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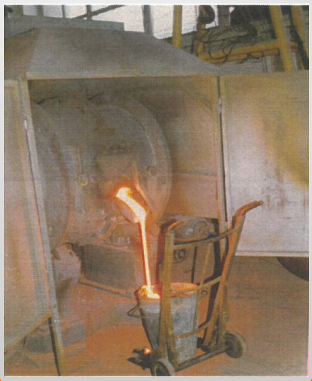

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Ksenija Đoković, Dragoslav Rakić**, Milenko Ljubojev****

ESTIMATION OF SOIL COMPACTION PARAMETERS BASED ON THE ATTERBERG LIMITS****

Abstract

This paper presents the relationship between the Atterberg limits and soil compaction parameters obtained by the correlation- regression analysis. The relations between the liquid limit w_l, plastic limit w_p, maximum dry density ρ_{dmax} and optimum moisture content w_{opt} are obtained on the basis of the results of laboratory tests measured on a large number of samples of clay core earthfill dams Rovni, Selova, Prvonek and Barje. The regression and correlation analysis were obtained empirical equations and diagrams. Based on the obtained, the value of the optimum moisture content and maximum dry density of knowing the Atterberg limits of plasticity can be estimated.

Keywords: *compaction parameters, maximum dry density, optimum moisture content, Atterberg limits, liquid limit, plastic limits, regression analysis*

1 INTRODUCTION

When making earthfill dams, the earth embankments and some other earthen structures in general, basically the problem is to define conditions of embedding material, and optimum conditions of compaction. Embedding, i.e. suitability of materials for building in and behavior of materials during compaction depends on geomechanical properties of materials. Some materials, such as sandy gravel is easier to compact, while in clay, especially clay of high plasticity, it is not [3]. Difficulties in the compaction of clayey material are closely related to the state of consistency index, where there is a dependency relationship of natural water content, plastic limit and liquid limits. This paper presents the relationship between the Atterberg limits (w_l, w_p), plasticity index (I_p) and soil compaction parameters (ρ_{dmax} and w_{opt}) obtained by the standard laboratory tests (SRPS U.B1.020:1980, SRPS U.B1. 038:1997).

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**** *The results shown in this paper are obtained as a part of the investigations conducted within the scope of the Project TR 36014 - Geotechnical Aspects of the Research and Development of Modern Technologies for the Construction and Rehabilitation of Municipal Solid Waste Landfills, funded by the Ministry of Education, Science and Technological Development of the Republic of Serbia.*

These dependencies were the subject of many previous studies. The first correlation relationship between the liquid limit, plastic limit and the optimum moisture content was established Jumikis (1946). Ring et al. (1962), in addition to the Atterberg limits in correlation, included the average particle diameter and percentage of fine grained particles [16]. Al - Khafaji (1993) gave a correlation equation for maximum dry density and optimum moisture content, based on liquid limits and plastic limits, for four sites in Iraq, compared to the correlation equations obtained for the soil in the U.S. (Ingles and Metcalf, 1972). In addition, he has developed the correlation diagrams that have a practical application in the estimation of compaction parameters [1]. Pandian et al. (1997) proposed a series of predicted curves of soil compaction using the liquid limit and plastic limits. They also gave the special equations for so-called wet and dry parts of the curve compaction [12]. Blotz et al. (1998) also proposed two equations for estimation the compaction parameters of soil using the liquid limit for different compaction effort: standard and modified [2]. Sridharan and Nagaraj (2005) proposed two empirical equations for estimation the parameters of compaction using only plastic limits [19]. In contrast to them, Matteo (2009) and Noor (2011) gave the predictive models for estimation the compaction parameters of fine grained soils for the Standard Proctor test, based on the plastic limit, plasticity index and specific gravity of soils ρ_s [10,11]. In recent years, in predicting the compaction parameters based on Atterberg limits, the method of artifical neural networks was used [8,9].

In this paper, the relations between the liquid limit w_l, the plastic limit w_p, maximum dry density ρ_{dmax} and optimum moisture content w_{opt} are obtained on the basis of the results of laboratory tests measured on representative samples of clay from the core earthfill dams Rovni, Selova, Prvonek and Barje [4,5,6,7]. The correlation and regression analysis was applied to define the statistical model using MS Excel (Analysis ToolPak), where the empirical equations and diagrams were obtained.

As indicators of relationship degree, i.e. correlation between the analyzed variables, the followings were used: r - coefficient of simple linear correlation (Pearson coefficient), R^2 - coefficient of determination and p - value which expresses the statistical significance of correlation i.e. level of significance [13]. Although simple linear regression models were obtained with a significant value to the strong coefficient of correlation ($0.73 < r < 0.85$) and the coefficient of determination R^2 ($0.53 < R^2 < 073$) and satisfying p-value ($p < 0.05$), the analysis is extended using the multiple linear regression, the introduction of calculation at the same time both w_l and w_p.

2 RESULTS OF GEOMECHANICAL LABORATORY TESTING

Geotechnical laboratory testing of samples of clay were carried out during the geomechanical control of earthfill dams. Since a large number of samples, tested for statistical analysis, were selected, 72 representative samples were taken from the embedded core layer of earthfill dams in various stages of filling.

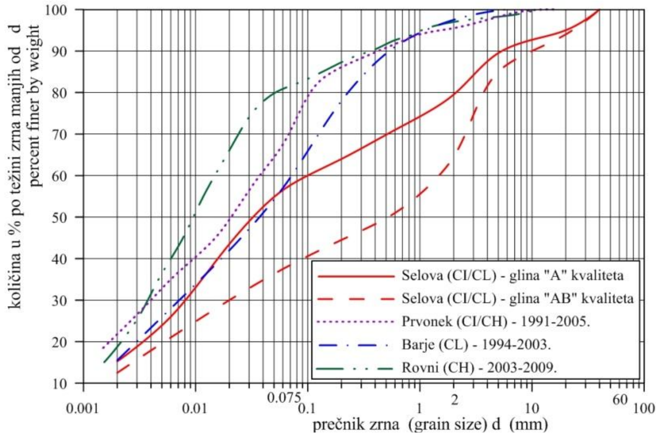


Figure 1 *Average grain size distribution curves of tested clayey material*

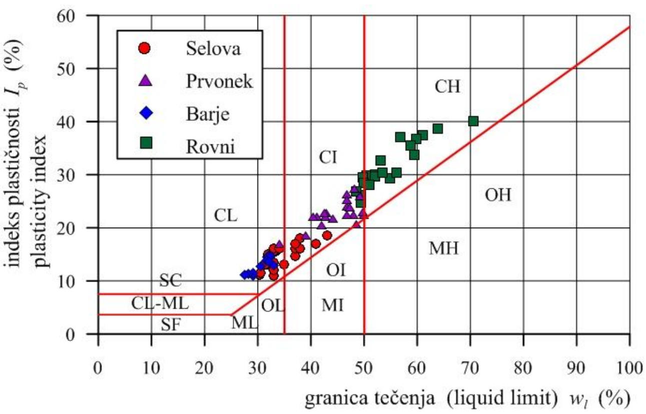


Figure 2 *Diagram of plasticity the tested clayey material*

Figure 1 shows the average particle size distribution curve, and Figure 2 shows a diagram of plasticity the tested materials from the clay core of earthfill dams Selova, Prvonek, Barje and Rovni.

According to the generally accepted classification of soil (SRPS U.B1. 001: 1990), based on the identification-classification experiments: the grain-size distribution and Atterberg limits of tested material present:

- Low plasticity sandy clays embedded in the core earthfill dam Barje - CL.
- Medium to high plasticity silty clay, CI/CH, which originate from the core Prvonek earthfill dam,
- High plasticity silty clay CH from the core earthfill dam Rovni
- Clays embedded in the core earthfill dam Selova are sandy silty, medium to low plasticity CI-CL.

To determine maximum dry density and optimum moisture content of materials, the laboratory experiments were carried out by the standard Proctor compaction procedure (standard compaction energy E = 592 kJ/m^3). The obtained results are shown in diagram in Figure 3.

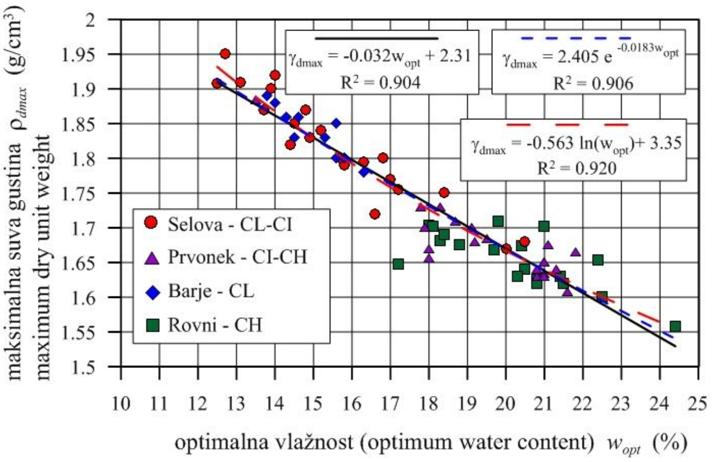


Figure 3 *Diagram of relationship between maximum dry density and optimum moisture content of clayey soil*

Furthermore, the mathematical relationship between ρ_{dmax} and w_{opt} is presented in Figure 3.

3 STATISTICAL ANALYSIS AND DEFINING THE MODEL

Regression analysis is statistical tool that is used to define the analytical - mathematical models, i.e. functions between the independent (x) and dependent (y) variables. Strength of dependence between variables is determined using the correlation analysis [13]. Discussion and interpretations model is based on the coefficient of correlation r and coefficient of determination R^2.

Value of coefficient of determination - R^2 indicates the representativeness of the model. The model is more representative of R^2 which is closer to one. The linear coefficient of correlation r is a measure of correlation strength between variables x and y. According to Vukadinovic, if $r \leq 0:30$ there was no significant correlation, if $0.5 < r < 0.7$ correlation is significant, when $0.7 < R < 0.9$ correlation is strong, in the case where $r > 0.9$ very strong correlation [20]. So if the correlation coefficient was closer to one, the correlation was stronger.

The statistical significance of the model is defined using p - value or significance level p. If $p < 0.05$, $p < 0.01$ or $p < 0.1$ is acceptable to the model and the safety of $P > 95\%$, $P > 99\%$, or $P > 90\%$. In the case where $p > 0.05$ correlation was not significant, and then regardless of the value coefficient of correlation, a model should not be accepted and interpreted.

Although simple linear regression models, obtained (according to Vukadinovic, 1990) with the strong correlation coefficient values ($0.73 < r < 0.85$) and the coefficient of determination R^2 ($0.53 < R^2 < 073$) and satisfying p-value ($p < 0.05$), the analysis is extended using the multiple linear regression.

According to the method of Multiple Linear Regression – MLR, the evaluation of required variable is obtained on the basis of simultaneous use of a number of other independent variables. As for the parameters of soil density (maximum dry density ρ_{dmax} and optimum moisture w_{opt}), six independent variables can be used in order to establish the most accurate according to their determination, as follows: E - energy compaction, G - percentage of gravel fractions, S - percentage of sand fraction, SF - percentage of fine fraction (clay and silt), w_l –liquid limit, w_p - limits of plasticity and I_p – plasticity index. According to Sivrakaya (2013), equation is as follows [17,18].

$$[\omega_{opt}, \rho_{dmax}] = f(E, G, S, FC, I_p, \omega_i, \omega_p) \quad (1)$$

The work has also introduced into equation both liquid limit (w_l) and plastic limits (w_p) simultaneously.

The relationship between liquid limit and compaction parameters

The first step analyzed the influence of w_l (independent variable) on the compaction parameters ρ_{dmax} and w_{opt} as dependent variables. Where the following equations were obtained:

$$\rho_{dmax} = 2.088-0.008w_l$$

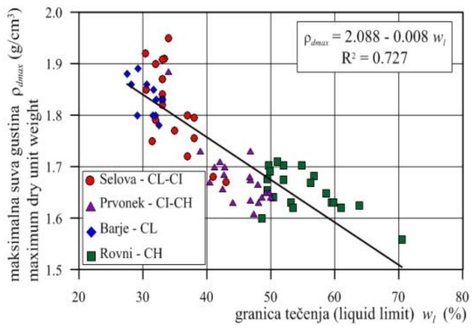
$$r = 0.85,\ R^2=0.73,\ p<0.05 \quad (2)$$

$$w_{opt} = 0.239w_l+7.757$$

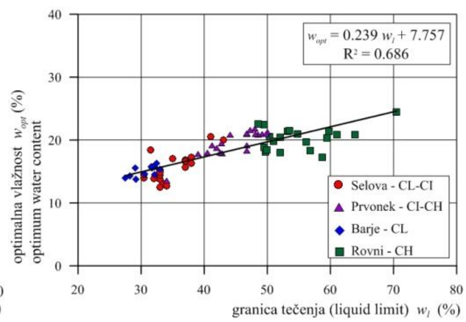
$$r = 0.83,\ R^2=0.69,\ p<0.05 \quad (3)$$

Correlation between ρ_{dmax} and w_l is a negative linear correlation (Fig. 4a) with high coefficient of correlation r and satisfactory p-value (p <0.05).

Correlation between w_{opt} and w_l is a positive linear correlation (Figure 4b) with slightly lower coefficient of correlation r, and satisfactory p-value (p <0.05).



(a) $\rho_{dmax}=f(w_l)$



(b) $w_{opt}= f(w_l)$

Figure 4 *Diagrams of relationship between the liquid limit and compaction parameters*

The relationship between the plastic limit and compaction parameters

The second step analyzes the influence of w_p (independent variable) on the compaction parameters ρ_{dmax} and w_{opt} as dependent variables. The following equations were obtained:

$$\rho_{dmax} = 2.229-0.023w_p$$

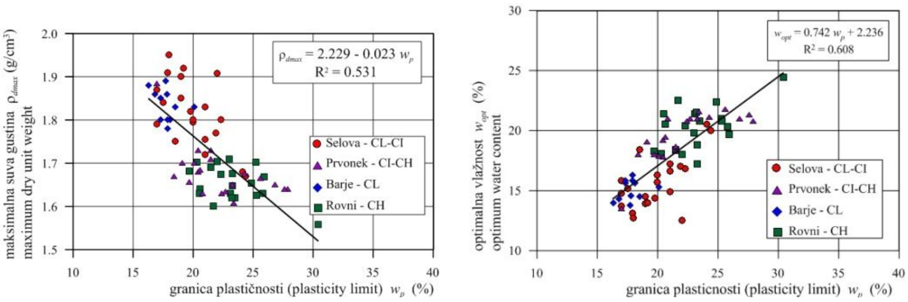
$$r = 0.73,\ R^2=0.53,\ p<0.05 \quad (4)$$

$$w_{opt} = 0.742w_p+2.236$$

$$r = 0.78,\ R^2=0.61,\ p<0.05 \quad (5)$$

Correlation between ρ_{dmax} and w_p is a negative linear correlation (Fig. 5a) with a strong coefficient of correlation (Vukadinovic, 1990) and satisfactory p-value (p <0.05).

Correlation between w_{opt} and w_l is a positive linear correlation (Fig. 5b) with slightly higher coefficient of correlation, and satisfactory p-value p <0.05).



(a) $\rho_{dmax}=f(w_p)$ (b) $w_{opt}= f(w_p)$

Figure 5 *Diagrams of relationship between the plastic limit and compaction parameters*

The relationship between the plasticity index and compaction parameters

The third step analyzes the influence of plasticity index I_p (independent variable) on parameters of density ρ_{dmax} and w_{opt} as dependent variables. As per definition, the plasticity index is the difference of liquid limit and plastic limit; it was interesting to analyze this effect. The following equations were obtained:

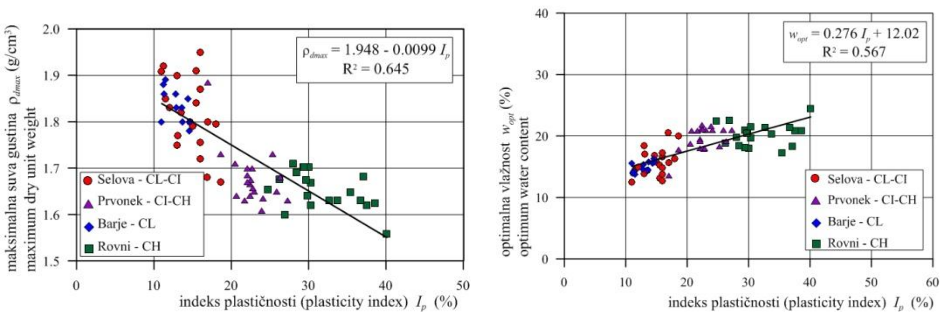
$\rho_{dmax} = 1.948\text{-}0.0099\ I_p$

$r = 0.78,\ R^2=0.65,\ p<0.05$ (6)

$w_{opt} = 0.276\ I_p+12.02$

$r = 0.73,\ R^2=0.57,\ p<0.05$ (7)

The relationship between ρ_{dmax} and I_p is a negative linear correlation (Fig. 6a) with strong coefficient of correlation r and satisfactory p-value (p <0.05).



(a) $\rho_{dmax}=f(I_p)$ (b) $w_{opt}= f(I_p)$

Figure 6 *Diagrams of relationship between the plasticity index and compaction parameters*

Correlation between w_{opt} and I_p is a positive linear correlation (Fig. 6b) with strong coefficient of correlation r, and satisfactory p-value (p <0.05).

In the fourth step, the analysis is extended using the method of multiple linear regression, introducing both w_l and w_p m into equation.

$\rho_{dmax} = 2.14\text{-}0.007w_l\text{-}0.005w_p$

$r = 0.86, R^2=0.73, p<0.05$ (8)

$w_{opt} = 4.18+0.16w_l+0.323w_p$

$r = 0{,}86, R^2=0{,}73, p<0{,}05$ (9)

The relation obtained for ρ_{dmax} negative linear correlation with a strong coefficient of correlation r = 0.86 and satisfactory p-value (p <0.05).

Correlation obtained for w_{opt} is a positive linear correlation with strong coefficient of correlation r = 0.86, and satisfactory p-value (p <0.05).

It is seen analyzing the obtained equations that optimum moisture increases until maximum dry density decreases with increasing plastic properties of the soil. The equation obtained for optimum moisture content w_{opt} has stronger correlation with plastic limit w_p, compared to the liquid limit w_l and plasticity index I_p. However, the equations derived to calculate maximum dry density ρ_{dmax} show stronger correlation relationship (higher coefficient of correlation) with the liquid limit w_l and plasticity index I_p.

Model extended the application of the Multiple Linear Regression, introducing into the equation both w_l and w_p giving the highest correlation coefficient r =0.86 and the coefficient of determination R^2 =0.73.

In addition to the linear regression, the logarithmic and exponential equations were also analyzed, but the best results with the highest coefficient of determination were given by linear equation. The linear correlation is far away from a practical point of view of the most acceptable.

CONCLUSION

Application of correlation - regression analysis was obtained by statistical models that define the relationship between the Atterberg limits: liquid limit w_l, the plastic limit w_p, plasticity index I_p and and soil compaction parameters: maximum dry density ρ_{dmax} and optimum moisture content w_{opt}. Statistical analysis was carried out at 72 representative sample derived from the core of the earth dams Rovni, Selova, Prvonek and Barje. The test materials are of low to high plastic clay. For the shown statistical models, there was strong linear correlation with strong coefficient of correlation r and satisfactory p - value. As between the considered variables there are essential connections between (physical- mechanical properties of the soil), and analysis was carried out, the sufficient number of data were obtained with high degree of reliability on representative samples; the resulting models can be used to estimate the parameters compaction in the preliminary stages of the project, or preliminary assessment of suitability of any material from borrow pits controlling the quality of the earthfill structures.

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Ksenija Đoković[*], Dragoslav Rakić[**], Milenko Ljubojev[***]

PROCENA PARAMETARA ZBIJANOSTI TLA NA OSNOVU ATTERBERGOVIH GRANICA KONZISTENCIJE[****]

Izvod

U radu je dat prikaz veze između Atterbergovih granica konzistencije i parametara zbijenosti tla dobijenih korelaciono-regresionom analizom. Veze između granice tečenja w_l, granice plastičnosti w_p, maksimalne suve gustine ρ_{dmax} i optimalne vlažnosti w_{opt} su dobijene na osnovu rezultata laboratorijskih ispitivanja sprovedenim na velikom broju uzoraka iz glinenog jezgra nasutih brana: Rovni, Selova, Prvonek i Barje. Primenom regresione i korelacione analize dobijene su empirijske jednačine i dijagrami. Na osnovu dobijenih jednačina moguće je proceniti vrednosti optimalne vlažnosti i maksimalne suve gustine poznavanjem Aterbergovih granica plastičnosti.

Ključne reči: *parametri zbijenosti, maksimalna suva gustina, optimalna vlažnost, granica tečenja, granica plastičnosti, regresiona analiza*

1. UVOD

Prilikom izrade nasutih brana, nasipa i nasutih objekata uopšte, osnovni problem predstavlja definisanje uslova ugrađivanja materijala, odnosno optimalnih uslova zbijanja. Ugradljivost tj. pogodnost materijala za ugradnju i ponašanje materijala prilikom zbijanja zavisi od geomehaničkih svojstava materijala. Pojedini materijali kao npr. peskoviti šljunkovi lakše se zbijaju, dok kod glina, posebno visokoplastičnih to nije slučaj [3]. Teškoće pri zbijanju glinovitih materijala usko su vezane za stanje konzistencije, pri čemu postoji zavisnost odnosa i prirodne vlažnosti, granice plastičnosti granice tečenja. U radu je dat prikaz zavisnosti između Atterbergovih granica konzistencije (w_l, w_p), indeksa plastičnosti (I_p) i parametara zbijenosti tla (ρ_{dmax} i w_{opt}), dobijenih standardnim laboratorijskim opitima (SRPS U.B1.020:1980, SRPS U.B1. 038:1997).

Ove zavisnosti bile su predmet mnogih ranijih istraživanja. Prvu korelacionu zavisnost između granice tečenja, granice plastičnosti i optimalne vlažnosti, uspostavio je Jumikis (1946). Ring i dr. (1962) su pored

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[****] *U radu su prikazani rezultati koji su deo istraživanja na projektu TR 36014 - Geotehnički aspekti istraživanja i razvoja savremenih tehnologija građenja i sanacija deponija komunalnog otpada, koje finansira Ministarstvo prosvete, nauke i tehnološkog razvoja R. Srbije.*

Aterbergovih granica konzistencije u korelaciju uključili i prosečnu veličinu (prečnik i procentualno učešće finozrnih čestica [16]. Al-Khafaji (1993) je dao jednačine korelacije za maksimalnu suvu gustinu i optimalnu vlažnost na osnovu granice tečenja i granice plastičnosti, za četiri lokacije u Iraku, poredivši ih sa korelacionim jednačinama koje su dobijene za tla u SAD (Ingles i Metcalf 1972). Pored toga, on je izradio i dijagrame zavisnosti koji imaju svoju praktičnu primenu prilikom procene parametara zbijenosti [1]. Pandian i dr. (1997) su predložili procenu zbijenosti tla preko serija krivih na osnovu granice tečenja i granice plastičnosti. Takođe, su dali i posebne jednačine za tzv. mokri i suvi deo krive zbijenosti [12]. Blotz i dr.(1998) su predložili dve jednačine za procenu parametara zbijenosti tla na osnovu granice tečenja ali za različite energije zbijanja: standardnu i modifikovanu [2]. Sridharan i Nagaraj (2005) su predložili dve empirijske jednačine za procenu parametara zbijanja korišćenjem samo granice plastičnosti [19]. Za razliku od njih, Matteo (2009) i Noor (2011) su dali korelacione modele procene parametara zbijenosti za sitnozrna tla za standardni Proctorov opit na osnovu granice plastičnosti, indeksa plastičnosti i gustine čvrstih čestica tla (ρ_s) [10,11]. Poslednjih godina za uspostavljanje zavisnosti Aterbergovih granica konzistencije i parametara zbijenosti tla koriste se neuronske mreže [8,9].

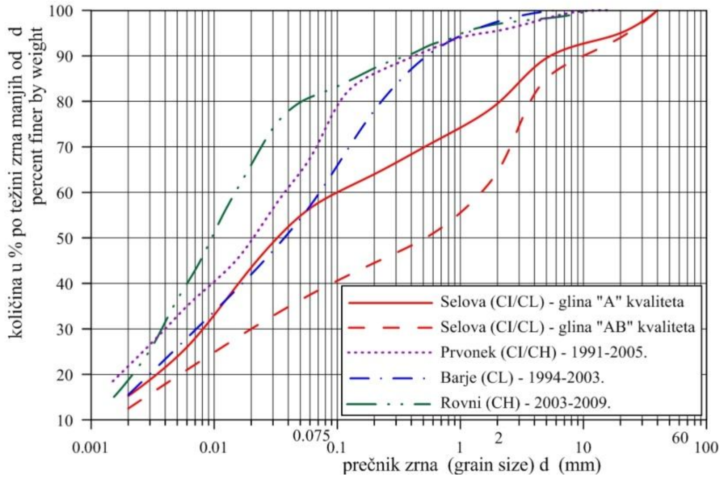
U ovome radu veze između granice tečenja w_l, granice plastičnosti w_p, indeksa plastičnosti I_p i maksimalne suve gustine ρ_{dmax} i optimalne vlažnosti w_{opt}, su dobijene na osnovu rezultata laboratorijskih ispitivanja sprovedenim na reprezentativnim uzorcima gline iz jegra nasutih brana: Rovni, Selova, Prvonek i Barje [4,5,6,7]. Za definisanje statističkog modela primenjena je korelaciono - regresiona analiza sprovedena pomoću MS Excel programa (Analysis ToolPak) pri čemu su dobijene empirijske jednačine i dijagrami.

Kao pokazatelji stepena zavisnosti - korelacije između analiziranih promenljivih korišćeni su: r - koeficijent proste linearne korelacije (Pearsonov koeficijent), R^2 - koeficijent determinacije i p - statistička značajnost korelacije odnosno prag značajnosti [13]. Iako su prostom linearnom regresijom dobijeni modeli sa značajnim vrednostima koeficijenta korelacije r ($0,73 < r < 0,85$) i koeficijenta determinacije R^2 ($0,53 < R^2 < 0,73$) i zadovoljavajućim pragom značajnosti p ($p < 0,05$), analiza je proširena metodom višestruke linearne regresije, uvođenjem u proračun istovremeno i granicu tečenje w_l i granicu plastičnosti w_p.

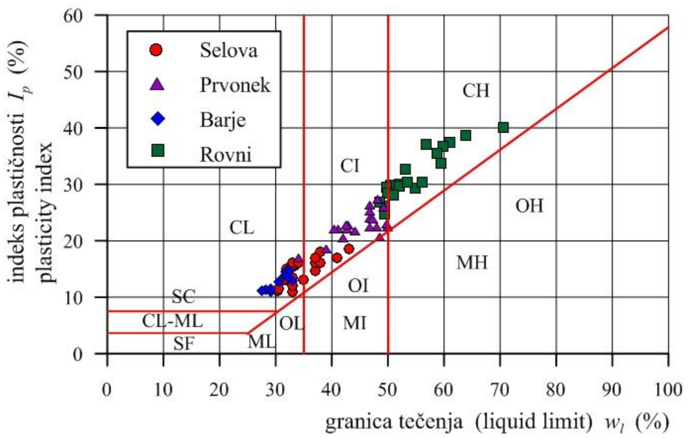
2. REZULTATI LABORATORIJSKIH GEOMEHANIČKIH ISPITIVANJA

Laboratorijska geomehanička ispitivanja uzoraka gline vršena su prilikom geomehaničke kontrole nasutih brana. Od velikog broja ispitanih uzoraka za statističku analizu je odabrano 72 uzorka koji predstavljaju reprezentativne uzorke uzete iz ugrađenih slojeva jezgra nasutih brana za različite faze nasipanja.

Na slici 1. su prikazane prosečne krive granulometrijskog sastava, a na slici 2. dijagram plastičnosti za ispitivane materijale glinenog jezga nasutih brana: Selova, Prvonek, Barje i Rovni.



Sl. 1. *Prosečne granulometrijske krive ispitivanih glinovitih materijala*

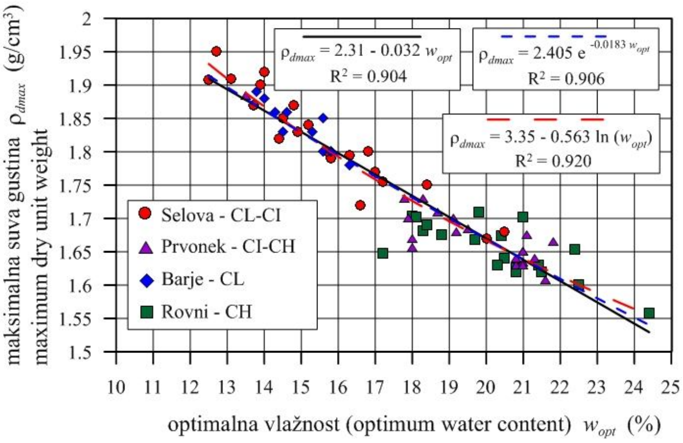


Sl. 2. *Dijagram plastičnosti ispitivanih glinovitih materijala*

Prema opštoj klasifikacija tla (SRPS U.B1.001:1990), a na osnovu identifikaciono-klasifikacionih opita: granulometrijskog sastava i Atterbergovih granica konzistencije, ispitivani materijali predstavljaju:

- niskoplastične peskovite gline ugrađene u jezgro nasute brane Barje - CL,
- srednje do visokoplastične prašinaste gline CI-CH koje potiču iz jezgra nasute brane Prvonek,
- visokoplastične gline CH iz jezgra nasute brane Rovni,
- gline ugrađene u jezgro nasute brane Selova su peskovito prašinaste, srednje do niske plastičnosti CI-CL.

Za određivanje maksimalne suve gustine i optimalne vlažnosti ugrađenih materijala, urađeni su laboratorijski opiti zbijanja po standardnom Proctor-ovom postupku (standardna energija zbijanja E = 592 kJ/m^3). Dobijeni rezultati su prikazani na dijagramu na slici 3.



Sl. 3. *Dijagram zavisnosti maksimalne suve gustine i optimalne vlažnosti glinovitih tla*

Pored toga, na slici 3. prikazana je i matematičkih zavisnosti između ρ_{dmax} i w_{opt}.

3. STATISTIČKA ANALIZA I DEFINISANJE MODELA

Regresiona analiza je statistički alat koji se koristi za definisanje analitičko-matematičkog modela tj. funkcije između nezavisnih (x) i zavisnih (y) promenljivih. Jačina zavisnosti između promenljivih određuje se korelacionom analizom [13]. Diskusija i interpretacija modela zasniva se na koeficijentu korelacije r i koeficijentu determinacije R^2.

Veličina koeficijenta determinacije R^2 govori o reprezentativnosti modela. Model je reprezentativniji što je R^2 bliže jedinici. Koeficijent linearne korelacije r je mera jačine korelacije između promenljivih x i y. Prema Vukadinoviću ukoliko je $r \leq 0,30$ nema značajne korelacije, ako je $0,5 < r < 0,7$ korelacija je značajna, kada je $0,7 < r < 0,9$ korelacija je jaka, a u slučaju kada je $r > 0,9$ vrlo jaka korelacija [20]. Dakle, što je koeficijent korelacije bliži jedinici korelaciona veza je jača.

Statistička značajnost modela definiše se pragom značajnosti p. Ukoliko je $p < 0,05$, $p < 0,01$ ili $p < 0,1$ model je prihvatljiv sa i sigurnošću od $P > 95\%$, $P > 99\%$ ili $P > 90\%$. U ovoj analizi usvojen je prag značajnosti od $p < 0,05$. U slučaju kada je $p > 0,05$ korelacija nije značajna i tada se bez obzira na vrednost koeficijenta korelacije model ne sme prihvatiti i tumačiti.

Iako su prostom linearnom regresijom dobijeni modeli (prema Vukadinoviću, 1990) sa jakim vrednostima koeficijenta korelacije r ($0,73<r<0,85$) i koeficijenta determinacije R^2 ($0,53<R<0,73$) i zadovoljavajućim pragom značajnosti p ($p<0,05$), analiza je proširena primenom metode višestruke linearne regresije.

Prema metodi višestruke linearne regresije - MLR (Multiple Linear Regression) procena tražene promenljive dobija se na osnovu istovremenog korišćenja nekoliko drugih varijabilnih promenljivih. Kada su u pitanju parametri zbijenosti tla (maksimalna suva gustina ρ_{dmax} i optimalna vlažnost w_{opt}), može se koristi sedam nezavisnih promenljivih kako bi se uspostavile najpreciznije zavisnosti za njihovo određivanje, i to: E - energija zbijanja, G - procentualno učešće šljunkovitih frakcija, S - procentualno učešće peskovitih frakcija, SF - procentualni sadržaj finih frakcija (gline i prašine), w_l - granica tečenja, w_p - granica plastičnosti i I_p

- indeks plastičnosti. Prema Sivrakaya-u (2013) jednačina glasi [17,18].

$$[\omega_{opt}, \rho_{dmax}] = f(E, G, S, FC, I_p, \omega_i, \omega_p) \quad (1)$$

U radu su istovremeno u jednačinu uvedene granica tečenja (w_l) i granica plastičnosti (w_p).

Zavisnost između granice tečenja i parametara zbijenosti

U prvom koraku analiziran je uticaj w_l (nezavisna promenljiva) na parametre zbijenosti ρ_{dmax} i w_{opt} kao zavisnih promenljivih. Pri čemu su dobijene jednačine:

$\rho_{dmax} = 2.088 - 0.008 w_l$

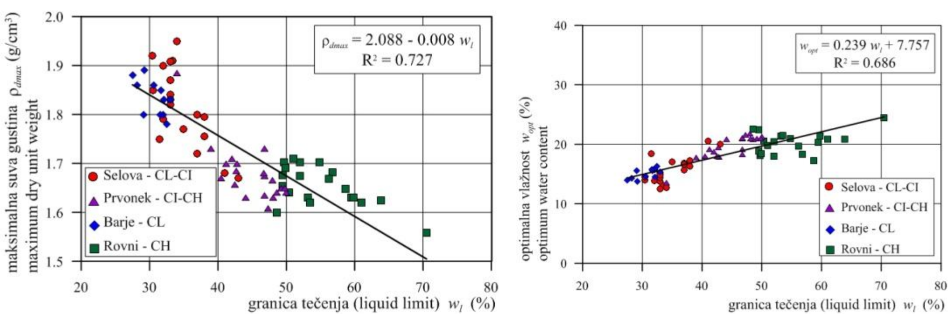
$r = 0.85$, $R^2 = 0.73$, $p < 0.05$ (2)

$w_{opt} = 0.239 w_l + 7.757$

$r = 0.83$, $R^2 = 0.69$, $p < 0.05$ (3)

Korelacija između ρ_{dmax} i w_l je negativna linearna korelacija (Slika 4a) sa visokim koeficijentom korelacije r i zadovoljavajućim pragom značajnosti ($p < 0.05$).

Korelacija između w_{opt} i w_l je pozitivna linearna korelacija (Slika 4b) sa neznatno nižim koeficijentom korelacije r, i zadovoljavajućim pragom značajnosti ($p < 0.05$).



(a) $\rho_{dmax}=f(w_l)$ (b) $w_{opt}= f(w_l)$

Sl. 4. *Dijagrami zavisnost između granice tečenja i parametara zbijenosti*

Zavisnost između granice plastičnosti i parametara zbijenosti

U drugom koraku analiziran je uticaj w_p (nezavisna promenljiva) na parametre zbijenosti ρ_{dmax} i w_{opt} kao zavisnih promenljivih. Pri čemu su dobijene jednačine:

$\rho_{dmax} = 2.229 - 0.023 w_p$

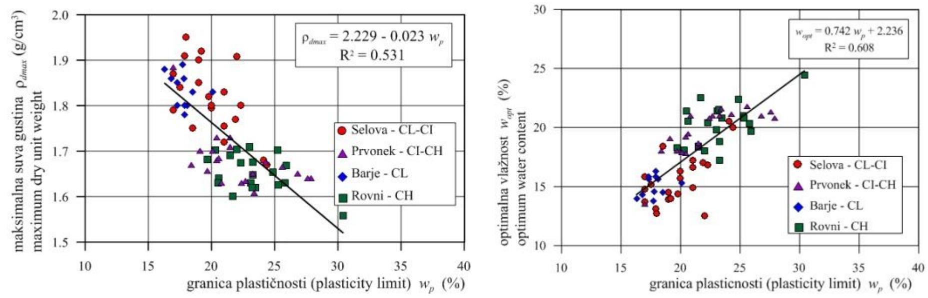
$r = 0.73$, $R^2 = 0.53$, $p < 0.05$ (4)

$w_{opt} = 0.742 w_p + 2.236$

$r = 0.78$, $R^2 = 0.61$, $p < 0.05$ (5)

Korelacija između ρ_{dmax} i w_p je negativna linearna korelacija (Slika 5a) sa jakim koeficijentom korelacije (Vukadinović, 1990) i zadovoljavajućim pragom značajnosti ($p < 0,05$).

Korelacija između w_{opt} i w_l je pozitivna linerana korelacija (Slika 5b) sa neznatno višim koeficijentom korelacije, i zadovoljavajućim pragom značajnosti ($p<0.05$).



(a) $\rho_{dmax}=f(w_p)$ (b) $w_{opt}= f(w_p)$

Sl. 5. *Dijagrami zavisnost između granice plastičnosti i parametara zbijenosti*

Zavisnost između indeksa plastičnosti i parametara zbijenosti

U trećem koraku analiziran je uticaj I_p (nezavisna promenljiva) na parametre zbijenosti ρ_{dmax} i w_{opt} kao zavisne promenljive. Kako po definiciji indeks plastičnosti predstavlja razliku granice tečenje i granice plastičnosti bilo je interesantno analizirati i ovaj uticaj. Dobijene su sledeće jednačine:

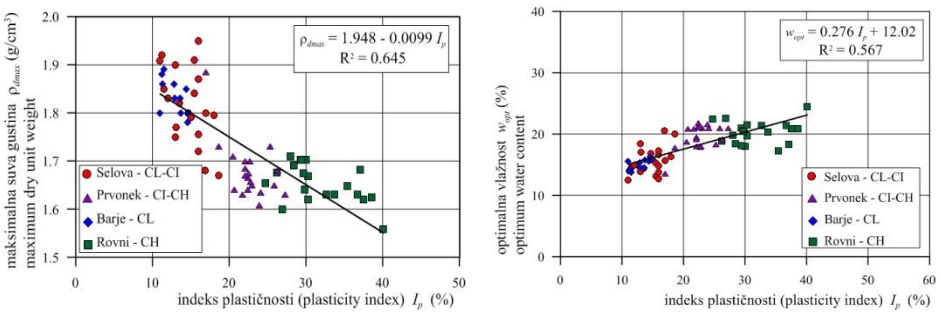
$\rho_{dmax} = 1.948\text{-}0.0099\ I_p$

r = 0.78, R^2=0.65, $p<0.05$ (6)

$w_{opt} = 0.276\ I_p+12.02$

r = 0.73, R^2=0.57, $p<0.05$ (7)

Relacija između ρ_{dmax} i I_p je negativna linearna korelacija (Slika 6a) sa jakim koeficijentom korelacije i zadovoljavajućim pragom značajnosti ($p<0.05$).



(a) $\rho_{dmax}=f(I_p)$ (b) $w_{opt}= f(I_p)$

Sl. 6. *Dijagrami zavisnost između indeksa plastičnosti i parametara zbijenosti*

Korelacija između w_{opt} i I_p je pozitivna linearna korelacija (Slika 6b) sa jakim koeficijentom korelacije, i zadovoljavajućim pragom značajnosti ($p<0.05$).

U četvrtom koraku analiza je proširena primenom metode višestruke linearne regresije, uvođenjem u jednačinu istovremeno i granice tečenja w_l i granice plastičnosti w_p.

$\rho_{dmax} = 2.14\text{-}0.007w_l\text{-}0.005w_p$

r = 0.86, R^2=0.73, $p<0.05$ (8)

$w_{opt} = 4.18+0.16w_l+0.323w_p$

$r = 0,86$, $R^2=0,73$, $p<0,05$ (9)

Relacija dobijena za ρ_{dmax} je negativna linearna korelacija sa jakim koeficijentom korelacije r = 0,86 i zadovoljavajućim pragom značajnosti ($p < 0,05$).

Korelacija dobijena za w_{opt} je pozitivna linearna korelacija sa jakim koeficijentom korelacije r = 0,86, i zadovoljavajućim pragom značajnosti ($p < 0,05$).

Analizom dobijenih jednačina uočavamo da optimalna vlažnost raste dok maksimalna suva gustina se smanjuje sa porastom plastičnih svojstava tla. Jednačina dobijena za optimalnu vlažnost w_{opt} ima jaču korelaciju sa granicom plastičnosti w_p u poređenju sa granicom tečenja w_l i indeksom plastičnosti I_p. Međutim, jednačine dobijene za izračunavanje maksimalne suve gustine ρ_{dmax}, pokazuju jaču korelacionu vezu (viši koeficijen korelacije) sa granicom tečenja w_l i indeksom plastičnosti I_p.

Model proširena primenom metode višestruke linearne regresije, uvođenjem u jednačinu istovremeno i w_l i w_p daje najviši koeficijent korelacije r = 0,86 i koeficijent determinacije $R^2=0,73$.

Pored linearne regresije analizirane su još i logaritamska i eksponencijalna jednačina, ali je daleko najbolje rezultate sa najvećim koeficijentom determinacije dala linearna jednačina. S obzirom na to, a i zbog praktičnih razloga, može se reći da je linearna zavisnost najprihvatljivija.

ZAKLJUČAK

Primenom korelaciono - regresione analize dobijeni su statistički modeli kojima se definiše zavisnost između Atterbergovih granica konzistencije: granice plastičnosti w_l, granice tečenja w_p, indeksa plastičnosti I_p i parametara zbijnosti tla: optimalne vlažnosti w_{opt} i maksimalne suve gustine ρ_{dmax}. Statistička analiza sprovedena je na ukupno 72 reprezenativna uzorka koji potiču iz jezgra nasutih brana: Rovni, Selova, Prvonek i Barje. Ispitivani materijali predstavljaju nisko do visoko plastične gline. Za prikazane statističke modele postoji jaka linearna korelaciona veza sa jakim koeficijentom korelacije r i zadovoljavajućim pragom značajnosti p. Kako između razmatranih promenljivih postoji i suštinska poveznost (fizičko-mehanička svojstva tla), i analiza je sprovedena na dovoljnom broju podataka koji su dobijeni sa visokim stepenom pouzdanosti na reprezentativnim uzorcima, dobijeni modeli se mogu primenjivati za procenu parametara zbijenosti u fazama idejnog projekta, ili za preliminarnu procenu pogodnosti materijala za nasipanje iz pozajmišta, kod kontrolisanja kvaliteta na nasutim objektima.

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EFFECT OF DISPLACEMENT THE FLOTATION DAM 2 ON THE ROUTE OF FUTURE COLLECTOR OF THE KRIVELJ RIVER, TESTED USING THE SOFTWARE PHASE2 v8.0[**]

Abstract

The need to expand the capacity of the flotation Field I is necessary due to increase the capacity of the Flotation Plant Veliki Krivelj. Based on the geotechnical data from previous investigations and as a proposal for displacement the existing Dam 2 to increase the capacity of the flotation Field 1, an analysis the effect of flotation and rock mass on the route of the new Krivelj River collector was carried out using the software package Phase 2.

Keywords: *stress condition, flotation dam, Krivelj River's collector, software Phase 2*

1 INTRODUCTION

Due to the increased production volume at the open pit Veliki Krivelj, the amount of flotation tailings increased that has to be disposed. The existing flotation tailing dump becomes small by the capacity to receive the new quantities of material. Due to this reason, it is necessary to find a technical-technological solution that is transient and should allow the smooth operation of the Flotation plant Veliki Krivelj for the period of 3 to 4 years, depending on the concept of tailing dump that is adopted.

There is an urgent need to approach the planning and development of the new tailingdump to solve the problem of disposal of tailings long-term, especially as the Flotation Plant Veliki Krivelj processes over 13 million tonnes of ore per year (10.6 + 2.5 Cerovo).

The possibilities were discussed of expanding the capacity of the existing tailing dump in the valley of the Krivelj River, downstream of the Flotation Plant.

From the Flotation Plant Veliki Krivelj to the location of tailing dump, the transport of tailings is done by gravity through a concrete channel, length of 9 km. Transport of tailings from the concrete channel to the sand dams of tailing dump is also gravity and it is performed through the cascades. From cascades, the pulp fed hydrocyclones, placed on the crests of sand dams that are used for separation of sludge and sand.

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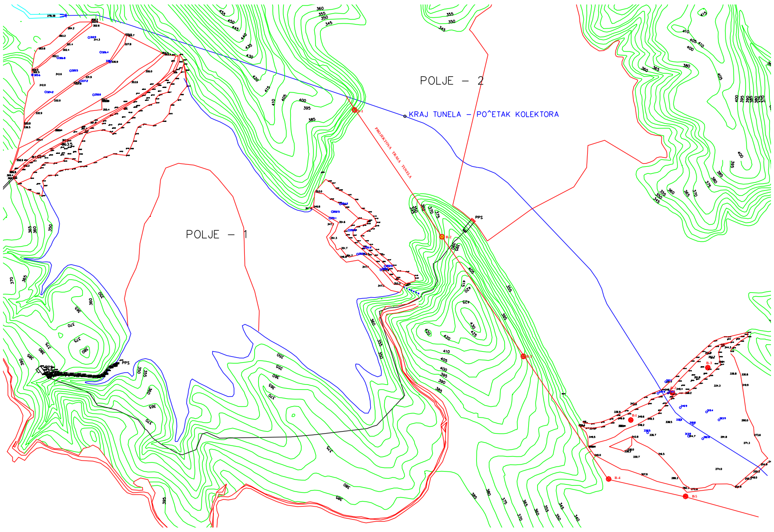


Figure 1 *Location map with the new route of collector of the Krivelj River*

Currently, 16 batteries of two cyclones are active on dam and they meet the technological needs of Flotation Plant at its full capacity (Krivelj 10.6 million tons and Cerovo 2.5 million tons of run-of-mine ore per year).

