A_3 are shown in Tab. 11 and presented by diagrams in Figs 12-15.

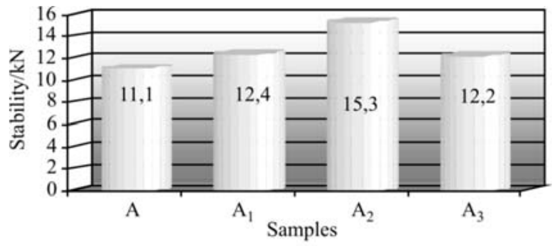

***Figure 6** Stability of asphalt samples*
***Slika 6.** Grafički prikaz stabilnosti asfaltnih uzoraka*

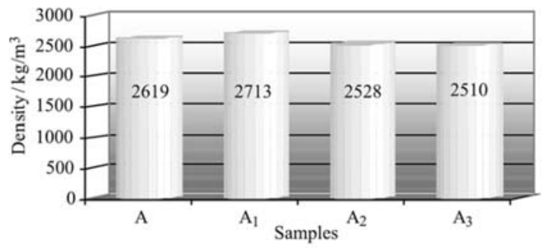

***Figure 7** Density of asphalt samples*
***Slika 7.** Grafički prikaz gustoća asfaltnih uzoraka*

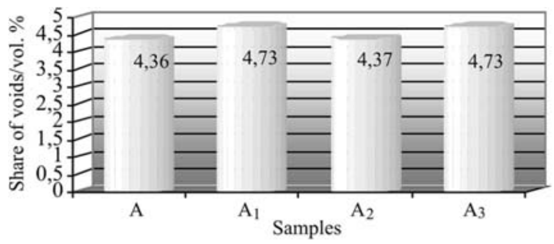

***Figure 8** Share of voids in the asphalt samples*
***Slika 8.** Grafički prikaz obujamskog udjela šupljina u asfaltnim uzorcima*

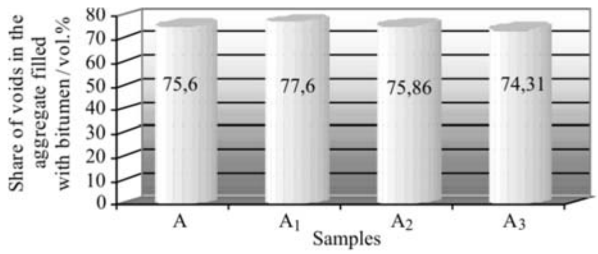

***Figure 9** Share of voids in the aggregates filled with bitumen*
***Slika 9.** Grafički prikaz obujamskog udjela šupljina u agregatu koje su ispunjene bitumenom*

***Table 10** Results of testing mechanical and physical properties of asphalt samples*
***Tablica 10.** Rezultati ispitivanja fizikalno–mehaničkih svojstava pripremljenih asfaltnih uzoraka*

Properties of asphalt samples	Sample A	Sample A_1	Sample A_2	Sample A_3	Condition
Stability by 60 °C/kN HRN EN 12697-34	11,10	12,40	15,30	12,20	Minimum 8,00
Density by 25 °C/kg/m^3 HRN EN 12697-5	2619	2713	2528	2510	
Share of voids/vol. % HRN EN 12697-8	4,36	4,73	4,37	4,73	3,00-6,00
Share of voids, filled with bitumen/vol. %	75,60	77,60	75,86	74,31	65,0-82,0
Density of stone mixture/kg/m^3	2883	3066	2782	2761	
Share of bitumen/mass % HRN EN 12697-1	5,48	6,44	8,36	8,77	

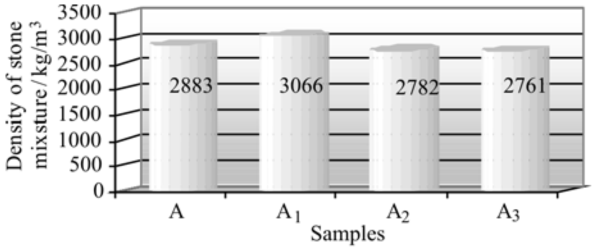

Figure 10 *Density of stone mixture in the asphalt samples*
Slika 10. *Grafički prikaz gustoća kamene smjese asfaltnih uzoraka*

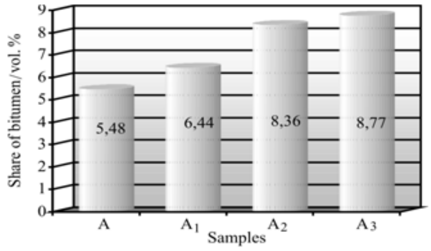

Figure 11 *Share of bitumen in the asphalt samples*
Slika 11. *Grafički prikaz obujamskog udjela bitumena u asfaltnim uzorcima*