Clarified water is returned into technological process as backwater using the floating pump units (2x4 pumps) and relay pumping stations.

Downstream of the village is the active Field 1 which is bounded by dams 1 and 2. The final elevation of dams in the Field 1 is 380-384 m.

One of the details of technical-technological solutions that are proposed to increase the capacity of the flotation Field 1 and displacement the flotation Dam 2. To determine what the effect of this displacement of dam is on the future route of the Krivelj River collector, the software Phase 2 was used for the analysis.

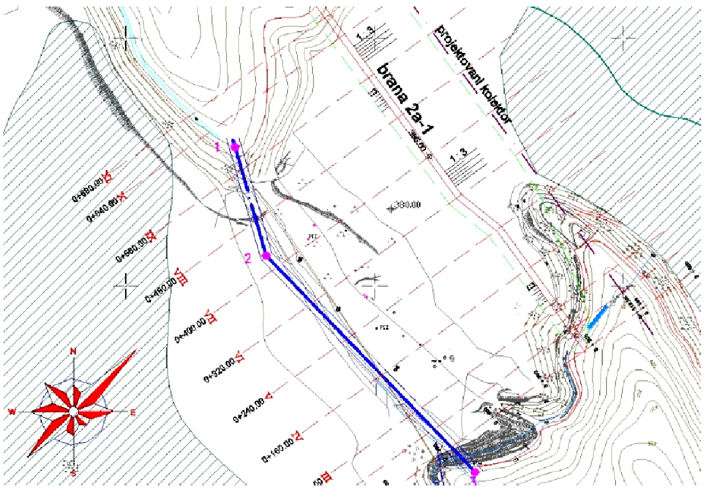


Figure 2 *Position of displacement the Dam 2 and profile 7, used in carrying out of all analyses*

2 STRESS ANALYSES OF CHARACTERISTIC PROFILE VII WITH THE SOFTWARE PHASE 2 v8.0

PHASE2 v8.0 is 2D program which is based on the stress analysis using the finite element method, for both underground and surface mining of rock or soil. It can be used for a wide range of engineering projects, including the construction of tunnels, slope stability using the finite element method, analysis of groundwater, network modeling, analysis of probabilities and wider. With this program, a complex situation of models in several stage can be quickly created and analyzed.

Values of input parameters per geological units, which are used for calculation on the profile VII-VII are given in Table 1. Parameters of mechanical and deformation properties are taken from the previous geomechanical investigations.

Table 1 *Input geomechanical parameters*

Material Name	Color	Initial Element Loading	Unit weight (kN/m^3)	Elastic Type	Young's Modulus (kPa)	Poisson's Ratio	Failure Criterion	Material Type
Hydrocyclone overflow		Field stress and body force	18	Isotropic	20.000	0,47	Mohr Coulomb	Plastic
Hydrocyclone underflow		Field stress and body force	23	Isotropic	50.000	0,40	Mohr Coulomb	Plastic
Degraded andesite		Field stress and body force	25	Isotropic	550.000	0,38	Mohr Coulomb	Plastic
Waste rock from the open pit		Field stress and body force	18,92	Isotropic	80.000	0,33	Mohr Coulomb	Plastic
Alluvion		Field stress and body force	20	Isotropic	70.000	0,40	Mohr Coulomb	Plastic

continuation of Table 1

Material Name	Color	Tensile Strength (kPa)	Tensile Strength residual (kPa)	Dilation Angle (deg)	Friction Angle peak (deg)	Friction Angle residual (deg)	Cohesion peak (kPa)	Cohesion residual (kPa)
Hydrocyclone overflow		0	0	0	25	25	0	0
Hydrocyclone underflow		5	0	0	20	20	5	5
Degraded andesite		50	0	0	27	27	50	50
Waste rock from the open pit		0	0	0	30	30	0	0
Alluvion		0	0	0	20	20	0	0

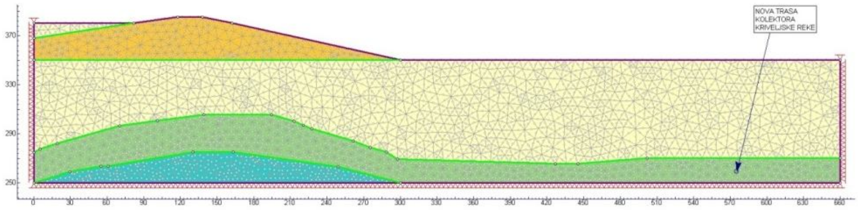
Profile VII was analyzed in two situations:

I. Current condition on the field of flotation Dam 2 and new route of the Krivelj River collector, and

II. Condition after displacement the flotation Dam 2 and new routes of the Krivelj River collector.

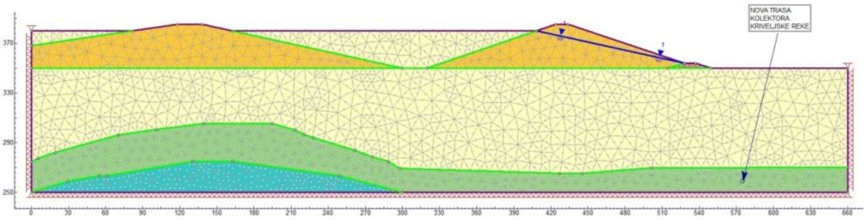
I SITUATION

DAM 2 PROFILE VII



II SITUATION

DISPLACED DAM 2 PROFILE VII



The presented analyses were performed as the ratio of the first and second situation, the relationship between Dam 2 and the new route of the Krivelj River collector. In Figures 3 and 4, an analysis of the profiles on the main normal stress was carried out.

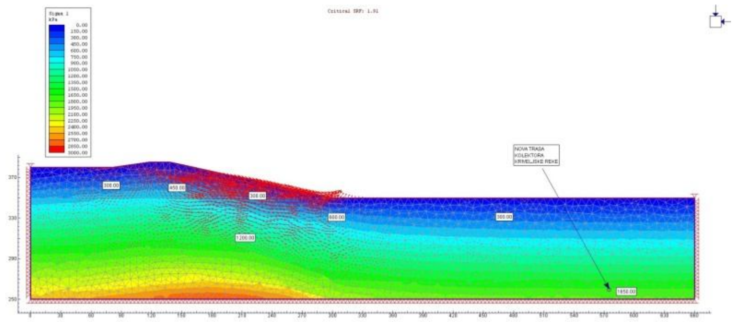


Figure 3 *The main normal stress* σ_1 *in the first situation*

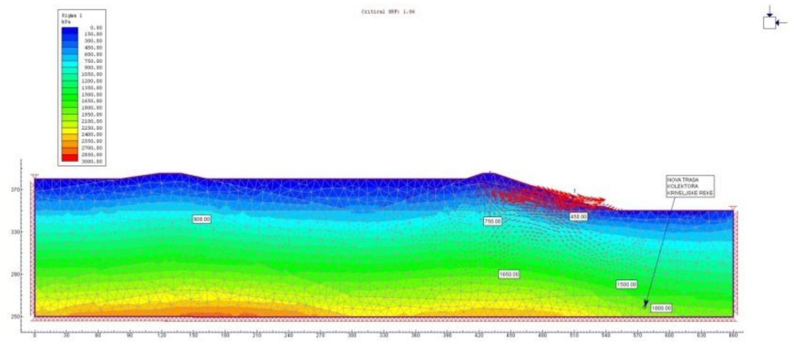


Figure 4 *The main normal stress* σ_1 *in the second situation*

The main normal stress σ_1 in the I situation in the new route of the Krivelj River collector is 1650 kPa, and in the II situation is 1800 kPa.

In Figures 5 and 6, an analysis of the profile of the main versatile stress was carried out.

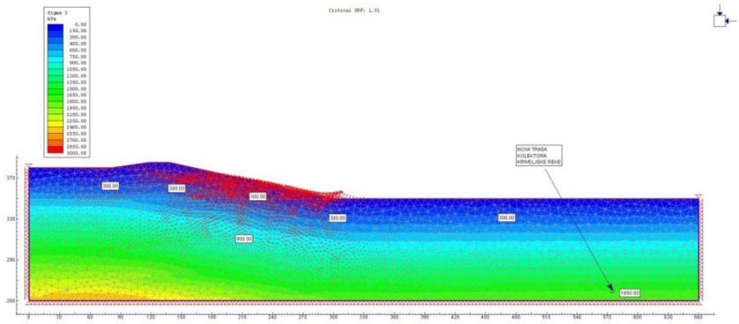


Figure 5 *The main versatile stress* σ_3 *in the I situation*

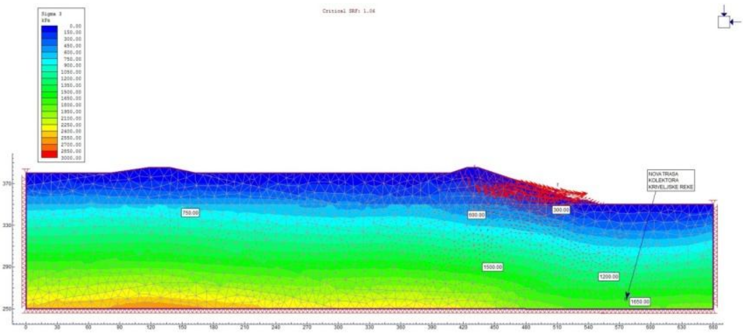


Figure 6 *The main versatile stress* σ_3 *in the II situation*

The main versatile stress σ_3 in the I situation in the new route of the Krivelj River collector is 1650 kPa, and in the II situation is 1650 kPa.

In Figures 7 and 8, an analysis of the profile on differential stress was carried out.

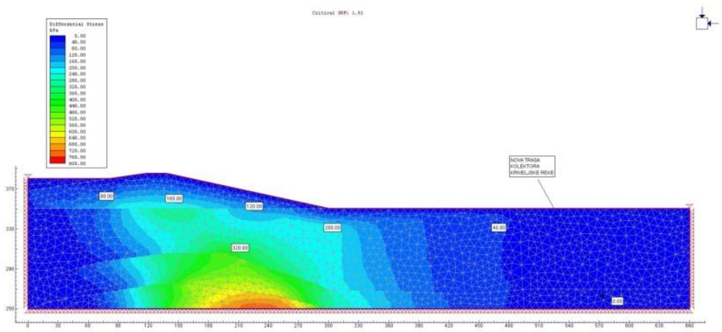


Figure 7 *Differential stress* σ_{1-3} *in the I situation*

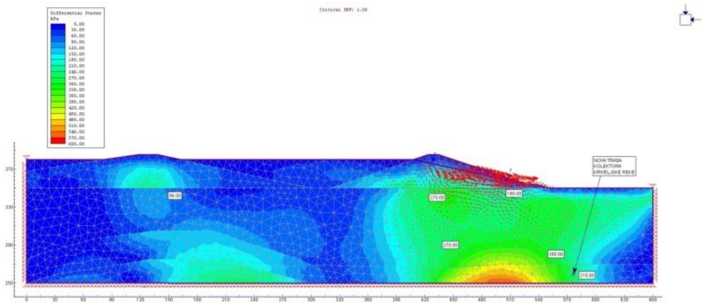


Figure 8 *Differential stress σ_{1-3} in the II situation*

Differential stress σ_{1-3} in the I situation in the new route of the Krivelj River collector is 0 [kPa], and in the II situation is 210 [kPa].

Table 2 gives a review of the results of obtained stresses in the field of passage the future collector of the Krivelj River.

Table 2 *Review of the Results*

Stress	I situation	II situation
Main normal stress σ_1	1650 kPa	1800 kPa
Main versatile stress σ_3	1650 kPa	1650 kPa
Differential stress σ_{1-3}	0 kPa	210 kPa

CONCLUSIONS

Based on the obtained results, it can be concluded that displacement of the flotation Dam 2 has no large effect on the stress conditions that occur just on a part of the field where the future collector of the Krivelj River is located.

Despite these results, it is necessary to carry out a continuous monitoring of the field of future route of the Krivelj River collector, as well as displacement route of the flotation Dam 2.

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UTICAJ POMERANJA FLOTACIJSKE BRANE 2 NA TRASU BUDUĆEG KOLEKTORA KRIVELJSKE REKE, TESTIRAN POMOĆU SOFTVERA PHASE2 v8.0**

Izvod

Potreba proširenja kapaciteta flotacijskog Polja I je neophodna zbog povećanja kapaciteta flotacije Veliki Krivelj. Na osnovu dobijenih geomehaničkih podataka iz ranijih istraživanja kao i predlog pomeranja postojeće brane 2 radi povećanja kapaciteta flotacijskog polja 1, pomoću softverskog paketa Phase2 izvršena je analiza uticaja flotacijske i stenske mase na novu trasu kolektora Kriveljske reke.
Ključne reči: *naponsko stanje, flotacijska brana, kriveljski kolektor, softver Phase 2*

1. UVOD

Zbog povećanja obima proizvodnje na površinskom kopu Veliki Krivelj, povećala se i količina flotacijske jalovine koju treba odložiti. Postojeće flotacijsko jalovište postaje malo po kapacitetu da primi nove količine materijala. Iz tog razloga je potrebno je naći tehničko tehnološko rešenje koje je prelazno i treba da omogući nesmetan rad flotacije Veliki Krivelj za period od 3 do 4 godine, zavisno od koncepta jalovišta koji se usvoji.

Hitno je potrebno pristupiti planiranju i izradi novog jalovišta kako bi se problem odlaganja jalovine dugoročno rešio, pogotovo što Kriveljska flotacija prerađuje preko 13 miliona tona rude godišnje (10,6 Krivelj + 2,5 Cerovo).

Razmatrane su mogućnosti za proširenje kapaciteta postojećeg jalovišta u dolini Kriveljske reke, nizvodno od flotacije.

Od flotacije "Veliki Krivelj" do lokacije jalovišta transport jalovine se obavlja gravitacijski kroz betonski kanal dužine 9 km. Transport jalovine od betonskog kanala do peščanih brana jalovišta je takođe gravitacijski i obavlja se posredstvom kaskada. Iz kaskada pulpa napaja hidrociklone smeštene na krunama peščanih brana u kojima se vrši razdvajanje na mulj i pesak.

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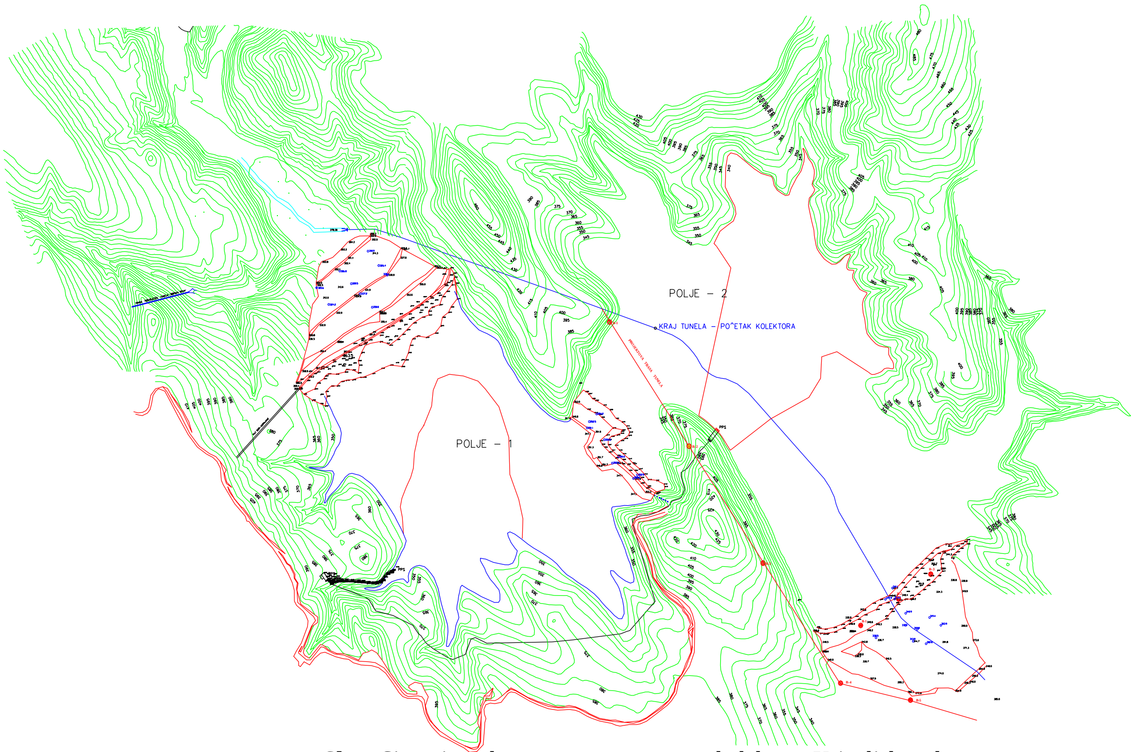
** *Ovaj rad je proistekao iz Projekta nauke broj 33021 „Istraživanje i praćenje promena naponsko deformacionog stanja u stenskom masivu "in-situ" oko podzemnih prostorija sa izradom modela sa posebnim osvrtom na tunel Kriveljske reke i Jame Bor", koga finansira Ministarstvo prosvete, nauke i tehnološkog razvoja Republike Srbije*



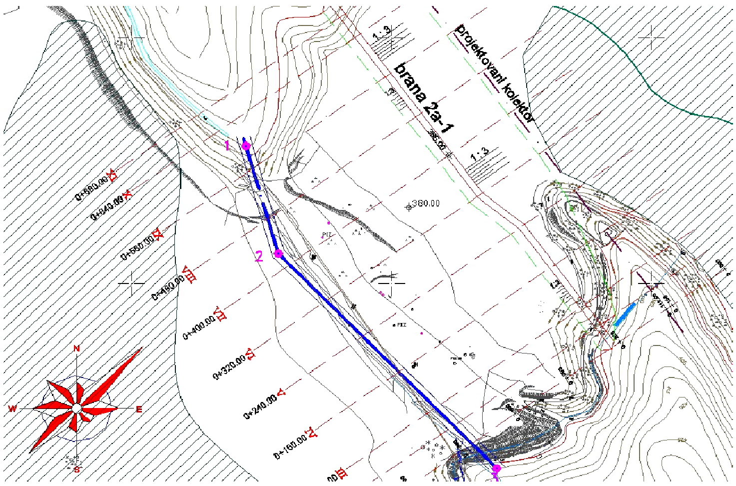
Sl. 1. *Situaciona karta sa novom trasom kolektora Kriveljske reke*

Trenutno na brani je aktivno 16 baterija od po dva ciklona i one zadovoljavaju tehnološke potrebe flotacije pri njenom punom kapacitetu (Krivelj 10,6 miliona tona i Cerovo 2,5 miliona tona rovne rude godišnje).

Izbistrena voda se pomoću plovečih pumpnih agregata (2x4 pumpe) i relejne pumpne stanice vraća u tehnološki proces kao povratna voda.

Nizvodno od sela nalazi se aktivno polje 1 koje je omeđeno branama 1 i 2. Završna kota brana na polju 1 je 380 – 384 m.

Jedno od detalja tehničko tehnoloških rešenja koja se predlažu za povećanje kapaciteta flotacijskog polja 1 je i pomeranje flotacijske brane 2. Da bi se utvrdilo koliki je uticaj tog pomeranja brane na buduću trasu kolektora Kriveljske reke, za analizu je upotrebljen softver Phase 2.



Sl. 2. *Pozicija pomeranja brane 2 i profil 7 po kome su vršene sve analize*

2. NAPONSKE ANALIZE KARAKTERISTIČNOG PROFILA VII SA SOFTVEROM PHASE 2 V8.0

PHASE2 v8.0 je 2D program koji svoj rad bazira na analizi napona uz pomoć metode konačnih elemenata, kako za podzemna tako i za površinska otkopavanja stena ili tla. Može se koristiti za široki spektar inženjerskih projekata, uključujući konstrukcije tunela, stabilnost kosina pomoću metode konačnih elemenata, analiza podzemnih voda, mrežno modeliranje, analiza verovatnoće i šire. Sa ovim programom se može brzo kreirati i analizirati kompleksno stanje modela u više faza.

Vrednosti ulaznih parametara po geološkim celinama, koji su korišćeni za proračun na profilu VII-VII su dati u tabeli 1. Parametri mehaničkih i deformacionih osobina su preuzeti iz ranijih geomehaničkih istraživanja.

Tabela 1. *Ulazni geomehanički parametri*

Material Name	Color	Initial Element Loading	Unit weight (kN/m^3)	Elastic Type	Young's Modulus (kPa)	Poisson's Ratio	Failure Criterion	Material Type
Preliv hidrociklona		Field stress and body force	18	Isotropic	20.000	0,47	Mohr Coulomb	Plastic
Pesak hidrociklona		Field stress and body force	23	Isotropic	50.000	0,40	Mohr Coulomb	Plastic
Degradirani andezit		Field stress and body force	25	Isotropic	550.000	0,38	Mohr Coulomb	Plastic
Jalovina sa kopa		Field stress and body force	18,92	Isotropic	80.000	0,33	Mohr Coulomb	Plastic
Aluvion		Field stress and body force	20	Isotropic	70.000	0,40	Mohr Coulomb	Plastic

nastavak tabele 1

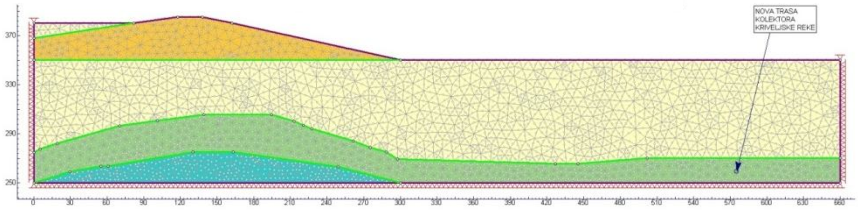
Material Name	Color	Tensile Strength (kPa)	Tensile Strength residual (kPa)	Dilation Angle (deg)	Friction Angle peak (deg)	Friction Angle residual (deg)	Cohesion peak (kPa)	Cohesion residual (kPa)
Preliv hidrociklona		0	0	0	25	25	0	0
Pesak hidrociklona		5	0	0	20	20	5	5
Degradirani andezit		50	0	0	27	27	50	50
Jalovina sa kopa		0	0	0	30	30	0	0
Aluvion		0	0	0	20	20	0	0

Profil VII analiziran je u dvema sutacijama:

I. Stanje trenutno na terenu flotacijske brane 2 i nove trase kolektora Kriveljske reke i
II. Stanje nakon pomeranja flotacijske brane 2 i nove trase kolektora Kriveljske reke.

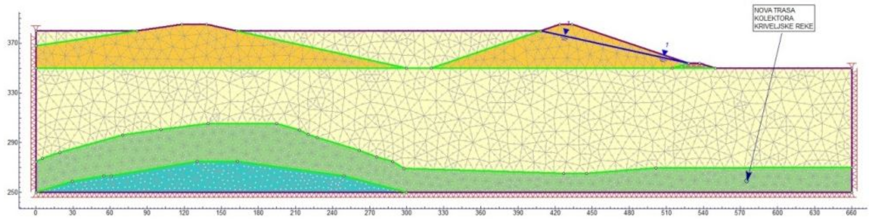
SITUACIJA I

BRANA 2 PROFIL VII



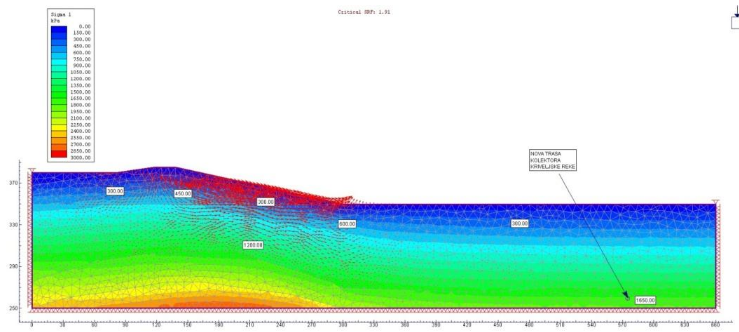
SITUACIJA II

IZMEŠTENA BRANA 2 PROFIL VII

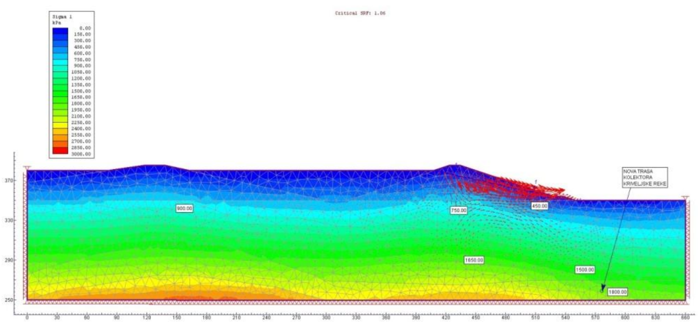


Prikazane analize su rađene kao odnos prve i druge situacije, odnos brane 2 i nove trase kolektora Kriveljske reke.

Na slikama 3 i 4 izvršena je analiza profila na glavni normalni napon.



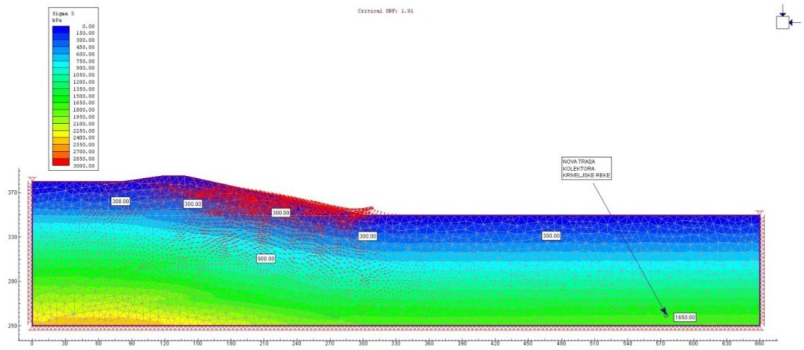
Sl. 3. *Glavni normalni napon* σ_1 *u prvoj situaciji*



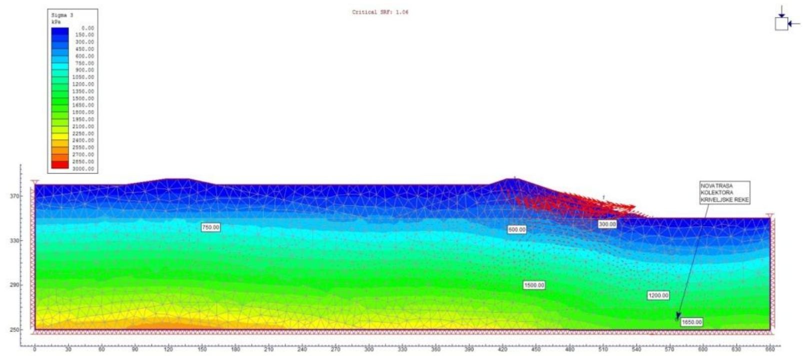
Sl. 4. *Glavni normalni napon* σ_1 *u drugoj situaciji*

Glavni normalni napon σ_1 u situaciji I kod nove trase kolektora kriveljske reke je 1650 kPa, a situacije II 1800 kPa.

Na slikama 5 i 6 izvršena je analiza profila na glavni svestrani napon.



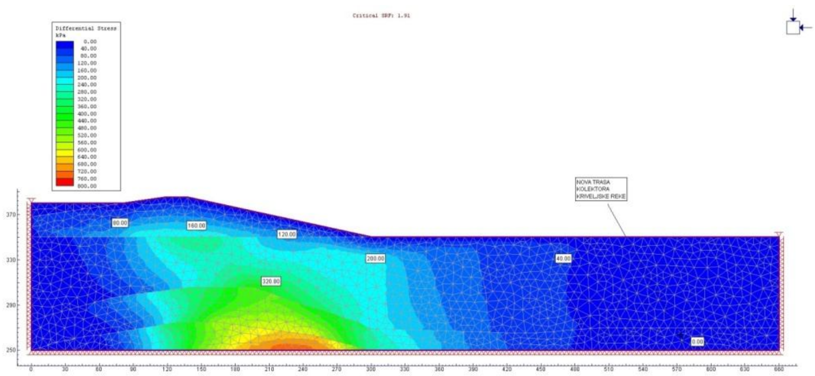
Sl. 5. *Glavni svestrani napon σ_3 u prvoj situaciji*



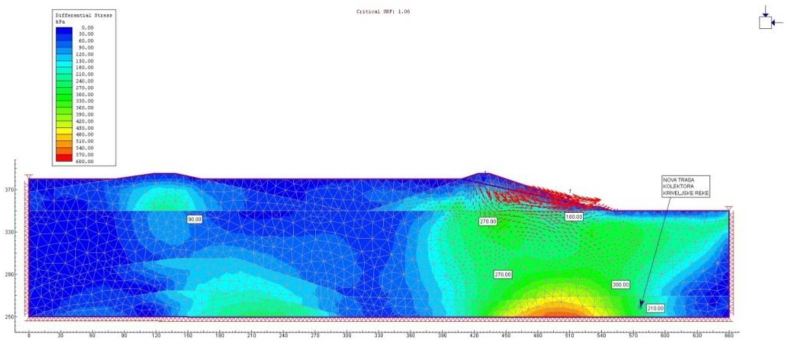
Sl. 6. *Glavni svestrani napon σ_3 u drugoj situaciji*

Glavni svestrani napon σ_3 u situaciji I kod nove trase kolektora kriveljske reke je 1650 kPa, a situacije II 1650 kPa.

Na slikama 7 i 8 izvršena je analiza profila na diferencijalni napon.



Sl. 7. *Diferencijalni napon σ_{1-3} u prvoj situaciji*



Sl. 8. *Diferencijalni napon σ_{1-3} u drugoj situaciji*

Diferencijalni napon σ_{1-3} u situaciji I kod nove trase kolektora kriveljske reke je 0 [kPa] a u situaciji II je 210 [kPa].

U tabeli 2 dat je pregled rezultata dobijenih napona na terenu prolaska budućeg kolektora Kriveljske reke.

Tabela 2. *Pregled rezultata*

Napon	**Situacija I**	**Situacija II**
Glavni normalni napon σ_1	1650kPa	1800kPa
Glavni svestrani napon σ_3	1650kPa	1650kPa
Diferencijalni napon σ_{1-3}	0 kPa	210kPa

3. ZAKLJUČNA RAZMATRANJA

Na osnovu dobijenih rezultata može se zaključiti da pomeranje flotacijske brane 2 nema velikog uticaja na naponska stanja koja se dešavaju baš na delu terena gde je lociran budući kolektor Kriveljske reke.

I pored ovih rezultata potrebno je vršiti konstantni monitoring terena buduće trase kolektora Kriveljske reke, kao i pomeranje flotacijske brane 2.

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ANALYSIS THE OPERATING PARAMETERS OF БелАЗ TRUCK AT THE OPEN PITS OF THE BROWN COAL MINE "BANOVICI" BASED ON PROCESSOR DATA

Abstract

This work presents a methodology of data collecting and processing from the load and fuel control system СКЗиТ, installed on БелАЗ 75131 trucks, owned by the Brown Coal Mine "Banovici"in Banovici. There is also a methodology of display the achieved operating parameters. Transport of coal and overburden is performed by these trucks. Total of eleven trucks has processors. Conclusions about working time, length of crossed routes, quantity of transported load, achieved cycles, etc. can be presented by data processing.

Keywords: *open pit, БелАЗ, truck, Brown Coal Mine "Banovici", processor*

1 INTRODUCTION

Production (overburden and coal) at the open pits of the Brown Coal Mine "Banovici" in Banovici, is realized by discontinuous technology with the use of classical cyclic loading-transport complex shovel-truck.

The open pit mining system is a sequence of works on excavation, transport and dumping of overburden, production and other (auxiliary) processes, which provide the designed (planned) capacity of the open pit.

At the open pits of Brown Coal Mine "Banovici" ("Grivice" and "Turija"), a longitudinal one sided mining system is applied with deepening by overlying contact of ore body (coal seam) and transport of overburden on the external dump.

Production process of overburden and coal consists of the following working processes: drilling and blasting (preparation of rock digging and loading), digging and loading (excavation), transport, dumping of overburden and dumping of coal (if necessary).

After coal loading onto trucks, it is transported from the working area and unloading into the crusher. Transport of coal from the crusher to the reloading bunker at the railway station "Draganja" is carried out by conveyor belt system, and further by rail to the separation. At the open pit "Turija", transport of coal to the reloading bunker is carried out by trucks. Transport of overburden is carried out by trucks directly from the working area at the open pit to the dump.

Open pits are mutually connected by midfield transport roads used for crossing of trucks and other mechanization from one to the other open pit, and also to the service complex "Besin" due to the preventive maintenance and repair. Works on overburden is realized in a way that after drilling and blasting, the overburden is

[*] *RGGF Tuzla B&H*

loaded by shovel onto trucks. Digging and loading of overburden is performed by shovels and hydraulic shovels with the previous blasting of rock mass above shovel level. At the open pits, the overburden from benches is transported to the dumping benches by trucks via transporting roads. At dump, truck goes on dump road to the dumping bench where dumping of overburden is done. All transport roads are constructed by overburden and covered with solid and persistent marls.

2 DATA OBTAINED FROM PROCESSOR ON БелАЗ TRUCKS

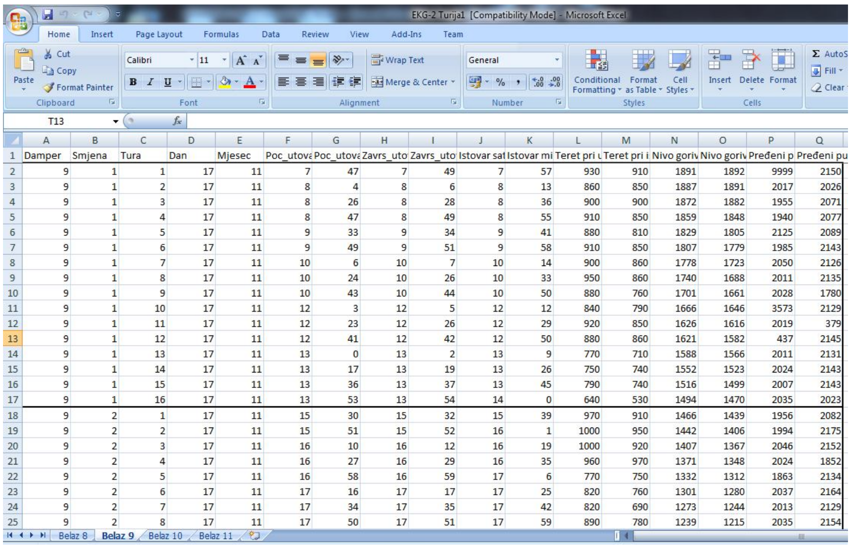
The Brown Coal Mine "Banovici" has eleven БелАЗ 75131 trucks with processors, respectively load and fuel control system СКЗиТ.

This system, except of monitoring transported load and fuel consumption, provides data on load and unload time as well as length of crossed routes for full and empty trucks.

Load and fuel control system СКЗиТ consists of the following elements: controller, panel management and indication, pressure sensors on shock absorbers, fuel level sensor in tank, inclinometer and signal of load quantity.

Figure 1 shows a module with the system panel СКЗиТ. Processor data on БелАЗ trucks are obtained in the form shown in Figure 2.

Figure 1 *Load module with the panel*



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	Damper	Smjena	Tura	Dan	Mjesec	Poc_utova	Poc_utova	Zavrs_uto	Zavrs_uto	Istovar sat	Istovar mi	Teret pri u	Teret pri i	Nivo goriv	Nivo goriv	Pređeni p	Pređeni pu
2	9	1	1	17	11	7	47	7	49	7	57	930	910	1891	1892	9999	2150
3	9	1	2	17	11	8	4	8	6	8	13	860	850	1887	1891	2017	2026
4	9	1	3	17	11	8	26	8	28	8	36	900	900	1872	1882	1955	2071
5	9	1	4	17	11	8	47	8	49	8	55	910	850	1859	1848	1940	2077
6	9	1	5	17	11	9	33	9	34	9	41	880	810	1829	1805	2125	2089
7	9	1	6	17	11	9	49	9	51	9	58	910	850	1807	1779	1985	2143
8	9	1	7	17	11	10	6	10	7	10	14	900	860	1778	1723	2050	2126
9	9	1	8	17	11	10	24	10	26	10	33	950	860	1740	1688	2011	2135
10	9	1	9	17	11	10	43	10	44	10	50	880	760	1701	1661	2028	1780
11	9	1	10	17	11	12	3	12	5	12	12	840	790	1666	1646	3573	2129
12	9	1	11	17	11	12	23	12	26	12	29	920	850	1626	1616	2019	379
13	9	1	12	17	11	12	41	12	42	12	50	880	860	1621	1582	437	2145
14	9	1	13	17	11	13	0	13	2	13	9	770	710	1588	1566	2011	2131
15	9	1	14	17	11	13	17	13	19	13	26	750	740	1552	1523	2024	2143
16	9	1	15	17	11	13	36	13	37	13	45	790	740	1516	1499	2007	2143
17	9	1	16	17	11	13	53	13	54	14	0	640	530	1494	1470	2035	2023
18	9	2	1	17	11	15	30	15	32	15	39	970	910	1466	1439	1956	2082
19	9	2	2	17	11	15	51	15	52	16	1	1000	950	1442	1406	1994	2175
20	9	2	3	17	11	16	10	16	12	16	19	1000	920	1407	1367	2046	2152
21	9	2	4	17	11	16	27	16	29	16	35	960	970	1371	1348	2024	1852
22	9	2	5	17	11	16	58	16	59	17	6	770	750	1332	1312	1863	2134
23	9	2	6	17	11	17	16	17	17	17	25	820	760	1301	1280	2037	2164
24	9	2	7	17	11	17	34	17	35	17	42	820	690	1273	1244	2013	2129
25	9	2	8	17	11	17	50	17	51	17	59	890	780	1239	1215	2035	2154

Figure 2

For one shift, about 255 data is got, which can be used for individual transformations, and later for analyses. Data from the truck processor are needed for previously preparation for analysis. Data are in such form that is necessary to do the transformation of data for time because of classification by hours and minutes in the columns (Figure 2). To present in a diagram, these data are needed to transform in the form of data TIME (0:00:00). In Microsoft Excel, it is necessary to add some new columns to get data in a form TIME (0:00:00) and time expressed in seconds. In displayed file with processors, it can be observed that the time, which shows seconds, is not recorded, in contrast with data which could be got on the basis of truck monitoring with built-in GPS receiver. Registered data are in two separate columns about mass of the load immediately after loading and at unloading, increased ten times. Mainly, the mass data of the load, immediately at the end of loading, show considerable differences in comparison with registered data at unloading. These two values are different because the sensor, when loading, registers higher value of load, because the load is unevenly distributed in the truck box. During the transport from the load place to the unload place, it occurs to more balanced distribution of load and then the registered load mass at the unloading is authoritative for further analysis. Data about driving time of full damper can be obtained from the subtraction registered unloading time and finished loading time. Values of crossed routes of full truck and empty truck are there in the file. If the values of length of crossed routes are divided with driving time of full truck, a driving speed of full truck can be obtained. If the difference between registered time of load beginning and time of previous unloading is defined, a driving time of empty truck can be obtained, that is longer than driving time of full truck, so it can be concluded that the speed of empty truck is low in comparison with the speed of full truck. Length of crossed routes of empty truck also have in itself the length for load maneuvering, so they are not adequate for determining the driving time of the same.

3 THE ACHIEVED OPERATING PARAMETERS OF THE TRUCKS БелАЗ 8, БелАЗ 9, AND БелАЗ 10

By data analyzing with processor, it is possible to show the achieved results of truck operation for each shift. Daily reports on operation of three trucks are shown in the next text.

Open pit Turija

Shovel ЭКГ 8И (2)

Truck БелАЗ 75131 (8)

Dump of the open pit Turija

Daily report

Total of transported load 3726 t

Average values of transported load 81 t per cycle

Total duration of loading (without truck changing time) 4650 s

Average duration of loading (without truck changing time) 99.13 s

Total fuel consumption 1408 l

Number of cycles (tours) 46

Total of crossed route of full truck 91720 m

Average crossed route of full truck (semi cycle full truck) 1 993.91 m

Total of crossed route of empty truck 101196 m – with coming under the shovel at the beginning of shift and coming under the shovel at the end of shift

Average crossed route of empty truck (semi cycle empty truck) 2026.6 m

Total driving time of full truck 19920 s

Average driving time of full truck (semi cycle full truck) 433.04 s

Average driving speed of full truck 4.60 m/s

Presentation of information in the form of graphs - truck БелАЗ 8

Figure 3 shows a graph of duration the loading and Figure 4 mass of load transported during one cycle. Figure 5 shows a graph of crossed routes in driving of full and empty truck and Figure 6 registered speeds.

Figures 7 and 8 show a graph on changes the level of fuel during loading and unloading of truck.

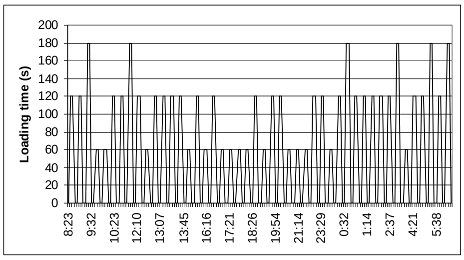


Figure 3

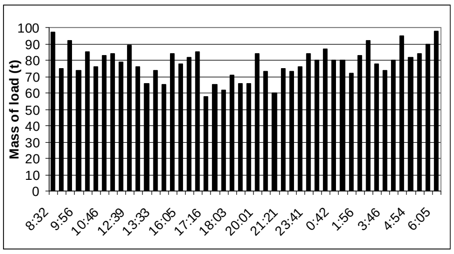


Figure 4

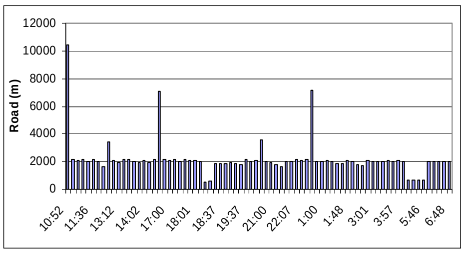


Figure 5

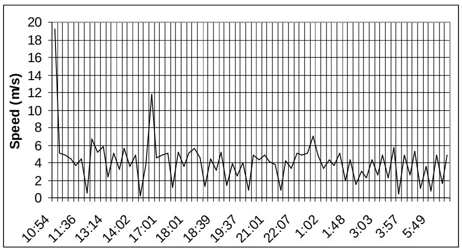


Figure 6

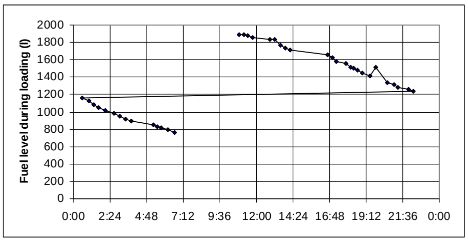


Figure 7

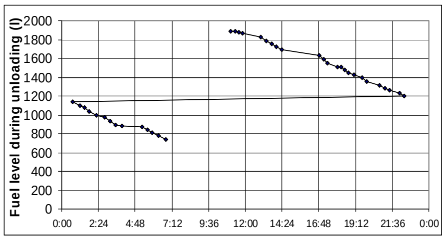


Figure 8

Open pit Turija
Shovel ЭКГ 8И (2)
Truck БелАЗ 75131 (9)
Dump of the open pit Turija

Daily report

Total of transported load 3612 t

Average values of transported load 7852 t per cycle

Total duration of loading (without truck changing time) 4980 s

Average duration of loading (without truck changing time) 108.26 s

Total fuel consumption 1454 l

Number of cycles (tours) 46

Total of crossed route of full truck 91885 m

Average crossed route of full truck (semi cycle full truck) 1997.50 m

Total of crossed route of empty truck 113481 m – with coming under the shovel at the beginning of shift and coming under the shovel at the end of shift

Average crossed route of empty truck (semi cycle empty truck) 2074.21 m

Total driving time of full truck 19860 s

Average driving time of full truck (semi cycle full truck) 431.74 s

Average driving speed of full truck 4.63 m/s

***Presentation of information in the form of graphs - truck* БелАЗ 9**

Figure 9 shows a graph of duration of loading and Figure 10 mass of load transported during one cycle. Figure 11 shows a graph of crossed routes in driving of full and empty truck and Figure 12 registered speeds.

Figures 13 and 14 show a graph on changes the level of fuel during loading and unloading of truck.

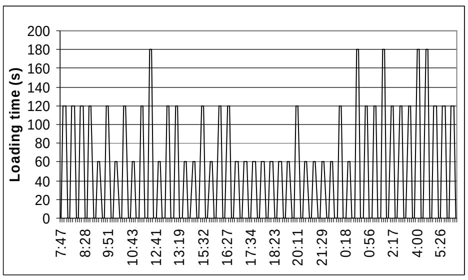


Figure 9

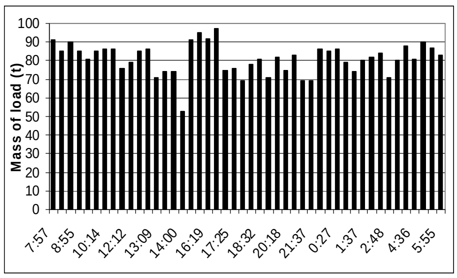


Figure 10

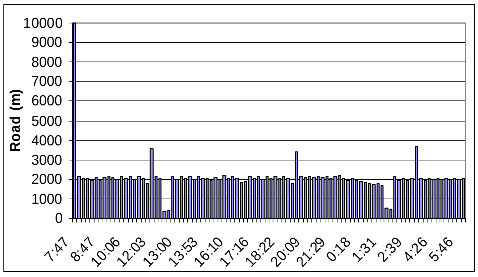


Figure 11

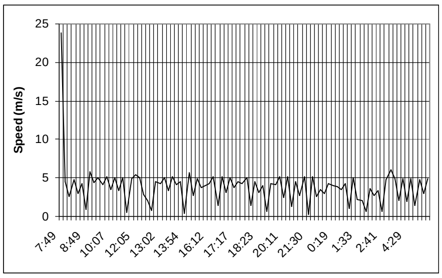


Figure 12

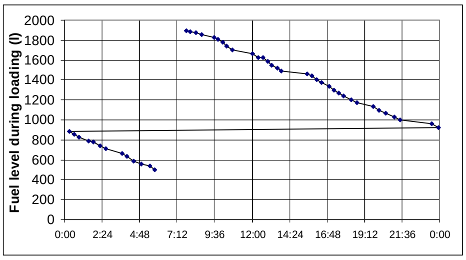


Figure 13

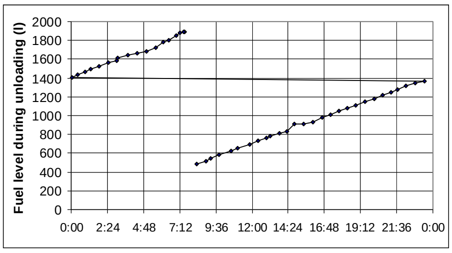


Figure 14

Open pit Turija
Shovel ЭКГ 8И (2)
Truck БелАЗ 75131 (10)
Dump of open pit Turija

Daily report

Total of transported load 2944 t

Average values of transported load 77.47 t per cycle

Total duration of loading (without truck changing time) 4200 s

Average duration of loading (without truck changing time) 110.53 s

Total fuel consumption 1155 l

Number of cycles (tours) 38

Total of crossed route of full truck 73037 m

Average crossed route of full truck (semi-cycle full truck) 1922.03 m

Total of crossed route of empty truck 92923 m – with coming under the shovel at the beginning of shift and coming under the shovel at the end of shift

Average crossed route of empty truck (semi-cycle empty truck) 1950.34 m

Total driving time of full truck 15600 s

Average driving time of full truck (semi-cycle full truck) 410.53 s

Average driving speed of full truck 4.68 m/s

Presentation of information in the form of graphics-truck **БелАЗ 10**

In Figure 15, the graph shows duration of loading and in Figure 16 mass of load transported during one cycle. In Figure 17, there is a graph of crossed routes in driving of full and empty truck and in Figure18 registered speeds.

In Figures 19 & 20, there is a graph about changes in the level of fuel during loading and unloading of truck.

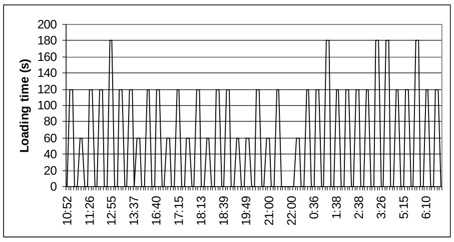


Figure 15

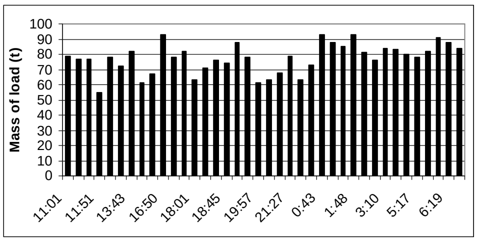


Figure 16

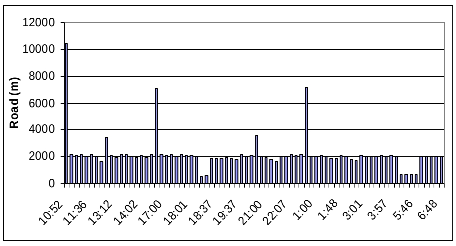


Figure 17

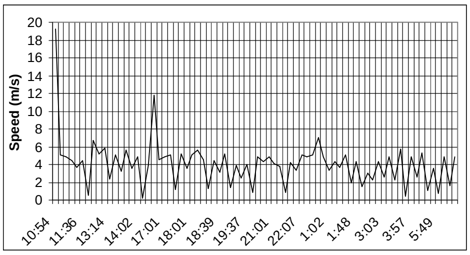


Figure 18

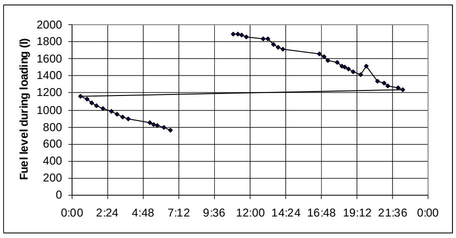


Figure 19

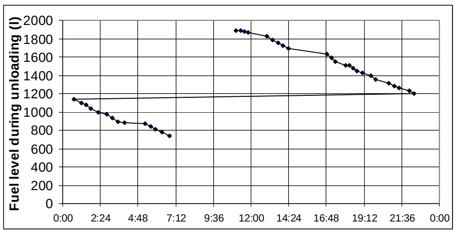


Figure 20

4 DISCUSSION

Analyzing the processor data of all three trucks БелАЗ in one day, it can be concluded that truck БелАЗ 8, in total 46 working cycles, achieved the biggest capacity (output), but truck БелАЗ 10 the smallest. In the observed day during the first shift, truck БелАЗ 10 was in service according to the reports of operational technical preparation service, and it achieved only 38 working cycles.

Although all three trucks served the same shovel, there is a significant difference in length of crossed route and dura tion of loading. According to the records about length of crossed routes of empty truck at the beginning of shifts, the truck БелАЗ 9 was the only truck at the beginning of first shift that came from the turn-over place Besin, and at the beginning of the second and third shift the turn-over performed at the shovel, it is different between the truck БелАЗ 8 and БелАЗ 10 on the other side which moved from the turn-over place Besin at the beginning of all three shifts. Figure 21 presents the shortest time of loading for БелАЗ 10, it is logical, because of this truck during the three shifts achieved 8 cycles fewer from the other two trucks. Minimum average time of loading was achieved for truck БелАЗ 8, and also minimum average moving speed.

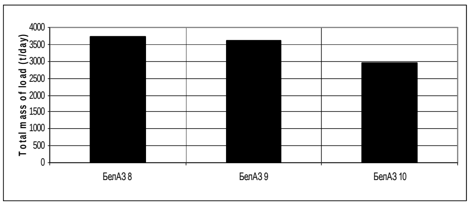


Figure 21

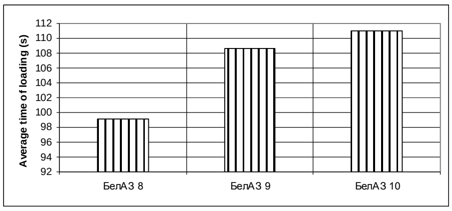


Figure 22

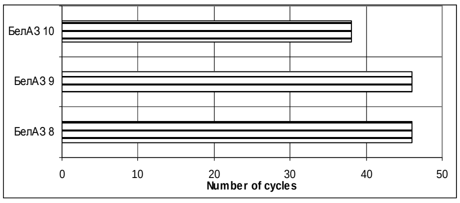


Figure 23

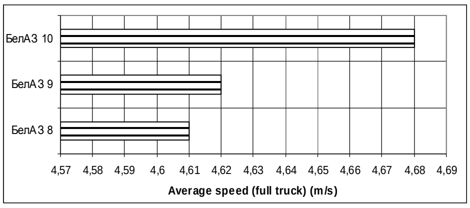


Figure 24

According to the processor data, the truck БелАЗ 11 crossed between 500 and 600 km, while the truck БелАЗ 8 crossed about 170 km (the same shovel and the same dump). The processor is broken on the truck БелАЗ 11, so the data from this truck cannot be used for further analysis until solving the problem.

According to the processor data, maximum amount of fuel is 1892 (l) that is registered on trucks БелАЗ, while in the tank can fit 1900 (l), but the average fuel consumption is shown in the next chart.

Table 1.

Shovel – dump	Truck		
	БелАЗ 8	**БелАЗ 9**	**БелАЗ 10**
Shovel ЭКГ 8И (2) – dump of the open pit Turija			
Average fuel consumption (l/km)	6.76	7.19	6.9
Average quantity of fuel for refueling in tank (l)	1448	1411	1154
Hydraulic shovel Terex RH 120E (1) – dump of the open pit Turija			
Average fuel consumption (l/km))	7.48	7.35	7.50
Average quantity of fuel for refueling in tank (l)	1844	1138	1437
Shovel Marion M 201 – dump of the open pit Grivice			
Average fuel consumption (l/km)	7.28	7.33	7.18
Average quantity of fuel for refueling in tank (l)	1494	1471	1508

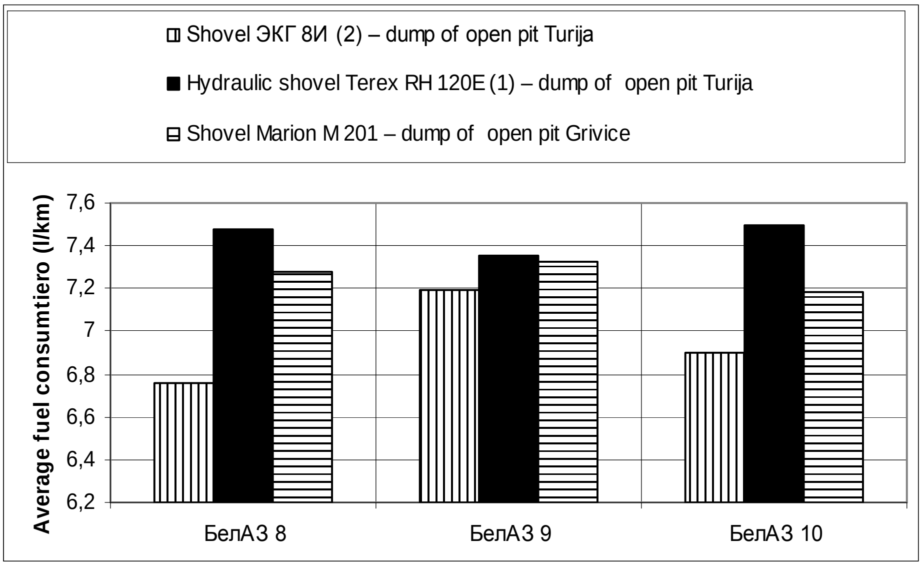


Figure 25

5 CONCLUSION

Total 11 trucks have processors; the processors are correct on the trucks БелАЗ 8, БелАЗ 9 and БелАЗ 10 and data from these processors can be used for analyses. The other trucks processors must be repaired because of using the data for analyses.

Five trucks Terex 3600 B and two trucks Mark 36 have not this kind of processors, so the data about working and slowdowns/cancellations cannot be analyzed in this way.

Data from the truck processors can be used for defining each working parameter of truck transport. By installation the Global Positioning System (GPS) receivers on the equipment in the Black Coal Mine „Banovici“, a new possibility of getting real and timing and spatial working insight is opened and also forming the Center for dispatchers in the Mine.

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UDK: 622.68(045)=861 DOI:10.5937/MMEB1304029M

Sunčica Mašić, Muhidin Brčaninović**

ANALIZA PARAMETARA RADA KAMIONA БелАЗ NA POVRŠINSKIM KOPOVIMA RMU "BANOVIĆI" NA OSNOVU PODATAKA SA PROCESORA

Izvod

U radu je data metodologija prikupljanja i obrade podataka iz sistema za kontrolu tereta i goriva СКЗиТ, a koji se nalaze na kamionima БелАЗ 75131 koje posjeduje Rudnik mrkog uglja (RMU) „Banovići" u Banovićima. Takođe, predstavljena je i metodologija prikaza ostvarenih parametara rada.

Ovim kamionima vrši se transportovanje i uglja i otkrivke (jalovine) na površinskim kopovima navedenog rudnika. Ukupno jedanaest kamiona posjeduju procesore. Obradom podataka mogu se izvesti zaključci o vremenima rada, dužinama pređenih puteva, količini prevezenog tereta, ostvarenim ciklusima itd.

Ključne riječi: *površinski kop, kamion, БелАЗ, RMU „Banovići", procesor*

1. UVOD

Proizvodnja (otkrivka i dobivanje uglja) na površinskim kopovima Rudnika mrkog uglja „Banovići" d.d. Banovići ostvaruje se diskontinuiranom tehnologijom sa primjenom klasičnog cikličnog utovarno-transportnog kompleksa bager-kamion.

Sistem površinske eksploatacije je redoslijed izvođenja radova na otkopavanju, transportu i odlaganju otkrivke, dobivanju i drugim (pomoćnim) procesima, kojim se obezbjeđuje projektovani (planirani) kapacitet površinskog kopa. Na površinskim kopovima RMU „Banovići" („Grivice" i „Turija") primjenjuje se uzdužni jednokrilni sistem eksploatacije sa produbljavanjem po krovinskom kontaktu rudnog tijela (ugljenog sloja) i transportom otkrivke na vanjska odlagališta.

Proizvodni proces otkrivke i uglja sastoji se od slijedećih radnih procesa: bušenje i miniranje (priprema stijene za kopanje i utovar), kopanje i utovar (bagerovanje), transport, odlaganje otkrivke i deponovanje uglja (po potrebi).

Nakon utovara uglja u kamione vrši se transport istog sa etaže i istovar u drobilično postrojenje. Transport uglja od drobiličnog postrojenja do pretovarnog bunkera na željezničkoj stanici „Draganja" vrši se sistemom transportera sa gumenom trakom, a dalje željeznicom do separacije, dok se na površinskom kopu „Turija" transport uglja u pretovarni bunker vrši kamionima. Transport otkrivke obavlja se direktnim prevozom kamionima sa etaže na površinskom kopu do etaže na odlagalištu.

Površinski kopovi su međusobno povezani veznim transportnim putevima koji služe za prelazak kamiona i druge mehanizacije sa jednog na drugi površinski kop, kao i do servisnog kompleksa „Bešin" radi preventivnog održavanja i opravki. Radovi na otkrivci se izvode tako što se nakon bušenja i miniranja otkrivka bagerima utovara u

**RGGF Tuzla BiH*

kamione. Kopanje i utovar otkrivke vrši se bagerima kašikarima i hidrauličnim bagerima uz prethodno miniranje stijenske mase iznad bagerskog nivoa. Kamionima se otkrivka sa etaže na površinskom kopu transportnim putevima prevozi do etaže na odlagalištu. Na odlagalištu kamion odlagališnim putem odlazi do odlagališne etaže na kojoj vrši odlaganje otkrivke. Svi transportni putevi su izrađeni od otkrivke i nasuti čvrstim i postojanim laporcima.

2. PODACI DOBIVENI SA PROCESORA NA KAMIONIMA БелАЗ

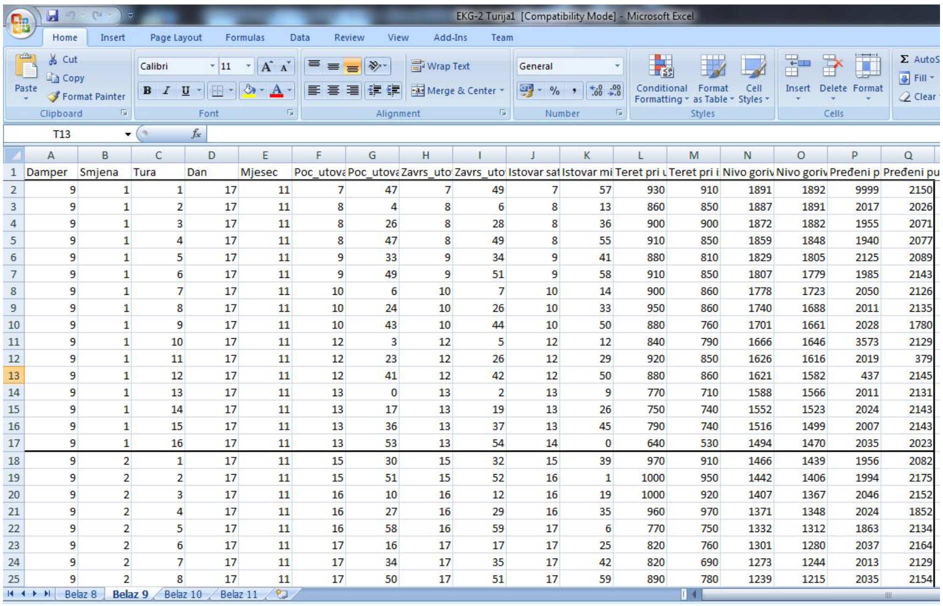
RMU „Banovići“ posjeduje 11 kamiona БелАЗ 75131 na kojima se nalaze procesori odnosno sistem za kontrolu tereta i goriva СКЗиТ.

Ovaj sistem pored praćenja prevezenog tereta i potrošnje goriva daje podatke i o vremenima utovara i istovara kao i dužinama pređenih puteva punih i praznih kamiona.

Sistem kontrole tereta i goriva СКЗиТ čine slijedeći elementi: kontroler, panel upravljanja i indikacije, davači pritiska na amortizerima, senzor nivoa goriva u rezervoaru, inklinometar i semafor za signalizaciju količine tereta.

Na slici 1 prikazan je modul sa panelom sistema СКЗиТ. Podaci sa procesora na kamionima БелАЗ dobijaju se u formi prikazanoj na slici 2.

Sl. 1. *Modul tereta sa panelom*



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	Damper	Smjena	Tura	Dan	Mjesec	Poc_utova	Poc_utova	Zavrs_uto	Zavrs_uto	Istovar sat	Istovar mi	Teret pri u	Teret pri i	Nivo goriv	Nivo goriv	Pređeni p	Pređeni pu
2	9	1	1	17	11	7	47	7	49	7	57	930	910	1891	1892	9999	2150
3	9	1	2	17	11	8	4	8	6	8	13	860	850	1887	1891	2017	2026
4	9	1	3	17	11	8	26	8	28	8	36	900	900	1872	1882	1955	2071
5	9	1	4	17	11	8	47	8	49	8	55	910	850	1859	1848	1940	2077
6	9	1	5	17	11	9	33	9	34	9	41	880	810	1829	1805	2125	2089
7	9	1	6	17	11	9	49	9	51	9	58	910	850	1807	1779	1985	2143
8	9	1	7	17	11	10	6	10	7	10	14	900	860	1778	1723	2050	2126
9	9	1	8	17	11	10	24	10	26	10	33	950	860	1740	1688	2011	2135
10	9	1	9	17	11	10	43	10	44	10	50	880	760	1701	1661	2028	1780
11	9	1	10	17	11	12	3	12	5	12	12	840	790	1666	1646	3573	2129
12	9	1	11	17	11	12	23	12	26	12	29	920	850	1626	1616	2019	379
13	9	1	12	17	11	12	41	12	42	12	50	880	860	1621	1582	437	2145
14	9	1	13	17	11	13	0	13	2	13	9	770	710	1588	1566	2011	2131
15	9	1	14	17	11	13	17	13	19	13	26	750	740	1552	1523	2024	2143
16	9	1	15	17	11	13	36	13	37	13	45	790	740	1516	1499	2007	2143
17	9	1	16	17	11	13	53	13	54	14	0	640	530	1494	1470	2035	2023
18	9	2	1	17	11	15	30	15	32	15	39	970	910	1466	1439	1956	2082
19	9	2	2	17	11	15	51	15	52	16	1	1000	950	1442	1406	1994	2175
20	9	2	3	17	11	16	10	16	12	16	19	1000	920	1407	1367	2046	2152
21	9	2	4	17	11	16	27	16	29	16	35	960	970	1371	1348	2024	1852
22	9	2	5	17	11	16	58	16	59	17	6	770	750	1332	1312	1863	2134
23	9	2	6	17	11	17	16	17	17	17	25	820	760	1301	1280	2037	2164
24	9	2	7	17	11	17	34	17	35	17	42	820	690	1273	1244	2013	2129
25	9	2	8	17	11	17	50	17	51	17	59	890	780	1239	1215	2035	2154

Sl. 2.

Za jednu smjenu dobije se oko 255 podataka koji se mogu iskoristiti za pojedine transformacije, a kasnije za analize. Podatke sa procesora kamiona neophodno je prethodno pripremiti za analizu. Podaci su u takvom obliku da je potrebno izvršiti transformaciju podataka za vrijeme jer su po kolonama razvrstani po satima i minutama (slika 2). Ove podatke da bi se dijagramski predstavili neophodno je transformisati u podatke oblika TIME (0:00:00). U Microsoft Excel-u potrebno je izvršiti ubacivanje novih kolona da bi se dobili podaci oblika TIME (0:00:00) i vrijeme izraženo u sekundama. U prikazanoj datoteci sa procesora može se primjetiti da se ne evidentira vrijeme koje pokazuje i sekunde, za razliku od podataka koji bi se dobili na osnovu praćenja kamiona koji bi imali ugrađene GPS prijemnike. U dvije zasebne kolone dati su registrovani podaci o masi tereta neposredno poslije utovara i pri istovaru uvećane 10 puta. Uglavnom, podaci o masi tereta neposredno po završetku utovara pokazuju znatne razlike u odnosu na registrovane podatke pri istovaru. Ove dvije vrijednosti se razlikuju zbog toga što senzor prilikom utovara registruje veću vrijednost tereta, jer je teret neravnomjerno raspoređen u sanduku kamiona. Prilikom transporta od mjesta utovara do mjesta istovara dolazi do ravnomjernije raspodjele tereta i pri tome registrovana masa tereta pri istovaru je mjerodavna za dalju analizu. Podaci o vremenima vožnje opterećenog kamiona (pun kamion) mogu se dobiti iz razlike registrovanog vremena istovara i vremena završetka utovara. U datoteci su prikazane vrijednosti pređenih puteva opterećenog (pun) i neopterećenog (prazan) kamiona. Dijeleći vrijednosti dužina pređenih puteva sa vremenima vožnje opterećenog (punog) kamiona mogu se dobiti brzine vožnje opterećenog (punog) kamiona. Ako odredimo razliku registrovanih vremena početka utovara i vremena prethodnog istovara dobijaju se vremena vožnje praznog (neopterećenog) kamiona koja su puno veća od vremena vožnje punog kamiona, te su dobijene brzine vožnje praznog kamiona male u odnosu na brzine punog kamiona. Dužine pređenih puteva neopterećenog (praznog) kamiona u sebi sadržavaju i dužine vezane za manevrisanje pri utovaru, tako da nisu adekvatne za određivanje brzina vožnje istog.

3. OSTVARENI PARAMETRI RADA KAMIONA БелАЗ 8, БелАЗ 9 i БелАЗ 10

Analizom podataka sa procesora moguće je prikazati ostvarene rezultata rada kamiona za svaku smjenu pojedinačno. Dnevni izvještaji o radu tri kamiona koji su razmatrani prikazani su u narednom tekstu.

Površinski kop Turija

Bager kašikar ЭКГ 8И (2)

Kamion БелАЗ 75131 (8)

Odlagalište površinskog kopa Turija

Dnevni izvještaj

Ukupno prevezeno tereta 3.726 (t)

Prosječna vrijednost prevezenog tereta 81 (t) po ciklusu.

Ukupno vrijeme trajanja utovara (bez vremena zamjene kamiona) 4.560 (s).

Prosječno vrijeme trajanja utovara (bez vremena zamjene kamiona) 99,13 (s).

Ukupna potrošnja goriva 1.408 (l).

Broj ciklusa (tura) 46.

Ukupno pređeni put kamiona pod teretom (pun kamion) 91.720 (m).

Prosječno pređeni put kamiona pod teretom - (poluciklus pun kamion) 1.993,91 (m)

Ukupno pređeni put kamiona bez tereta (prazan kamion) 101.196 (m) - sa dolaskom pod bager na početku smjene i dolaskom pod bager na kraju smjene.

Prosječno pređeni put kamiona bez tereta - (poluciklus prazan kamion) 2.026,6 (m).

Ukupno vrijeme vožnje kamiona pod teretom (pun kamion) 19.920 (s).

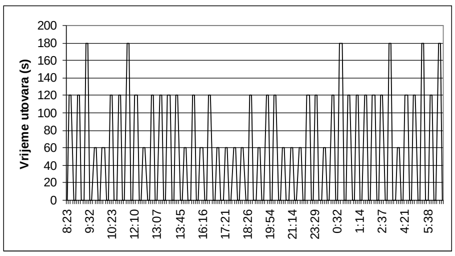
Prosječno vrijeme vožnje kamiona pod teretom (poluciklus pun kamion) 433,04 (s).

Prosječna brzina vožnje kamiona pod teretom (pun kamion) 4,60 (m/s).

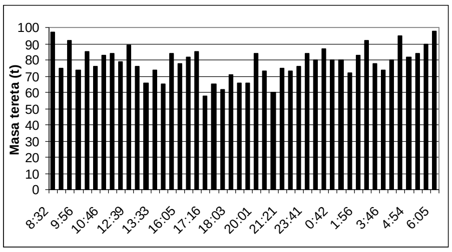
Predstavljanje informacija u vidu grafika - kamion БелАЗ 8

Na slici 3 dat je prikaz vremena trajanja utovara, a na slici 4 masa tereta prevezena u toku jednog ciklusa. Na slici 5 dat je prikaz pređenih puteva pri kretanju punog i praznog kamiona, a na slici 6 registrovane brzine.

Na slici 7 i 8 dat je prikaz promjene nivoa goriva pri utovaru i istovaru kamiona.



Sl. 3.



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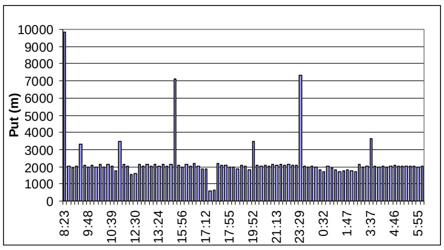

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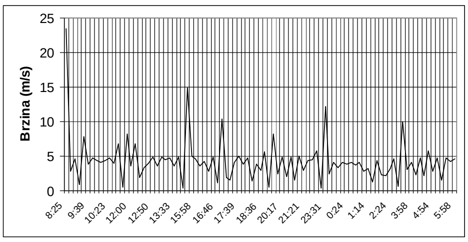

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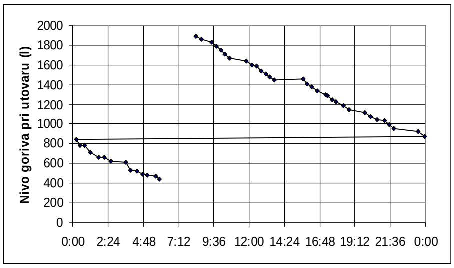

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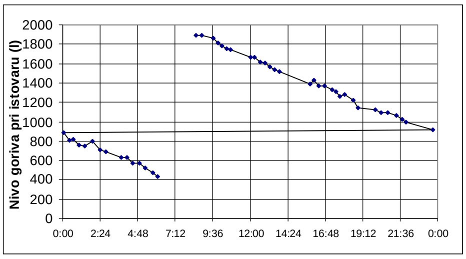


Sl. 8.

Površinski kop Turija
Bager kašikar ЭКГ 8И (2)
Kamion БелАЗ 75131 (9)
Odlagalište površinskog kopa Turija

Dnevni izvještaj

Ukupno prevezeno tereta 3.612 (t).

Prosječna vrijednost prevezenog tereta 78,52 (t) po ciklusu.

Ukupno vrijeme trajanja utovara (bez vremena zamjene kamiona) 4.980 (s).

Prosječno vrijeme trajanja utovara (bez vremena zamjene kamiona) 108,26 (s).

Ukupna potrošnja goriva 1.454 (l).

Broj ciklusa (tura) 46.

Ukupno pređeni put kamiona pod teretom (pun kamion) 91.885 (m).

Prosječno pređeni put kamiona pod teretom-(poluciklus pun kamion) 1997,50 (m)

Ukupno pređeni put kamiona bez tereta (prazan kamion) 113481 (m) - sa dolaskom pod bager na početku smjene i dolaskom pod bager na kraju smjene.

Prosječno pređeni put kamiona bez tereta - (poluciklus prazan kamion) 2.074,209 (m).

Ukupno vrijeme vožnje kamiona pod teretom (pun kamion) 19.860 (s)

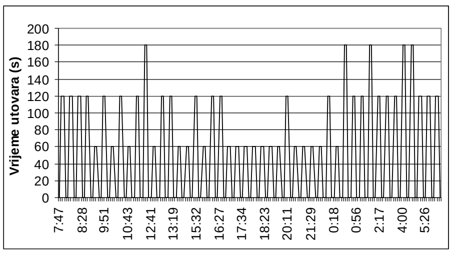
Prosječno vrijeme vožnje kamiona pod teretom (poluciklus pun kamion) 431,74 (s)

Prosječna brzina vožnje kamiona pod teretom (pun kamion) 4,63 (m/s)

Predstavljanje informacija u vidu grafika-kamion БелАЗ 9

Na slici 9 dat je prikaz vremena trajanja utovara, a na slici 10 masa tereta prevezena u toku jednog ciklusa. Na slici 11 dat je prikaz pređenih puteva pri kretanju punog i praznog kamiona, a na slici 12 registrovane brzine.

Na slici 13 i 14 dat je prikaz promjene nivoa goriva pri utovaru i istovaru kamiona.



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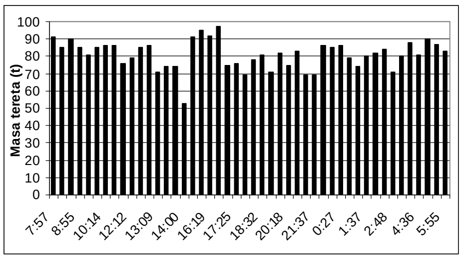

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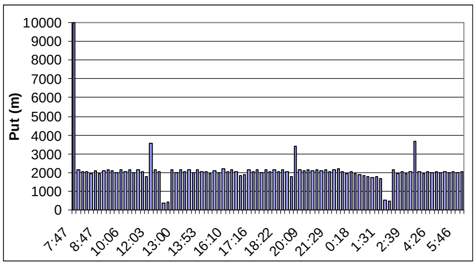

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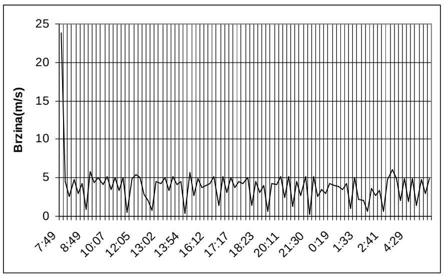

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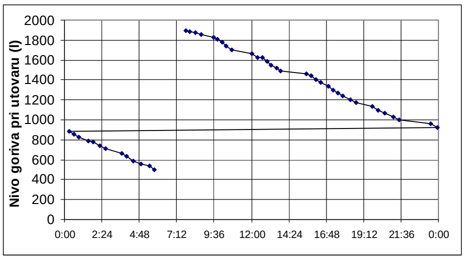
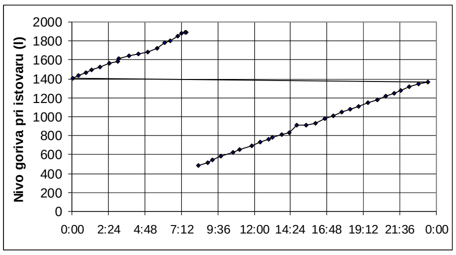


Sl. 13.



Sl. 14.

Površinski kop Turija
Bager kašikar ЭКГ 8И (2)
Kamion БелАЗ 75131 (10)
Odlagalište površinskog kopa Turija

Dnevni izvještaj

Ukupno prevezeno tereta 2.944 (t).

Prosječna vrijednost prevezenog tereta 77,47 (t) po ciklusu.

Ukupno vrijeme trajanja utovara (bez vremena zamjene kamiona) 4.200 (s).

Prosječno vrijeme trajanja utovara (bez vremena zamjene kamiona) 110,53 (s).

Ukupna potrošnja goriva 1.155 (l).

Broj ciklusa (tura) 38.

Ukupno pređeni put kamiona pod teretom (pun kamion) 73.037 (m).

Prosječno pređeni put kamiona pod teretom - (poluciklus pun kamion) 1922,03 (m)

Ukupno pređeni put kamiona bez tereta (prazan kamion) 92.923 (m) - sa dolaskom pod bager na početku smjene i dolaskom pod bager na kraju smjene.

Prosječno pređeni put kamiona bez tere-ta - (poluciklus prazan kamion) 1.950,34 (m).

Ukupno vrijeme vožnje kamiona pod teretom (pun kamion) 15.600 (s).

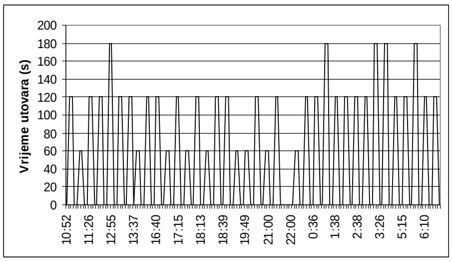
Prosječno vrijeme vožnje kamiona pod teretom (poluciklus pun kamion) 410,53 (s).

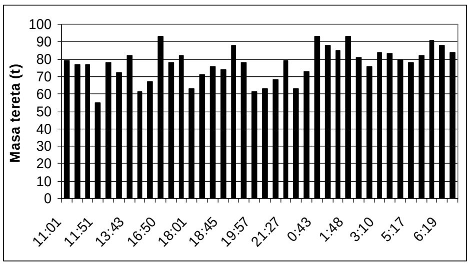
Prosječna brzina vožnje kamiona pod teretom (pun kamion) 4,68 (m/s).

Predstavljanje informacija u vidu grafika-kamion БелАЗ 10

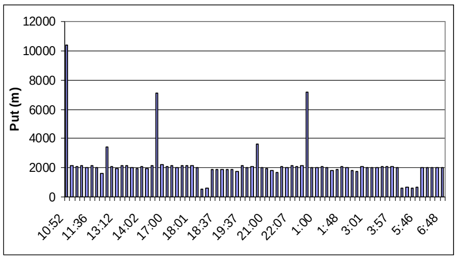
Na slici 15 dat je prikaz vremena trajanja utovara, a na slici 16 masa tereta prevezena u toku jednog ciklusa. Na slici 17 dat je prikaz pređenih puteva pri kretanju punog i praznog kamiona, a na slici 18 registrovane brzine.

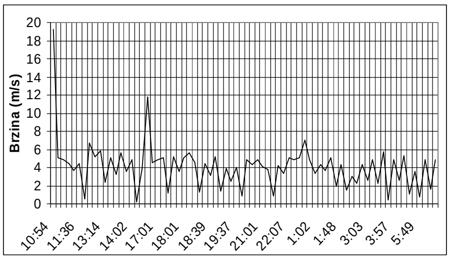
Na slici 19 i 20 dat je prikaz promjene nivoa goriva pri utovaru i istovaru kamiona.



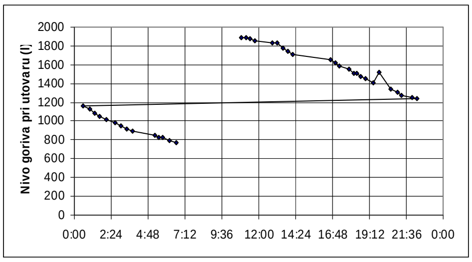


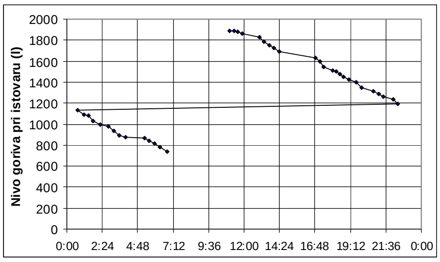
Sl. 15. **Sl. 16.**





Sl. 17. **Sl. 18.**



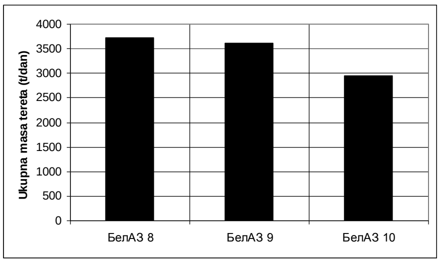


Sl. 19. **Sl. 20.**

4. DISKUSIJA

Analizirajući podatke sa procesora sva tri kamiona БелАЗ 75131 za jedan dan može se zaključiti da je kamion БелАЗ 8 u ukupno 46 ciklusa rada ostvario najveći kapacitet, a kamion БелАЗ 10 najmanji. Kamion БелАЗ 10 posmatranog dana u toku prve smjene nalazio se na servisu prema evidenciji službe operativno tehničke pripreme, te je ostvario samo 38 ciklusa rada. Iako su sva tri kamiona opsluživala isti bager evidentna je razlika u dužinama pređenih puteva i vremenu trajanja utovara. Prema evidenciji o dužinama pređenih puteva praznog kamiona na početku smjena, kamion БелАЗ 9 je samo na početku prve smjene imao dolazak sa primopredajnog mjesta Bešin, a na početku druge i treće smjene primopredaja je izvršena kod bagera, za razliku od kamiona БелАЗ 8 i БелАЗ 10 koji su na početku sve tri smjene dolazili sa primopredajnog mjesta Bešin.

Sa slike 21 može se uočiti da je ukupno vrijeme utovara najmanje za БелАЗ 10, što je i logično, jer je ovaj kamion u toku tri smjene ostvario 8 ciklusa manje od ostala dva kamiona. Najmanje prosječno vrijeme utovara je ostvareno za kamion БелАЗ 8, kao i najmanja prosječna brzina kretanja.



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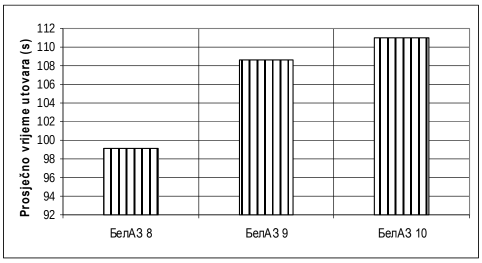

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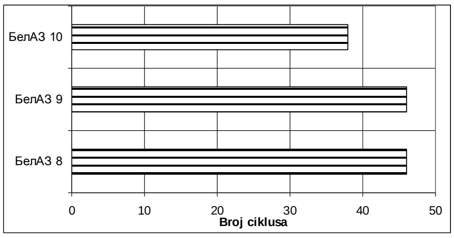

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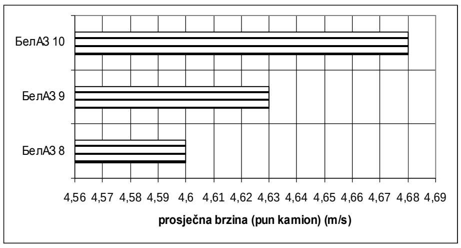


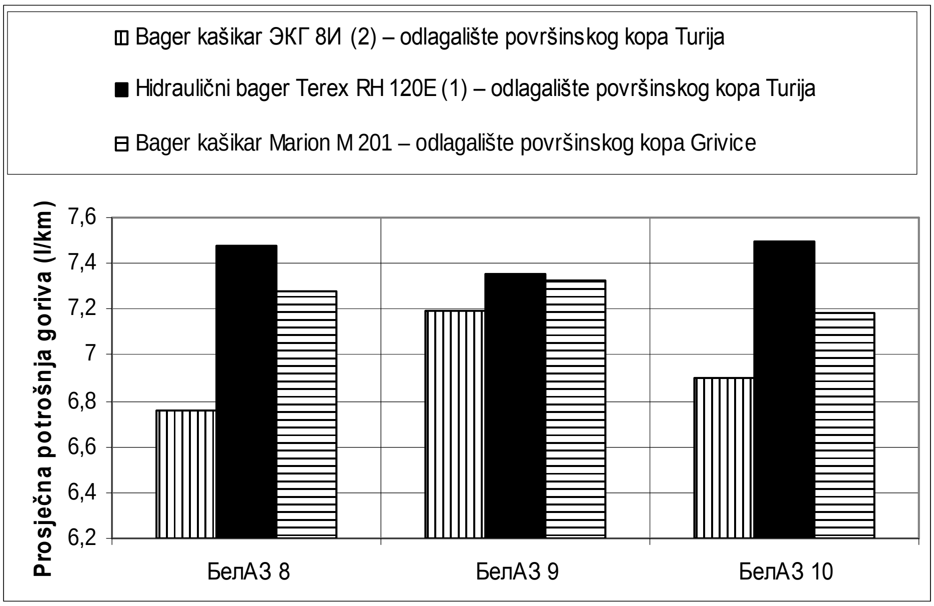
Sl. 24.

Prema podacima sa procesora kamiona БелАЗ 11 u toku dana on pređe 500 do 600 km, dok БелАЗ 8 pređe oko 170 km (isti bager isto odlagalište). Na kamionu БелАЗ 11 procesor nije ispravan tako da se podaci sa ovog kamiona ne mogu iskoristiti za dalju analizu dok se ne otkloni kvar.

Prema podacima sa procesora maksimalna količina goriva koja se registruje u kamionima БелАЗ je 1.892 (l) dok u rezervoar može stati 1.900 (l), a prosječna potrošnja goriva prikazana je u sljedećem grafikonu.

Tabela 1.

Bager – odlagalište	Kamion		
	БелАЗ 8	**БелАЗ 9**	**БелАЗ 10**
Bager kašikar ЭКГ 8И (2) – odlagalište površinskog kopa Turija			
Prosječna potrošnja goriva (l/km)	6,76	7,19	6,9
Prosječna količina goriva koja se dopunjava u rezervoar (l)	1448	1411	1154
Hidraulični bager Terex RH 120E (1) – odlagalište površinskog kopa Turija			
Prosječna potrošnja goriva (l/km)	7,48	7,35	7,50
Prosječna količina goriva koja se dopunjava u rezervoar (l)	1844	1138	1437
Bager kašikar Marion M 201 – odlagalište površinskog kopa Grivice			
Prosječna potrošnja goriva (l/km)	7,28	7,33	7,18
Prosječna količina goriva koja se dopunjava u rezervoar (l)	1494	1471	1508



Sl. 25.

5. ZAKLJUČAK

Ukupno jedanaest kamiona posjeduje procesore, od kojih su na kamionima БелАЗ 8, БелАЗ 9 i БелАЗ 10 procesori u ispravnom stanju, te se podaci sa ovih procesora mogu koristiti za analize. Kod ostalih kamiona potrebno je izvršiti popravku procesora da bi podaci o radu bili dostupni za analize.

Pet kamiona Terex 3600 B i dva kamiona tipa Mark 36 ne posjeduju ovakve procesore, te se podaci o radu i zastojima /otkazima ne mogu analizirati na ovaj način.

Podaci sa procesora kamiona mogu se iskoristiti za određivanje pojedinih parametara rada kamionskog transporta. Ugradnjom Global Positioning System (GPS) prijemnika na opremu kojom raspolaže RMU „Banovići“ otvara se mogućnost dobijanja stvarne i vremenske i prostorne slika rada, kao i formiranje dispečerskog centra u rudniku.

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ASSUMPTIONS FOR DEFINING THE MINE ASSESSMENT PROCEDURE WITH HYBRID MODEL

Abstract

Basic characteristic of modern mine is its dynamic activities, both in time and space. Quality of operation of such system is directly related to all risks impacting the system or mining project. Therefore, a risk analysis is necessary for each investment, hence the mines with the underground and surface technologies. Most appropriate solutions should be selected for each deposit or mine, in such manner to incorporate numerous aspects, including natural, regional, technical, economical, marketing, ecological, demographic and political aspects.

This paper reviews these issues, based on detailed scientific and expert research and using the suitable scientific methods and techniques, resulting in assumptions for development the Hybrid Model for Mine Assessment. This model is based on performance indicators for mines and mining regions.

Keywords: *Hybrid Model of Mine Assessment, risk assessment, aspects of impact, performance indicators*

INTRODUCTION

Numerous assessments, analyses, feasibility and pre-feasibility studies, studies and programs of revitalization, production improvement and consolidations for achievement the profitable operation, were developed for majority of mines in Serbia (metals, coal, non-ferrous). The main task of these documents is to present potentials of mines and possible profit in case of investment, to the market of capital (new owners, strategic partners, investment funds, banks) and also to the Government.

The majority of results indicated positive business results of the mine, just several years after investment. However, these did not include dynamic changes of capital market, materials, neither the changes on market of mineral resources.

Previous debts of mining companies with banks and creditors were neglected, and as such did not burden income and cash flow of the new project. This provided distorted interpretation of future condition. Results of such analyses, conceived in such manner, did not provide all required information which is necessary to a potential investor to make decision whether should or should not invest in these projects. This argument is proofed by the fact that very few of these mines completed transition and transformation process of ownership.

This means that the most important issue for decision making on investment into these mines is capability of investment return, indicated by cash flow of the

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project. However, interpretation of the cash flow could have limitations, as well as data on ownership of mining company presented in the project. Consequence of this is that the investment return must be provided from the company assets or profit generation capability. In case of bad scenario, such payment at the moment cannot be made from the assets of these companies.

Concept of compensation for risky investment (risky capital investments) has various interpretations for those who lend money (banks, investment funds) or provide guarantees (issuing state guarantee), in relation to the mining companies, who borrow money. Since both parties (banks and mining companies) expect the major role in developing the specific project, banks expect the same level of information as provided to the management of the mining company. The largest misconception is that the banks are accept the interest as risk for credit, while participating mining companies expect large income from the invested capital, as long as the project develops as planned [1].

Most of Serbian mining companies consider that assessments, studies, projects and programs, conceived in described manner, are sufficient document for the investor. This approach is often misused, and difficult for understanding. There are numerous examples with presented weak performances of the project, due to partiality of project team, but also because the projects are based on the unrealistic calculation and schedules.

Acceptable document for investment – bankable document is document which provides all required information and necessary verifications to the investors and engineers. Experts will determine whether the risk is acceptable and the project is complete, with foreseen financial resources [2].

Such document, developed to attract investors, should provide the answers to numerous technical and other questions. Following this attitude, several information groups can be identified, which must be processed. The most important information which should be considered is surely reserves of mineral resource and geology. Detailed description of planned processes, locations, proofs, verifications and possibility that come into not available categories of reserves, are also essential information for the investor in order to understand the most important risks in mining project.