Table 11 *Results of particle size distribution for asphalt samples A, A_1, A_2 and A_3*
Tablica 11. *Rezultati raspodjele veličina čestica za uzorke asfalta A, A_1, A_2 i A_3*

Sieve size, mm	0,09	0,25	0,71	2,0	4,0	8,0	11,2	16,0	22,4	31,5
Sample A Passing/mass %	7,1	11,2	19,4	36,2	52,9	80,8	97,6	99,8	100,0	100,0
Sample A_1 Passing/mas %	9,9	13,4	19,7	33,7	52,1	79,1	100,0	100,0	100,0	100,0
Sample A_2 Passing/mass %	7,2	12,8	21,4	36,9	54,7	82,0	97,8	99,9	100,0	100,0
Sample A_3 Passing/mass %	7,2	13,2	19,9	34,1	53,6	82,1	97,7	100,0	100,0	100,0

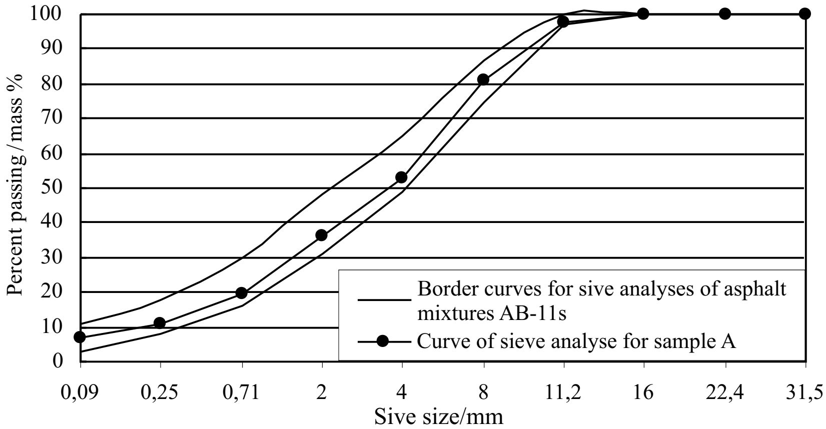

Figure 12 *Particle size distribution for control sample A, asphalt mixture AB-11s*
Slika 12. *Granulometrijski sastav kontrolnog uzorka A asfaltne mješavine AB-11s*

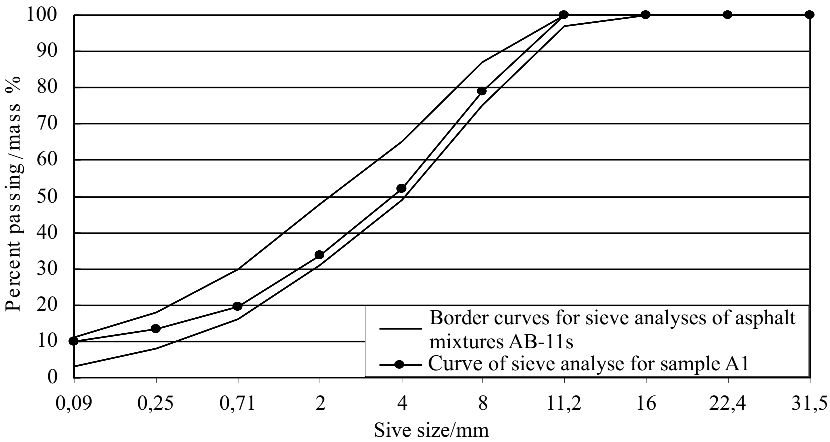

Figure 13 *Particle size distribution for sample A_1 of asphalt mixture AB-11s in which the fractions of the natural aggregates of 4-8 mm and 8-11 mm were replaced with blast furnace slag*
Slika 13. *Granulometrijski sastav uzorka A_1 asfaltne mješavine AB 11s kod kojeg su frakcije prirodnog agregata od 4-8 mm i 8-11 mm zamijenjene sa šljakom visoke peći*

From the obtained curves it is evident that the curves of the four samples are within the prescribed border area of asphalt mixture AB-11s.

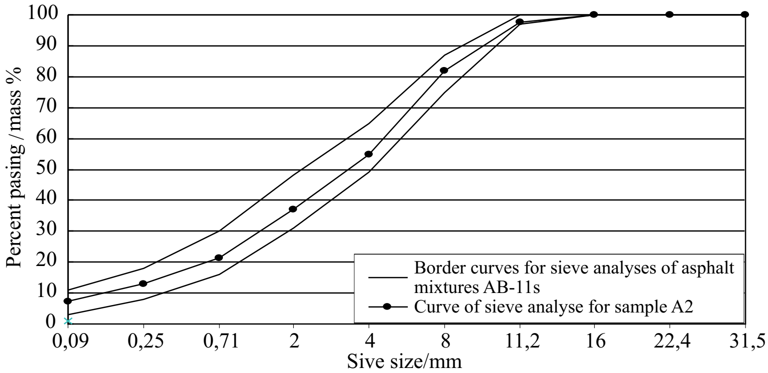

Figure 14 *Particle size distribution for sample A_2 asphalt mixture AB-11s*

Slika 14. *Granulometrijski sastav uzorka A_2 asfaltne mješavine AB-11s kod kojeg je kameno brašno zamijenjeno s amorfnom SiO_2 prašinom*