Completeness of production costs overview and technological process are next the most important components for project evaluation. Production costs, as well as information on mine operation plan during whole mine life, are also very important for risk assessment of the project, i.e. risks in financial evaluation. The main questions are whether technology is designed in accordance to properties and specifics of project type and deposit, and whether the project leader has appropriate qualification for such project.

The following important components of the project are cost of capital and designed cash flow. What is the overall cost? How reliable are they (what is their accuracy)? Is the cash flow based on norms (regulations) for the mining company? Does cash flow include some uncertainty which can lead to failure of the project – this issue has importance, especially in developing countries. What is included into economy analysis for investment return? Whether acceptable deviations are included and processed for working capital payments, costs of monetary transfers and taxes? Are the infrastructure cost determined carefully (reasonably)? [3]

Environmental protection gained importance with large impact on mining industry, as well as financial institutions. This became the fact, since financial institutions can exert the political influence on its own, considering their role in financing projects which has sensitivity regarding environment (such as WB and EBRD).

Banks are demanding respect of environmental standards defined by the World Bank, since banks cannot bare financial or political risk generated by development of the mine with insufficient environmental protection or mines irresistible to potential threats [4].

Clearly defined of planned process execution is required, with realistic impacts estimations on dynamics, which will identify the major obstacles and stages check points of project executions. Even after consideration of all mentioned issues with satisfactory results, additional information are necessary regarding all auxiliary risks, i.e. the risks which could exert threat to the project in significant extent. These are mainly elevated risk on state level, which could discourage potential investors. In case of Serbia, these risks are still present, impairing investment climate, reducing interest with investors for mining companies [5].

Additionally, the newly presented projects as well as projects for international market must be in accordance with all environmental requirements, while production process must be designed in accordance to the standards of developed countries, not just in accordance to the national legislation. These remarks are leading to the initial statement that mineral potential, deposit of mineral resources or mine, should be considered as important, if such object has attributes which attracts someone's interest, either as potential investor or strategic buyer of resource [6].

Therefore, the aspects regarding the existing mines and possibility of presence the mining industry with basic facilities and objects, such as accesses, human settlements, power supply, road and telecommunication infrastructure, etc. Their availability reduces requirements for new infrastructure, but also availability of trained personnel in immediate proximity. This is true, although considering the fact that most of employees will require training for up-to-date mining mechanization and equipment. These are initial strengths and opportunities of mining business [7].

It is evident that reduction of risk and less expensive funding on the market will surely make certain mining projects more attractive to some extent. As a result, there will be more successful mines in the future.

ASSUMPTIONS FOR SELECTION OF MODEL PARAMETERS

Starting point for definition of key factors and performance indicators, required of selection the Model parameters was successful transition process which is not only dependent to individual mines, but also to overall encirclement, which to larger or lesser extent has impact on individual cases of mine consolidation.

It is necessary to form the input performance indicators for each mine, which are related to the existing condition of the mine and potential of changes. These are necessary for determination the technical and productive level of mine, as well as economical one. These data are mainly related to the quantitative and quality parameters and indicators, used for determination the condition and perspective of individual subsystems or integral production system [8].

The final forming of Model requires:

- adding (or excluding) some indicators, depending on availability of proper information;
- determining the indicators by criteria (total for all mines, as the overall interpretation of underground mines), including all specifics (problems);
- determining the indicators for the model and assigning to them the previously selected weight factors. These indicators must be determined for

each mine, but according to the identical methodology;
- adoption of (own) standards for ranking the mines, i.e. determining the criterion of minimal number of "positive points", according to which specific mine can be qualified as capable for consolidation;
- determining the indicators presenting impact of regional development within the area of the mine (composite indexes will be used, calculated as interdependence level between the mine and local community);
- adoption the risk assessment of the country, which includes financial and economical assessments, to justify the investment in specific country.

Prior to any attempt to define the model, two approaches for presentation of mine business results must be analyzed.

The first one is presentation of mining project just by the economy parameters. This approach does not provide the accurate view on the project at this level, due to the operational and accumulated losses. The second approach, which is accepted for this purpose, includes the forecasts based on financial parameters of the mining company. Formula for bankruptcy probability can be used if the analyzed company appears in poor condition, in order to determine so called Z-value of the company. Z-value is an indicator on how the company is close to bankruptcy, i.e. represents financial strength of the company.

Dominant role regarding to the potential for changes will have those indicators presenting changes related to the increased utilization of facilities and productivity, but the most important indicators will be those on economy and finance. It should be mentioned that the country risk assessment has directly impact on interest rates, and consequently on value of internal rate of return of the project.

Analysis on mines condition, based on the available valid information, must meet the requirement regarding the Model unification, thus enabling comparison between coal, metal and non-ferrous mines.

Assessment the indicators of importance

There are two starting principles during development of assessment the mining investment projects for determining the hybrid evaluation model, which can be used in multiple ways.

The first one indicates that various different properties must be included, mainly all major positive and negative factors which could have impact on mines, viewed as companies or projects. Reason for this is not just that relevant data are missing or not of sufficient quality or could not be directly compared, but because these factors must be researched in regard to the complex interdependence, reflecting the current situation of rapid change, as well as potential of mines.

The second principle stipulates development of composite index of analyzed variables, as an instrument for subsequent comparison (benchmarking) of mines according to the complex criteria [9]. Purpose of this approach is to enable comparison of various mines and local communities according to their attributes.

The use of relevant indicators (geological, technical, technological, geographical, economical, demographical, and other) generates the initial quantum of data. Therefore, this methodology should start with definition of relevant indicator list for selected analysis factors. These are defined in usual way, while their calculated effects should be added in order to obtain the tool for evaluation and ranking. Such analysis should enable comparison of selected mines and reaching conclusions regarding detected problems for each individual mine [10].

Compression of various indexes into composite index method

Compression of various indexes into the single measure, designed as tool for comparison the mines in different region, creates at least two major problems. The first one is that indexes are measured in different units and also vary in completely different ranges. The second problem is presented by the fact that these indexes could have different impact, since some cause increase of the risk, while the others reduce it, with various intensities.

Solving the first problem included standardization of all numerical indexes, meaning that these are presented as deviations from the mean value, divided with their standard deviation. In this way, all indexes have identical mean value (zero) and same average variation around mean value (one). Furthermore, any sum of indexes will also have zero mean value in the sample. Therefore, each composite index, containing any number of standardized indexes can be easily interpreted as positive (above) or negative (below) deviation from the mean value – mines or region of the mine.

The second problem, determination of TK and sign for each index included into composite index, is solved by heuristic way. Several iterations were performed in application of this methodology: definition of index list, evaluation of their sign and TK, calculation and analysis of results.

Definition of final list of indexes

This task starts with the initial but incomplete list if indexes, which can be described with relevant data. However, all indexes do not have the same importance. The following principles were used for selection the important indexes which will be included into composite index:

Frugality. Among all collected indexes, 23 will be used as important ones for mines, and 36 for mining region. The others are excluded either because lack of data or redundancy, since it is used for description similar characteristic as other index.

Balance. All aspects of the mine and belonging regions should be presented with approximately same number of indexes, i.e. their weighted sum. Similarly, some indexes present the current situation while the others are related to the future. Therefore, both grouping aspects should be used.

Detail. The final set of selected indexes for composite index should contain maximum of independent variations of all used variables. This means that sufficient information should be included in order to create complex risk assessment.

Performance indicators provide information on mining potential quality and possibility of its consolidation. These are important due to their indication on level of completeness of goal (success or failure). In case of subjective evaluation, expressed as a rule in linguistic variables, definition of performance indicators is reduced to multi criteria task with quality criteria. Model incorporates scale for transformation of linguistic expressions into numerical form applying the Fuzzy theory and grouped decision in case of uncertainties. The goal was to create list of indexes which encompass all characteristics of mines, and particularly situation in the region of the mine and potential for changes in the future.

According to the above mentioned, base for the Model for mines evaluation and their importance in local community is synergy of methods, techniques and methodologies, such as the quantified SWOT analysis, methodology of harmonized goal, theory of the Fuzzy sets and initial parameter determination for the Benchmarking. Synthesis of these techniques and methods resulted in Hybrid Model which is used for Mine Assessment [11].

Quality evaluation of the factors

All technical and technological solutions, included in design of a new mine or reconstruction of the existing one, should have all quantity and quality parameters and indicators.

Parameters and indicators of quality represent technological properties of the mine, providing the main features. Forecasting and description of technological, spatial, production and economical character of the analyzed mine are enabled there.

This type of forecast and evaluation for short and long-term could be of significant importance for investor and his evaluation of internal and external surroundings of the company/project and for definition the development policy, strategy, investment planning and selection of best alternatives. This is one of the means to be used for determination the scope of investment and future decisions.

Therefore, the forecasting method (Delphi) will be used for quality evaluation of factors both for establishment the underground mine consolidation method and determining the regional importance of the mine. Evaluation of quality will be based on questionnaires, evaluation criteria and expert knowledge. This knowledge is acquired by formation of teams, for evaluation the quality factors. Evaluation includes typical criteria and it will be used for assessment the different topics, such as the mine potential, perspectives on regional level, up to the environmental impact. Experts were hired for this purpose, with significant experience and knowledge on mining issues, as well as experts regarding the environmental protection. All of these experts were employed on positions of condition and operation control of the mine, including their legal obligations.

Experts determined impact by grading each criteria, according to own experience. Grades were from 1 to 5, where 1 is the worst and 5 is the best grade. It is considered that the Interval scale is suitable approach for quantifying the quality attributes. The most commonly used scales are 1-5 and 1-10, since the attribute extremes are not determined in most cases for specific criteria.

Quantification of quality criteria can also be performed according to the other procedures, where the fuzzification includes the uncertainties present with linguistic presentation of variables.

Therefore, **decision matrix becomes quantified by each criteria and such matrix is called the quantified decision matrix**.

In order to solve the problem, it is necessary to normalize values of attributes – indicators, i.e. to perform their "equalization" or to remove their dimensions out. As the result of this, values of all indicators are reduced to interval from 0 to 1. Normalization of quantified matrix can be performed in two ways: vector normalization and linear normalization.

There is a threat to omit relation of two criteria in appropriate way if one quality criterion describes the one set of expression with belonging quantification scale, while the other criterion has different number of set members and different scale. Therefore, it is necessary to determine the unique way for quantification of quality attributes.

Experts evaluate the certain quality values, hence it is considered that problems of multi criterion analysis should require standard scale and grades, and having in mind mentioned extremes with possibility that attribute can be assigned any value in the mentioned interval. It is feasible to develop standard set of linguistic expressions which can be quantified in given scale (such as: very strong, strong, moderate, weak and very weak).

Quality evaluation of ranking criteria

There are few cases when all indicators are of same importance for decision making. Decision maker can assign weights to the indicators, according to own evaluation or use some other evaluation method.

Current business requires from decision maker to make the important business decisions more often in permanently changing environment and situations when the accurate data on all impacting parameters are not available. On the other hand, wrong decisions could be catastrophic and irrevocable. Therefore, decision makers must be capable to make a decision with small risk, which is accomplished with modern methods, using multi criteria methods and group decision making. Certainly, multi criteria methods are not sufficient, since decision makers will always have dominant role through definition of problem, determination of weight coefficients and ranking of quality indicators.

Most of the methods, used for decision making, require information on relative importance of each indicator. However, indicator selection method or their differentiation during grouping according to their information type is neither clearly established nor unique. Therefore, formation of composite index is creative and practical activity, which is based on arbitrary indicator selection, with outcome depending most on experience of researcher and data quality.

Selection of factors for the Model

Relevant scale of observations for selection the model factors included higher and lower aggregation levels (surroundings – aspects – factors – indicators). Various available data sets were used for the mines and mining regions.

In order to evaluate risks related to mine development, which must be considered as the result of previous development and probability of future improvements, two major criteria must be used:

I. Inferred conditions and current situation,
II. Potential for positive change.

Each of indicators in the initial list of relevant factors requires definition of appropriate statistical measure, in relation to the available data. The goal is to create list of indicators which would encompass all properties required for evaluation the mines and mining regions.

The main aspects for definition the model to be analyzed are divided into two groups:

Internal:

i. Technical and production aspects,
ii. Aspects of work efficiency,
iii. Financial and business aspects.

External:

iv. Regulatory aspects (Political and economic environment),
v. Regional aspects (Regional development balance),
vi. Market aspects (Geographical location of the deposit).

Due to the complexity of applied theoretical categories and difficulties related to their measurement, both risk components (difficulties in present situation and potential for future development) should be approximated by various physical and mathematical indicators presenting internal and external group of factors.

Key factors for internal analysis are mainly related to the *geological potential, technical capabilities of the mine, work efficiency, investment potential and future development.* Key factors for external analysis are mainly related to the *political environment, regional development and geographical location*.

Table 1 *Selection of factors and performance indicators for the Model*

	Factors		***Performance indicators***
Internal	Mineral resources and condition for mining *	quantitative	- Composite index of regional dependence
	Exploration level	quantitative	- Exploration level
	Production system and production trend	qualitative	- Reserves - Geological conditions - Working conditions - Trends - Working and environment protection
	Utilization of facilities	quantitative	- Planned level of utilization
	Diversity and quality of product	qualitative	- Diversity and quality of product
	Expected life of mine	quantitative	- Life of mine
	Quality of management structure	quantitative	
	Qualification of work force	quantitative	- Indexes of engaged work force
	Productivity	quantitative	
	Investment potential	qualitative	- Potential for mechanizing - Possible production rates - Investment potential
	Financial strength	quantitative	- Zeta Altman test
	Profitability	quantitative	- IRR/DS (CAP Model)
External	Political risk**	quantitative	
	Economical risk**	quantitative	- Composite index of country risk
	Business risk**	quantitative	
	Economic development of local community*	quantitative	
	Social development of local community *	quantitative	- Composite index of regional development
	Environmental protection*	quantitative	
	Education level*	quantitative	
	Product demand (locally / globally)	qualitative	
	Competitiveness and price stability	qualitative	- Expert's evaluation
	Appropriate transport infrastructure	qualitative	
	Industrial connections	qualitative	

* *These factors are presented by composite indexes calculated during analysis of regional aspect*

** *These factors are presented by indexes acquired from Agency which evaluates risk of the country*

CONCLUSION

It is extremely important to provide the complete and reliable information about suitability and importance of the project, to the investors, but also to the decision makers in investing region, especially in contemporary, complex and risky conditions of investment in mining.

Determination of importance and suitability process, hence mining investment risks, is very complex, mainly because of fuzzy characters of indicators, numerous attribute and complexity of correlations.

Uncertainty is present during decision making process, even when complete sets of parameters are made available, since some criteria for alternatives assessment are depending on subjective evaluation of experts and relative weight of selected criteria. Subjectivity cannot be avoided in solving the real problems, but uncertainties must be taken into consideration for decision making process. Such uncertainties are modeled with the Fuzzy set theory.

Analysis presented in this paper is important for formulation of strategy. Analysis of external opportunities and threats is mainly performed to detect whether the mining company can exploit opportunities and avoid threats, facing uncontrolled external environment. Analysis of internal strength and weaknesses is performed to determine ways of how internal tasks are performed inside the company (such as management, work efficiency, exploration and development). Quantified SWOT analysis can provide the sufficient information to evaluation the position of company in comparison to the competitors. Also, it can be used as a base for future development. Application of various techniques and models, unified into universal model provides necessary complexity, thus justifying the Hybrid Model name.

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PRETPOSTAVKE ZA DEFINISANJE POSTUPKA OCENE RUDNIKA SA HIBRIDNIM MODELOM

Izvod

Osnovno obeležje savremenog rudnika je njegova dinamičnost, kako po vremenu tako i po prostoru. Kvalitet funkcionisanja takvog jednog sistema direktno je u funkciji svih rizika koji na sistem/rudarski projekat mogu da utiču. Samim tim analiza rizika je neophodna za svaki investicioni poduhvat, pa tako i za rudnike kako sa površinskom tako i rudnika sa podzemnom eksploatacijom. Za svaki rudnik ili ležište je potrebno izabrati najpovoljnija rešenja koja obuhvataju široki spektar uticajnih aspekata od prirodnih, regionalnih, tehničkih, ekonomskih, tržišnih, ekoloških, demografskih i političkih.

Razmatrajući ova pitanja, u ovom radu se na osnovu detaljnih naučno-stručnih istraživanja i primenom odgovarajućih naučnih metoda i tehnika, daju pretpostavke na osnovu kojih je razvijen Hibridni model ocene rudnika baziran na indikatorima performansi za rudnike i rudarske regione.

Ključne reči: *Hibridni model ocene rudnika, analiza rizika, aspekti uticaja, indikatori performasi*

UVOD

Za veliki broj rudnika u Srbiji (metali, ugljevi, nemetali) u prethodnom periodu urađene su mnogobrojne procene, analize, studije i programi moguće revitalizacije, unapređenja proizvodnje i konsolidacije sa efektima dostizanja ekonomične eksploatacije iz ovih rudnika. One su imale za cilj da predstave tržištu kapitala (novim vlasnicima, strateškim partnerima, investicionim fondovima, bankama), ali i samoj državi, potencijale rudnika i mogući profit koji bi se ostvario investiranjem u njih.

U većini slučajeva se prikazivalo pozitivno poslovanje rudnika posle samo nekoliko godina investiranja, bez uzimanja u obzir dinamičkih promena na tržištu kapitala, repromaterijala ali i tržištu samih mineralnih sirovina.

Prethodna zaduživanja ovih preduzeća kod banaka i komercijalnih poverilaca su zanemarivana i kao takva nisu opterećivala prihode i gotovinski tok novca novog projekta, što je u startu davalo iskrivljenu sliku budućeg stanja. Tako koncipirani, rezultati ovih analizanisu davali sve potrebne informacije koje su neophodne potencijalnim investitorima da odluče da li će ili neće ući u finansiranje ovakvih projekata. Kao potvrda tome, evidentan je mali broj ovih rudnika kod kojih je proces tranzicije i transformacije vlasništva okončan.

Znači da za donošenje odluka o investiranju u ove rudnike najbitnija je mogućnost povraćaja investiranih sredstava, što sledi iz prikaza gotovinskog toka projekta. Međutim, značenje gotovinskog toka je ograni-

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čeno, kao i podaci o imovini rudarskog preduzeća prikazanog u projektu. To znači da se povraćaj sredstava mora obezbediti iz ostale imovine preduzeća ili iz njegove profitne sposobnosti. Ako stvari krenu loše, ta naplata se, danas, ne može ostvariti od vrednosti imovine ovih preduzeća.

Pojam nadoknade za ulaganja pod rizikom (rizična ulaganja kapitala) imaju različita tumačenja za one koji novac daju ili pozajmljuju (banke, investicioni fondovi) ili garantuju (davanje državne garancije) u odnosu na rudarske kompanije koji taj novac troše. Budući da i banke i rudarske kompanije/preduzeća očekuju da će projekat zavisiti od njih, banke zahtevaju istovetne informacije koje zahteva i menadžment rudarskog preduzeća. Najveća razlika je što banke prihvataju kamatu na kredit kao rizik, dok, ako stvari idu kako treba, participirajuće rudarske kompanije očekuju dobijanje vrlo velikih prihoda od uloženog kapitala. [1]

Većina rudarskih preduzeća u Srbiji smatra da su ovako koncipirane procene, analize, studije i programi za investitore dovoljan dokument. To je bio često zloupotrebljavan i malo razumljiv koncept. Postoje brojni loši primeri gde su generalno pokazane slabe performanse projekata kako zbog pristrasnosti projektnog tima tako i zbog toga što su bile zasnovane na nerealističnim proračunima i rokovima.

Dokument koji bi bio prihvatljiv za finansiranje (bankable) je onaj koji na zadovoljavajući način daje sve informacije i potrebne revizije (verifikacije) za investitore i njegove inženjere koji će utvrditi da li je prihvatljiv rizik i da li je projekat celovit, sa predviđenim finansijskim sredstvima.[2]

Ovakav dokument koji pretenduje da privuče investitora treba da odgovori na mnoga pitanja, tehnička i druga. Držeći se tog stava, mogu se izdvojiti grupe informacija, koje moraju biti obrađene. Svakako da rezerve meneralne sirovine i geologija predstavljaju najvažniju podlogu koju treba uzeti u razmatranje. Detaljni opisi predviđenih procesa, lokacija događaja, dokazi, uverenja i mogućnost da neke kategorije rezervi nisu raspoložive su suštinske informacije za investitore da mogu razumeti glavne rizike u rudarskom projektu.

Kompletnost prikaza proizvodnih troškova i tehnološki proces su sledeći najvažniji elementi u vrednovanju (evaluaciji) projekta. Proizvodni troškovi kao i informacije o planu rada rudnika za ceo vek trajanja su takođe izuzetno važni za sagledavanje rizika u projektu, odnosno rizika u ekonomskoj proceni. Da li je u projektovanju tehnologije rada ostvaren pristup i specifičnost prosuđivanja što je bitno baš za ovaj tip projekta, za ovaj tip rudnog tela, da li je obrađivač studije baš najkvalifikovaniji?

Sledeće od važnih elemenata su troškovi kapitala i gotovinski tok projektovanih prihoda i rashoda (cash flow). Kakvi su mu ukupni troškovi? Koliko mu se može verovati (kolika se može pripisati tačnost)? Da li je baziran na normama (propisima) za preduzeće? Da li u tome ima nešto nepredviđeno, ili neizvesno što može dovesti do neostvarenja projekta (odstupanja od datog cash flow) - posebno je to važno u zemljama u razvoju. Šta ulazi u ekonomske analize za povraćaj sredstava u koje se investira? Da li su obrađena moguća najveća prihvatljiva odstupanja za plaćanja za obrtna sredstva, za troškove transfera finansijskih sredstava, za iznos dodatnih taksi? Da li su troškovi infrastrukture uzeti sa dovoljno pažnje (rezonski)? [3]

Zaštita životne sredine došla je dotle da mora imati bitnog uticaja i na rudarsku industriju, ali i na finansijske institucije. Ovo je jedna posebna istina, jer finansijske institucije mogu i same učestvovati u političkim pritiscima, ako se ima u vidu njihova uloga u finansiranju projekata koji su osetljivi na zaštitu životne sredine (primer WB i EBRD). Banke traže poštovanje standarda za zaštitu životne sredine koje je propisala Svetska banka, jer one ne mogu preuzeti finansijski ili politički rizik koji bi nastao gradnjom rudnika sa neadekvatnom zaštitom životne sredine ili rudnika neotpornog na potencijalne opasnosti. [4]

Potreban je jasno definisan plan odvijanja predviđenog procesa, sa realnim procenama uticaja na dinamiku, koji će imati identifikovane glavne moguće prepreke i mesta faznog proveravanja toka procesa. Čak i kad se na sva navedena pitanja dao zadovoljavajući odgovor, potrebne su i dodatne informacije za sve prateće rizike, odnosno rizike koji mogu projekat ugroziti u većoj meri. To su pre svega povećani rizici na nivou države koji mogu odvratiti potencijalne investitore. Na primeru Srbije, oni su još uvek izraženi te shodno tome u većoj meri pogoršavaju investicionu klimu i ne ohrabruju u zadovoljavajućoj meri investitore za investiranje u ovakva preduzeća. [5]

Ovome treba dodati, da projekti koji su novi na tržištu i projekti koji računaju na međunarodno tržište moraju ispuniti zahteve svih mera zaštite životne sredine, a proizvodni proces mora biti usaglašen sa standardima ne samo na nacionalnom nivou, nego moraju biti u skladu sa standardima razvijenih zemalja. Na osnovu pomenutog, dolazimo do početnog stava da mineralni potencijal, ležište mineralnih sirovina ili rudnik, treba smatrati kao važnim, ako on ima takve aspekte koji mogu privući nečiji interes sa tržišta bilo kao potencijalnog investitora bilo kao strateškog kupca sirovine. [6]

Samim tim i aspekti koji sagledavaju već postojeće rudnike i mogućnosti prisustva rudarstva, sa osnovnim postrojenjima i objektima kao što su prilazi, naseljena mesta, elektro-energetska, putna i telekomunikaciona infrastruktura itd. Njihova dostupnost čini da su niski zahtevi za novom infrastrukturom, ali i raspoloživost obučenog kadra u neposrednoj blizini, čak uzimajući u obzir činjenicu da će većina ljudi zahtevati obuku za modernu rudarsku mehanizaciju i opremu, predstavljaju početne snage i šanse uspešnog rudarskog biznisa. [7]

Evidentno je da će smanjenje rizika investiranja i jeftiniji novac na tržištu svakako do izvesne granice približiti i učiniti neke rudarske projekte atraktivnijim nego danas, što će kao rezultat imati veći broj uspešnih rudnika u budućnosti.

PRETPOSTAVKE ZA IZBOR PARAMETARA MODELA

Za definisanje ključnih uticajnih faktora i indikatora performansi potrebnih za izbor parametara Modela, pošlo se od uspešnosti procesa tranzicije koji ne zavisi samo od rudnika pojedinačno, već i od sveukupnog okruženja koje u većoj ili manjoj meri utiče na pojedinačne slučajeve konsolidacije rudnika.

Za svaki rudnik potrebno je, radi utvrđivanja tehničko - proizvodnog i ekonomsko - finansijskog nivoa rudnika, kao prve etape pri utvrđivanju moguće konsolidacije rudnika, formiranje ulaznih indikatora performansi koji su vezani za postojeće stanje rudnika i za potencijale promena. Ti podaci se uglavnom odnose na kvantitativne i kvalitativne parametre i pokazatelje na osnovu kojih se određuje stanje i perspektive pojedinih podsistema ili integralnog proizvodnog sistema. [8]

U konačnom oblikovanju Modela će biti potrebno:

- dodati (ili izbaciti) neke indikatore za koje postoje ili ne postoje validne informacije;
- utvrditi indikatore po kriterijumima (zbirno za sve rudnike kao ukupna slika rudnika sa podzemnom eksploatacijom) sa svim svojim specifičnostima (problemima);
- određivanje indikatora, sa kojima ulazimo u model, dodeljujemo im prethodno utvrđene težinske ocene. Biće neophodno da se ovi indikatori utvrde za svaki rudnik, ali pod uslovom da se to uradi po istoj metodologiji;
- usvojiti (sopstvene) standarde za rangiranje rudnika, odnosno odrediti kriterijum minimalnog broja „pozitivnih poena“ koji daju kvalifikaciju da

taj rudnik u perspektivi može biti konsolidovan;

- utvrditi indikatore koji prikazuju uticaj regionalne razvijenosti oblasti gde se rudnici nalaze (koristiće se kompozitni indeksi dobijeni kod određivanja stepena međuzavisnosti rudnika i lokalnih zajednica);
- usvojiti procenu rizika zemlje kojom se procenjuje finansijska i, šire gledano, ekonomska opravdanost plasiranja sredstava u neku zemlju.

Pre bilo kakvog definisanja Modela moraju se sučeliti dva pristupa prikazivanja stanja ekonomsko-finansijskog poslovanja rudnika.

Prvi način bio bi prikazivanje stanja rudarskog projekta samo kroz ekonomske pokazatelje, što u ovom trenutku ne bi dalo pravu sliku o samom aktuelnom projektu zbog operativnih i akumuliranih značajnih gubitaka. Drugi način, koji je ovde i prihvaćen, da se vrše i predviđanja na temelju finansijskih pokazatelja rudarskog preduzeća. Ako preduzeće koje se analizira izgleda da je u lošem finansijskom stanju, može se koristiti formula za verovatnoću bankrotstva da bi se utvrdila tzv. Z-vrednost preduzeća. Z-vrednost predstavlja indikator koliko je preduzeće blizu bankrotstvu tj. predstavlja finansijsku snagu preduzeća.

Za potencijale promena svakako dominantnu ulogu imaće oni indikatori koji prikazuju promene u delu povećanja iskorišćenosti kapaciteta, produktivnosti, ali među najvažnijim indikatorima biće ekonomsko-finansijski pokazatelji. Treba napomenuti da se procena rizika zemlje direktno odražava na visinu kamatnih stopa, samim tim i na visinu zahtevane interne stope rentabilnosti projekta.

Na osnovu izvršene analize stanja rudnika iz raspoloživog fonda validnih informacija koje rudnik poseduje, zaključuje se koji rudnici imaju dovoljno informacija, a ujedno zadovoljavaju uslove unifikatnosti Modela, obzirom da se na listi rudnika mogu naći i rudnici uglja i rudnici metala i rudnici nemetala.

PROCENA ZNAČAJA INDIKATORA

U razvijanju ocene rizika rudarskih investicionih projekata kod utvrđivanja hibridnog modela ocene rudnika, koja bi mogla biti višestruko upotrebljiva, treba poći od dva glavna principa.

Prvi, mora se uzeti u obzir veliki broj različitih karakteristika, praktično, svi glavni pozitivni i negativni faktori koji mogu imati značajan uticaj na rudnike posmatrane kao preduzeća/projekte. Ne samo zato što relevantni podaci nedostaju ili nisu odgovarajućeg kvaliteta ili se ne mogu direktno uporediti, već zato što se mnoge karakteristike moraju istraživati zbog veoma složenih međuzavisnosti ekonomskih i neekonomskih faktora koji određuju sadašnju situaciju, brze promene, kao i perspektive ovih rudnika u Srbiji.

Drugi princip je da, u cilju poređenja različitih rudnika ili lokalnih zajednica (opština) prema njihovim raznim karakteristikama, treba razviti kompozitni indeks posmatranih varijabli, kao instrument za kasnije poređenje (benchmarking) rudnika na bazi složenih kriterijuma.[9]

Korišćenjem relevantnih indikatora (geoloških, tehničko-tehnoloških, geografskih, ekonomskih, demografskih, socioloških, političkih, ekoloških, statističkih i dr.) utvrđuje se početni kvantum podataka. Stoga, ova metodologija treba da pođe od definisanja liste relevantnih indikatora za izabrane faktore posmatranja. Oni se definišu na uobičajeni način primeren analizi ocene efekata, a njihovi izračunati efekti treba da budu sabrani, kako bi se dobilo sredstvo za ocenu i rangiranje jedinica posmatranja. Takva analiza bi trebalo da omogući i poređenje izabranih rudnika i postavljanje dijagnoze prema ustanovljenim problemima svakog rudnika ponaosob. [10]

Metod sažimanja različitih indikatora u kompozitni indeks

U sažimanju različitih indikatora u jedinstvenu meru, koja je konstruisana kao sredstvo za poređenje rudnika u različitim regionima, javljaju se bar dva velika problema. Prvi je u tome što su razni indikatori mereni različitim jedinicama merenja i variraju u sasvim različitim opsezima, tako da se ne mogu objediniti na smislen način. Drugi problem je što načini njihovog uticaja mogu biti različiti, jer neki od tih faktora uzrokuju povećanje, a neki smanjenje rizika, i to s različitim intenzitetom.

U rešavanju prvog problema, standardizovani su svi numerički indikatori, što znači da su predstavljeni kao odstupanje od aritmetičke sredine, deljeno njihovom standardnom devijacijom. Na taj način, svi indikatori imaju istu srednju vrednost (nula) i istu prosečnu varijaciju oko srednje vrednosti (jedan). Štaviše, bilo koja suma indikatora imaće takođe nultu srednju vrednost u uzorku. Stoga svaki kompozitni indeks, koji sadrži bilo koji broj standardizovanih indikatora, lako može da se interpretira kao pozitivno (*iznad*) ili negativno (*ispod*) odstupanja od srednje vrednosti posmatranih jedinica – rudnika ili regiona u kome se nalazi.

Drugi problem, određivanje TK i znaka za svaki indikator koji ulazi u kompozitni indeks, rešen je heuristički na način koji će biti kasnije objašnjen. Korišćeno je nekoliko koraka u primeni postavljene metodologije: definisanje konačne liste indikatora, ocenjivanje njihovog znaka i TK, dobijanje i analiza rezultata.

Definisanje konačne liste glavnih indikatora

Za definisanje konačne liste glavnih indikatora kreće se od početne, ali nepotpune liste indikatora, o kojima se mogu sakupiti relevantni podaci za rudnike i regione u kojima se nalaze. Međutim, nisu svi pokazatelji podjednako važni. U izboru najvažnijih indikatora koji će kreirati kompozitni indeks, korišćeni su sledeći principi:

Štedljivost. Od svih sakupljenih merila, 23 indikatora će biti korišćeno kao najvažniji pokazatelji za rudnike, a za rudarske regione je odabrano 36 indikatora. Ostali su eliminisani ili zbog nepostojanja pokazatelja ili kao suvišni, jer mere iste osobine odnosno opisuju vrlo slične karakteristike.

Uravnoteženost. Svi karakteristični interni ili eksterni aspekti rudnika ili opština treba da budu predstavljeni približno istim brojem indikatora, tj. njihovom ponderisanom sumom. Slično, neki indikatori predstavljaju sadašnje stanje, a neki izglede za budućnost (potencijale promena). Stoga oba navedena aspekta grupisanja treba da se koriste.

Iscrpivost. Konačni skup izabranih indikatora koji kreiraju kompozitni indeks treba da sadrži maksimum nezavisnih varijacija svih korišćenih varijabli, što znači da treba da uključi dovoljno infor-macija da bi se konstruisala složena ocena rizika.

Indikatori performansi daju informacije o kvalitetu potencijala rudnika i mogućnosti njihove konsolidacije. Indikatori su bitni pošto ukazuju na stepen ostvarenja ciljeva (uspeh ili neuspeh). U situacijama kada je potrebno da eksperti daju svoje subjektivne procene, iskazane, po pravilu, lingvističkim varijablama, definisanje indikatora performansi se svodi na višekriterijumski zadatak sa kvalitativnim kriterijuma. U primeni modela se razmatra skala za prevođenje lingvističkih izraza u numerički oblik, primenom **FUZZY teorije** i grupnog odlučivanja u situacijama neizvesnosti. Cilj je bio stvoriti listu indikatora koja bi obuhvatila sve karakteristike rudnika za ocenjivanje celokupne situacije, a posebno stanja u rudarstvu na regionu i potencijalima budućih promena.

Na osnovu navedenog, osnovu za utvrđivanje Modela ocene rudnika i značaja rudnika za lokalnu zajednicu, predstavlja sinergija metoda, tehnika i metodologija kao što su kvantifikovana SWOT analiza, metodologija usklađenih ciljeva, teorija FUZZY skupova i utvrđivanje polaznih parametara za poređenje "Benchmarking".Sa sintezom ovih tehnika i metoda napravljen je Hibridni Model koji će se koristiti za ocenu rudnika. [11]

KVALITATIVNA PROCENA UTICAJNIH FAKTORA

Sva tehničko-tehnološka rešenja koja se daju pri projektovanju novog rudnika ili revitalizacije i rekonstrukcije postojećeg treba da sadrže sve elemente, kako kvantitativne tako i kvalitativne parametre i pokazatelje.

Kvalitativni parametri i pokazatelji predstavljaju tehnološke karakteristike rudnika koje mu daju glavna obeležja, pri čemu se mogu predviđati i opisno izraziti tehnološki, prostorni, proizvodni i ekonomski karakter posmatranog rudnika.

Ta vrsta procene i predviđanja na kratak i dugi rok može biti od izuzetnog značaja za investitora i njegovu procenu internog i eksternog okruženja za preduzeće/projekat, kod definisanja razvojne politike, strategije preduzeća, planiranju investicija i izboru najboljih alternativa. To je jedan od načina na osnovu koga može da se definiše veličina investicije i opredeli investiciona odluka.

Samim tim će se metoda predviđanja (Delphi) koristiti kod kvalitativne procene uticajnih faktora kako kod utvrđivanja modela konsolidacije rudnika sa podzemnom eksploatacijom tako i kod utvrđivanja regionalnog značaja rudnika. Ova kvalitativna procena baziraće se na osnovu definisanih upitnika, postavljenih kriterijuma za ocenu, kao i ekspertskih znanja.

Do ekspertskih znanja se dolazi formiranjem ekspertnih timova, gde će angažovani eksperti pomoći u ocenjivanju kvalitativnih faktora. Uzimajući u obzir karakteristične kriterijume, izvršiće se procena po različitim oblastima i to za potencijale rudnika, perspektive na regionalnom nivou do procene uticaja na životnu sredinu.

Kao pomoć, po pitanju ekspertske ocene, pozvani su eminentni stručnjaci sa dosta praktičnog iskustva i dobrim poznavanjem prilika u rudnicima i njihovih potencijala, sa jedne strane kao i eksperti za zaštitu životne sredine. Možda je značajno napomenuti da se svi angažavani eksperti trenutno nalaze na pozicijama kontrole stanja i funkcionisanja rudnika i ispunjavanju zakonskih i drugih tehničkih propisa.

Oni će uticaj proceniti davanjem ocena za svaki kriterijum i to na osnovu sopstvenih iskustava. Ocene su od 1 do 5, u zavisnosti od kriterijuma (1 – najlošija ocena; 5 – najbolja ocena).

Smatra se da je *Interval skala* pogodan način da se izvrši kvantifikacija kvalitativnih atributa. Najčešće se koriste skale od 1-5 ili (1-10), jer obično nisu poznati ekstremi atributa za posmatrani kriterijum.

Kvantifikacija kvalitativnih kriterijuma se može vršiti na niz drugih načina od kojih je fazifikacija način da se uvaže neodređenosti koje su prisutne kod iskazivanja lingvističkih promenljivih.

Dakle, **matrica odlučivanja postaje kvantifikovana po svakom kriterijumu i takvu matricu nazivamo kvantifikovana matrica odlučivanja**.

Da bi se zadatak mogao rešavati potrebno je izvršiti normalizaciju vrednosti atributa - indikatora, odnosno izvršiti "ujednačavanje" ili "učiniti indikatore bezdimenzionalnim", što znači da se vrednosti indikatora svedu na interval 0-1. Normalizacija kvantifikovane matrice, može se vršiti na dva načina i to: vektorskom normalizacijom i linearnom normalizacijom [*].

Dakle, ako za jedan kvalitativan kriterijum koristimo jedan standardni skup izraza i pripadajuću skalu za kvantifikaciju,

[*] *Linearna normalizacija je izabrana kod normalizacije parametara Fuzzy modela.*

a za drugi kvalitativan kriterijum drugi skup koji se razlikuje po broju elemenata skupa ali i po rasponu skale, onda postoji opasnost da se ne uspostavi relativni odnos između ta dva kriterijuma na korektan način. Zato se mora utvrditi jedinstven način kvantifikovanja kvalitativnih atributa.

Eksperti daju ocene o nekakvim kvalitativnim vrednostima, te se smatra da je za probleme višekriterijumske analize dobro uvesti standardnu skalu vrednosti i davati ocene, imajući u vidu navedene ekstreme, uz mogućnost da atribut uzme bilo koju vrednost u navedenom intervalu. Svakako da je moguće formirati standardni skup lingvističkih izraza koji se mogu kvantifikovati u datoj skali (na primer za ocenu uticaja: *veoma jak, jak, umeren, slab, veoma slab*).

KVALITATIVNA PROCENA KRITERIJUMA ZA RANGIRANJE

Retki su slučajevi kada svi faktori imaju isti uticaj na proces donošenja odluka. Donosilac odluke može sam da dodeli odgovarajuće težine faktorima na osnovu sopstvene procene ili da koristi neku od metoda procene.

Savremeni način poslovanja zahteva od donosilaca odluka da sve češće donose važne poslovne odluke u uslovima stalnih promena u okruženju i situacijama kada se ne može doći do egzaktnih podataka za sve parametre koji utiču na donošenje neke poslovne odluke. Sa druge strane, pogrešne odluke mogu biti katastrofalne i nenadoknadive, tako da donosioci odluka moraju biti sposobni da odluke donose sa malim rizikom, a to se postiže savremenim metodama gde se koriste višekriterijumske metode i grupno odlučivanje. Naravno da korišćenje metoda višekriterijumske analize nisu same po sebi dovoljne, jer će uvek donosioci odluka imati odlučujuću ulogu kroz definesanje samog problema, određivanje težinskih koeficijenata i davanju ocena za kvalitativne kriterijume.

Većina metoda koje se koriste pri donošenju odluka zahtevaju informaciju o relativnoj važnosti svakog faktora uticaja. Međutim, metod izbora indikatora, ili njihovog razlikovanja prilikom grupisanja prema tipu informacije koju sobom nose, nipošto nije sasvim određen niti jedinstven. Zato je formiranje kompozitnih indeksa kreativna i praktična aktivnost, koja se zasniva na arbitrarnom izboru indikatora, a čiji ishod zavisi najviše od iskustva istraživača i od kvaliteta podataka.

IZBOR UTICAJNIH FAKTORA MODELA

Kod izbora uticajnih faktora Modela, kao relevantna skala opservacija, korišćena je podela, prvo na višem, a zatim i na nižem nivou agregacije (okruženje - aspekti - faktori - indikatori). Upotrebljeni su različiti raspoloživi skupovi podataka za: rudnike i rudarske regione.

Da bi se ocenili rizici za dalji razvoj rudarstva, koji se moraju posmatrati i kao rezultat ranijeg razvoja i kao verovatnoća budućeg napretka, treba upotrebiti dva glavna kriterijuma:

I. Nasleđeni uslovi i trenutno stanje,

II. Potencijali za pozitivne promene.

Za svaki od indikatora u početnoj listi relevantnih faktora, treba definisati odgovarajuću statističku meru, u zavisnosti od raspoloživih podataka. U stvari, treba koristiti sve raspoložive relevantne podatke o rudnicima i opštinama u Srbiji, i to iz raznih izvora – od relevantne projektno tehničko-finansijske dokumentacije o rudnicima do Republičkog zavoda za statistiku, raznih Vladinih agencija, Instituta, rudarskih kompanija, stručnih i naučnih časopisa itd. Cilj je stvoriti listu indikatora koja bi obuhvatila sve karakteristike potrebne za ocenjivanje kako rudnika tako i regiona u kojima se nalaze rudnici.

Ključni aspekti kod definisanja Modela koji će biti predmet dalje analize su izdvojeni i predstavljeni u dve grupe, i to kao:

Interni:

i. tehničko-proizvodni aspekti,

ii. aspekti efikasnosti rada,

iii. finansijsko-poslovni aspekti,

Eksterni:

iv. regulatorni aspekti (političko-ekonomsko okruženje),
v. regionalni aspekti (uravnoteženost regionalnog razvoja),
vi. tržišni aspekti (geografska lokacija tržišta).

Zbog složenosti korišćenih teorijskih kategorija i teškoća njihovog merenja u praksi, obe komponente rizika (teškoće sadašnjeg stanja i perspektive za budući razvoj) treba da budu aproksimirane raznim fizičko-matematičkim indikatorima koji će predstavljati unutrašnju - internu i spoljašnju - eksternu grupu uticajnih faktora.

Ključni faktori analize unutrašnje procene se uglavnom odnose na *geološki potencijal, tehničke mogućnosti rudnika, efikasnost rada, investicioni potencijal i budući razvoj*. Ključni faktori analize spoljašnje procene se uglavnom odnose na *političko okruženje, regionalnu razvijenost i geografsku lokaciju.*

Tabela 1. *Izbor faktora i indikatora učinka za model*

	Faktori		*Indikatori učinka*
Unutrašnji	Mineralni resursi u uslov za rudarstvo *	kvantitativan	- Kompozitni indeks regionalnog razvoja
	Nivo istraživanja	kvantitativan	- Nivo istraživanja
	Proizvodni sistem i trend proizvodnje	kvalitativan	- Rezerve - Geološki uslovi - Radni uslovi - Trendovi - Zaštitna radne i životne sredine
	Iskorišćenost postrojenja	kvantitativan	- Planiran nivo iskorišćenosti
	Raznovrsnost i kvalitet proizvoda	kvalitativan	- Raznovrsnost i kvalitet proizvoda
	Očekivani radni vek rudnika	kvantitativan	- Radni vek rudnika
	Kvalitet rukovodeče strukture	kvantitativan	
	Kvalifikacija radne snage	kvantitativan	- Indeksi angažovane radne snage
	Produktivnost	kvantitativan	
	Investicioni potencijal	kvalitativan	- Potencijal za mehanizaciju - Moguće stope proizvodnje - Investicioni potencijal
	Finansijska jačina	kvantitativan	- Zeta Altman test
	Isplativost	kvantitativan	- IRR/DS (CAP Model)
Spoljni	Politički rizik**	kvantitativan	
	Ekonomski rizik**	kvantitativan	- Kompozitni indeks rizika zemlje
	Poslovni rizik**	kvantitativan	
	Ekonomski razvoj lokalne zajednice*	kvantitativan	
	Društveni razvoj lokalne zajednice *	kvantitativan	- Kompozitni indeks regionalnog razvoja
	Zaštita životne sredine*	kvantitativan	
	Nivo obrazovanja*	kvantitativan	
	Potražnja proizvoda (lokalno / globalno)	kvalitativan	
	Konkurentnost i stabilnost cena	kvalitativan	- Stručna procena
	Odgovarajuća saobraćajna infrastruktura	kvalitativan	
	Industrijske veze	kvalitativan	

* *Ovi faktori su predstavljeni kompozitnim indeksima proračunatih tokom analize regionalnog aspekta*
** *Ovi faktori su predstavljeni indeksima dobijenim od Agencije koja procenjuje rizik zemlje*

ZAKLJUČAK

U savremenim, vrlo složenim i rizičnim uslovima investiranja u rudarstvo, i to kako za investitore, tako i za sredine u koje se investira, od izuzetnog je značaja da se u postupku odlučivanja o izboru i realizaciji rudarskih investicionih projekata raspolaže sa potpunim i pouzdanim ocenama podobnosti i značaja projekta.

Proces utvrđivanja značaja i podobnosti, a samim tim i investicionih rizika u rudarstvo, je izuzetno kompleksan, zbog, po pravilu Fuzzy prirode indikatora, uključivanje velikog broja atributa i složenosti korelativnih veza.

Neizvesnost je prisutna i kada se donosi odluka pri svim poznatim parametrima za donošenje odluka, pošto pojedini kriterijumi za ocenu alternativa zavise od subjektivne procene eksperata, kao i relativne težine izabranih kriterijuma. Subjektivnost eksperata se kod rešavanja realnih problema ne može izbeći, ali se neodređenosti moraju uzeti u obzir prilikom procesa donošenja odluka. Ovakve se neodređenosti modeliraju teorijom Fuzzy skupova.

SWOT analiza je veoma značajna za formulaciju strategije. Analiza spoljašnjih mogućnosti i pretnji se vrši, uglavnom, da bi se otkrilo može li rudarsko preduzeće iskoristiti mogućnosti i izbeći pretnje pri suočavanju sa nekontrolisanim spoljašnjim okruženjem. Analiza unutrašnje snage i slabosti se vrši radi utvrđivanja načina na koji preduzeće obavlja unutrašnji posao (npr. menadžment, efikasnost rada, istraživanje i razvoj). Kvantifikovana SWOT analiza može pomoći preduzeću da proceni sopstvenu poziciju među konkurencijom, ali može poslužiti i kao osnova za budući razvoj. Upravo primena različitih tehnika i metoda, objedinjena u univerzalni Model daje mu potrebnu složenost da bi se mogao nazvati Hibridni Model.

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DEPENDENCE OF THE BOND WORK INDEX OF GRINDABILITY ON GRAIN-SIZE DISTRIBUTION OF THE STARTING SAMPLE OF SIZE CLASS -3.35 mm***

Abstract

The research results of the effect of grain-size distribution of the starting sample of size class -3.35 mm on the value of the Bond work index OF grindability, obtained by the method of shortened procedure by prof. N. Magdalinović, clearly indicate that the characteristics of starting sample significantly affects the value of resistance to comminution.

Differences in values of the Bond work index of grindability for low-grade copper ore of 5.4 kWh/t or about 42 % and high-grade copper ore of 3.77 kWh/t or about 35%, from the point of the theory of comminution and practical application in designing and selection of process equipment are of particular importance.

Keywords: *copper ore, Bond index, grindability, grain-size distribution, coefficient of line direction.*

1 INTRODUCTION

Research whose results are presented in a paper [Stanojlović et al., 2013] show that high difference in grain-size distribution of definitive product of crushing for various copper ores affects the grain-size distribution of the starting sample of size class -3.35 mm for determining the Bond work index of grindability. It was also found that naturally higher resistance, low-grade copper ore, due to various conditions, in blasting, mining, industrial processing of raw materials to the laboratory sample preparation, can cause finest grain-size distribution of the starting sample of size class -3.35 mm, and lower value of the Bond work index of grindability, which is contrary to the theory of comminution. Misleading information about resistance mate-

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****This paper presents the results of the Projects TR 33007 “Implementation of Modern Technical-Technological and Environmental Solutions in the Existing Production Systems of the Copper Mine Bor and Copper Mine Majdanpek” and TR 33038 “Improving Technology of Exploitation and Processing of Copper Ore with Monitoring the Living and Working Environment in the RTB Bor Group”, funded by the Ministry of Education, Science and Technological Development of the Republic of Serbia. The authors are grateful to the Ministry for financial support.*

rials to comminution have negative effects on technological design of grinding process and selection of process equipment, as well as the efficiency of industrial plants.

In accordance with the previous conclusions, the research in this paper will be focused on defining the effect of grain size-distribution of the starting sample of size class -3.35 mm, on value of the Bond work index of grindability of low-grade and high-grade copper ore from the Copper Mine Bor, Serbia. Studies were conducted on the synthetic starting samples formed for determining the Bond work index of grindability of size class -3.35 mm, both tested materials.

2 EXPERIMENTAL

2.1 Material

Tested samples are the final industrial crushing products of low-grade and high-grade copper ore from the Copper Mine Bor, with the upper limit of size class of 35 mm. Copper ore was mined from the underground mine Jama in Bor that has the significant reserves of low-grade copper ore with the average copper content of about 0.95 to 1.00 %, and small reserves of high-grade copper ore, several hundred thousand tons, with the average copper content of 2 to 5%, gold 1-3 g/t and silver from 2.7 to 7.23 g/t, which are in the process of exploitation. Samples of low-grade and high-grade copper ore were crushed to the upper limit size class of 3.35 mm using the standard procedure in a laboratory jaw crusher and which were prepared for determining the Bond work index of grindability.

The grain-size distribution was determined on prepared samples of low-grade and high-grade copper ore and samples were separated for determining the Bond work index of grindability. Synthetic starting samples were formed from the same samples with different grain-size distribution on which the Bond work index of grindability was also determined. The samples were formed using the Gaudin-Schumann equation. At selected value of the coefficient of the line direction, m, from the grain size cumulative curves, the partial participation of narrow size class was determined for all synthetic sample separately.

2.2 Equipment and Methods

Grain-size distributions of all samples, that were the subject matter, were determined by sieve analysis of dry method on laboratory Tyler sieve series of selected sizes.

The sieving experiments were performed using a mechanical vibratory sieve shaker, type ”Retsch“, with specific frequency.

Determining the Bond work index of grindability was performed in the Bond' ball mill by dry grinding process [Bond, 1949; 1952; 1961]. As the method for determining the Bond' work index of grindability, the shortened procedure by prof. N. Magdalinović [Magdalinović, 1989] was used.

3 RESULTS AND DISCUSSION

3.1 Grain-size Distribution of Low-grade and High-grade Copper Ore

The samples of final product of industrial crushing, the upper limit of size 35 mm, as well as prepared samples of size class -3.35 mm for determining the Bond work index, were sieved by dry method on selected series of standard sieves and test results are presented on diagrams in Figures 1 and 2.

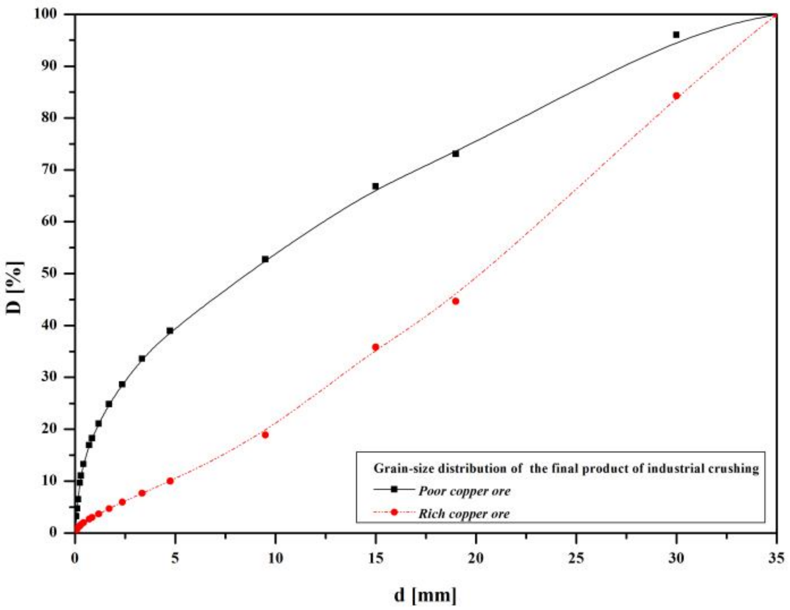

Figure 1 *Grain-size distribution of the final crushing products of low-grade and high-grade copper ore*

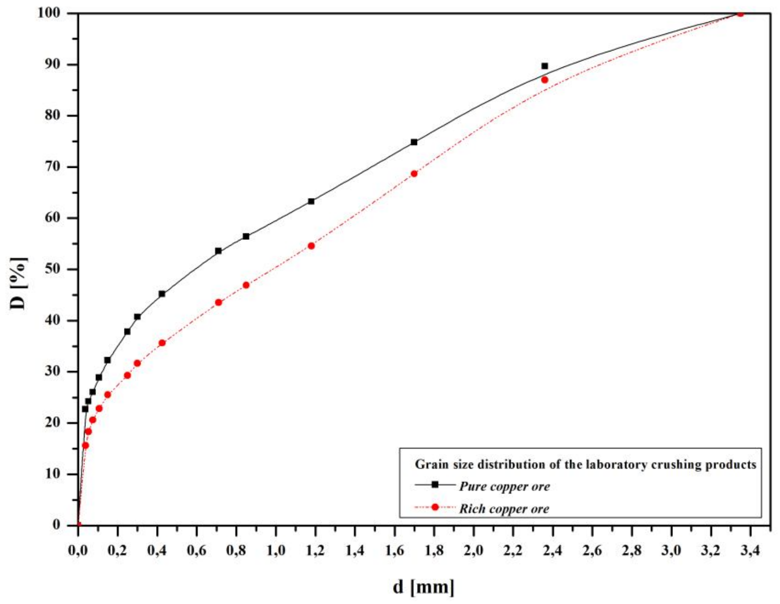

Figure 2 *Grain-size distributions of the starting samples of size class - 3.35 mm for determining the Bond work index of grindability*

Test results [Stanojlović et al., 2013] show a significant difference in the grain-size distribution of the final crushing products, Figure 1, as well as the prepared samples of size class –3.35 mm for determining the Bond work index, Figure 2. The difference in grain size characteristics will be shown through the coefficient of line direction, m, of the grain-size distribution of cumulative curves, defined using the Gaudin-Schumann equation:

$$D = 100\ (d / d_{max})^m\ (\%) \qquad (1)$$

where:

D - Cumulative passing values (%)

d – sieve opening (mm)

D_{max} –upper limit size of sample (mm)

m – coefficient of the line direction of the grain size distribution

Coefficient of the line direction of the grain size distribution for the final crushing product of low-grade copper ore has value m = 0.5, while the value of same parameter for high-grade copper ore is m = 1.2.

The prepared, starting samples of size class -3,35 mm for the determination of the Bond's work index grindability of the poor and rich copper ore have the different grain size distribution. Coefficient of the line direction of grain size cumulutive curves of low-grade copper ore is m = 0.4, while the same parameter for high-grade copper ore is m = 0.5.

It can be concluded from diagrams shown in Figures 1 and 2 that the samples of low-grade copper ore are the finest compared to the samples of high-grade copper ore products, which could lead to the conclusion of lesser resistance to comminution of low-grade compared to high-grade copper ore. This hypothesis is in contrast to the previous theoretical and practical knowledge of these raw materials, which was the main motive for further research.

3.2 Bond's Work Index of Grindability the Low-grade and High-grade Copper Ore

Bond's theory of comminution is widely accepted in the theory and practice of comminution process of raw material. According to this, the comminution energy is defined using the relation:

$$W = W_i \cdot \left(\frac{10}{\sqrt{P}} - \frac{10}{\sqrt{F}} \right), \text{ (kWh/t)} \quad (2)$$

where:

W - specific energy consumption (kWh/t)

W_i - Bond work index, (kWh/t)

F - feed 80% passing size, (μm)

P - product 80% passing size, (μm).

The Bond work index (W_i), is a material constant which is determined by laboratory testing procedure and in the ball mill, defined by F. C. Bond [Bond, 1949, 1952, 1961]. For determining the Bond work index of grindability, the shortened procedure prof. N. Magdalinović [Magdalinović, 1985, 1989] was used in this work.

3.3 The Effect of Grain-size Distribution of the Starting Sample of size class - 3.35 mm, on Value of the Bond Work Index of Grindability

Using the equation (1) with the given parameter values, m (m = 0,2; 0,4; 0,6; 0,8; 1,0), the grain-size distributions of synthetic formed starting samples of low-grade and high-grade copper are determined for determining the Bond work index of grindability. The cumulative and partial passing values of certain size class for formation the synthetic samples are given in Table 1, and the grainsize distribution curves of the same samples are shown on diagrams in Figure 3.

Table 1 *Grain size distribution of synthetic starting samples of low-grade and high-grade copper ore*

Grain size fraction d (mm)	m				
	0.2	0.4	0.6	0.8	1.0
	Cumulative passing values $D=100\ (d/d_{max})^m$ (%)				
-3.350+1.700	100.00	100.00	100.00	100.00	100.00
-1.700+0.850	87.31	76.24	66.56	58.12	50.75
-0.850+0.425	76.01	57.78	43.92	33.38	25.37
-0.425+0.150	66.17	43.79	28.97	19.17	12.69
-0.150+0.106	53.73	28.87	15.51	8.33	4.48
-0.106+0.075	50.12	25.12	12.59	6.31	3.16
-0.075+0	46.77	21.88	10.23	4.79	2.24
Grain size fraction d (mm)	**Partial passing values W (%)**				
-3.350+1.700	12.69	23.76	33.44	41.88	49.25
-1.700+0.850	11.30	18.46	22.65	24.74	25.37
-0.850+0.425	9.84	13.99	14.94	14.21	12.69
-0.425+0.150	12.45	14.92	13.46	10.84	8.21
-0.150+0.106	3.60	3.74	2.92	2.02	1.31
-0.106+0.075	3.35	3.25	2.36	1.52	0.93
-0.075+0	46.77	21.88	10.23	4.79	2.24

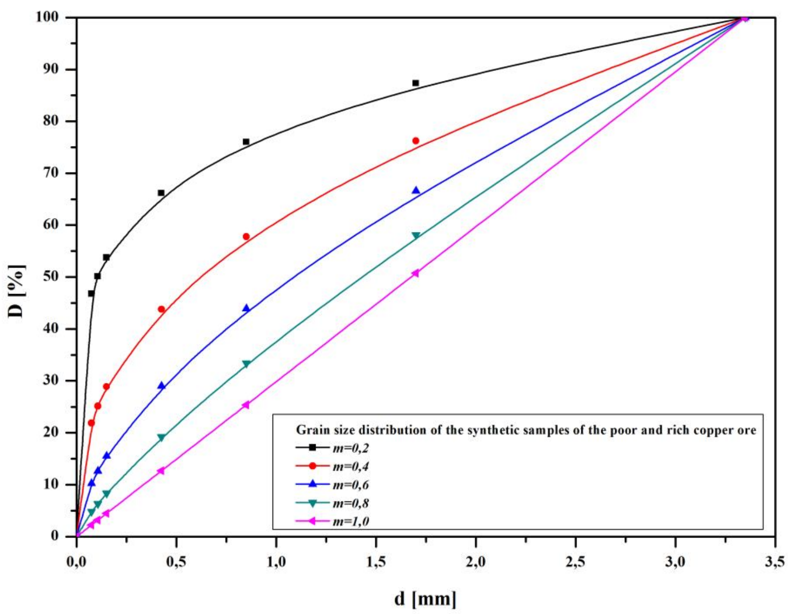

Figure 3 *Grain-size distribution curves of synthetic starting samples of low-grade and high-grade copper ore*

Test results of the Bond work index of grindability using the shortened procedure by prof. N. Magdalinović, formed on synthetic starting samples of low-grade cop per ore are shown in Table 2, and the obtained data on the same synthetic samples of high-grade copper ore are given in Table 3.

Table 2 *Bond's work index of grindability of low-grade copper ore in the function of parameter m*

Parameters	m				
	0.2	**0.4**	**0.6**	**0.8**	**1.0**
Pc (μm)	106.00	106.00	106.00	106.00	106.00
G (g)	1.60	1.32	1.13	1.07	1.16
P (μm)	69.8	82.8	83.1	86.0	75.0
F (μm)	1172.2	2008.9	2373.8	2560.7	2677.6
Wi (kWh/t)	**12.59**	**15.24**	**17.01**	**17.99**	**15.47**

Table 3 *Bond's work index of grindability of high-grade copper in the function of parameter m*

Parameters	m				
	0.2	**0.4**	**0.6**	**0.8**	**1.0**
Pc (μm)	106.00	106.00	106.00	106.00	106.00
G (g)	2.09	1.72	1.44	1.30	1.64
P (μm)	76.0	77.0	78.5	78.5	77.0
F (μm)	1172.2	2008.9	2373.8	2677.6	2560.7
Wi (kWh/t)	**10.70**	**11.71**	**13.48**	**14.47**	**11.83**

The obtained values of the Bond work index grindability, for low-grade, as well as high-grade copper ore, clearly indicate that grain-size distribution of the starting sample of size class –3.35 mm defined by the coefficient of line direction, m, affects the value of resistance to comminution.

Differences in values of the Bond work index of grindability, for low-grade copper ore, 5.4 kWh/t, and for high-grade copper ore, 3.77 kWh/t, from the aspect of comminution theory as well as the practical application are respectable and should be considered.

All tests confirm that the same grain-size distribution of the starting sample of size class -3,35 mm for determining the Bond work index, low-grade copper ore have higher value of resistance to comminution compared to high-grade copper ore, what is in accordance with the current, both theoretical and practical experience in these raw materials.

3.4 Dependence of the Bond Work Index of Grindability on Coefficient of Line Direction, m, for the Starting Sample of Size Class – 3.35 mm

The research results on synthetic samples of low-grade and high-grade copper ore of size class –3.35 mm, are shown on diagram in Figure 4.

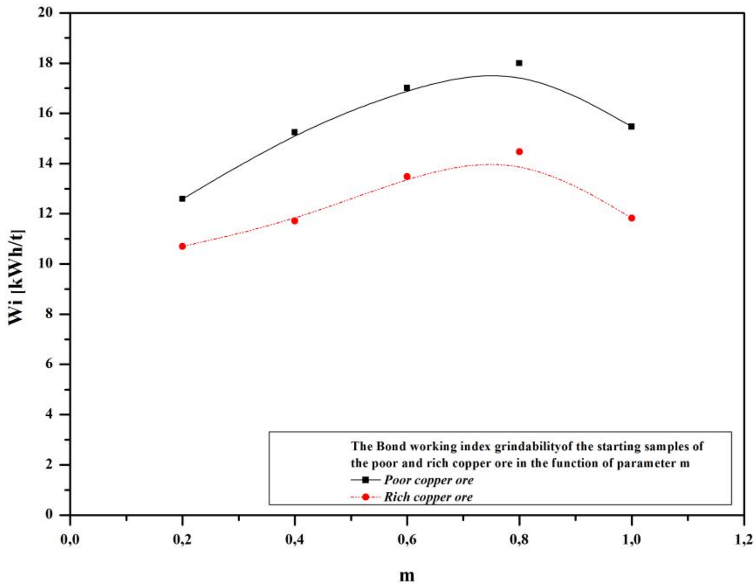

Figure 4 *Dependence of the Bond work index of grindability on coefficient of line direction of grain-size distribution, m, the starting sample of size class – 3.35 mm*

Two facts can be stated by analysis of these results. All values of the Bond work index of grindability of low-grade copper ore were higher than the same parameter for high-grade copper ore with the same grain-size distribution characteristics. It also confirms dependence of the Bond work index on grain-size distribution of the starting sample of size class -3.35 mm, represented by the coefficient of line direction, m, of the grain-size distribution curve.

The functional dependence of these indicators for low-grade and high-grade copper ore has a similar trend.

4 CONCLUSION

The shape and form of occurrence in deposit, blasting and mining method as well as primary comminution of raw materials under different conditions can cause that raw materials, more resistant to comminution, have finest grain-size distribution compared to raw material with lower resistance.

Relatively selective comminution of raw materials in a laboratory crushers in the preparation of samples of size class -3.35 mm, for determining the Bond work index of grindability, this phenomenon cannot be changed, so the starting sample for determining the parameters of resistance to comminution has an inadequate grain-size distribution. Research on low-grade and high-grade copper ore from the Copper Mine Bor has confirmed this statement.

Research of the Bond work index of grindability on low-grade and high-grade copper ore using the method of shortened procedure by prof. N. Magdalinović [Magdalinović, 1989] (Table 2 and the 3), indicate that grain-size distribution of the starting sample -3.35 mm, affects the value of this parameter of grindability. Dependence of the Bond work index of grindability compared to grain-size distribution of the starting sample, represented by the coefficient of line direction, m, is shown on diagram in Figure 4. Differences in values of the Bond work index of grindability, for low-grade copper ore, 5.4 kWh/t or approximately 42%, compared to high-grade copper ore, 3.77 kWh/t or approximately 35%, from the point of both, theory and practical application are respectable and should be considered.

All tests confirm that with the identical grain-size distributions, identical coefficients of the line directions, m, of the starting samples of size class – 3.35 mm, which are used for determining the Bond work index of grindability, low-grade copper ores have higher resistant to comminution compared to the same parameters of high-grade copper ore.

The functional dependence of the Bond work index of grindability of coefficients of the line directions, m, for low-grade and high-grade copper ore have similar trend. In future, research on several different raw materials will consider the possibility of defining a model of mentioned functional dependencies.

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ZAVISNOST BOND-OVOG RADNOG INDEKSA MELJIVOSTI OD GRANULOMETRIJSKOG SASTAVA POČETNOG UZORKA KLASE KRUPNOĆE – 3,35 mm***

Izvod

Rezultati istraživanja uticaja granulometrijskog sastava početnog uzorka klase krupnoće – 3,35 mm na vrednost Bond-ovog radnog indeksa meljivosti, definisanog primenom metode skraćenog postupka prof. Magdalinović, nedvosmisleno upućuju na zaključak da ova karakteristika početnog uzorka značajno utiče na vrednost pokazatelja otpornosti prema usitnjavanju.

Razlike u vrednostima Bond-ovog radnog indeksa meljivosti, za siromašnu rudu bakra od 5,4 kWh/t, odnosno oko 42 % i bogatu rudu bakra, od 3,77 kWh/t, odnosno oko 35 %, su sa stanovišta kako teorije usitnjavanja tako i praktične primene u projektovanju i izboru procesne opreme od posebnog značaja.

Ključne reči: *ruda bakra, Bond, indeks meljivosti, granulometrsijski sastav, koeficijent pravca prave.*

1. UVOD

Istraživanja čiji su rezultati prezentovani u radu [Stanojlović i dr., 2013], pokazuju da velika razlika u granulometrijskim sastavima definitivnih proizvoda drobljenja različitih ruda bakra utiče na granulometrijski sastav polaznog uzorka klase krupnoće - 3,35 mm za određivanje Bond-ovog radnog indeksa meljivosti. Takođe je konstatovano da prirodno otpornija, siromašna ruda bakra, zbog različitih uslova, pri miniranju, eksploataciji, industrijskoj preradi sirovine do laboratorijske pripreme uzorka, može usloviti finozrniji granulometrijski sastav polaznog uzorka klase krupnoće - 3,35 mm, a isti manju vrednost Bond-ovog radnog indeksa meljivosti, što je u suprotnosti sa teorijom usitnjavanja. Pogrešne informacije o otpornosti sirovina na usitnjavanje imaju negativne posledice kako na projektovanje

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*** *U ovom radu su prikazani rezultati projekata TR 33007 „Implementacija savremenijih tehničko-tehnoloških i ekoloških rešenja u postojećim proizvodnim sistemima Rudnika bakra Bor i Rudnika bakra Majdanpek“ i TR 33038 „Usavršavanje tehnologija eksploatacije i prerade rude bakra sa monitoringom životne i radne sredine u RTB Bor Grupa“ finansiranih od strane Ministarstva prosvete, nauke i tehnološkog razvoja Republike Srbije. Autori se zahvaljuju pomenutom Ministarstvu na finansijskoj podršci.*

tehnoloških procesa usitnjavanja i izbor procesne opreme, tako i na efikasnost rada industrijskih postrojenja.

Shodno predhodnim konstatacijama istraživanja u ovom radu biće usmerena u pravcu definisanja uticaja granulometrijskog sastava polaznog uzorka klase krupnoće - 3,35 mm, na vrednost Bond-ovog radnog indeksa meljivosti siromašne i bogate rude bakra RB Bor, Srbija. Istraživanja su vršena na sintetički formiranim polaznim uzorcima za definisanje Bond-ovog radnog indeksa meljivosti, klase krupnoće - 3,35 mm, obe ispitivane sirovine.

2. EKSPERIMENTALNI DEO

2.1. Materijal

Uzorci na kojima su vršena istraživanja su definitivni, industrijski proizvodi drobljenja siromašne i bogate rude bakra RB Bor, gornje granične krupnoće – 35 mm. Rude bakra su eksploatisane iz Jame Rudnika Bor, koja raspolaže sa značajnim rezervama siromašne rude sa sadržajem bakra oko 0,95-1,00 %, i manjim rezervama, nekoliko stotina hiljada tona u fazi eksploatacije, bogate rude sa sadržajem bakra od 2-5 %, zlata 1-3 g/t i srebra od 2,7-7,23 g/t. Standardnom procedurom u laboratorijskoj čeljusnoj drobilici uzorci siromašne i bogate rude bakra su usitnjeni do gornje graniče krupnoće 3,35 mm, čime su pripremljeni za određivanje Bond-ovog radnog indeksa meljivosti.

Na ovako pripremljenim uzorcima siromašne i bogate rude bakra određeni su granulometrijski sastavi i izdvojeni uzorci za određivanje Bond-ovog radnog indeksa meljivosti. Od istih uzoraka formirani su sintetički polazni uzorci različitih granulometrijskih sastava na kojima je takođe određivan Bond-ov radni indeks meljivosti. Uzorci su formirani tako što je primenom Gaudin-Schumannove jednačine, pri odabranim vrednostima koeficijenta pravca krivih granulometrijskih sastava, m, definisano parcijalno učešće uskih klasa krupnoće za svaki sintetički uzorak posebno.

2.2. Oprema i postupci

Granulometrijski sastavi svih uzoraka koji su bili predmet ispitivanja određeni su sitovnim analizama suvim postupkom na laboratorijskim sitima odabrane veličine otvora, serije Tyler.

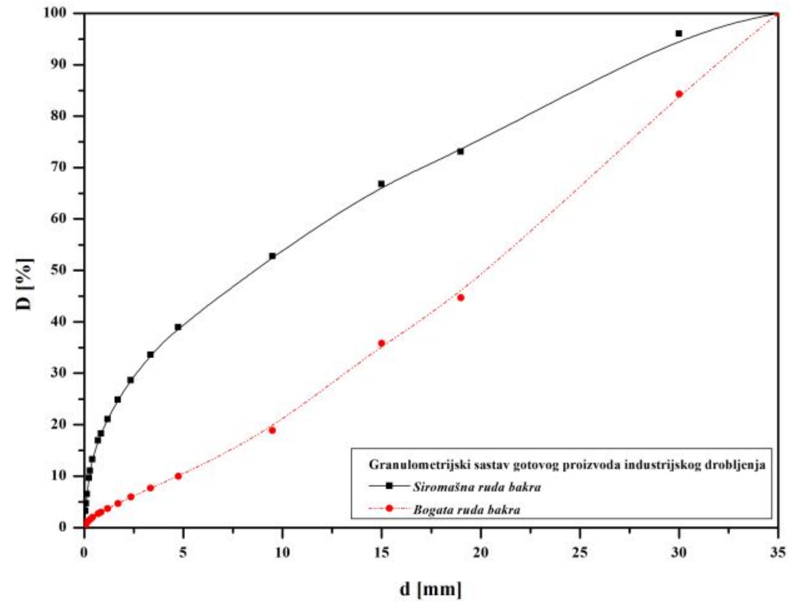
Opiti prosejavanja izvođeni su primenom mehaničkog vibracionog uređaja tipa Retsch određene frekvence.

Određivanje Bond-ovog radnog indeksa meljivosti vršeno je u Bond-ovom mlinu sa kuglama, postupkom suvog mlevenja [Bond, 1949; 1952; 1961]. Kao metod za određivanje Bond-ovog radnog indeksa meljivosti korišćen je skraćeni postupak prof. N. Magdalinovića [Magdalinović, 1989].

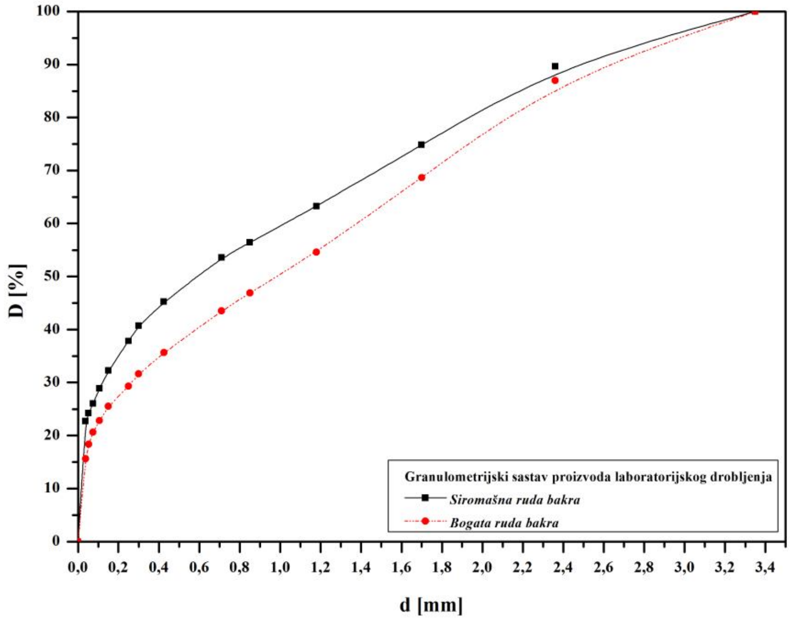
3. REZULTATI I DISKUSIJA

3.1. Granulometrijski sastavi siromašne i bogate rude bakra

Uzorci definitivnih proizvoda drobljenja gornje granične krupnoće 35 mm, i pripremljeni uzorci klase krupnoće -3,35 mm, za određivanje Bond-ovog radnog indeksa, prosejani su suvim postupkom na odabranim serijama sita, a rezultati ispitivanja prezentovani dijagramima na slikama 1 i 2.



Sl. 1. *Granulometrijski sastavi definitivnih proizvoda drobljenja siromašne i bogate rude bakra*



Sl. 2. *Granulometrijski sastavi početnih uzoraka klase - 3,35 mm za određivanje Bond-ovog radnog indeksa meljivosti*

Rezultati ispitivanja [Stanojlović i dr., 2013] pokazuju veliku razliku u granulometrijskim sastavima kako definitivnih proizvoda drobljenja, slika 1, tako i pripremljenih uzoraka klase krupnoće - 3,35 mm za određivanje Bond-ovog radnog indeksa, slika 2. Razliku u granulometrijskim karakteristikama prikazaćemo preko koeficijenta pravca krivih granulometrijskih sastava, definisanih primenom jednačine Gaudin-Schumanna:

$$D=100\ (d/d_{max})^{m}\ (\%) \qquad (1)$$

gde su:

- D - kumulativni prosev (%)
- d - otvor sita (mm)
- d_{max} - gornja granična krupnoća uzorka (mm)
- m - koeficijent pravca krive granulometrijskog sastava

Koeficijent pravca krive granulometrijskog sastava definitivnog proizvoda drobljenja siromašne rude bakra ima vrednost m = 0,5, dok je vrednost istog parametra za bogatu rudu m = 1,2.

Pripremljeni polazni uzorci, klase krupnoće - 3,35 mm, za određivanje Bond-ovog radnog indeksa meljivosti siromašne i bogate rude bakra, takođe su različitih granulometrijskih sastava. Koeficijent pravca krive granulometrijskog sastava siromašne rude je m = 0,4, dok je isti parametar za bogatu rudu m = 0,5.

Sa dijagrama prikazanih na slikama 1 i 2, može se konstatovati da su uzorci siromašne rude finozrniji u odnosu na uzorke istih proizvoda bogate rude bakra, što može navesti na zaključak o manjoj otpornosti prema usitnjavanja siromašne u odnosu na bogatu rudu bakra. Ova pretpostavka je u suprotnosti sa dosadašnjim teorijskim i praktičnim saznanjima o ovim sirovinama, što je predstavljalo osnovni motiv za dalja istraživanja.

3.2. Bond-ov radni indeks meljivosti siromašne i bogate rude bakra

Bond-ova teorija usitnjavanja je široko prihvaćena u teoriji i praksi procesa usitnjavanja prirodnih sirovina. Prema istoj, energija usitnjavnja se definiše primenom relacije:

$$W = W_i \cdot \left(\frac{10}{\sqrt{P}} - \frac{10}{\sqrt{F}} \right), \text{(kWh/t)} \qquad (2)$$

gde su:

- W - specifična potrošnja energije (kWh/t)
- W_i - Bond-ov radni indeks meljivosti sirovine (kWh/t)
- F - veličina otvora sita kroz koje prolazi 80 % sirovine pre usitnjavanja (μm)
- P - veličina otvora sita kroz koje prolazi 80 % sirovine posle usitnjavanja (μm)

Bond-ov radni indeks (W_i), je materijalna konstanta koja se utvrđuje laboratorijskim ispitivanjima po proceduri i u uređaju koji je definisao F.C. Bond, [Bond, 1949; 1952; 1961].

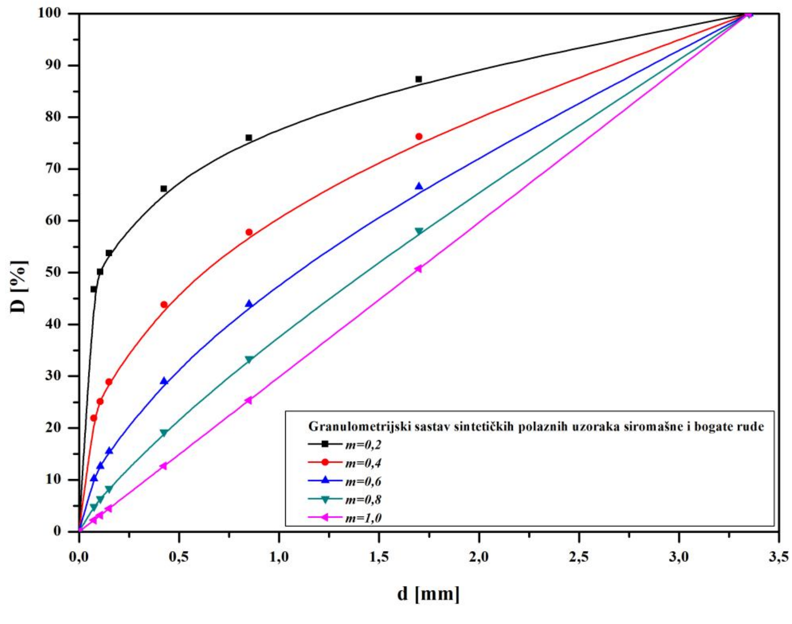
Kao metod za određivanje Bond-ovog radnog indeksa meljivosti, u ovom radu, korišćen je skraćeni postupak, prof. N. Magdalinovića [N. Magdalinović, 1985; 1989].

3.3. Uticaj granulometrijskog sastava polaznog uzorka klase krupnoće - 3,35 mm, na vrednost Bond-ovog radnog indeksa meljivosti

Primenom jednačine (1), uz zadate vrednosti parametara, m, (m = 0,2; 0,4; 0,6; 0,8; 1,0), definisani su granulometrijski sastavi, sintetički formiranih, polaznih uzoraka siromašne i bogate rude bakra za određivanje Bond-ovog radnog indeksa meljivosti. Kumulativne i parcijalne vrednosti učešća pojedinih klasa krupnoće za formiranje sintetičkih uzoraka date su u tabeli 1, a krive granulometrijskih sastava istih uzoraka dijagramima su prikazane na slici 3.

Tabela 1. *Granulometrijski sastav sintetičkih polaznih uzoraka siromašne i bogate rude bakra*

Veličina otvora sita d (mm)	m				
	0,2	0,4	0,6	0,8	1,0
	Kumulativni prosev sita $D=100\ (d/d_{max})^m$ (%)				
-3,350+1,700	100,00	100,00	100,00	100,00	100,00
-1,700+0,850	87,31	76,24	66,56	58,12	50,75
-0,850+0,425	76,01	57,78	43,92	33,38	25,37
-0,425+0,150	66,17	43,79	28,97	19,17	12,69
-0,150+0,106	53,73	28,87	15,51	8,33	4,48
-0,106+0,075	50,12	25,12	12,59	6,31	3,16
-0,075+0	46,77	21,88	10,23	4,79	2,24
Klasa krupnoće (mm)	**Parcijalno učešće klasa krupnoće W (%)**				
-3,350+1,700	12,69	23,76	33,44	41,88	49,25
-1,700+0,850	11,30	18,46	22,65	24,74	25,37
-0,850+0,425	9,84	13,99	14,94	14,21	12,69
-0,425+0,150	12,45	14,92	13,46	10,84	8,21
-0,150+0,106	3,60	3,74	2,92	2,02	1,31
-0,106+0,075	3,35	3,25	2,36	1,52	0,93
-0,075+0	46,77	21,88	10,23	4,79	2,24



Sl. 3. *Krive granulometrijskih sastava sintetičkih polaznih uzoraka siromašne i bogate rude bakra*

Rezultati ispitivanja Bond-ovog radnog indeksa meljivosti primenom skraćenog postupka prof. N. Magdalinovića, na sintetički formiranim polaznim uzorcima siromašne rude bakra prikazani su u tabeli 2, a isti pokazatelji dobijeni na sintetičkim uzorcima bogate rude dati su u tabeli 3.

Tabela 2. *Bond-ov radni indeks meljivosti siromašne rude bakra u funkciji parametra m*

Parametri	**m**				
	0,2	**0,4**	**0,6**	**0,8**	**1,0**
Pc (μm)	106,00	106,00	106,00	106,00	106,00
G (g)	1,60	1,32	1,13	1,07	1,16
P (μm)	69,8	82,8	83,1	86,0	75,0
F (μm)	1172,2	2008,9	2373,8	2560,7	2677,6
Wi (kWh/t)	**12,59**	**15,24**	**17,01**	**17,99**	**15,47**

Tabela 3. *Bond-ov radni indeks meljivosti bogate rude bakra u funkciji parametra m*

Parametri	**m**				
	0,2	**0,4**	**0,6**	**0,8**	**1,0**
Pc (μm)	106,00	106,00	106,00	106,00	106,00
G (g)	2,09	1,72	1,44	1,30	1,64
P (μm)	76,0	77,0	78,5	78,5	77,0
F (μm)	1172,2	2008,9	2373,8	2677,6	2560,7
Wi (kWh/t)	**10,70**	**11,71**	**13,48**	**14,47**	**11,83**

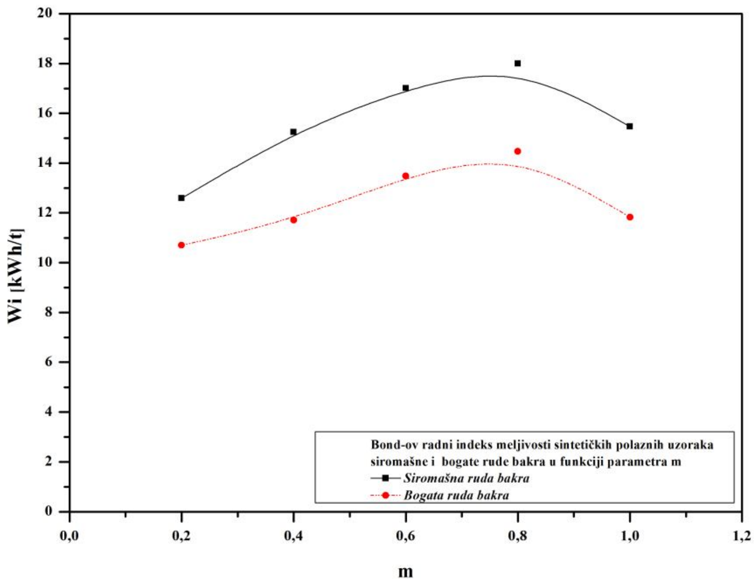
Dobijene vrednosti Bond-ovog radnog indeksa meljivosti, kako za siromašnu, tako i bogatu rudu bakra, nedvosmisleno ukazuju da granulometrijski sastav polaznog uzorka klase krupnoće -3,35 mm definisan preko koeficijenta pravca m, utiče na vrednost pokazatelja otpornosti prema usitnjavanju.

Razlike u vrednosti Bond-ovog radnog indeksa meljivosti, za siromašnu rudu bakra, od 5,4 kWh/t, i bogatu rudu bakra od 3,77 kWh/t, su sa stanovišta kako teorije usitnjavanja tako i praktične primene respektabilne i treba ih uvažavati.

Svi eksperimenti potvrđuju da pri istim granulometrijskim sastavima polaznih uzoraka klase krupnoće -3,35 mm za određivanje Bond-ovog radnog indeksa, siromašne rude imaju veću vrednost otpornosti prema usitnjavanju u odnosu na bogate rude bakra, što je u skladu sa dosadašnjim, kako teorijskim tako i praktičnim iskustvima na ovim sirovinama.

3.3. Zavisnost Bond-ovog radnog indeksa meljivosti od koeficijenta pravca krive granulometrijskog sastava, m, polaznog uzorka klase krupnoće - 3,35 mm

Rezultati istraživanja na sintetičkim uzorcima siromašne i bogate rude bakra, klase krupnoće -3,35 mm, prikazani su dijagramima na slici 4.



Sl. 4. *Zavisnost Bond-ovog radnog indeksa meljivosti od koeficijenta pravca krivih granulometrijskih sastava, m, polaznog uzorka klase krupnoće -3,35 mm*

Analizom rezultata istraživanja mogu se konstatovati dve činjenice. Sve vrednosti Bond-ovog radnog indeksa meljivosti za siromašnu rudu bakra su veće u odnosu na isti pokazatelj za bogatu rudu bakra istih granulometrijskih karakteristika. Takođe, potvrđuje se zavisnost Bond-ovog radnog indeksa od granulometrijskog sastava početnog uzorka klase krupnoće - 3,35 mm, predstavljenog preko koeficijenta pravca krivih granulometrijskih sastava, m.

Funkcionalna zavisnost navedenih pokazatelja za siromašnu i bogatu rudu bakra ima sličan trend.

ZAKLJUČAK

Oblik i forma pojavljivanja u ležištu, miniranje i način eksploatacije kao i primarno usitnjavanje sirovine u različitim uslovima mogu usloviti da sirovine otpornije prema usitnjavanju imaju finozrniji granulometrijski sastav od sirovina sa manjom otpornošću.

Relativno selektivno usitnjavanje sirovine u laboratorijskim drobilicama pri formiranju uzoraka klase krupnoće -3,35 mm, za određivanje Bond-ovog radnog indeksa meljivosti ne retko, navedenu pojavu ne može promeniti, tako da i početni uzorak za određivanje pokazatelja otpornosti prema usitnjavanju, ima neadekvatan granulometrijski sastav. Istraživanja na siromašnoj i bogatoj rudi bakra RTB – Bor ovu konstataciju potvrđuju.

Istraživanja Bond-ovog radnog indeksa meljivosti za siromašnu i bogatu rudu bakra, primenom metode skraćenog postupka prof. Magdalinovića [Magdalinović, 1989] (tabela 2 i 3), ukazuju da granulometrijski sastav početnog uzorka -3,35 mm, utiče na vrednost ovog pokazatelja meljivosti. Zavisnost Bond-ovog radnog indeksa meljivosti od granulometrijskog sastava početnog uzorka, predstavljenog preko koeficijenta pravca, m, prikazana je dijagramima na slici 4. Razlike u vrednostima

Bond-ovog radnog indeksa meljivosti, za siromašnu rudu bakra od 5,4 kWh/t, odnosno cca 42 %, i bogatu rudu bakra od 3,77 kWh/t, odnosno cca 35 %, su sa stanovišta kako teorije tako i praktične primene respektabilne i treba ih uvažavati.

Svi opiti potvrđuju da pri istim granulometrijskim sastavima, istim koeficijentima pravaca, m, početnih uzoraka klase krupnoće -3,35 mm za određivanje Bond-ovog radnog indeksa meljivosti, siromašne rude imaju veću otpornost prema usitnjavanju u odnosu na isti pokazatelj za bogatu rudu bakra.

Funkcionalne zavisnosti Bond-ovog radnog indeksa meljivosti od koeficijenata pravaca krivih granulometrijskih sastava kako siromašne tako i bogate rude bakra imaju sličan trend. U budućim istraživanjima na više različitih sirovina sagledaće se mogućnost definisanja modela navedenih funkcionalnih zavisnosti.

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REVIEW OF SOLIDIFICATION AND STABILIZATION METHODS OF HAZARDOUS WASTE**

Abstract

The paper presents stabilization and solidification (S/S) methods of hazardous waste, depending on the type of waste and content of hazardous and harmful components as the pretreatment method of hazardous waste prior to disposal on landfills. Also, the paper present the impact of selected additives and the aging conditions of the process product on the effectiveness of the S/S processes. Process efficiency was measured by mobility of hazardous and harmful components. Representation of some processes of stabilization and solidification in the pretreatment of hazardous waste prior to disposal in the world are shown. The aim of this paper is systematization of data and selection of optimal Solidification/Stabilization process for further research in the field of reduction the impact of mining waste on the environment.

Keywords: *stabilization, solidification, hazardous waste treatment*

INTRODUCTION

Stabilization/solidification (S/S) is a technique that uses physical and chemical properties of cementitious binders or chemical transformation to integrate trace elements from waste, whose disposal is prohibited without pretreatment.

Solidification and stabilization are generic names that are applied to a wide range of technologies that are closely related to the chemical and/or physical processes to reduce the potential negative environmental impact by disposal of radioactive, hazardous and mixed waste on landfills without pretreatment [1, 2, 3].

Stabilization is the chemical process of reduction the hazardous characteristics of waste. The hazardous component transforms from less soluble form and/or a form which is less toxic.

In situ stabilization is the well-known method for immobilization of contaminants, which prevents further spreading of pollution through soil and groundwater. The most common method of in situ stabilization in olves mixing of contaminated soil or waste with cement or other materials that have similar chemical and physical properties (fly ash...). The chemical and physical properties of cement or other materials include the adsorption ability and ability to reduce the mobility of hazardous and harmful component.

Solidification is the process/operation that transforms hazardous waste into a solid

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form using the additives and does not necessarily involve the chemical reaction between additives and solidification of hazardous waste.

Depending on granulation of material which will be treated, solidification is divided into micro-encapsulation and macro-encapsulation solidification [4].

Solidification is applied on tailing dumps, where solids are mixed with additives, and as the result of mixing emerging geopolymeric matrix (soil cement). After adjusting the mixing ratio, the mixture forms a solid monolithic layer.

S/S is a very important process which allows transformation of waste into inert material, independently of solubility value of each individual metal, or components in the waste. Also, the great importance fact is that some physical or chemical parameters (permeability, compression strength) can be easily controled by selection of chemical additives and its ratio in mixture (waste/additive).