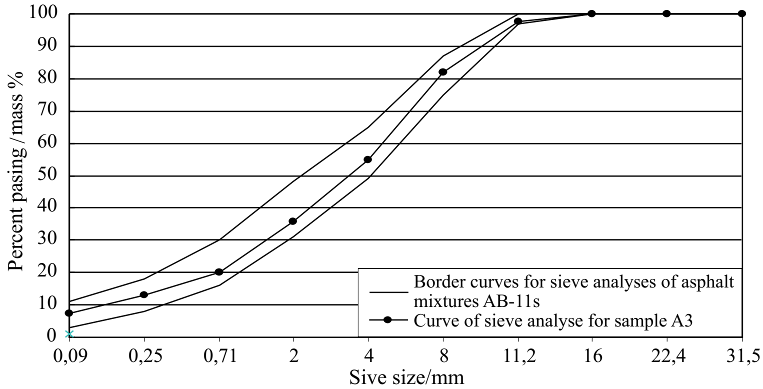

Figure 15 *Particle size distribution for sample A_3 asphalt mixture AB-11s*

Slika 15. *Granulometrijski sastav uzorka A_3 asfaltne mješavine AB-11s kod kojeg je kameno brašno zamijenjeno s elektrofiltarskim pepelom*

7 Conclusion
Zaključak

Based on testing the influence of waste materials: slag, fly ash and silica fume on the physical and mechanical properties of asphalt mixture AB 11s the following conclusion can be made:

- Aggregate and filler in asphalt mixture AB 11s can be replaced with waste materials: slag, fly ash and silica fume.
- Slag as aggregate in asphalt mixture AB 11s increases the density and stability of the mixture.
- The replacement of aggregates and fillers from waste materials can be achieved through saving in the production of asphalt mixtures AB 11s and contribute to environmental protection.

For a general conclusion it is necessary to perform further tests on other types of asphalt mixtures.

8 References
Literatura

[1] Dunster, A. M. The Use of Blast furnace Slag and Steel Slag as Aggregates. // Proceedings of the Fourth European Symposium on Performance of Bituminous and Hydraulic, Materials in Pavements, Nottingham, 2002., 257-260.

[2] Emery, J. J. Slag Utilization in Pavement Construction. // Extending Aggregate Resources, ASTM STP 774, American Society for Testing and Materials, 1982., 95-118.

[3] Lee, A. R. Slag for Roads – Its Production, Properties and Uses. // Journal of Institution of Highway Engineers, 16, 2(1968) 2-14.

[4] Lee, A. R. Blast Furnace and Steel Slag: Production, Properties and Uses. Halsted Press, New York,

[5] Rockliff, D.; Moffett, A.; Thomas, N. Recent Developments in the Use of Steel (BOS) Slag Aggregate in Asphalt Mixtures in the UK. // Proceedings of the Fourth European Symposium on Performance of Bituminous and Hydraulic Materials in Pavements, Nottingham, 2002., 251-255.

[6] Noureldin, A. S.; McDaniel, R. S. Performance Evaluation of Steel Furnace Slag – Natural Sand Asphalt Surface Mixtures. // Journal of the Association of Asphalt Paving Technologists, 68, (1990), 276-303.

[7] General technical conditions for work on foads, Croatian Civil Engineering Institute, Zagreb, Janka Rakuše 1, Zagreb 2001. Book III.

[8] HRN EN 12697-1:2007, Soluble binder content.

[9] HRN EN 12697-2:2003, Determination of particle size distribution.

[10] HRN EN 12697-6:2003, Determination of the bulk density bituminous specimens.

[11] HRN EN 12697-8:2003, Determination of void characteristics of bituminous specimens.

[12] HRN EN 12697-26:2004, Stiffness.

[13] HRN EN 12697-29:2003, Determination of the dimensions of a bituminous specimen.

[14] HRN EN 12697-30:2004, Specimen preparation by impact compactor.

[15] HRN EN 12697-34:2004, Marshall test.

Authors' addresses
Adresa autora

Dr. sc. Miroslav Mikoč, Associate Profesor
University of Josip Juraj Strossmayer in Osijek
Civil Engineering Faculty in Osijek
Crkvena 21, 31000 Osijek, Croatia
e-mail: mmikoc@gfos.hr

Dalibor Marković, student
Cestar d.o.o. Slavonski Brod
35000 Slavonski Brod
e-mail: cestar@cestarsb.hr