The strength of solidification process product has a direct influence on the process efficiency and can be increased by reduction the water ratio in mixture, increasing the solidification temperature or increasing of calcium chloride or Portland cement ratio as an additive.

Fly ash is a good replacement to Portland cement from an economic point of view, and its use has reduced the use of Portland cement in the industry by 25 to 55% [5].

The S/S process is primarily designed for treatment of hazardous waste (including radioactive waste). The effectiveness of S/S process is reflected in a significant reduction of negative impact of deposited (hazardous) waste on the environment (soil, surface water, groundwater) and indirectly on flora, fauna and human health.

This paper presents the results of previous research the application of S/S processes on different types of waste. Also, the efficiency of additives, depending on the ratio and type of waste, is shown. The aim of paper is to systematized data for better choice of optimal Solidification/Stabilization process for further research and application in the field of reduction the impact of mining waste on the environment.

RESULTS AND DISCUSSION

Efficiency of Additive According to the Type of Waste

Treatment of sludge and waste with high content of liquid phase. The S/S process is applied on liquid waste, or waste with high content of liquid phase, whose disposal in landfills without prior treatment is not possible. In such cases, the cement is used as a binding additive because the water reaction with the cement produces the hydrated cement by chemically binding. Compression strength of at least 0.34 MPa (50 psi) is evidence that treatment of the free liquid phase often comes due to the chemical bonds between the liquid phase and cement, the liquid phase becomes less likely adsorbed [5].

Treatment of waste with inorganic pollutants content mostly. The most common application of S/S process is treatment of inorganic materials contaminated with hazardous components. Inorganic materials contaminated with heavy metals are often categorized as hazardous due to the increased leaching potential of heavy metals (leaching test) and showing the toxic characteristics (toxicity test). Treatment of waste by solidification or stabilization process results into reducing the mobility of heavy metals and reducing the leaching potential of inorganic material. After pretreatment, the material does not show hazardous characteristics and can be disposed of nonhazardous waste landfill. In the case of implementation the remediation process as the sustainability of the land, S/S process is often the only solution of available technologies for remediation of large amounts of contaminated soil with heavy metals, sludge or sediment. As an additive, in this case the cement is recommended because it reduces the mobili ty of the metal ions, forming less soluble metal hydroxide, carbonate or silicate. During the S/S process metal from waste can be transformed from ionic form in the mineral structure and physical encapsulation. Furthermore, pretreatment may reduce the toxicity of metal by change in the valence [5].

Treatment of waste with organic pollutants content mostly. Remediation of materials containing mainly organic pollutants is possible applying a cement additive. During the S/S process the material cures by changing the physical properties of cement. In particular, it is recommended, if the waste is with high content of free water, which enters the process of hydration, the cement material creating a highly integrated physical monolith.

The S/S method has shown high efficiency in reducing the mobility of hazardous and harmful substances from the waste of content of halogenated semi-volatile polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), pesticides, organic cyanide and etc.

Disadvantage of cement is inefficient application on waste treatment with high content of fats and oils, when hydration process of cement is not possible. Cement particles are coated with oil or grease, which do not allow contact between cement and water. Some organic compounds influence on the curing time of the cement, whereby the whole process of solidification can be considerably extended. Due to these reasons, it is necessary to do a complete qualitative and quantitative analysis, before the selection of additives. Also, the use of calcium carbonate results into occurrence of exothermic reaction during the process of hydration with simultaneously emission a significant amount of energy. If the waste consists of significant quantities of volatile hazardous and harmful components, the same will be emitted into atmosphere during the S/S. If there is no other alternative to lime as an additive in the S/S process, it is necessary to provide the facilities for collection and treatment of waste gas [5].

Treatment of waste with content of heavy metals – Applying the both procedures of stabilization and solidification on wastes with content of heavy metals it comes to largely transformation forms of heavy metals (mostly in the form of less soluble hydroxide) and mobility of ions of heavy metals is reduced.

Solidification and stabilization of heavy metals by hydrates of Portland cement is shown in Figure 1.

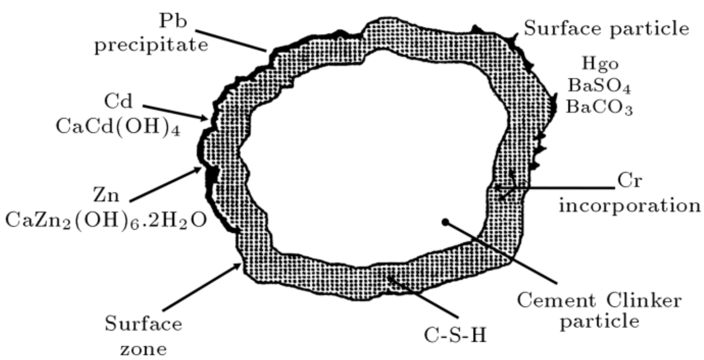

Figure 1 *Solidification and stabilization of heavy metals by hydrates of Portland cement [6]*

Preferred S/S methods depending on the type of waste are shown in Table 1 [7].

Table 1 *Preferred S/S methods depending on the type of waste*

Type of S/S method	Application
Solidification with cement additive	Sludges, contaminated soil
Solidification process with lime additive	Some inorganic wastes, waste from desuphurization treatment of wastes gases
Solidification with thermoplastic materials	Radioactive waste
Encapsulation	Sludges, liquids, some particular materials
Vitrification	Radioactive waste, extremely hazardous waste

Model for Additive Selection Depending on the Type of Waste

The model of waste, selected to represent the neutralization precipitates was an ochreous mine water waste (OMW-fine-grained, Fe- and Ca-rich neutralization precipitates from bioleaching with relatively low levels of hazardous components) and an industrial jarosite residue (JR - with higher levels of hazardous components). Silica sand (SS) was used as the bulk mineral material in the CLSM formulations. A commercially available cement (PC), PFA and Lime (L) were used as binder. Test results of stabilization of hazardous wastes with different content of hazardous components using different additives are shown in table 2 [8].

Table 2 *Test results of stabilization the hazardous waste with different content of hazardous components using different additives*

Mix	% Dry solids						Ratio of water to solid
	PC	FA	SS	OMW	JR	L	
5PC-FA	5	15	80	-	-	-	0.20
5PC-FA-OMW	5	15	70	10	-	-	0.30
5PC-FA-JR	5	15	70	-	10	-	0.25
10PC-FA-JR	10	15	65	-	10	-	0.30
10L-FA-JR	-	15	65	-	10	10	0.43
5PC-FA-L-JR	5	15	65	-	10	5	0.41

Concentrations of heavy elements As, Cd, Co, Cu, Mn, Mo and Ni were below limit values, even from specimens containing jarosite waste having elevated levels of these elements. Adsorption onto hydrated iron (III) oxide abundant in the specimens accounted for the low mobility of arsenate. The metals should also be adsorbed, aided in most cases by low solubility at high pH prevalent in lime and cement.

However, cationic Ba exceeded limits for all specimens (including the cement/fly ash control) and amphoteric Cr, Pb and Zn gave excessive concentrations for some formulations, particularly with jarosite.

Results of investigation the opportunities, applying different additives (lime, UFS - foundry sand from US Steel Balkan - Stara Zelezara d.o.o) for waste stabilization process and chemical analysis of leaching solution after treatment the solid samples with different additives after 4 cycles, are presented in Table 3. The treated waste samples are from Bor area generated during mining activities with increasing content of copper (0.12%), iron (4.06%), lead (0.07 %) and zinc (0.07 %) [9].

Table 3 *Heavy metal mobility after treatment the solid samples with different additives after 4 cycles*

Mixture	Metal	mg/L			
		1	2	3	4
Dam 3 A	Cu	11.8	11.6	10.8	10.8
	Fe	8.1	4.4	6.5	4.3
	Pb	<1	<1	<1	<1
	Zn	5.2	5.1	6.6	5.9
Dam 3 A + (100% lime)	Cu	0.24	0.21	0.27	0.27
	Fe	<0.05	<0.05	<0.05	<0.05
	Pb	<1	<1	<1	<1
	Zn	0.34	<1	<1	<1
Dam 3 A + (100% UFS)	Cu	12.93	16.14	18.44	16.98
	Fe	7.395	5.882	2.689	2.857
	Pb	<1	<1	<1	<1
	Zn	11.19	13.19	13.79	13.15
Dam 3 A + (90% UFS + 10% lime)	Cu	n.d	n.d	n.d	0.077
	Fe	0.336	0.336	0.336	0.336
	Pb	0.714	0.714	0.714	0.714
	Zn	0.128	0.085	0.128	0.255
Dam 3 A + (75% UFS + 25 lime)	Cu	n.d	0.077	n.d	n.d
	Fe	0.336	0.336	0.504	0.336
	Pb	n.d	n.d	n.d	n.d
	Zn	0.213	0.043	0.085	0.170

The best results were obtained using the lime as an additive, as might be expected, because it is an inorganic waste with high content of heavy metals.

Factors Affecting the Stabilization and Solidification Efficiency

Proper selection of reagents. *Stabilization of waste generated as the result of mining activity with high content of aqueous phase*. Lime neutralization is the most common method which is recommended for stabilization the hazardous waste, particularly the inorganic waste with content of heavy metals, which is confirmed by research of M. Korać et al. [9]. In addition, in the process of solidification, at the surface of the grains, in the presence of silicon and aluminum, a liquid barrier calcium silicate gel or calcium-aluminate gel can occur, there by increasing the efficiency of process [10].

Metal hydrolysis solubility curve is shown in Figure 2, the influence of pH value on heavy metal mobility can be also seen [5].

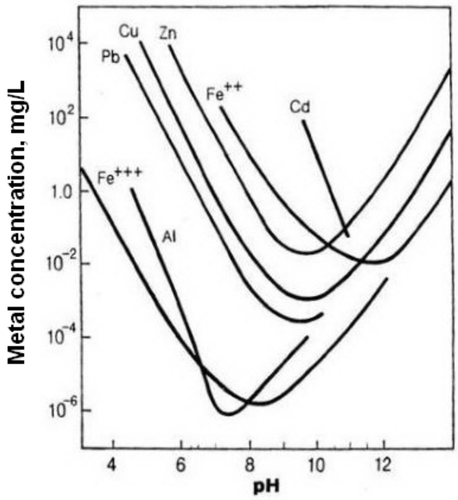

Figure 2 *Metal hydrolysis solubility curve*

Aging time of stabilization and solidification product - Postreatment of resulting product of solidification and stabilization process may have a significant effect on efficiency of waste treatment procedures. The aging conditions and aging time are the parameters that should be investigated. Relationship between metal mobility and sludge aging is shown in Figure 3.

The aging time about 6 month at temperature about 25°C, in atmospheric conditions, decrease mobility of hazardous components from sludge less than 10 mg/L [5].

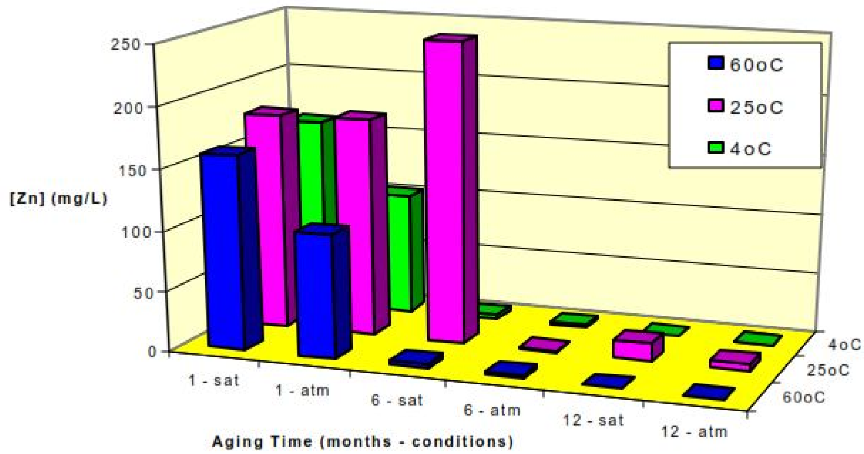

Figure 3 *Relationship between metal mobility and sludge aging*

Application of solidification and stabilization process in hazardous waste treatment before disposal on landfill is shown in Figure 4 [11].

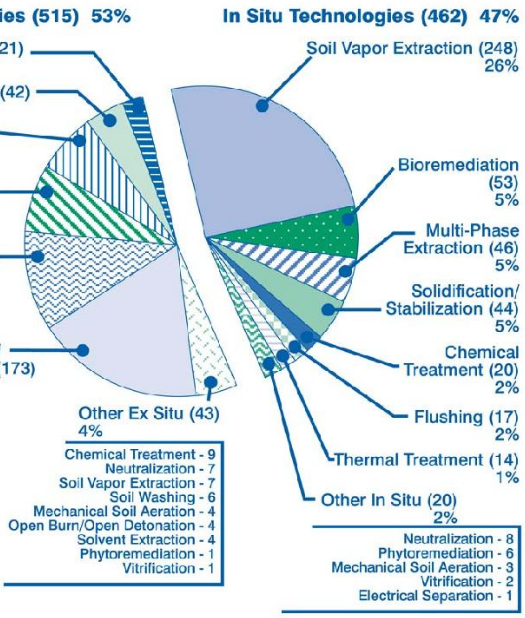

Figure 4 *Application of solidification and stabilization process in hazardous waste treatment before disposal on landfill*

CONCLUSIONS

The aim of application the solidification is to change the physical character of waste and prevent formation of large quantities of leachate on landfills, with high content of hazardous and harmful components, which results in a double effect, protect the environment, and on the other side reduce the economic effect of disposal process of hazardous waste as there is no need for installation and operation the systems for wastewater/leachate from the landfill. The selection of stabilization and solidification process, i.e. additives is one of the key elements that most affect the efficiency of the applied treatment. Due to this reason, the most important step in stabilization and solidification the waste materials is a qualitative and quantitative analysis of waste material. Based on that, it can make selection additives for the S/S process. It is necessary to investigate the impact of aging time and aging conditions resulting product S/S processes on the mobility of hazardous and harmful components of waste, thus making it possible to increase the effectiveness of the pretreatment.

S/S processes shall not be applied on waste containing volatile organic compounds, because during the S/S process the emission of significant amount of energy and emission of volatile hazardous and harmful components into atmosphere can occur. If there is no other alternative for this process, it is necessary to provide the facilities for collection and treatment of waste gas.

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PREGLED METODA SOLIDIFIKACIJE I STABILIZACIJE OPASNOG OTPADA**

Izvod

U radu su prikazane metode stabilizacije i solidifikacije (S/S) opasnog otpada u zavisnosti od vrste otpada i sadržaja opasnih i štetnih komponenti, kao metoda predtretmana opasnog otpada pre odlaganja na deponiju. Prikazan je uticaj aditiva na efikasnost procesa S/S u zavisnosti od vrste otpada, uslova starenja produkta procesa S/S. Efikasnost S/S procesa merena je mobilnošću opasnih i štetnih komponenti nakon postupka solidifikacije/stabilizacije. Prikazana je i zastupljenost pojedinih postupaka stabilizacije i solidifikacije u procesu predtretmana opasnog otpada pre odlaganja. U radu su sistematizovani podaci vezani za procese stabilizacije i solidifikacije sa ciljem izbora najoptimalnijeg procesa za dalja istraživanja u oblasti smanjenja uticaja otpada nastlog kao posledica rudarskih aktivnosti na životnu sredinu.

Ključne reči: *stabilizacija, solidifikacija, opasan otpad, tretman.*

UVOD

Stabilizacija/solidifikacija (S/S) su procesi u kome se primenom fizičkih i hemijskih osobina cementnih veziva ili hemijskom transformacijom uz pomoć aditiva smanjuje mobilnost opasnih i štetnih supstanci iz otpada, čije je deponovanje bez predtretmana zabranjeno.

Solidifikacija i stabilizacija su procesi koji obuhvataju širok spektar tehnologija, koje su usko povezane sa hemijskim i/ili fizičkim procesima smanjenja potencijalnih negativnih uticaja na životnu sredinu odlaganjem radioaktivnog, opasnog ili mešovitog otpada na zemlju, bez predtretmana [1, 2, 3].

Stabilizacija je proces pri kome se primenom hemijskih postupaka smanjuju karakteristike otpada/materijala koje ga čine opasnim. Procesom stabilizacije opasna komponenta se transformiše u manje rastvorni oblik i/ili oblik koji je manje toksičan.

In situ stabilizacija je poznata metoda za imobilizaciju zagađivača, kojom se sprečava dalje širenje zagađenja kroz zemljište i podzemne vode. Najzastupljenija in situ metoda stabilizacije podrazumeva mešanje kontaminiranog zemljišta ili otpada sa cementom kao aditivom ili drugim materijalima koji imaju slične hemijske i fizičke osobine (lebdeći pepeo .....), što podrazumeva sposobnost adsorbcije i smanjenje pokretljivosti opasnih i štetnih komponenti.

Solidifikacija je proces/operacija kojim se opasan otpad, primenom aditiva tranfor-

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miše u čvrstu formu i ne uključuje nužno hemijsku reakciju između aditiva i opasnog otpada koji se solidifikuje. Solidifikacija se deli na mikroenkapsulaciju i makroenkapsulaciju u zavisnosti od granulacije materijala koji se tretira [4].

Solidifikacija se primenjuje na jalovištima, gde se čvrste materije mešaju sa aditivima, a kao rezultat mešanja nastajanju geopolimerne matrice (zemljišni cement). Nakon podešavanja odnosa mešanja, mešavina formira čvrsti monolitni sloj.

S/S je važan tehnološki postupak koji omogućava transformaciju otpada u inertni materijal, nezavisno od pojedinačnih vrednosti rastvorljivosti metala, odnosno komponente u otpadu. Takođe je od velike važnosti činjenica da se neki fizički ili hemijski parametari (propustljivost, otpor na kompresiju) mogu lako kontrolisati izborom hemijskog aditiva i njegovog udela u mešavini (otpad/aditiv).

Čvrstoća proizvoda procesa solidifikacije ima direktan uticaj na efikasnost procesa i može se povećati smanjenjem udela vode, povećanjem temperature na kojoj se odvija proces očvšćavanja ili povećanjem udela kalcijum hlorida ili Portland cementa kao aditiva.

Leteći pepeo je sa ekonomske tačke dobra alternativa Portland cementu jer smanjuje njegovu upotrebu za 25 do 55%. [5].

Proces S/S namenjen je prvenstveno za tretman opasnog otpada (uključujući i radioaktivni otpad). Efikasnost S/S procesa ogleda se u znatnom umanjenju negativnog uticaja deponovanog (opasnog) otpada na životnu sredinu (zemljište, površinske vode, podzemne vode) i posredno na živi svet i zdravlje ljudi.

U radu su prikazani rezultati prethodnih istraživanja u smislu mogućnosti primene procesa S/S na različite vrste otpada, efikasnost aditiva u zavisnosti od udela i vrste otpada. Osnovni cilj je sistematizacija podataka i izbor najoptimalnijeg procesa solidifikacije/stabilizacije za dalja istraživanja u oblasti smanjenja uticaja otpada nastlog kao posledica rudarskih aktivnosti na životnu sredinu.

REZULTATI I DISKUSIJA

Efikasnost aditiva u zavisnosti od vrste otpada

Tretman otpadnih muljeva i otpada sa velikim sadržajem tečne faze. Proces S/S nalazi opravdanu primenu kod otpada u tečnom stanju ili otpada sa velikim sadržajem tečne faze, čije odlaganje na deponije bez prethodnog tretmana nije moguće. U ovakvim slučajevima efikasna je primena cementa kao aditiva za vezivanje tečne faze, jer cement reaguje sa vodom, hemijski vezujući vodu u hidratisani cementni proizvod. Otpor na kompresiju od najmanje 0,34 MPa (50 psi) je dokaz da tretiranjem slobodne tečne faze na pomenuti način dolazi češće do vezivanja tečne faze hemijskim vezama, ređe tečna faza biva adsorbovana [5].

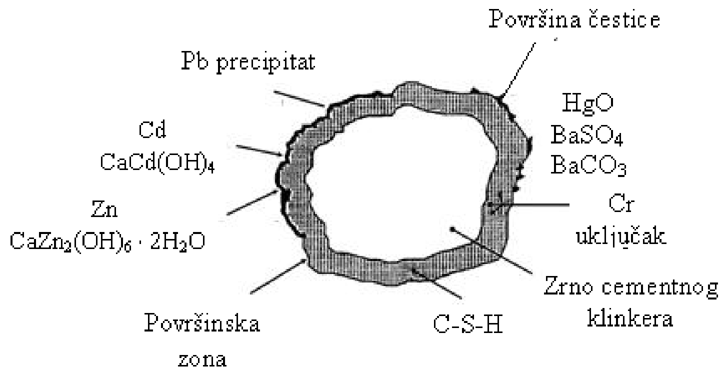
Tretman otpada sa sadržajem pretežno neorganskih zagađivača. Najčešća primena S/S procesa je primena na materijalima kontaminiranih neorganskim opasnim komponentama. Generalno, za neorganski – kontaminirane materijala, opasnost leži u sadržaju teških metala. Neorganski materijali kontaminirani teškim metalima često se kategorišu kao opasni zbog povećanog lužnog potencijala teških metala (test lužljivosti) i ispoljavanja toksičnih karakteristika (test toksičnosti). Procesom S/S dolazi do smanjenja mobilnosti teških metala i smanjenja lužnog potencijala neorganskog materijala. Posle predtretmana, materijal ne ispoljava opasne karakteristike i može se odlagati na deponiju neopasnog otpada. U slučaju sprovođenja remedijacije, kao postupka održivosti zemljišta, S/S je često jedino rešenje i dostupna tehnologija za remedijaciju velike količine zemljišta kontaminirane teškim metalima, mulja ili taloga. Kao aditiv se u ovom slučaju preporučuje cement, jer smanjuje mobilnost metalnih jona, formiranjem teškorastvornih hidroksida metala, karbonata ili silikata. U toku procesa S/S dolazi do prelaska metala iz jonskog oblika u mineralnu strukturu i fizičke enkapsulacije. Takođe, predtretmanom se može smanjiti toksičnost nekih metala promenom valentnog stanja [5].

Tretman otpada sa sadržajem pretežno organskih zagađivača. Tretman materijala sa sadržajem pretežno organskih zagađivača moguć je primenom cementa kao aditiva. U toku procesa S/S dolazi do očvršćavanja materijala, kroz promene fizičkih osobina cementa. Naročito se preporučuje ukoliko otpad ili materijal sadrži slobodnu vodu, koja ulazi u proces hidratacije, stvarajući sa cementom materijal visoko fizički integrisan monolit. Postupak je pokazao visoku efikasnost u smanjenju mobilnosti opasnih i štetnih materija iz otpada sa sadržajem halogenovanih poluisparljivih i teškoisparljivih policikličnih aromatičnih ugljovodonika (PAH), polihlorovanih bifenila (PCB), pesticida, organskih cijanida i dr.

Nedostatak cementa je neefikasnost primene u slučajevima kada otpad ima visoki sadržaj masti i ulja, kada je onemogućen proces hidratacije cementa. Čestice cementa bivaju obložene uljima ili mastima čime je onemogućen kontakt između cementa i vode. Neke organske komponente utiču na vreme vezivanja cementa, čime ceo postupak solidifikacije može znatno da se produži. Iz navedenih razloga, neophodno je pre izbora aditiva uraditi kompletnu kvalitativnu i kvantitativnu hemijsku analizu otpada, čime se sprečava nastanak neželjenih efekata na samom terenu. Takođe, upotrebom negašenog kreča kao aditiva dolazi do egzotermne reakcije tokom procesa hidratacije, čime se oslobađa znatna količina energije. Ako su u otpadu prisutne lako-isparljive opasne i štetne komponente, iste će tokom procesa S/S biti emitovane u atmosferu. Ako ne postoji druga alternativa negašenom kreču kao aditivu u procesu S/S, neophodno je obezbediti uređaje za sakupljanje i tretman gasova /vazduha[5].

Tretman otpada sa sadržajem teških metala – Primenom kobinovanog postupka stabilizacije i solidifikacije otpada sa sadržajem teških metala, u velikoj meri dolazi do transformacije oblika u kome se teški metali nalaze i prelazak u oblike (najčešće su to teškorastvorni hidroksidi) u kojima je smanjena mobilnost jona teških metala.

Solidifikacijom se dodatno smanjuje mobilnost teških metala iz novonastalih teškorastvornih oblika (slika 1).



Sl. 1. *Proizvod procesa stabilizacije i solidifikacije opasnog otpada sa sadržajem teških metala, primenom Portland cementa kao aditiva [6]*

U tabeli 1 prikazane su preporučene metode S/S u zavisnosti od vrste otpada [7].

Tabela 1. *Preporučene metode S/S u zavisnosti od vrste otpada*

Metoda stabilizacije	Primena
Solidifikacija sa cementom	Muljevi, kontaminirana zemljišta
Solidifikacija sa krečom	Otpad od desulfurizacije otpadnih gasova, drugi neorganski otpad
Solidifikacija sa termopalstičnim materijalima	Radioaktivni otpad
Enkapsulacija	Muljevi, tečnosti, određene materije
Vitrifikacija	Ekstremno opasan otpad, radioaktivni otpad

Model za izbor aditiva u zavisnosti od vrste otpada

U cilju lakšeg izbora aditiva u zavisnosti od vrste otpada sprovedena su istraživanja od strane autora B. K. C. Chan i ostalih. Ispitivani materijali za izradu modela za izbor aditiva bili su sledeći: JR-otpad sa najvećim sadržajem opasnih komponenti nastao kao posledica rudarskih aktivnosti, OMW-fino granulisani otpad sa niskim sadržajem opasnih komponenti. Ispitani aditivi su SS-kvarcni pesak, PC-komercijalno dostupni Portland cement, FA-leteći pepeo i L-kreč.

U tabeli 2 prikazani su rezultati ispitivanja stabilizacije opasnog otpada sa različitim sadržajem opasnih komponenti primenom različitih aditiva i sa različitim udelom [8].

Tabela 2. *Rezultati ispitivanja stabilizacije opasnog otpada sa različitim sadržajem opasnih komponenti primenom različitih aditiva*

Mix	% Osušenog kontaminiranog zemljišta/otpada						Udeo voda/otpad
	PC	FA	SS	OMW	JR	L	
5PC-FA	5	15	80	-	-	-	0.20
5PC-FA-OMW	5	15	70	10	-	-	0.30
5PC-FA-JR	5	15	70	-	10	-	0.25
10PC-FA-JR	10	15	65	-	10	-	0.30
10L-FA-JR	-	15	65	-	10	10	0.43
5PC-FA-L-JR	5	15	65	-	10	5	0.41

Koncentracije teških elemenata As, Cd, Co, Cu, Mn, Mo i Ni u otpadu nakon predtretmana, dobijene sprovođenjem propisanih procedura ispitivanja opasnih i toksičnih karakteristika otpada bili su ispod granice dozvoljenih vrednosti za podzemne vode i zemljište, čak i iz uzoraka otpada koji ima povećani sadržaj opasnih komponenti.

Adsorpcija na hidratisani gvožđe (III) oksid prisutnog u uzorcima smanjila je mobilnost jona arsena. Međutim sadržaj barijuma je iznad propisanih granica u svim ispitivanim slučajevima. Takođe, amfoterni Cr, Pb i Zn su preko granica dozvoljenih kada je ispitivani uzorak bio JR.

Rezultati ispitivanja kontaminiranog zemljištu sa manjim sadržajem opasnih komponenti, a nakon sprovedenog postupka predtretmana, dao je zadovoljavajuće rezultate.

U tabeli 3 prikazani su rezultati ispitivanja primene različitih aditiva (kreč, UFS-livnički pesak iz železare Smederevo) za stabilizaciju otpada nastao rudarskim aktivnostima sa područja Bora, Srbija, sa sadržajem teških metala: bakar (0.12%), gvožđe (4.06%), olovo (0.07%) i cink (0.07%) [9].

Tabela 3. *Mobilnost jona teških metala nakon stabilizacije u 4 ciklusa primenom različitih aditiva.*

Mešavina	Metal	mg/L			
		1	2	3	4
Materijal sa brane 3A	Cu	11.8	11.6	10.8	10.8
	Fe	8.1	4.4	6.5	4.3
	Pb	<1	<1	<1	<1
	Zn	5.2	5.1	6.6	5.9
Materijal sa brane 3A + (100% kreč)	Cu	0.24	0.21	0.27	0.27
	Fe	<0.05	<0.05	<0.05	<0.05
	Pb	<1	<1	<1	<1
	Zn	0.34	<1	<1	<1
Materijal sa brane 3A + (100% UFS)	Cu	12.93	16.14	18.44	16.98
	Fe	7.395	5.882	2.689	2.857
	Pb	<1	<1	<1	<1
	Zn	11.19	13.19	13.79	13.15
Materijal sa brane 3A + (90% UFS + 10% kreč)	Cu	n.d	n.d	n.d	0.077
	Fe	0.336	0.336	0.336	0.336
	Pb	0.714	0.714	0.714	0.714
	Zn	0.128	0.085	0.128	0.255
Materijal sa brane 3A + (75% UFS + 25 kreč)	Cu	n.d	0.077	n.d	n.d
	Fe	0.336	0.336	0.504	0.336
	Pb	n.d	n.d	n.d	n.d
	Zn	0.213	0.043	0.085	0.170

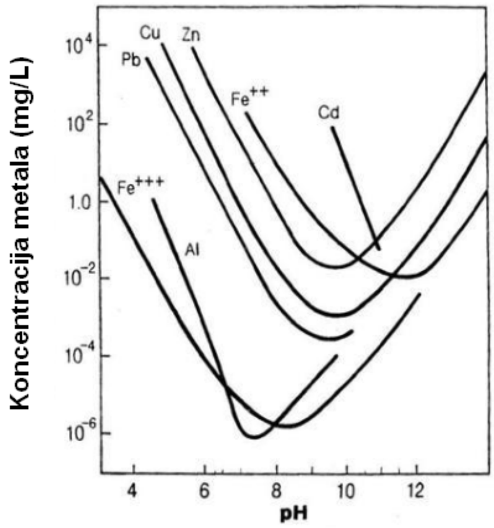
Najbolji rezultati su dobijeni primenom kreča kao aditiva, što se moglo i očekivati, jer se radi o otpadu neorganskog porekla sa povećanim sadržajem teških metala.

Faktori koji utiču na efikasnost stabilizacije i solidifikacije

<u>*Pravilan izbor reagensa.*</u> *Stabilizacija otpada nastao kao posledica rudarskih aktivnosti sa velikim sadržajem vodene faze.* Postupak koji se preporučuje u slučaju stabilizacije opasnog otpada, naročito neorganskog otpada sa sadržajem teških metala, je *neutralizacija krečom* iz razloga stvaranja teškorastvornih hidroksida u alkalnim uslovima sredine, što je istraživanje M. Korać i ostali, prikazano u tabeli 3, potvrdilo.

Dodatno, u postupku solidifikacije može nastati po površini zrna, u prisustvu silicijuma i aluminijuma, nepropusna barijera kalcijum-silikatni gel ili kalcijum-aluminatni gel, čime se povećava efikasnost postupka [10].

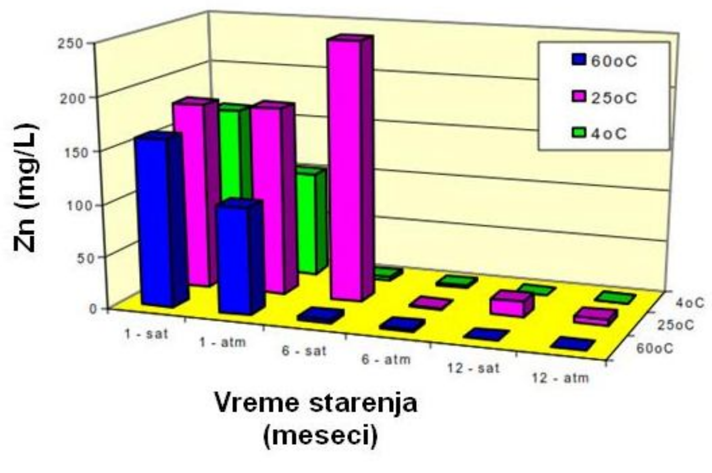
Kriva rastvorljivosti hidroksida teških metala u zavisnosti od pH vrednosti sredine prikazana je na slici 2, čime se jasno uočava uticaj pH vrednosti na mobilnost teških metala [5].



Sl. 2. *Kriva rastvorljivosti hidroksida teških metala u zavisnosti od pH* vrednosti [5]

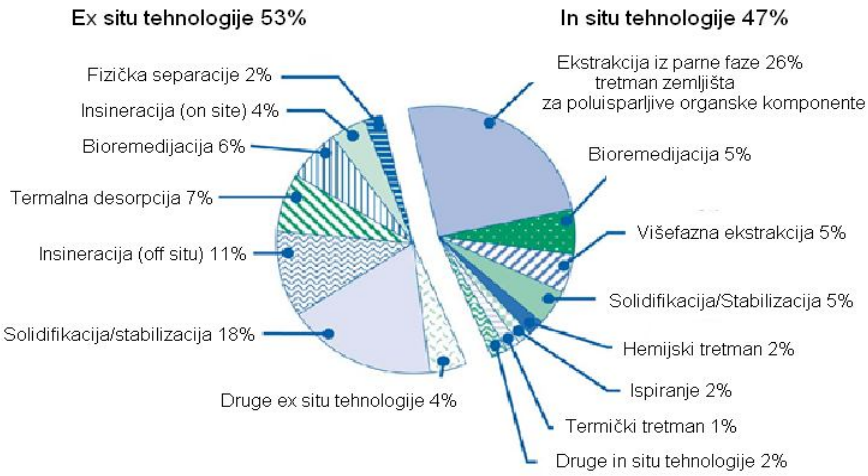
<u>*Vreme starenja produkta stabilizacije i solidifikacije*</u> – Tretman nastalog produkta nakon procesa solidifikacije i stabilizacije otpadnog materijala može imati značajni efekat na efikasnost postupka. Na slici 3 prikazan je uticaj temperature i uslova sušenja i vremena starenja na mobilnost cinkovih jona u mulju.

Sa slike se jasno uočava da starenje od 6 meseci pri temperaturi od 25°C, pri atmosferskim uslovima, smanjuje mobilnost jona cinkana na ispod 10 mg/L [5].



Sl. 3. *Uticaj temperature i uslova sušenja i vremena starenja na mobilnost cinkovih jona u mulju [5]*

Na slici 4 grafički je prikazana zastupljenost pojedinih postupaka stabilizacije i solidifikacije u procesu predtretmana opasnog otpada pre odlaganja [11].



Sl. 4. *Zastupljenost pojedinih postupaka stabilizacije i solidifikacije u procesu predtretmana opasnog otpada pre odlaganja [11]*

ZAKLJUČAK

Promenom fizičkog karaktera otpada primenom solidifikacije, sprečava se nastanak velike količine procednih voda na deponiji, sa visokim sadržajem opasnih i štetnih komponenti; čime se postiže dvostruki efekat, štiti se životna sredina, a sa druge strane smanjuje ekonomski efekat procesa zbrinjavanja opasnog otpada, jer nema potrebe za instalacijom i radom sistema za prečišćavanje otpadnih/procednih voda sa deponije.

Izbor postupka stabilizacije i solidifikacije, tj. aditiva jedan je od ključnih elemenata koji najviše utiču na efikasnost primenjenog postupka. Iz tog razloga najbitniji korak u procesu stabilizacije i solidifikacije otpadnog materijala predstavlja kvalitativna i kvantitativna analiza otpadnog materijala, na osnovu koje se može izvršiti izbor pravog aditiva za proces S/S.

Neophodno je proveriti uticaj starenja i uslova starenja nastalog produkta S/S procesa na mobilnost opasnih i štetnih komponenti iz otpad, čime je moguće povećati efikasnost procesa predtretmana.

Procesi S/S se ne primenjuju na otpadne materijale sa sadržajem poluisparljivih i lakoisparljivih organskih komponenti. Osnovni razlog je što usled procesa S/S može doći do oslobađanja toplotne energije, čime bi se povećao uticaj opasnog otpada na životnu sredinu emisijom opasnih i štetnih komponenti u vazduh.

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Rodoljub Stanojlović, Jovica Sokolović**

A STUDY OF FLOTATION KINETICS OF THE HYDROCYCLONE OVERFLOW AND UNDERFLOW IN THE PROCESSING OF HIGH-GRADE COPPER ORE**

Abstract

The results of flotation kinetics the hydrocyclone underflow and overflow in high-grade copper ore processing from the Copper Mine Bor (RB Bor), suggest the possibility of improving the current technological flotation process. This is confirmed by the following results: the distribution of copper in classification product in ration 80:20 % in favor of hydrocyclone underflow as well as higher copper content in the sample and individual class of hydrocyclone underflow compared to the same parameters of hydrocyclone overflow.

Participation of optimal size class – 0.075 mm in hydrocyclone underflow is 32.47 %, with copper content of 4.38 %, resulting that about 65 % of total copper in this class to the feed of hydrocyclone is distributed in hydrocyclone underflow and 35 % in the same class in hydrocyclone overflow.

Copper recoveries, obtained in laboratory batch flotation tests from hydrocyclone overflow and underflow, are 90.77% and 7.94 %, respectively. Calculated in relation to total copper in the feed of hydrocyclone, 17.30 % Cu can be valorized from hydrocyclone overflow by flotation process, with the same process, 59.58 % Cu is valorized from hydrocyclone underflow, what is 3.44 times more.

The results indicate higher copper recovery and slightly better flotation kinetics of hydrocyclone overflow. However, due to better liberation of solid phase and optimization the pulp density in the flotation process, each class of hydrocyclone underflow gives higher contribution to the copper recovery compared to the relevant class of hydrocyclone overflow, calculated on copper, contained in the same class of hydrocyclone feed.

Parallel flotation of hydrocyclone overflow and underflow can improve the existing technological process of high-grade copper ore processing in the Copper Mine Bor.

Keywords: *Copper Mine Bor, high-grade copper ore, hydrocyclone, overflow, underflow, flotation, kinetics.*

INTRODUCTION

The increased average content of copper (2 - 5 % Cu) and gold (1 - 7 g/t Au), as well as significant difference in densities of these components in relation to the density of associated aluminosilicate minerals, cause the reduced efficiency of hydrocyclone classifi-

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cation in high-grade copper ore processing. This occurrence causes that liberated and overground particles with higher density, copper minerals from 4100 to 5800 kg/m^3, gold about 19000 kg/m^3, instead of hydrocyclone overflow, are distributed in the hydrocyclone underflow and unnecessary back into the grinding process [1-5]. Negative consequences of technical and technological imperfections of hydrocyclone as a classifier are multiple, including: increasing of energy consumption and charge in the grinding process per ton of processed copper ore, reducing the capacity and overgrinding of useful components affects the recovery in e flotation process [1-5].

The mass distribution of solid phase and useful components in the industrial process was about 20 to 80% in favor of hydrocyclone underflow as well as the granulometric characteristics of classification products, indicating the insufficient efficiency of classification process.

By laboratory batch flotation tests of hydrocyclone overflow and underflow from the industrial process of high-grade copper ore are defined the technological parameters and flotation process kinetics.

Analysis the technological parameters and flotation kinetics, both on integrated classification products, hydrocyclone overflow and underflow and on narrow size classes, considering the industrial distribution of solid phase and useful components in them, enables a realistic assessment of research justification toward technological improvement of the existing flotation processes of high-grade copper ore.

GRINDING AND CLASSIFICATION OF HIGH-GRADE COPPER ORE

Two-stage wet grinding (rod and ball mill with classification in hydrocyclones operating in a closed cycle with ball mill) are the integral part of industrial processing of high-grade copper ore. Hydrocyclone overflow as the final product of grinding process is distributed in the flotation of copper and precious metals, and hydrocyclone underflow is returned to the grinding process in the ball mill. Grinding and classification of high-grade copper ore is shown in Figure 1.

Capacity of industrial processing of high-grade copper ore in the Copper Mine Bor is 80 t/h. Designed fineness of the final grinding product is 60 % with class participation -0.074 mm.

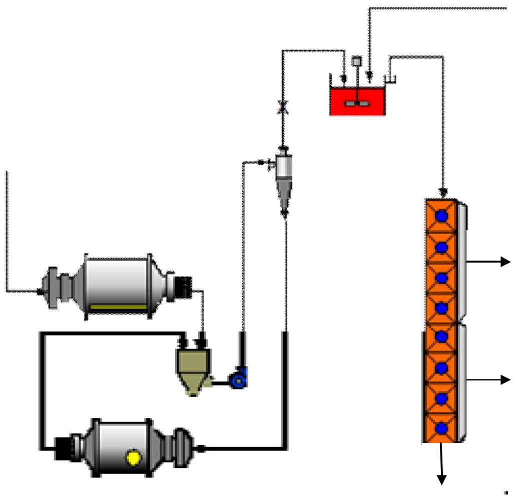


Figure 1 *Flowsheet of grinding and classification process of high-grade copper ore*

Mass distribution of solid phase and useful components in the classification process, as well as grain size distribution and chemical composition of grinding products, i.e. hydrocyclone overflow and underflow were defined by recording the industrial process of grinding and classification the highgrade ore, Tables 1 and 2.

Table 1 *Distribution of solid phase mass and useful components by classification products*

Product	Distribution		
	Mass (%)	**Copper, Cu (%)**	**Gold, Au (%)**
Overflow	19.99	19.05	9.77
Underflow	80.01	80.95	90.23
Feed	100.00	100.00	100.00

Table 2 *Grain-size distribution and chemical composition of hydrocyclone products*

Size class, (mm)	Overflow			Underflow			Feed		
	m (%)	**Cu (%)**	**R_{Cu} (%)**	**m (%)**	**Cu (%)**	**R_{Cu} (%)**	**m (%)**	**Cu (%)**	**R_{Cu} (%)**
+0.150	2.11	0.38	0.25	40.08	2.68	32.12	32.49	2.65	26.05
-0.150 +0.075	13.65	0.65	2.82	27.45	3.09	25.37	24.69	2.82	21.07
-0.075 +0.038	21.96	3.10	21.61	20.08	3.97	23.84	20.46	3.78	23.41
-0.038 +0.000	62.28	3.81	75.32	12.39	5.04	18.67	22.36	4.36	29.47
Total:	**100.00**	**3.15**	**100.00**	**100.00**	**3.34**	**100.00**	**100.00**	**3.31**	**100.00**

EXPERIMENTAL TESTING

Flotation tests were carried out on the samples of hydrocyclone overflow and underflow from the industrial process of high-grade copper ore processing.

Standard flotation tests were carried out in laboratory machine DENVER DR-12 with cell volume of 2,6 l. During this laboratory flotation batch tests, the impeller speed and aeration rate and pH (1300 min^{-1} and 260 l/min, respectively) were kept constant. pH was adjusted at about pH 10.5. Solid content in a pulp (by weight) was constant of 25% in a flotation test with hydrocyclone overflow and 50% in a flotation test with hydrocyclone underflow. The reagents used in the kinetics test were collectors PEX (170 g/t in a flotation of hydrocyclone overflow) and PAX (350 g/t in a flotation of hydrocy-clone underflow) and Dowfroth D-250 as frother (20 g/t). In each flotation kinetics test, the pulp was first agitated in the flotation cell for 10 minutes, after which the required dosage of flotation reagents was added and the slurry was conditioned one additional minute. The froth products were collected after 1, 3, 5, 10 and 20 minutes in the flotation. The froth flotation products were screened, filtered, dried and weighed. Chemical analyses were conducted for all size classes of flotation products. The results of mass distribution and copper by size classes of flotation products are shown in Tables 3 and 4.

Table 3 *Grain-size distribution and chemical composition of hydrocyclone overflow*

Size class, (mm)	Concentrate			Tailings			Feed (Overflow)		
	m (%)	Cu (%)	R_{Cu} (%)	m (%)	Cu (%)	R_{Cu} (%)	m (%)	Cu (%)	R_{Cu} (%)
+0.150	0.24	1.92	0.16	1.87	0.18	1.17	2.11	0.38	0.25
-0.150 +0.075	2.03	3.16	2.25	11.62	0.21	13.65	13.65	0.65	2.81
-0.075 +0.038	10.34	6.26	22.66	11.62	0.28	21.96	21.96	3.10	21.60
-0.038 +0.000	33.89	6.32	74.93	28.39	0.81	62.28	62.28	3.81	75.34
Total:	**46.50**	**6.14**	**100.00**	**53.50**	**0.54**	**100.00**	**100.00**	**3.15**	**100.00**

Table 4 *Grain-size distribution and chemical composition of hydrocyclone underflow*

Size class, (mm)	Concentrate			Tailing			Feed (Underflow)		
	m (%)	Cu (%)	R_{Cu} (%)	m (%)	Cu (%)	R_{Cu} (%)	m (%)	Cu (%)	R_{Cu} (%)
+0.150	10.86	3.49	15.36	29.22	2.35	79.04	40.08	2.68	31.94
-0.150 +0.075	17.95	4.32	31.42	9.50	0.78	8.53	27.45	3.09	25.46
-0.075 +0.038	16.89	4.49	30.72	3.19	1.22	4.48	20.08	3.97	23.89
-0.038 +0.000	7.38	7.52	22.50	5.01	1.38	7.95	12.39	5.04	18.71
Total:	**53.08**	**4.65**	**100.00**	**46.92**	**1.85**	**100.00**	**100.00**	**3.34**	**100.00**

COPPER FLOTATION KINETICS FROM HYDROCYCLONE OVERFLOW AND UNDERFLOW

In accordance with the aim of investigation on the hydrocyclone overflow and underflow, divided flotation tests were carried out in the selected time intervals. Each of the obtained concentrates and tailings were dried, weighted and screened for the flotation process of characteristic size class. Each size class of the individual concentrate and tailings, as a function of time, were analyzed on the copper content as the basic useful component.

Based on the obtained flotation test results, shown in Table 1-4, the values of copper recovery were calculated by narrow size classes, as well as the integral values, as a function of flotation time were used in defining the copper flotation kinetics from hydrocyclone overflow and underflow. The calculated values of technological parameters are given in Tables 5 and 6.

Table 5 *Grain-size distribution, chemical composition and technological parameters of divided flotation of hydrocyclone overflow*

Size class, d (mm)	Products	m (%)	Cu (%)	I_{Cu} (%)	I_{Cu} (%)		
					I_k=100 %	I_u^p=100 %	I_u^c=100 %
+0,150	K1	0,08	2,88	0,12	0,08	0,07	0,01
-0,150+0,075		0,91	4,72	2,22	1,50	1,36	0,26
-0,075+0,038		6,51	8,09	27,32	18,44	16,74	3,19
-0,038+0		13,32	10,18	70,34	47,47	43,09	8,22
		20,82	**9,26**	**100,00**	**67,49**	**61,26**	**11,68**
+0,150	K2	0,09	1,82	0,26	0,06	0,05	0,01
-0,150+0,075		0,64	2,43	2,52	0,54	0,49	0,09
-0,075+0,038		2,68	3,95	17,21	3,70	3,36	0,64
-0,038+0		9,20	5,35	80,01	17,23	15,64	2,98
		12,61	**4,88**	**100,00**	**21,53**	**19,54**	**3,73**
+0,150	K3	0,03	1,03	0,23	0,01	0,01	0,00
-0,150+0,075		0,20	1,51	2,28	0,10	0,09	0,02
-0,075+0,038		0,49	1,59	5,93	0,27	0,25	0,05
-0,038+0		3,43	3,51	91,56	4,22	3,83	0,73
		4,15	**3,17**	**100,00**	**4,60**	**4,18**	**0,80**
+0,150	K4	0,03	1,02	0,26	0,01	0,01	0,00
-0,150+0,075		0,24	1,03	2,16	0,09	0,08	0,02
-0,075+0,038		0,51	1,07	4,76	0,19	0,17	0,03
-0,038+0		4,31	2,49	92,82	3,78	3,43	0,65
		5,09	**2,27**	**100,00**	**4,07**	**3,69**	**0,70**
+0,150	K5	0,01	0,61	0,15	0,00	0,00	0,00
-0,150+0,075		0,04	0,84	0,45	0,01	0,01	0,00
-0,075+0,038		0,15	0,97	2,26	0,05	0,04	0,01
-0,038+0		363	1,78	97,14	2,25	2,05	0,39
		3,83	**1,74**	**100,00**	**2,31**	**2,10**	**0,40**
+0,150	∑K	0,24	1,92	0,16	0,16	0,14	0,02
-0,150+0,075		2,03	3,16	2,25	2,25	2,03	0,39
-0,075+0,038		10,34	6,26	22,66	22,66	20,56	3,92
-0,038+0		33,89	6,32	74,93	74,93	68,04	12,97
		46,50	**6,14**	**100,00**	**100,00**	**90,77**	**17,30**
+0,150	J	1,87	0,18	1,17		0,11	0,02
-0,150+0,075		11,62	0,21	8,40		0,76	0,15
-0,075+0,038		11,62	0,28	11,19		1,03	0,20
-0,038+0		28,39	0,81	79,24		7,33	1,38
		53,50	**0,54**	**100,00**		**9,23**	**1,75**
+0,150	U	2,11	0,38	0,25		0,25	0,04
-0,150+0,075		13,65	0,65	2,81		2,79	0,54
-0,075+0,038		21,96	3,10	21,60		21,59	4,12
-0,038+0		62,28	3,81	75,34		75,37	14,35
		100,00	**3,15**	**100,00**		**100,00**	**19,05**

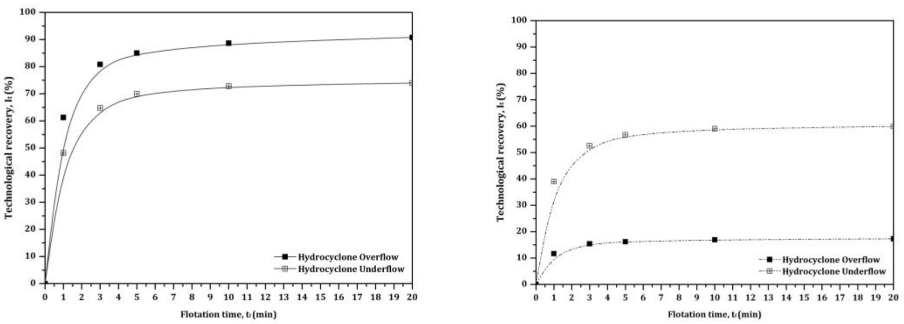
Table 6 *Grain-size distribution, chemical composition and technological parameters of divided flotation of hydrocyclone underflow*

Grain size class, d (mm)	Products	m (%)	Cu (%)	I_{Cu} (%)	I_{Cu} (%)		
					I_k=100%	I_u^p=100%	I_u^c=100 %
+0,150	K1	5,55	3,47	11,19	7,81	5,78	4,37
-0,150+0,075		12,75	4,36	34,60	22,53	16,67	13,50
-0,075+0,038		12,32	4,46	34,20	22,27	16,44	13,34
-0,038+0		3,50	8,82	19,21	12,52	9,25	7,49
		34,12	**4,71**	**100,00**	**65,13**	**48,14**	**39,00**
+0,150	K2	2,60	3,80	17,75	4,00	2,96	2,40
-0,150+0,075		3,85	4,10	28,36	6,40	4,73	3,83
-0,075+0,038		3,58	4,41	28,37	6,40	4,73	3,83
-0,038+0		1,44	9,86	25,52	5,76	4,26	3,45
		11,47	**4,85**	**100,00**	**22,56**	**16,68**	**13,51**
+0,150	K3	1,30	3,95	29,81	2,08	1,54	1,25
-0,150+0,075		0,91	5,04	26,67	1,86	1,38	1,11
-0,075+0,038		0,69	5,35	21,44	1,50	1,11	0,90
-0,038+0		0,53	7,18	22,08	1,54	1,15	0,92
		3,43	**5,02**	**100,00**	**6,98**	**5,18**	**4,18**
+0,150	K4	1,18	2,66	32,81	1,27	0,94	0,76
-0,150+0,075		0,38	3,77	14,94	0,58	0,43	0,35
-0,075+0,038		0,24	4,93	12,33	0,48	0,35	0,29
-0,038+0		0,90	4,25	39,92	1,55	1,15	0,93
		2,70	**3,54**	**100,00**	**3,88**	**2,87**	**2,32**
+0,150	K5	0,23	2,06	13,13	0,19	0,14	0,11
-0,150+0,075		0,06	1,82	3,07	0,04	0,03	0,03
-0,075+0,038		0,06	3,04	5,03	0,07	0,05	0,04
-0,038+0		1,01	2,79	78,77	1,15	0,85	0,69
		1,36	**2,63**	**100,00**	**1,45**	**1,07**	**0,87**
+0,150	∑K	10,86	3,49	15,35	15,35	11,36	8,89
-0,150+0,075		17,95	4,32	31,41	31,41	23,24	18,82
-0,075+0,038		16,89	4,49	30,72	30,72	22,68	18,40
-0,038+0		7,38	7,52	22,52	22,52	16,66	13,47
		53,08	**4,65**	**100,00**	**100,00**	**73,94**	**59,58**
+0,150	J	29,22	2,35	79,04		20,58	16,96
-0,150+0,075		9,50	0,78	8,53		2,22	1,79
-0,075+0,038		3,19	1,22	4,48		1,21	0,94
-0,038+0		5,01	1,38	7,95		2,05	1,68
		46,92	**1,85**	**100,00**		**26,06**	**21,37**
+0,150	U	40,08	2,68	31,94		31,94	25,85
-0,150+0,075		27,45	3,09	25,46		25,46	20,61
-0,075+0,038		20,08	3,97	23,89		23,89	19,34
-0,038+0		12,39	5,04	18,71		18,71	15,15
		100,00	**3,34**	**100,00**		**100,00**	**80,95**

RESULTS AND DISCUSSION

The distribution of solid phase mass in hydrocyclone overflow and underflow, approximately 20:80 %, and higher presence of copper and especially gold in hydrocyclone underflow in relation to hydrocyclone overflow confirms the fact that hydrocyclone, besides classification, also performs a partial concentration of useful components in the function of differrent density. This occurrence is more pronounced with more negative effects in the processing of high-grade copper ore, what confirms the presence of enough ground raw material of size class size -0.074 mm in hydrocyclone underflow approximately 32.47 % as well as significantly higher copper content in this size class, in relation to the content of the same component in the same class of hydrocyclone overflow, Tables 1 and 2.

Based on the results of divided batch flotation on hydrocyclone overflow and underflow, Tables 5 and 6, Figure 2 shows the copper flotation kinetics from these products of classification. Copper flotation kinetics from hydrocyclone overflow and underflow are shown on diagrams in Figure 2a, while the same indicators, calculated on total copper in feed material, are shown with diagrams in Figure 2b.



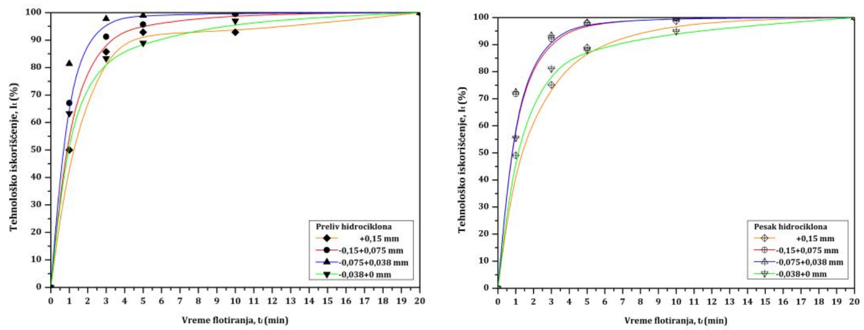
a) *b)*

Figure 2 *Copper flotation kinetics from hydrocyclone overflow and underflow*

a) compared to the copper content in hydrocyclone products,
b) compared to the copper content in hydrocyclone feed

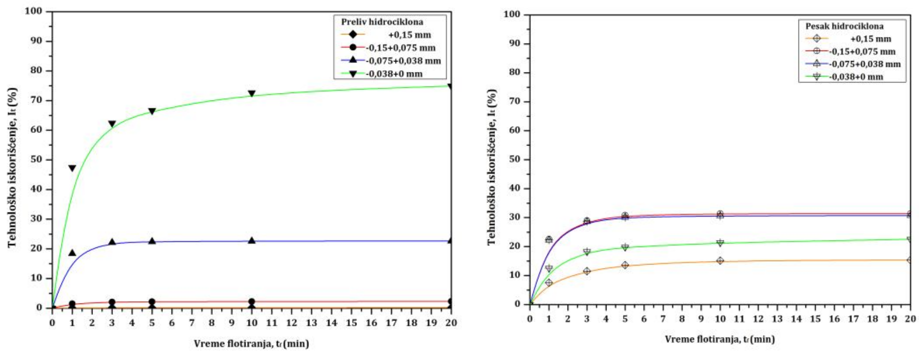
Higher copper recovery from hydrocyclone underflow, approximately 70 %, satisfactory flotation kinetics, Figure 2 (a), in particular, several times higher recovery of copper, about 60 % from hydrocyclone underflow, compared to 17.30 % from hydrocyclone overflow in the relation of the copper content in the feed of the hydrocyclone, justified investigation of the possibilities for improvement of processing of the rich copper ore in the Copper Mine Bor.

For a detailed overview of the research results is defined distribution of the copper, both in integral samples and by the narrow classes of the same products, Tables 1 and 2. Copper flotation kinetics are also defined from narrow size classes of hydrocyclone overflow and underflow, diagrams in Figures 3, 4 and 5.



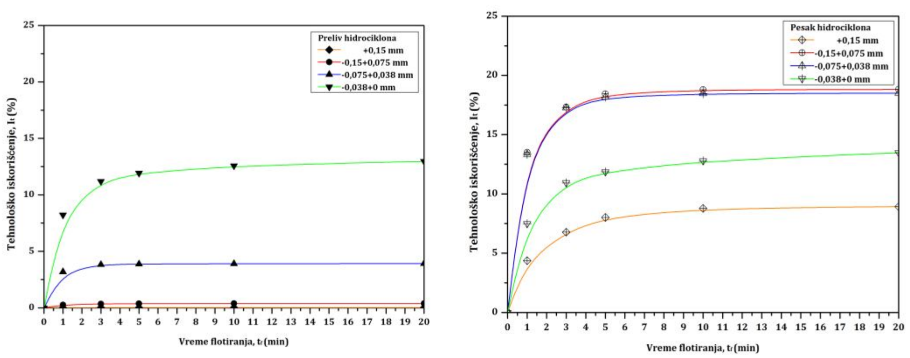
a) *b)*

Figure 3 *Copper flotation kinetics from narrow size classes*
a) hydrocyclone overflow, b) hydrocyclone underflow



a) *b)*

Figure 4 *Copper recovery by narrow size classes of classification products*
a) in hydrocyclone overflow, for IOF = 100%, b) in hydrocyclone underflow, IUF = 100%



a) *b)*

Figure 5 *Copper recovery by size classes, compared to the copper content in feed of hydrocyclone: a) hydrocyclone overflow b) hydrocyclone underflow*

The best copper flotation kinetics from hydrocyclone overflow is achieved on class (-0.075+0.038) mm, and hydrocyclone underflow on classes (-0.150+0.075) mm and (-0.075+0.038) mm, respectively, diagrams in Figure 3 (a and b).

Due to copper distribution per certain size classes of classification products, Table 2 and 3, the highest contributio n to the copper recovery from hydrocyclone overflow is from the finest class –0.038 mm, approximately 75%, while from the optimal grain size for flotation kinetics, the class (-0.075+0.038) mm, the contribution is realized to total recovery of 22.66 %. Contribution to total copper recovery from hydro-cyclone overflow from the other size class is almost insignificant, 2.25 % from the class (-0.150+0.075) mm and 0.16 % from the class +0.150 mm. In hydrocyclone underflow, coarser classes have the best flotation kinetics, t diagram in Figure 3 (b), while the contribution to total recovery from narrow size class are more balanced. From the class (-0.150+0.075) mm, contribution is achieved to total recovery of 23.24 %, from the class (-0.075+0.038) mm, approximately 22.68%, from the class (-0.038+0) mm 16,66 %, while the most coarser class +0.150 mm from hydrocyclone underflow contribute with significant 11.36 % in total recovery.

The results presented on diagram in Figure 5 (a and b) showing the value of copper in narrow size class of hydrocyclone overflow and underflow, calculated based on total available copper in the feed of cyclone, have particular importance. Besides confirmation the previous conclusions about higher total copper recovery from hydrocyclone underflow, compared to hydrocyclone overflow, Figure 2 (b), it can be concluded that the individual contribution of copper from each class of hydrocyclone underflow is higher than the same indicator, obtained in the same class of hydrocyclone overflow.

CONCLUSION

The research results clearly confirm the possibility of improving the flotation process of high-grade copper ore, with additional flotation of hydrocyclone underflow. This conclusion is based on the fact that copper distribution in classification product is approximately 20:80% in favor of hydrocyclone underflow, higher copper content in integral sample of hydrocyclone underflow, 3.34 % Cu, as compared to hydrocyclone overflow 3.15% Cu, as well as all narrow size classes of the same product. It is particularly important to note the increased participation and copper content in the optimal liberated classes of hydrocyclone underflow compared to the same class hydrocyclone overflow.

Participation of class – 0.075 mm in the hydrocyclone underflow is about 32,5 %, with copper content of 4.38 %, while the participation of the same class in hydrocyclone overflow is about 84.2 % with the content of the same useful component of 3.62 %. Compared to the copper contained in this size class in the feed of cyclone, about 65 % is distributed in hydrocyclone underflow and 35 % in the hydrocyclone overflow. The stated facts have shown great overgrinding of raw materials in the industrial process of grinding, as well as inefficiency and clarity of classification, due to inadequate operating parameters, as well as technological imperfections of this device in treatment of polymineral ores with different density.

The results of flotation experiments on hydrocyclone overflow and underflow indicate a few significant occurrences.

Slightly better kinetics and higher copper recovery from hydrocyclone overflow were consequence of increased liberation the solid phase and optimization the pulp density in flotation process. A significant lower contribution of copper from the optimal size class (0.075+0.038) mm for flota tion process, compared to the same parameter, was achieved on the finest size class -0.038 mm, confirming the previous conclusion about overgrinding of raw materials in grinding process. Too high content of the class -0.075 mm in hydrocyclone overflow, approximately 84.2 %, with about 62% finer than 0.038 mm, has negative consequences both in the increased energy consumption in grinding process as well as decreased flotation efficiency.

Higher content of optimally liberated size class (-0.075+0) mm in hydrocyclone underflow, about 32.5%, with participation of class below 0.038 mm higher than 12%, are indicators of inefficient classification and causes both of sufficient kinetics and high copper recovery in the flotation process from hydrocyclone underflow.

With the statement that in the industrial process of high-grade copper ore, due to continuity of industrial process, the flotation results from hydrocyclone overflow and underflow can be differ from the obtained in the laboratory flotation tests, the real possibility and technological justification can be stated with certainty for improvement the existing technology of high-grade copper ore processing from RTB Bor, with additional flotation of hydrocyclone underflow.

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ISTRAŽIVANJE KINETIKE FLOTIRANJA PRELIVA I PESKA HIDROCIKLONA PRI PRERADI BOGATE RUDE BAKRA**

Izvod

Rezultati istraživanja kinetike flotiranja preliva i peska hidrociklona pri preradi bogate rude bakra RB-Bor, upućuju na mogućnost unapređenja postojećeg tehnološkog procesa flotiranja. Raspodela bakra u proizvodima klasiranja 80 : 20 %, u korist peska hidrociklona, veći sadržaj bakra u uzorku i svakoj klasi peska hidrociklona u odnosu na isti pokazatelj preliva hidrociklona, to potvrđuju.

Učešće optimalno oslobođene klase krupnoće -0,075 mm u pesku hidrociklona od 32,47 %, sa sadržajem bakra od 4,38 %, rezultiraju da se oko 65 % od ukupnog bakra koji nosi ova klasa u ulazu u hidrociklon distribuira u pesku, a 35 % u istoj klasi preliva hidrociklona.

Iskorišćenje bakra u opitima flotiranja preliva iznosi 90,77 %, a peska hidrociklona 73,94 %. Obračunato u odnosu na ukupan bakar u ulazu u hidrociklon, flotiranjem preliva hidrociklona valorizuje se 17,30 % Cu, a istim postupkom iz peska hidrociklona se iskoristi 59,58 % Cu, što je 3,44 puta više.

I pored većeg iskorišćenja bakra i nešto bolje kinetike flotiranja preliva hidrociklona zbog bolje oslobođenosti čvrste faze i optimizacije gustine pulpe u procesu flotiranja, svaka klasa peska hidrociklona daje veći doprinos iskorišćenju bakra u odnosu na odgovarajuće klase preliva hidrociklona, obračunato na bakar sadržan u istim klasama ulaza u hidrociklon.

Paralelnim flotiranjem preliva i peska hidrociklona može se unaprediti postojeći tehnološki proces prerade bogate rude bakra RB-Bor.

Ključne reči: *Rudnik bakra Bor, bogata ruda bakra, hidrociklon, preliv, pesak, flotacija, kinetika.*

UVOD

Povećan sadržaj bakra, od 2 -5 % Cu i zlata od nekoliko (1 - 7 g/t Au), kao i velika razlika u gustinama ovih komponenata u odnosu na gustine prateće alumosilikatne jalovine, uslovljavaju smanjenu efikasnost oštrine klasiranja u hidrociklonu pri preradi

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**U ovom radu su prikazani rezultati projekata TR 33007 „Implementacija savremenijih tehničko-tehnoloških i ekoloških rešenja u postojećim proizvodnim sistemima Rudnika bakra Bor i Rudnika bakra Majdanpek“ i TR 33038 „Usavršavanje tehnologija eksploatacije i prerade rude bakra sa monitoringom životne i radne sredine u RTB Bor Grupa“ finansiranih od strane Ministarstva prosvete, nauke i tehnološkog razvoja Republike Srbije. Autori se zahvaljuju pomenutom Ministarstvu na finansijskoj podršci.

bogate rude bakra (naš rad). Ova pojava uslovljava da se čestice većih gustina, minerala bakra, ρ=4100 kg/m^3 – 5800 kg/m^3, i zlata ρ≈19000 kg/m^3, oslobođene i dovoljno usitnjene za proces flotiranja umesto u preliv distribuiraju u pesak hidrociklona i nepotrebno vraćaju u proces mlevenja [1-5]. Negativne posledice tehničko-tehnološke nesavršenosti hidrociklona kao uređaja za klasiranje su višestruke i ogledaju se u povećanju potrošnje energije i šarže u procesu mlevenja po toni prerađene rude, smanjenju kapaciteta prerade, a preusitnjavanje korisnih komponenata negativno se odražava na iskorišćenje u procesu flotiranja [1-5].

Masena raspodela čvrste faze i korisnih komponenata u industrijskom procesu prerade ove sirovine od oko 20 % prema 80 % u korist peska hidrociklona, kao i granulometrijske karakteristike ovih proizvoda klasiranja, ukazuju na nedovoljnu efikasnost procesa klasiranja.

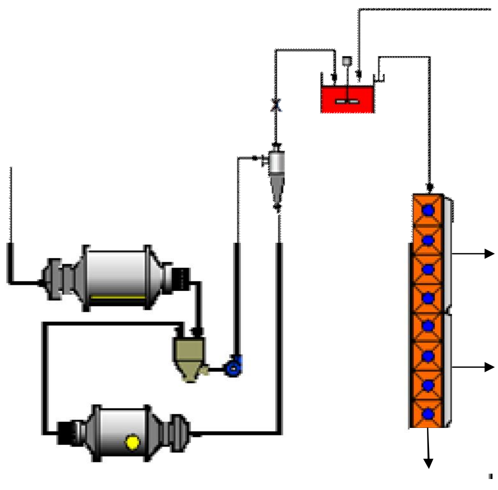
Laboratorijskim opitima flotiranja preliva i peska hidrociklona industrijskog procesa prerade bogate rude bakra definisani su tehnološki pokazatelji i kinetike procesa flotacijske koncentracije.

Analiza tehnoloških pokazatelja i kinetika procesa flotiranja, kako na integralnim proizvodima, prelivu i pesku hidrociklona, tako i po uskim klasama krupnoće, uvažavajući industrijsku raspodelu čvrste faze i korisnih komponenata u istim, omogućava realno sagledavanje opravdanosti istraživanja u pravcu tehnološkog unapređenja postojećeg procesa flotacijske koncentracije bogate rude bakra.

MLEVENJE I KLASIRANJE BOGATE RUDE BAKRA

Ovaj deo pripreme bogate rude bakra sadrži dvostadijalno mlevenje u mlinu sa šipkama i mlinu sa kuglama, koji radi u zavorenom ciklusu sa hidrociklonom koji služi za klasiranje proizvoda mlevenja. Preliv hidrociklona se kao gotov proizvod mlevenja distribuira u proces flotacijske koncentracije bakra i plemenitih metala, a pesak hidrociklona se vraća u proces mlevenja u mlin sa kuglama, slika 1.

Kapacitet industrijske prerade bogate rude bakra RB Bor je 80 t/h. Projektovana finoća gotovog proizvoda mlevenja je 60 % učešće klase – 0,074 mm.



Sl. 1. *Šema procesa mlevenja i klasiranja bogate rude bakra*

Snimanjem industrijskog procesa mlevenja i klasiranja bogate rude bakra definisana je raspodela mase čvrste faze i korisnih komponenata u procesu klasiranja, kao i granulometrijski i hemijski sastav proizvoda mlevenja, preliva i peska hidrociklona, tabela 1 i 2.

Tabela 1. *Raspodela mase čvrste faze i korisnih komponenata po proizvodima klasiranja*

Proizvod	Raspodela		
	Masa čvrste faze (%)	**Bakra Cu (%)**	**Zlata Au (%)**
Preliv HC	19,99	19,05	9,77
Pesak HC	80,01	80,95	90,23
Ulaz u HC	100,00	100,00	100,00

Tabela 2. *Granulometrijski i hemijski sastav proizvoda klasiranja*

Klasa krupnoće, (mm)	Preliv HC			Pesak HC			Ulaz u HC		
	m (%)	**Cu (%)**	**R_{Cu} (%)**	**m (%)**	**Cu (%)**	**R_{Cu} (%)**	**m (%)**	**Cu (%)**	**R_{Cu} (%)**
+0,150	2,11	0,38	0,25	40,08	2,68	32,12	32,49	2,65	26,05
-0,150 +0,075	13,65	0,65	2,82	27,45	3,09	25,37	24,69	2,82	21,07
-0,075 +0,038	21,96	3,10	21,61	20,08	3,97	23,84	20,46	3,78	23,41
-0,038 +0,000	62,28	3,81	75,32	12,39	5,04	18,67	22,36	4,36	29,47
Ukupno:	**100,00**	**3,15**	**100,00**	**100,00**	**3,34**	**100,00**	**100,00**	**3,31**	**100,00**

EKSPERIMENTALNA ISPITIVANJA

Na uzorcima preliva i peska hidrociklona industrijskog procesa prerade bogate rude bakra izvršeni su opiti flotiranja..

Opiti flotiranja su izvođeni na prelivu i pesku hidrociklona u laboratrorijskoj mašini tipa „Denver“ zapremine 2,6 l, pri aeraciji pulpe od 260 l/min i agitaciji od 1300 o/min. pH vrednost pulpe iznosila je 10,5. Sadržaji čvrstog u pulpi su iznosili 25 % u opitu flotiranja preliva hidrociklona i 50 % u opitu flotiranja peska hidrociklona. Korišćeni su sledeći reagensi: kolektori KEX (170 g/t u flotaciji preliva hidrociklona) i KAX (350 g/t u flotaciji peska hidrociklona) i Dowfroth D-250 kao penušač (20 g/t). Vreme kondicioniranja pulpe iznosilo je 10 minuta, nakon čega je dodata potrebna doza flotacijskih reagenasa i pulpa je kondicionirana još jedan dodatni minut. U opitima kinetike flotiranja bakra, flotacijski proizvodi (koncentrati) su dobijeni posle 1, 3, 5, 10 i 20 minuta flotiranja. Proizvodi opita flotiranja, koncentrati i jalovina su prosejavani na odabranoj seriji sita „Tyler“, mokrim postupkom. Nakon sušenja i merenja mase, uzorci pojedinih klasa krupnoće proizvoda flotiranja, su dati na hemijsku analizu. Rezultati raspodele mase čvrste faze i bakra po klasama krupnoće proizvoda flotiranja prikazani su u tabelama 3 i 4.

Tabela 3. *Granulometrijski i hemijski sastav proizvoda flotiranja preliva hidociklona*

Klasa krupnoće, (mm)	Koncentrat			Jalovina			Ulaz (Preliv HC)		
	m (%)	Cu (%)	R_{Cu} (%)	m (%)	Cu (%)	R_{Cu} (%)	m (%)	Cu (%)	R_{Cu} (%)
+0,150	0,24	1,92	0,16	1,87	0,18	1,17	2,11	0,38	0,25
-0,150 +0,075	2,03	3,16	2,25	11,62	0,21	13,65	13,65	0,65	2,81
-0,075 +0,038	10,34	6,26	22,66	11,62	0,28	21,96	21,96	3,10	21,60
-0,038 +0,000	33,89	6,32	74,93	28,39	0,81	62,28	62,28	3,81	75,34
Ukupno:	**46,50**	**6,14**	**100,00**	**53,50**	**0,54**	**100,00**	**100,00**	**3,15**	**100,00**

Tabela 4. *Granulometrijski i hemijski sastav proizvoda flotiranja peska hidrociklona*

Klasa krupnoće, (mm)	Koncentrat			Jalovina			Ulaz (Pesak HC)		
	m (%)	Cu (%)	R_{Cu} (%)	m (%)	Cu (%)	R_{Cu} (%)	m (%)	Cu (%)	R_{Cu} (%)
+0,150	10,86	3,49	15,36	29,22	2,35	79,04	40,08	2,68	31,94
-0,150 +0,075	17,95	4,32	31,42	9,50	0,78	8,53	27,45	3,09	25,46
-0,075 +0,038	16,89	4,49	30,72	3,19	1,22	4,48	20,08	3,97	23,89
-0,038 +0,000	7,38	7,52	22,50	5,01	1,38	7,95	12,39	5,04	18,71
Ukupno:	**53,08**	**4,65**	**100,00**	**46,92**	**1,85**	**100,00**	**100,00**	**3,34**	**100,00**

KINETIKA FLOTIRANJA BAKRA IZ PRELIVA I PESKA HIDROCIKLONA

Shodno cilju istraživanja, na prelivu i pesku hidrociklona su vršeni opiti razdeljene flotacije u odabranim vremenskim intervalima. Svaki od dobijenih koncentrata i jalovina pojedinih opita flotiranja su nakon sušenja i merenja masa klasirani na odabrane, za proces flotiranja, karakteristične klase krupnoće. Svaka klasa krupnoće pojedinačnih, u funkciji vremena, dobijenih koncentrata i jalovine su analizirani na sadržaj bakra kao osnovne korisne komponente.

Na osnovu rezultata ispitivanja, prikazanih u tabelama 1-4, preračunate su vrednosti iskorišćenja bakra, kako po uskim klasama krupnoće, tako i integralne vrednosti, u funkciji vremena flotiranja, kao osnove za definisanje kinetike procesa flotiranja bakra iz preliva i peska hidrociklona. Obračunate vrednosti tehnoloških pokazatelja date su u tabelama 5 i 6.

Tabela 5. *Granulometrijski, hemijski sastav i tehnološki pokazatelji razdeljene flotacije*

Klasa krupnoće d (mm)	Proizvod	m (%)	Cu (%)	I_{Cu} (%)	I_{Cu} (%)		
					I_k=100 %	I_u^p=100 %	I_u^c=100 %
+0,150	K1	0,08	2,88	0,12	0,08	0,07	0,01
-0,150+0,075		0,91	4,72	2,22	1,50	1,36	0,26
-0,075+0,038		6,51	8,09	27,32	18,44	16,74	3,19
-0,038+0		13,32	10,18	70,34	47,47	43,09	8,22
		20,82	**9,26**	**100,00**	**67,49**	**61,26**	**11,68**
+0,150	K2	0,09	1,82	0,26	0,06	0,05	0,01
-0,150+0,075		0,64	2,43	2,52	0,54	0,49	0,09
-0,075+0,038		2,68	3,95	17,21	3,70	3,36	0,64
-0,038+0		9,20	5,35	80,01	17,23	15,64	2,98
		12,61	**4,88**	**100,00**	**21,53**	**19,54**	**3,73**
+0,150	K3	0,03	1,03	0,23	0,01	0,01	0,00
-0,150+0,075		0,20	1,51	2,28	0,10	0,09	0,02
-0,075+0,038		0,49	1,59	5,93	0,27	0,25	0,05
-0,038+0		3,43	3,51	91,56	4,22	3,83	0,73
		4,15	**3,17**	**100,00**	**4,60**	**4,18**	**0,80**
+0,150	K4	0,03	1,02	0,26	0,01	0,01	0,00
-0,150+0,075		0,24	1,03	2,16	0,09	0,08	0,02
-0,075+0,038		0,51	1,07	4,76	0,19	0,17	0,03
-0,038+0		4,31	2,49	92,82	3,78	3,43	0,65
		5,09	**2,27**	**100,00**	**4,07**	**3,69**	**0,70**
+0,150	K5	0,01	0,61	0,15	0,00	0,00	0,00
-0,150+0,075		0,04	0,84	0,45	0,01	0,01	0,00
-0,075+0,038		0,15	0,97	2,26	0,05	0,04	0,01
-0,038+0		363	1,78	97,14	2,25	2,05	0,39
		3,83	**1,74**	**100,00**	**2,31**	**2,10**	**0,40**
+0,150	∑K	0,24	1,92	0,16	0,16	0,14	0,02
-0,150+0,075		2,03	3,16	2,25	2,25	2,03	0,39
-0,075+0,038		10,34	6,26	22,66	22,66	20,56	3,92
-0,038+0		33,89	6,32	74,93	74,93	68,04	12,97
		46,50	**6,14**	**100,00**	**100,00**	**90,77**	**17,30**
+0,150	J	1,87	0,18	1,17		0,11	0,02
-0,150+0,075		11,62	0,21	8,40		0,76	0,15
-0,075+0,038		11,62	0,28	11,19		1,03	0,20
-0,038+0		28,39	0,81	79,24		7,33	1,38
		53,50	**0,54**	**100,00**		**9,23**	**1,75**
+0,150	U	2,11	0,38	0,25		0,25	0,04
-0,150+0,075		13,65	0,65	2,81		2,79	0,54
-0,075+0,038		21,96	3,10	21,60		21,59	4,12
-0,038+0		62,28	3,81	75,34		75,37	14,35
		100,00	**3,15**	**100,00**		**100,00**	**19,05**

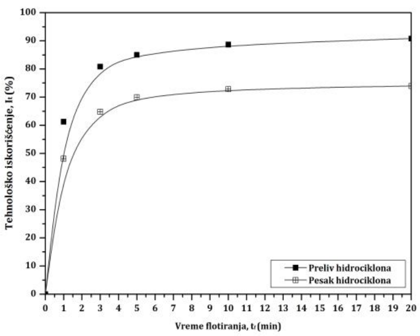
Tabela 6. *Granulometrijski, hemijski sastav i tehnološki pokazatelji razdeljene flotacije peska hidrociklona*

Klasa krupnoće d (mm)	Proizvod	m (%)	Cu (%)	I_{Cu} (%)	I_{Cu} (%)		
					I_k=100%	I_u^p=100%	I_u^c=100 %
+0,150	K1	5,55	3,47	11,19	7,81	5,78	4,37
-0,150+0,075		12,75	4,36	34,60	22,53	16,67	13,50
-0,075+0,038		12,32	4,46	34,20	22,27	16,44	13,34
-0,038+0		3,50	8,82	19,21	12,52	9,25	7,49
		34,12	**4,71**	**100,00**	**65,13**	**48,14**	**39,00**
+0,150	K2	2,60	3,80	17,75	4,00	2,96	2,40
-0,150+0,075		3,85	4,10	28,36	6,40	4,73	3,83
-0,075+0,038		3,58	4,41	28,37	6,40	4,73	3,83
-0,038+0		1,44	9,86	25,52	5,76	4,26	3,45
		11,47	**4,85**	**100,00**	**22,56**	**16,68**	**13,51**
+0,150	K3	1,30	3,95	29,81	2,08	1,54	1,25
-0,150+0,075		0,91	5,04	26,67	1,86	1,38	1,11
-0,075+0,038		0,69	5,35	21,44	1,50	1,11	0,90
-0,038+0		0,53	7,18	22,08	1,54	1,15	0,92
		3,43	**5,02**	**100,00**	**6,98**	**5,18**	**4,18**
+0,150	K4	1,18	2,66	32,81	1,27	0,94	0,76
-0,150+0,075		0,38	3,77	14,94	0,58	0,43	0,35
-0,075+0,038		0,24	4,93	12,33	0,48	0,35	0,29
-0,038+0		0,90	4,25	39,92	1,55	1,15	0,93
		2,70	**3,54**	**100,00**	**3,88**	**2,87**	**2,32**
+0,150	K5	0,23	2,06	13,13	0,19	0,14	0,11
-0,150+0,075		0,06	1,82	3,07	0,04	0,03	0,03
-0,075+0,038		0,06	3,04	5,03	0,07	0,05	0,04
-0,038+0		1,01	2,79	78,77	1,15	0,85	0,69
		1,36	**2,63**	**100,00**	**1,45**	**1,07**	**0,87**
+0,150	∑K	10,86	3,49	15,35	15,35	11,36	8,89
-0,150+0,075		17,95	4,32	31,41	31,41	23,24	18,82
-0,075+0,038		16,89	4,49	30,72	30,72	22,68	18,40
-0,038+0		7,38	7,52	22,52	22,52	16,66	13,47
		53,08	**4,65**	**100,00**	**100,00**	**73,94**	**59,58**
+0,150	J	29,22	2,35	79,04		20,58	16,96
-0,150+0,075		9,50	0,78	8,53		2,22	1,79
-0,075+0,038		3,19	1,22	4,48		1,21	0,94
-0,038+0		5,01	1,38	7,95		2,05	1,68
		46,92	**1,85**	**100,00**		**26,06**	**21,37**
+0,150	U	40,08	2,68	31,94		31,94	25,85
-0,150+0,075		27,45	3,09	25,46		25,46	20,61
-0,075+0,038		20,08	3,97	23,89		23,89	19,34
-0,038+0		12,39	5,04	18,71		18,71	15,15
		100,00	**3,34**	**100,00**		**100,00**	**80,95**

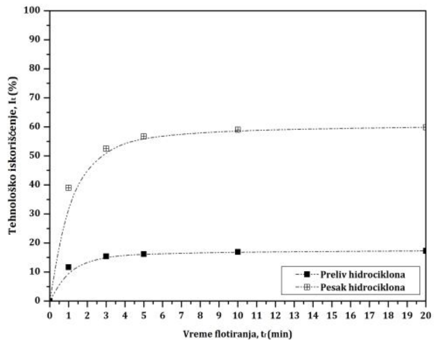
REZULTATI I DISKUSIJA

Raspodela mase čvrste faze u prelivu i pesku hidrociklona od cca 20:80 %, kao i veća zastupljenost bakra, a posebno zlata u pesku u odnosu na preliv hidrociklona potvrđuju činjenice da hidrociklon pored klasifikacije vrši i delimičnu koncentraciju komponenata u funkciji različitih gustina. Ova pojava je izraženija i sa mnogo više negativnih efekata pri preradi bogate rude bakra, što potvrđuje velika zastupljenost dovoljno usitnjene sirovine klase krupnoće -0,074 mm u pesku hidrociklona od cca 32,47 %, kako i znatno veći sadržaj bakra u ovoj klasi krupnoće peska, u odnosu na sadržaj iste komponente u istoj klasi preliva hidrociklona, tabela 1 i 2.

Na osnovu rezultata laboratorijskih opita razdeljene flotacije preliva i peska hidrociklona, tabela 5 i 6, na slici 2 su prikazane kinetike flotiranja bakra iz ovih proizvoda cikloniranja. Kinetike flotiranja bakra iz preliva i peska hidrociklona prikazane su dijagramima na slici 2a, dok su isti pokazatelji preračunati na sadržaj bakra u ulaznoj sirovini, prikazani dijagramima na slici 2b.



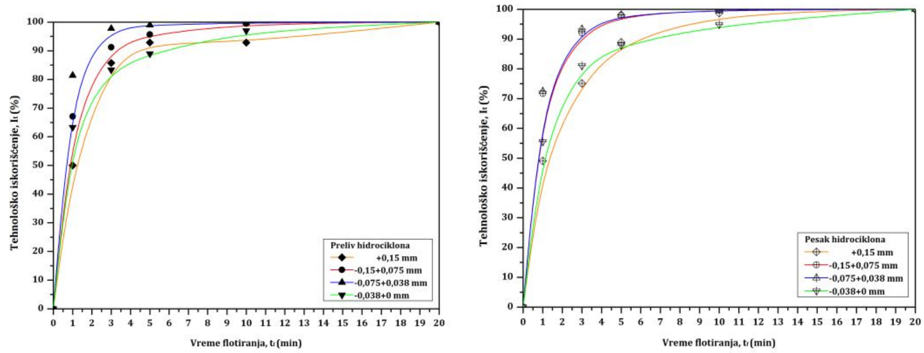
a)



b)

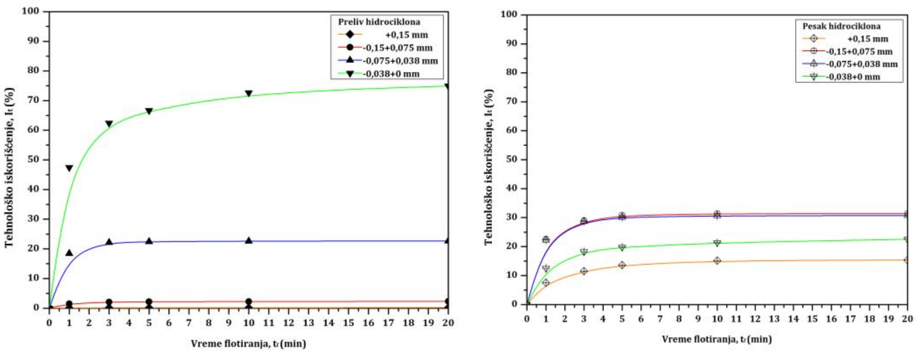
Sl. 2. *Kinetika flotiranja bakra iz preliva i peska hidrociklona:*
a) u odnosu na sadržaj bakra u proizvodima ciklona,
b) u odnosu na sadržaj bakra u ulazu u ciklon

Veliko iskorišćenje bakra iz peska hidrociklona, cca 70 %, zadovoljavajuća kinetika flotiranja, dijagram 2 (a), a posebno, višestruko veće iskorišćenje bakra, oko 60 % iz peska, u odnosu na 17,30 % iskorišćenja iz preliva hidrociklona u odnosu na sadržaj bakra u ulazu u ciklon, opravdavaju istraživanja mogućnosti unapređenja tehnologije prerade bogate rude bakra RB-Bor. U cilju studioznijeg sagledavanja rezultata istraživanja, definisana je raspodela bakra, kako u integralnim uzorcima, proizvodima klasiranja, tako i po uskim klasama istih proizvoda, tabela 1 i 2. Takođe, su definisane kinetike flotiranja bakra iz uskih klasa krupnoće preliva i peska hidrociklona, dijagrami na slikama 3, 4 i 5.



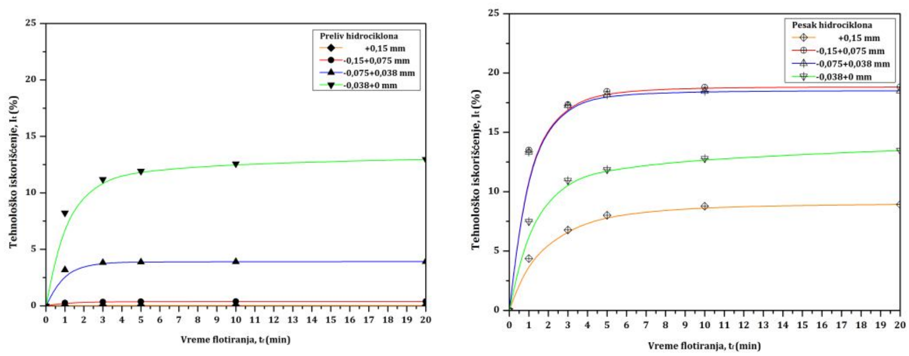
a) *b)*

Sl. 3. *Kinetika flotiranja bakra iz uskih klasa krupnoće:*
a) preliva hidrociklona, b) peska hidrociklona



a) *b)*

Sl. 4. *Iskorišćenja bakra po uskim klasama krupnoće proizvoda klasiranja*
a) u prelivu hidrociklona, za IPs = 100 %, b) u pesku hidrociklona, za IPr = 100 %



a) *b)*

Sl. 5. *Iskorišćenje bakra po klasama krupnoće u odnosu na sadržaj bakra u ulazu u hidrociklon*
a) preliv hidrociklona, b) pesak hidrociklona

Najbolja kinetika flotiranja bakra iz preliva hidrociklona ostvaruje se na klasi (-0,075+0,038) mm, a na pesku hidrociklona na klasama (-0,150+0,075) mm i klasi (-0,075+0,038) mm, dijagrami na slici 3 (a i b).

Zbog raspodele bakra po pojedinim klasama krupnoće proizvoda klasiranja, tabela 2 i 3, najveći doprinos iskorišćenju bakra iz preliva hidrociklona ostvaruje se iz najfinije klase, -0,038 mm, cca 75 %, dok se iz optimalne po krupnoći i kinetici procesa flotiranja, klasi (-0,075+0,038) mm, ostvaruje doprinos ukupnom iskorišćenju od 22,66 %. Doprinos ukupnom iskorišćenju bakra iz preliva hidrociklona iz ostalih klasa krupnoće je skoro zanemarljiv, 2,25 % iz klase (-0,150+0,075) mm i 0,16 % iz klase +0,150 mm. U pesku hidrociklona nešto krupnije klase imaju najbolju kinetiku flotiranja, dijagram na slici 3 (b), dok je doprinos ukupnom iskorišćenju uskih klasa krupnoće ravnomerniji. Iz klase (-0,150+0,075) mm ostvaruje se doprinos ukupnom iskorišćenju od 23,24 %, iz klase (-0,075+0,038) mm, oko 22,68 %, iz klase (-0,038+0) mm 16,66 %, dok se iz najkrupnije klase +0,150 mm ukupnom iskorišćenju iz peska hidrociklona doprinosi sa značajnih 11,36 %.

Od posebnog značaja su rezultati prikazani dijagramima na slici 5 (a i b), kojima su prikazane vrednosti iskorišćenja bakra po uskim klasama krupnoće preliva i peska hidrociklona, preračunate u odnosu na ukupno raspoloživi bakar u ulazu u ciklon. Pored potvrde predhodne konstatacije o većem ukupnom iskorišćenju bakra iz peska u odnosu na preliv hidrociklona, slika 2 (b), može se konstatovati da je i pojedinačni doprinos iskorišćenju bakra iz svake klase peska hidrociklona veći u odnosu na isti pokazatelj koji se ostvaruje u istim klasama preliva hidrociklona.

ZAKLJUČAK

Rezultati istraživanja nedvosmisleno potvrđuju mogućnost unapređenja procesa flotiranja bogate rude bakra, dodatnim flotiranjem peska hidrociklona. Ova konstatacija je zasnovana na činjenicama da je raspodela bakra u proizvodima klasiranja cca 20 : 80 %, u korist peksa hidrociklona, većem sadržaju bakra kako u integralnom uzorku peska hidrociklona, 3,34 % Cu, u prelivu 3,15 % Cu, tako i u svim uskim klasama krupnoće istog proizvoda. Posebno je značajno istaći povećano učešće i sadržaj bakra u optimalno oslobođenim klasama peska u odnosu na iste klase preliva hidrociklona.

Učešće klase -0,075 mm u pesku hidrociklona iznosi oko 32,5 %, sa sadržajem bakra od 4,38 %, dok je učešće iste klase u prelivu hidrociklona oko 84,2 %, sa sadržajem iste korisne komponente od 3,62 %. U odnosu na bakar sadržan u ovoj klasi krupnoće ulaza u ciklon, oko 65 % se distribuira u pesku a 35 % u prelivu hidrociklona. Navedene činjenice pokazuju veliko preusitnjavanje sirovine, u industrijskom procesu mlevenja, kao i nedovoljnu efikasnost i oštrinu klasiranja, kako zbog neadekvatnih radnih parametara, tako i tehnološke nesavršenosti ovog uređaja pri tretiranju polimineralnih sirovina različitih gustina.

Rezultati opita flotiranja preliva i peska hidrociklona ukazuju na nekoliko značajnih pojava.

Nešto bolja kinetika i veće iskorišćenje bakra iz preliva hidrociklona su posledica veće oslobođenosti čvrste faze i optimizacije gustine pulpe u procesu flotiranja. Značajno manji doprinos iskorišćenju bakra, iz opti-malne za proces flotiranja, klase (-0,075+0,038) mm, u odnosu na isti pokazatelj ostvaren na najfinijoj klasi krupnoće - 0,038 mm, potvrđuju predhodnu konstataciju o preusitnjavanju sirovine u procesu mlevenja. Prevelik sadržaj klase - 0,075 mm u prelivu hidrociklona, cca 84,2 %, od kojih je oko 62 % finije od 0,038 mm, imaju negativne posledice kako u povećanoj potrošnji energije u procesu mlevenja tako i smanjenoj efikasnosti flotiranja.

Povećan sadržaj optimalno oslobođene klase krupnoće -0,075 mm u pesku hidrociklona, od oko 32,5 %, sa učešćem klase -0,038 mm većim od 12 %, su kako pokazatelji neefikasnog klasiranja tako i uzročnici kako zadovoljavajuće kinetike, tako i visokom iskorišćenju bakra u procesu flotiranja peska hidrociklona.

Uz konstataciju da bi se u industrijskom procesu prerade bogate rude bakra, zbog kontinualnosti procesa, rezultati flotiranja preliva i peska hidrociklona razlikovali u odnosu na laboratorijski dobijene, sa sigurnošću se može konstatovati relna mogućnost i tehnološka opravdanost unapređenju postojeće tehnologije prerade bogate rude bakra RTB-a Bor, dodatnim flotiranjem peska hidrociklona.

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HIGH ENERGETIC EFFICIENCY OF HF INDUCTIVE WELDING

Abstract

This paper deals with a new impeder for HF inductive welding of steel tubes. Experimental researches were carried out on generators with impeders made of ferrite. The authors of paper introduce magneto dielectric FA-USA instead of ferrite, thus projecting a new impeder. Based on many years of experimental research with the new impeders, the solid energetic savings were achieved in welding compared with various ferrite and other impeders. Savings and welding with lesser power in the case of new impeders make it possible to increase the production rate of line for welded tubes.
Keywords: *efficiency, energy, power, welding, frequency, impeder, investigation*

1 INTRODUCTION

This paper deals with projection and realization of a new impeder for HF inductive welding of steel tubes aiming to achieving the energetic savings. The idea of welding tubes using HF currents has a long and wide developmental path in the world [1, 5]. There are two methods with HF welding, and these are contact and inductive, differing among themselves in as much the way the electromagnetic energy is distributed from the generator to the edges of steel strip which is being welded. The welding method is chosen on the basis of production program as well as on the strategy of manufacturer of generators.

This paper will present the results achieved with HF inductive welding. The research was done on lamp generators with frequencies of 400-450 kHz.

Generators for inductive welding consist of HV transformers, a high voltage rectifier, an oscillator with a lamp, a transformer for impedance adaptation, an auxiliary inductor and an inductor itself. Power regulation is done through thyristor voltage regulators, connected in the primary of HV transformer. Regulated voltage of the secondary after rectification is an anode voltage for an oscillator.

The final part of generator for welding the tubes is shown in Figure 1.

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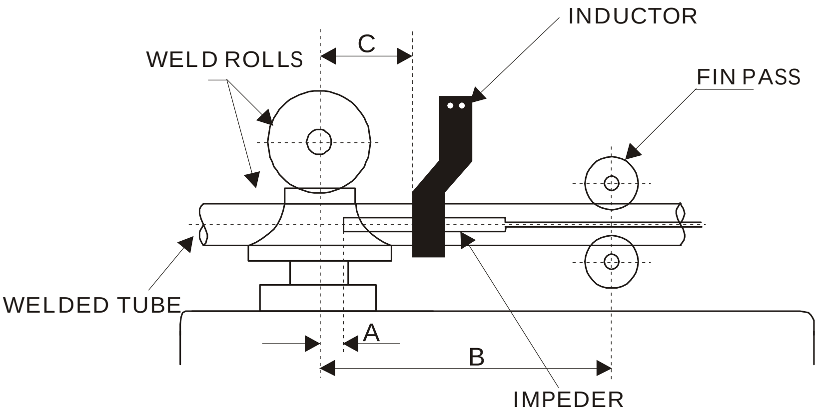

Figure 1 *A detail of device for HF inductive welding*

The inductor is connected through the auxiliary inductor to the transformer secondary for adaptation. Inside the inductor, there is a formed tube made of steel strip. By means of rollers for welding, a necessary pressure is made onto the edges of strip, which are heated up to melting. By heating and pressing the edges of steel strip by forging, the connection is made and the tube is thus welded.

The impeder is built-in inside the steel tube, in the zone below inductor. Function of the impeder is to decrease the current in the internal and external contour of tube, while it increases the inductive current in so called "V" loop. Current on the resistance of steel strip causes heating, so that in the contact point "V" loop melting occurs. Melting realizing the required pressure on the rollers, has resulted in welded edges of strip, or welded steel tube.

View of details the "V" loop of steel tube with the contact point of connection and characteristic currents is shown in Figure 2, the current on pipe exterior, electricity inside the pipe and welding current in the "V" loop.

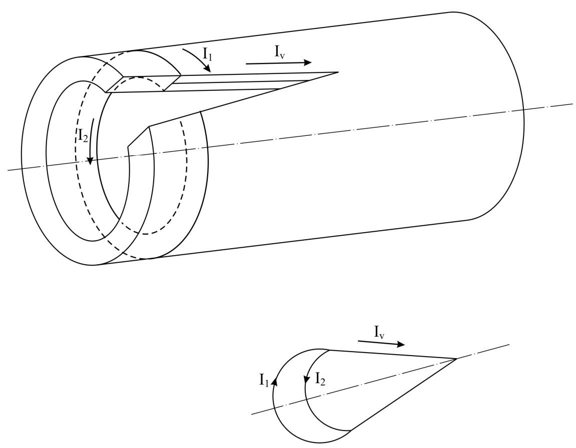

Figure 2 *View of details of the "V loop" with characteristic currents*

In the view of heating tube, the current I_v is the main welding current. Practically, the current distribution in Figure 2 will be made depending on the construction of impeder its electromagnetic characteristics. Using the magneto dielectric material, instead the previously used ferrites, results in optimum energy distribution in the weld zone. Therefore, the optimization is done by reducing the required welding power, because the flux is more properly distributed by induction from inducer, the losses are reduced, what makes the solution more original.

Impeder is made of a protective epoxy tube, which has a connector for cooling the fluid, into which, up to now, a ferrite core as a magneto conductor was placed. Dimensions in Figure 1 are determined by each manufacturer of generators, as well as by generator user itself. It is up to the researchers to find out better results.

There are many papers and projects which were focused on improvements the impeder which is actually a part of electromagnetic circuit in the process of energy emitting aiming at tube welding. In this paper, the researches were carried out on tubes with diameters of 17-48 mm, the welding on them was done with ferrite and new impeders. The new impeders now have the magneto dielectric of the type Fluxtrol instead of ferrite, and in this way, the required power for welding is much saved. The inductive method for this kind of tube diameter range is affirmed and proven as very suitable for production.

2 INVESTIGATION THE NEW IMPEDER

Analysis and long-term research have proven that one of the central places in HF welding belongs to the impeder. The authors of the paper have, through research, introduced a new impeder into HF welding with the difference, as compared to the ferrite impeder, is in ferrite replacement by the magneto dielectric material.

Table 1 shows the characteristics of magnetodielectric of the firm Fluxtrol (MDM) out of which the new impeder was realized. Experiments and investigations of the new impeders were went smoothly from Fluxtrol F, Fluxtrol B, Ferrotron 559, and no energetic savings were achieved.

Table 1 *Characteristics of magnetodielectric*

MDM materials	FLUXTROL				
	F	**B**	**C**	**A'**	**A**
Permeability	13÷14	23÷25	18	30÷50	60÷120
El. Res. [kΩcm]	>100	20÷40	250		0,5÷1
Spec. grav. [gr/cm^3]	5÷5,2	5,8÷5,9	3,9÷4	6÷6,2	6,8÷7,1
Saturation B_s [T]	0,4				1,6

Much better results were achieved applying the impeder of Fluxtrol A. The best results, in terms of energy savings, were achieved using magneto dielectric type A, so that it became the optimal solution of a new impeder.

Figure 3 represents the new impeders where, out of the impeder tube, magnetodielectrics can be seen of the square shaped cross-section just before the final closing of impeder. Connection for hose can be seen where the cooling fluid circulates and which takes away the excessive heat. Completely finished impeders are shown in Figure 4 and as such are ready for welding.

Figure 3 *Epoxy tubes of the new impeder with magneto dielectric FA before closing*

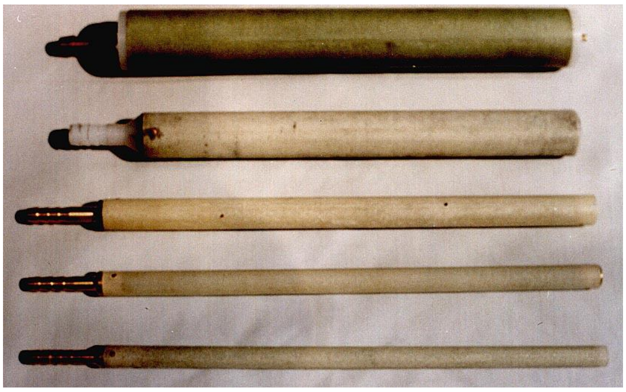

Figure *4 Completely finished new impeder*

To evaluate the effectiveness of impeder, the well known criteria will be used from [1], where the specific power is taken [kW/mm (m/min)] in a function of production rate [m/min]. The criterion from [6] will be also used where in welding, the heating coefficient [kW/m/min] in the function of rate will be followed. The authors of this paper have introduced a new criterion where the energy spending is followed per ton of produced tube [kWh/t], which is in the function of production rate [m/min].

To such a good impeder, the authors of the paper oppose a new impeder with magneto dielectric [7,8], and after several years of research and experiments, they have found out that a new impeder uses less of needed power for welding, which the numeric results will also confirm.

In order to carry out the strict tests and comparisons, through the long-time research in the field of welding, the best referent impeder with ferrites was defined. The referent impeder, on the basis of the results from [9-14] from the experiments, is the impeder with TDK ferrites.

2.1 Results of the experimental researches

The initial experiments were carried out with magneto dielectrics of the type

Fluxtrol F, Fluxtrol B and Ferrotron 559; nevertheless, impeders with these materials did not save any power. Some better results were achieved applying the impeders with Fluxtrol A' material, where there are energy savings as compared to TDK ferrite impeder. However, as these results are worse than those from [6], where some special impeders were presented, any analysis will not be done.

After many years of experimental research, the authors of the paper have found out that the impeder with Fluxtrol A material gives the best results, so all results will be related to this new impeder. Due to the efficiency, the steel tube with, diameter of 21.6 x 2.65 mm, will be adopted here as the representative, and all results of power saving will be related to the above mentioned tube.

Over a longer period of time, and many times, the production of a steel tube with diameter of 21.6 mm and wall thickness of 2.65 mm, was monitored. Aiming at analyzing the energy savings, Table 2 shows the data for power from generator rectifiers for ferrite and a new impeder for various production rates.

Table 2 *Comparative values of rectifier powers for ferrite and a new impeder and achieved savings in the function of rate*

v[m/min]	P_a [kW]	P_b [kW]	$\delta = \frac{P_a - P_b}{P_a} 100$ [%]
10	60	44	24
20	89	58	35
30	120	72	40
40	148	85	43
50	177	98	45
60	205	112	45
70	225	126	45

P_a in Table 2 presents the power for ferrite impeder in [kW], while P_b refers to the new FA impeder.

Defined percentage savings in welding power is

$$\delta = \frac{P_a - P_b}{P_a} 100 \quad [\%], \qquad (1)$$

that represents the percentage of lesser expenditure spending of a new impeder as compared with ferrite impeder, what for selected tube at higher rate gives 45 %.

For graphic presentation, Figure 5 presents the function where rectifier power is shown on ordinate, curve "a" for ferrite impeder and curve "b" for a new impeder, in the function of production rate, where saving of needed welding power is clearly seen.

Figure 6 shows saving as per relation (1) in the function of welding rate.

It can be concluded that the saving is lesser with lower rates, while the optimum wel-ding with new impeders is with rates of

$$v \geq 40 \ \text{[m/min]} \qquad (2)$$

Summarizing the results on production tube with diameter of 21.6 mm, where the effect of a new FA impeder is compared to TDK ferrite impeder, the conclusion can be drawn that a significant energy saving is got with a new impeder in the needed power for welding. The used power of new impeder from generator of rectifier is 45 % less as compared with ferrite impeder consumption.

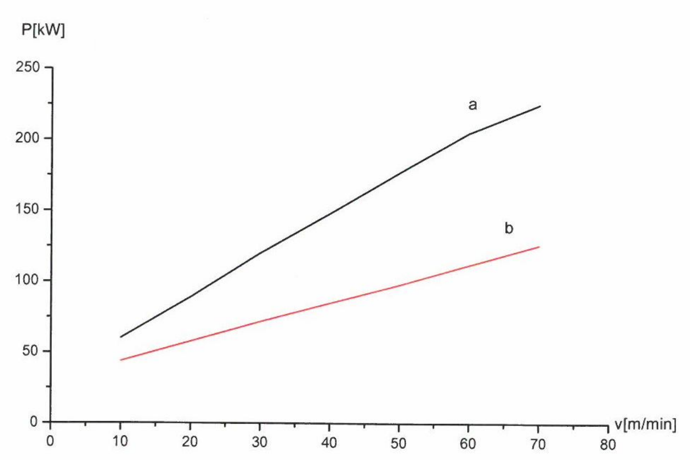

Figure 5 *Power from rectifier in the function of production rate (a-TDK fer.imp, b-FA impeder)*

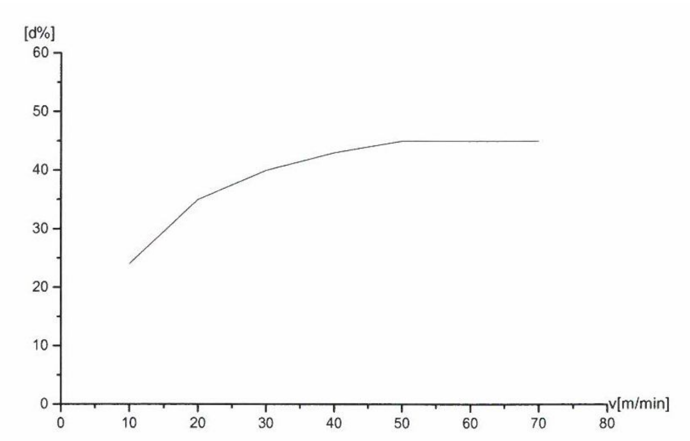

Figure 6 *Relative percentual power saving in the function of production speed*

The experiment was carried out with impeders with diameter of 12 mm, while the ferrite core in ferrite impeder was of the star like cross-section with diameter of 10 mm, while with the new FA impeder, the mate-rial was of the square cross-section 7x7 mm. Length of ferrite impeder was 200 mm, while length of the new impeder was 150 mm.

The welded tube was, in both cases, mechanically tested under the pressure on flattening.The weld with the new impeder and complete flattening was not opened, which is not the case with ferrite impeder weld. A tube was broken on the basic material without any welds during many mechanical tests, even with testing with complete flattening. However, the weld that was the result of welding with the new FA impeder was highly scored by the Control Department of FAHOP according to the ISO Standard.

The obtained saving using the new impeder makes the production of significantly higher production rates, which results in the increase of productivity of technological lines for production the steel tubes.

2.2 Application of Criteria for Evaluation the Achieved Results

The authors will use the already mentioned three criteria for evaluation the achieved results of the new FA impeder in production a tube with diameter of 21.6 mm.

Figure 7 presents dependence of spent energy per tone in the function of rate.

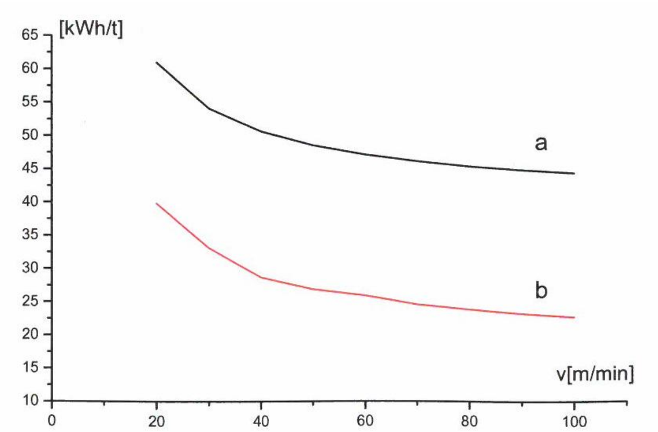

Figure 7 *Energy consumption as per tone of tube in the function of production rate a) TDK ferrite impeder; b) FA impeder*

Dependence of heat coefficient from [6] is presented in Figure 8.

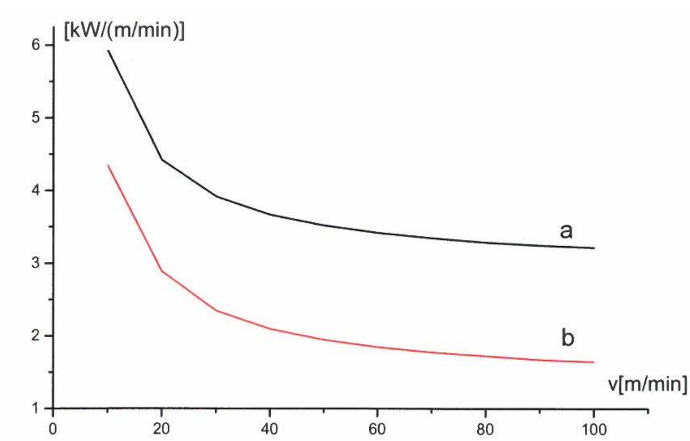

Figure 8 *Heat coefficient in the function of the production speed (a-TDK ferrite impeder, b-FA impeder)*

Graph of specific power as per [1] is presented in Figure 9.

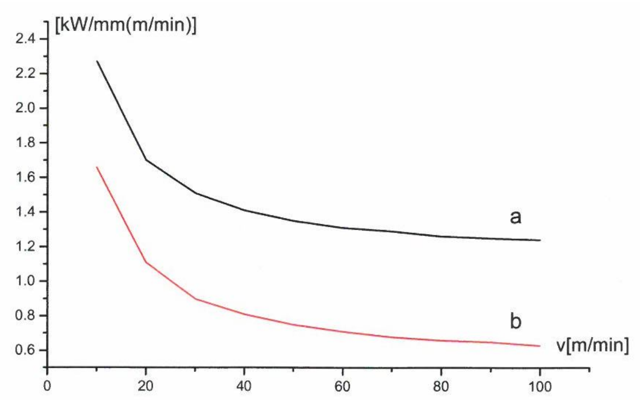

Figure 9 *Specific power in the function of the production speed (a-TDK ferrite impeder, b-FA impeder)*

The curve “a” corresponds to the ferrite impeder, while the curve “b” corresponds to the new FA impeder. It can be concluded that the new impeder is much more efficient what the above mentioned three criteria confirm. Two of these three criteria are used in literature as well-known, while the one criterion is introduced by the authors of the paper as the original and new.

Besides the mentioned energy savings of 45 % using the new FA impeder, in comparison to the best TDK ferrite impeder, applying the above mentioned three criteria, all mentioned criteria give a good evaluation of efficiency the new impeder application. The authors to the useful conclusion, through their researches, that it is more effective to weld at rates higher than 40 m/min when the optimum is achieved. Optimum is achieved when the value from (1) reaches the asymptote, which can also be applied with other criteria. The authors from [6] do not perceive these conclusions, but give the results for rates that are higher than or equal to 50 m/min.

Figure 10 illustrates the photos of original inner welds, so called penetration with the ferrite impeder and new FA impeder. The first photo was obtained with ferrite impeder, and the second with the new FA impeder. The inner weld was obtained with the new impeder with less superelevations, it is narrower and more continuous, and mechanical tests of flattening further confirm this statement by the fact that the weld is considerably more persistent.

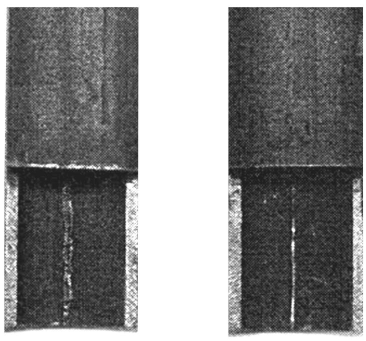

Figure 10 *Weld in the interior of the pipe for the ferrite and new impeder*

The new impeder with FA magneto dielectric will be compared to the results given in [6]. The paper presents the results of application the special impeders with amorphous foils and 3% Si foil, used with the ferrite impeder from Japan.

The authors of this paper will, for the aim of clearance, present the comparative characteristics of their scientific - research results and results from reference [6] In Table 3. Applying all three criteria, it can be concluded that the new FA impeder is better. The power saving in [6]is 32 %, which in comparison to the new FA impeder FA of 45 % gives the conclusion that the solution of the author of this work is more efficient as per 41 %. It should be added that the solution, given in this paper, is cheaper than the aforementioned.

Table 3 *Presentation the results of comparable criteria for TDK and a new FA impeder and results from [6]*

Criteria / Impeder material	$\frac{kWh}{t}$	$\frac{kW}{mm\ (m/min)}$	$\frac{kW}{m/min}$	**Length [mm]**
Ferrite - [7]	83.3	3.57	15	400
3% Si-foil	57.11	2.45	10.3	400
Ferrite - TDK	50	1.35	3.52	200
Magn. diel. – FA	27	0.75	1.95	150

Applying the new impeder, energetic savings up to 45 % are achieved in comparison to the ferrite impeder, which justifies the research results The new impeder also gives savings when compared to some special impeders from [6], so a very useful application is opened with impeders made of magneto dielectrics.

3 CONCLUSION

The main aim of the authors of this paper is to design and investigate a new impeder with magneto dielectrics which will have significant energy savings in power while welded in relation to TDK ferrite impeder. Based on many years of experimental researches, among the magneto dielectrics of the firm Fluxtrol, the authors have found out that an optimal material is Fluxtrol A for impeder production and this is the way how the new impeder is made.

It has been shown and proven that the application of the new impeder brings the significant energetic savings as compared to ferrite impeders, as well as when compared to some special impeders. Applying the well known criteria and the newly introduced criterion, it is determined that the new impeder has better performances regarding to the ferrite impeder.

If the annual savings are calculated for the referent tube with diameter of 21.6 mm, the clear financial saving is approx. $ 350,000. The achieved saving of energy of 45 % makes possible the increase of production, that is, the production rate of the steel tubes up to 90 % what justifies the efforts of researchers.

Although the experiments were carried out with a lamp generator, the results change the aspect to the inductive method of welding for the range of researched diameters of tubes. The results also change the value of total efficiency coefficient of lamp generators for welding, from the point of view of input power and power which is given to the steel tube itself in the process of HF inductive welding.

The authors of the paper present to the qualified and scientific public the new solution for impeders with magneto dielectrics of the type Fluxtrol A, which, used in practice, brings many energy savings that are con firmed by the experimental results. Energetic savings make the possibilities of increasing the welding rate, and therefore the production of steel tubes, which implies an increase in productivity of technological lines for production of steel pipes.

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VISOKA ENERGETSKA EFIKASNOST KOD VF INDUKTIVNOG ZAVARIVANJA

Izvod

U ovom radu se opisuje nov impeder za VF induktivno zavarivanje čeličnih cevi. Eksperimentalna istraživanja su vršena na generatoru koji je imao feritne impedere. Autori rada umesto ferita uvode magnetodielektrik Fluxtrol FA USA projektujući time novo rešenje impedera. Na osnovu dužeg eksperimentalnog istraživanja sa novim impederima postignute su solidne energetske uštede pri zavarivanju u poređenju sa više različitih feritnih i drugih impedera. Ušteda i zavarivanje sa manjim snagama primenom novih impedera stvara mogućnost da se poveća proizvodna brzina linije za izradu čeličnih cevi.

Ključne reči: *efikasnost, energija, snaga, zavarivanje, frekvencija, impeder, istraživanje*

1. UVOD

Ovaj rad se bavi projektovanjem i realizacijom novog impedera za VF induktivno zavarivanje čeličnih cevi sa ciljem da se postigne energetska ušteda. Ideja da se cevi zavaruju VF strujama ima dug i veliki razvojni put u svetu [1-5]. Kod VF zavarivanja postoje dve metode i to kontaktna i induktivna, a koje se razlikuju po načinu predaje elektromagnetne energije sa generatora na ivice čelične take koje se zavaruju. Metoda zavarivanja se bira u zavisnosti od proizvodnog programa i same strategije proizvođača generatora.

U ovom radu će se prikazati rezultati koji su postignti kod VF induktivnog zavarivanja. Istraživanja su obavljena na generatorima sa cevima čije su frekvencije od 400-500 kHz.

Generatori za induktivno zavarivanje se sastoje od VN transformatora,ispravljača visokog napona, cevnog oscilatora, transformatora za prilagođenje impedanse, pomoćnog induktora i induktora. Regulacija snage se obavlja tiristorskim regulatorima napona koji su povezani u primaru VN transformatora. Regulisani napon sekundara posle ispravljanja čini anodni napon za napajanje oscilatora.

Završni i finalni deo generatora za zavarivanje cevi je prikazan na sl. 1.

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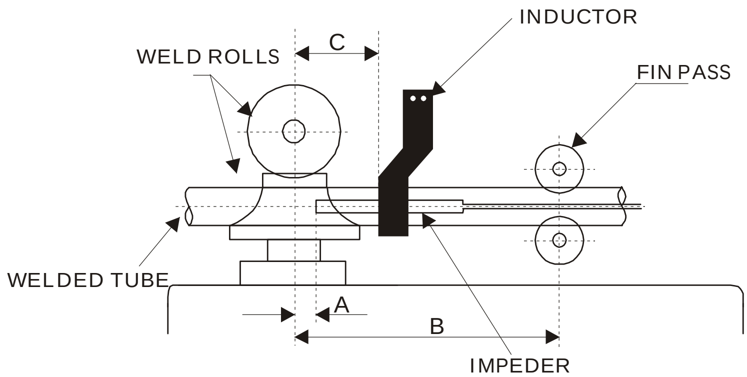
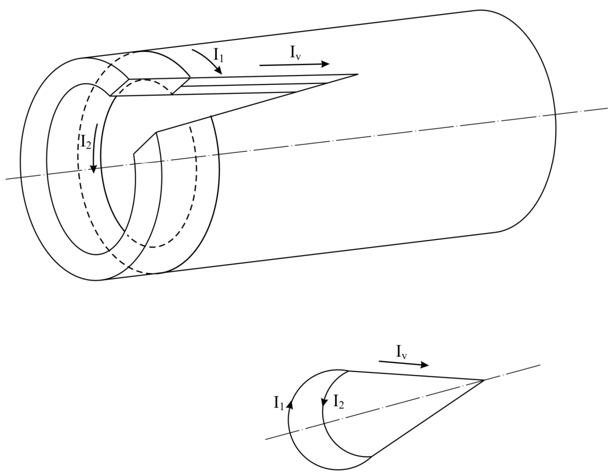


Sl. 1. *Detalj uređaja za VF induktivno zavarivanje*

Induktor se povezuje preko pomoćnog induktora na sekundar transformatora za prilagođenje. Unutar induktora prolazi formirana cev od čelične trake. Valjcima za zavarivanje se ostvaruje potreban pritisak na ivice trake koje se zagrevaju do topljenja. Zagrevanjem i pritiskanjem ivica čelične trake, putem kovanja, se obavlja spajanje i time je cev zavarena.

Unutar čelične cevi, a u zoni ispod induktora, se ugrađuje impeder. Funkcija impedera je da smanji struje u unutrašnjoj i spoljašnjoj konturi cevi, a poveća indukovanu struju u tzv "V" petlji. Struja na otporu čelične trake izaziva grejanje tako da se u kontaktnoj tački "V" petlje vrši topljenje. Topljenje, o stvarivanjem potrebnog pritiska na valjcima, ima za posledicu zavarene ivice trake, odnosno zavarenu čeličnu cev.

Prikaz detalja "V" petlje čelične cevi sa kontaktnom tačkom spajanja i karakterističnim strujama je prikazan na sl. 2, struja po spoljašnosti cevi, struja po unutrašnjosti cevi i struja zavarivanja u "V" petlji.



Sl. 2. *Prikaz detalja "V" petlje sa karakterističnim strujama*

U prikazu grejanja cevi struja I_v predstavlja glavnu struju zavarivanja. Praktično raspodela struja sa sl. 2 će se vršiti zavisno od konstrukcije impedera i njegovih elektromagnetnih karakteristika. Upotrebom magnetodielektričnog materijala namesto do sada korišćenih ferita dobija se optimalna distribucija energije na zonu zavarivanja. Zato se vrši optimizacija smanjenjem potrebne snage zavarivanja, jer se fluks indukcijom iz induktora pravilnije raspoređuje, smanjuju se gubici, što rešenje čini originalnijim.

Impeder je sastavljen od zaštitne čaure, koja ima priključak za rashladnu tečnost, u koju je do sada smeštan ferit kao magnetoprovodnik. Dimenzije sa sl. 1 određuje svaki proizvođač generator, a i sam korisnik generatora. Na istraživačima je da iznalaženjem i kreativnim delovanjem postignu što bolje rezultate.

Postoji mnogo radova i projekata koji su usmeravani na poboljšanje impedera, koji je ustvari deo elektromagnetnog kola u procesu predaje energije u cilju zavarivanja čelične cevi. U ovom radu istraživanja su vršena na cevima prečnika 17 - 48 mm, i na kojima se zavarivalo feritnim i novim impederima. Novi impederi sada umesto ferita imaju magnetodielektrik tipa Fluxtrol, čime se dobija ušteda u potrebnoj snazi za zavarivanje. Za ovaj opseg dijametara cevi induktivna metoda se afirmiše i čini prikladnom za proizvodnju.

2. ISTRAŽVANJE NOVOG IMPEDERA

Analizom i dugogodišnjim istraživanjem je potvrđeno da jedno od centralnih mesta u VF zavarivanju pripada i impederu. Autori rada su istraživanjem uveli u VF zavarivanje nov impeder čija je razlika u odnosu na feritni impeder to što ferit zamenjuje magnetodielektričnim materijalom.

U tabeli 1 su prikazane karakteristike magnetodielektrika firme Fluxtrol (MDM) od kojih se realizuje i nov impeder. Eksperimenti i istraživanja novog impedera su tekli redom od Fluxtrola F, Fluxtrola b, Ferrotrona 559 i sa njima nije ostvarena energetska ušteda.

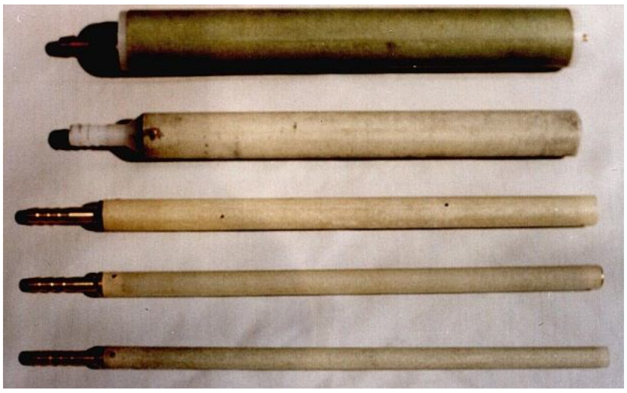
Tabela 1. *Karakteristike magnetodielektrika*

MDM magnetodielektrik	Tip magnetodielektrika Fluxtrol				
	F	**B**	**C**	**A'**	**A**
Permeabilnost	13÷14	23÷25	18	30÷50	60÷120
El. otpor [kΩcm]	>100	20÷40	250		0,5÷1
Spec. težina [gr/cm^3]	5÷5,2	5,8÷5,9	3,9÷4	6÷6,2	6,8÷7,1
Mag. indukcija B_s [T]	0,4				1,6

Izvesno poboljšanje je ostvareno primenom impedera od Fluxtrola A'. Najbolji rezultati u smislu energetske uštede su postignuti primenom magnetodielektrika tipa A, tako da je on postao optimalno rešenje jednog novog impedera.

Na slici 3 su prikazni novi impederi, gde se van čaure impedera vide magnetodielektrici ćiji je presek kvadratnog oblika, neposredno pred završno zatvaranje impedera. Vidi se priključak za crevo gde cirkuliše rashladni fluid radi odvođenja suvišne toplote. Kompletno završeni impederi su prikazani na sl. 4 i kao takvi su spremni za zavarivanje.

Sl. 3. *Epoksidne čaure sa novim impederom od magnetodielektrika FluxtrolA pre zatvaranja*



Sl. 4. *Kompletno završen nov impeder*

Radi ocene efikasnosti impedera koristiće se poznati kriterijum iz [1] gde se uzima specifična snaga [kW/mm (m/min)] u funkciji proizvodne brzine [m/min]. Takođe će se koristiti kriterijum iz [6] gde se pri zavarivanju prati toplotni koeficijent [kW/m/min] u funkciji brzine. Autori rada uvode nov kriterijum gde se prati utrošak energije po toni proizvedene cevi [kWh/t] u funkciji proizvodne brzine [m/min].

Tako dobrom feritnom impederu, autori rada suprostavljaju nov impeder sa magnetodielektrikom [7,8], i posle nekoliko godina istraživanja i eksperimenata nalaze da nov impeder znatno manje troši potrebnu snagu za zavarivanje što će potvrditi i numerički rezultati.

Da bi se obavila stroga testiranja i upoređenja, kroz višegodišnje istraživanje u oblasti zavarivanja, definisan je najbolji referentni impeder sa feritima. Naš referentni impeder na bazi rezultata iz [9-14], i naših eksperimenata je impeder sa TDK feritima.

2.1. Rezultati eksperimentalnih istraživanja

Početni eksperimenti su obavljeni sa magnetodielektrikom tipa Fluxtrol F

Fluxtrol B i Ferrotron 559, ali impederi sa ovim materijalima nisu dali uštedu u snazi. Nešto bolji rezultati su postignuti primenom impedera sa Fluxtrol A' materijalom, gde ima energetskih ušteda u odnosu na TDK feritni impeder. No, kako su ti rezultati slabiji od rezultata iz [6], gde se prezentuju neki specijalni impederi tako da njih nećemo analizirati.

Posle višegodišnjih eksperimentalnih istraživanja autori rada su pronašli da najbolje rezultate daje impeder Fluxtrol A, tako da svi rezultati će se odnositi na ovaj nov impeder. Zbog efikasnosti, ovde će se usvojiti čelična cev prečnika 21,6x2,65 mm kao naš reprezent i svi rezultati uštede u snazi odnosiće se na ovu pomenutu cev.

Kroz duži vremenski period, i više puta, je praćena proizvodnja čelične cevi prečnika 21,6 mm i debljina zida 2,65 mm. Radi analize energetskih ušteda u tabeli T_2 su prikazani podaci za snagu iz ispravljača generatora za feritni i nov impeder za različite proizvodne brzine.

Tabela 2. *Uporedne vrednosti snaga iz ispravljača za feritni i nov impeder i postignuta ušteda u funkciji brzine*

v[m/min]	**P_a [kW]**	**P_b [kW]**	$\delta = \frac{P_a - P_b}{P_a} 100$ **[%]**
10	60	44	24
20	89	58	35
30	120	72	40
40	148	85	43
50	177	98	45
60	205	112	45
70	225	126	45

U tabeli T_2 P_a predstavlja snagu u [kW] za feritni impeder, a P_b za nov impeder FA.

Definisana procentualna ušteda u snazi zavarivanja je:

$$\delta = \frac{P_a - P_b}{P_a} 100 \quad [\%], \qquad (1)$$

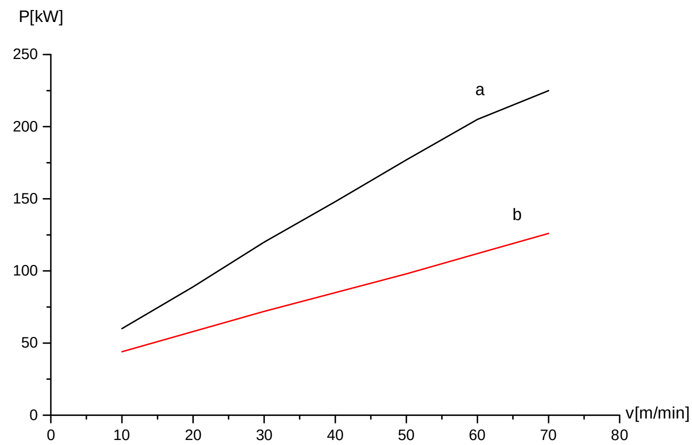
koja predstavlja za koliko procenata manje troši nov impeder u odnosu na feritni impeder, što za izabranu cev pri većoj brzini daje 45%.

Radi grafičke prezentacije na sl. 5 je prikazana zavisnost, gde se na ordinati nanose snage iz ispravljača, kriva "a" za feritni impeder i "b" za nov impeder, u funkciji proizvodne brzine, gde se jasno vidi ušteda u potrebnoj snazi zavarivanja.

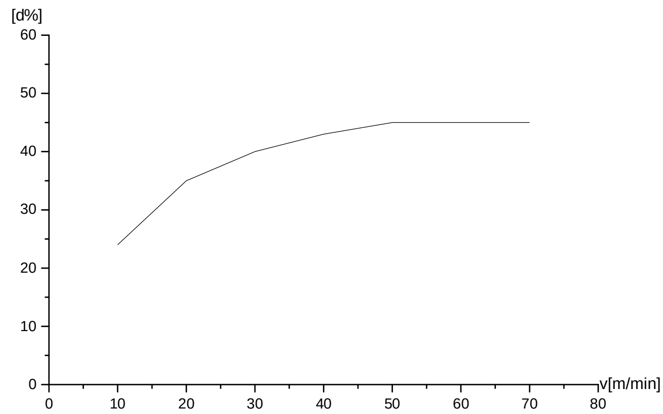
Slika 6 prikazuje uštedu po relaciji (1) u funkciji brzine zavarivanja. Zaključuje se da je ušteda manja na malim brzinama, a da je optimalno zavarivati novim impederom na brzinama:

$$v \geq 40 \ \text{[m/min]} \qquad (2)$$

Rezimirajući rezultate na proizvodnji cevi prečnika 21,6 mm, gde se upoređuje efekat novog FA impedera u odnosu na TDK feritni impeder, zaključak je da se novim impederom dobija znatna energetska ušteda u potrebnoj snazi za zavarivanje. Za 45% manje se angažuje snaga iz ispravljača generatora pri korišćenju novog impedera u odnosu na potrošnju sa feritnim impederom.



Sl. 5. *Snage iz ispravljača u funkciji proizvodne brzine (a-TDK fer.imp., b-FA impeder)*



Sl. 6. *Relativna procentualna ušteda snage u funkciji proizvodne brzine*

Eksperiment je obavljen sa impederima čiji je prečnik 12 mm. Kod feritnog impedera ferit je bio zvezdast prečnika 10 mm, a kod novog FA impedera materijal je bio kvadratnog preseka 7x7 mm. Dužina feritnog impedera je iznosila 200 mm a novog impedera 150 mm.

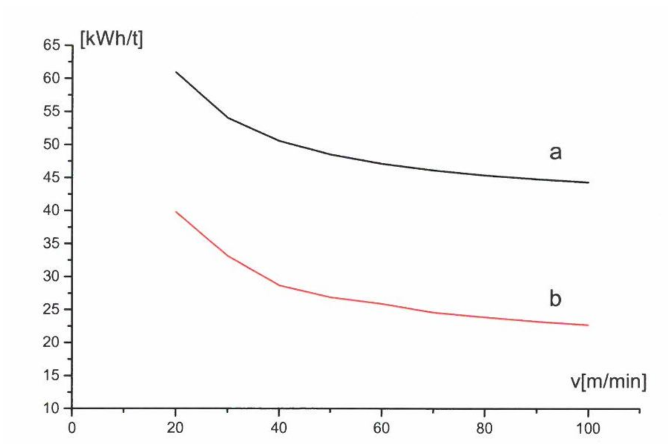
Zavarena cev, je za oba slučaja, testirana mehaničkim probama pod pritiskom na spljoštavanje. Var sa novim impederom i kod potpunog spljoštavanja nije se otvorio, što nije slučaj sa varom koji se dobio primenom feritnog impedera. Dešavalo se pri mnogim mehaničkim probama da prsne cev na osnovnom materijalu gde nema vara i to kod proba sa potpunim spljoštavanjem. Inače, var dobijen zavarivanjem sa novim FA impederom dobio je visoke ocene od Službe kontrole FAHOP po ISO standardu.

Dobijena ušteda u snazi primenom novog impedera omogućava da se može proizvoditi i znatno većim proizvodnim brzinama što rezultuje povećanjem produktivnosti tehnoloških linija za izradu čeličnih cevi.

2.2. Primena kriterijuma za ocenu postignutih rezultata

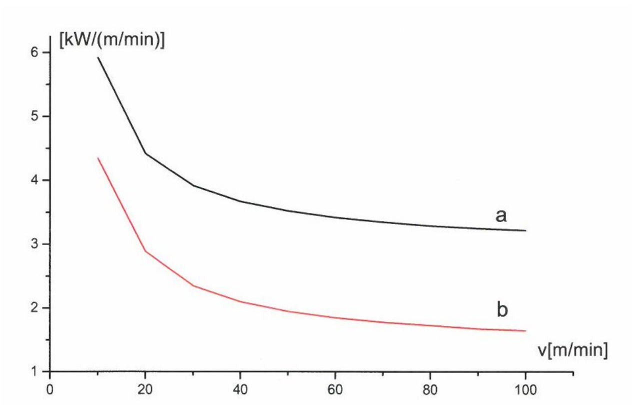
Autori će radi ocene postignutih rezultata novog FA impedera koristiti prehodno navedena tri kriterijuma pri proizvodnji cevi prečnika 21,6 mm.

Sl. 7 prikazuje zavisnost utrošene energije po toni cevi u funkciji brzine.



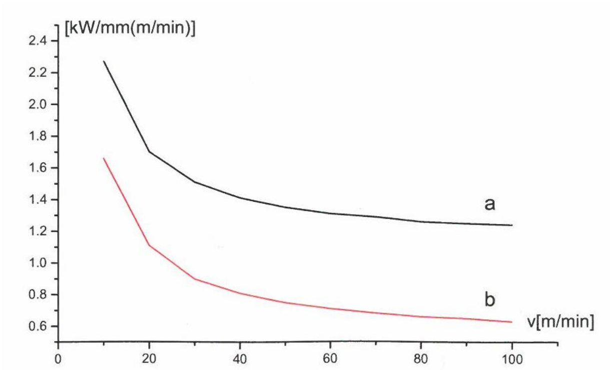
Sl. 7. *Potrošnja energije po toni cevi u funkciji brzine proizvodnje (a-TDK feritni impeder, b-FA impeder)*

Zavisnost toplotnog koeficijenta iz [6] je data na slici sl. 8.



Sl. 8. *Toplotni koeficijent u funkciji proizvodne brzine (a-TDK feritni impeder, b-FA impeder)*

Grafik specifične snage iz [1] je predstavljen slikom sl. 9.

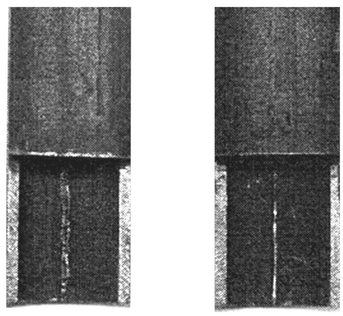


Sl. 9. *Specifična snaga u funkciji proizvodne brzine (a-TDK feritni impeder, b-FA impeder)*

Krive "a" odgovaraju feritnom impederu, a "b" novom FA impederu. Zaključujemo da je novi impeder znatno efikasniji jer to potvrđuju napred navedena tri kriterijuma, od kojih se dva koriste u literaturi kao poznati, a jedan uvode autori rada kao originnalan i nov.

Pored pomenute energetske uštede od 45% primenom novog FA impedera, u odnosu na najbolji TDK feritni impeder, primenom navedena tri kriterijuma, svi navedeni kriterijumi daju dobru ocenu efikasnosti primene novog impedera. Takođe su autori, kroz svoja istraživanja došli do korisnog zaključka da je korisno zavarivati na brzinama većim od 40 m/min, kada se obezbeđuje optimalnost. Optimalnost se dobija kada vrednost iz (1) dostigne asimptotu, što isto važi i za ostale kriterijume. Autori iz [6] ne uočavaju ove zaključke već daju rezultate za brzine veće ili jednake 50 m/min.

Sl. 10 ilustruje fotografije originalnih unutrašnjih varova, tzv. provar, sa feritnim impederom i novim FA impederom. Prva od fotografija je dobijena feritnim impederom, a druga pomoću novog FA impedera. Unutrašnji var dobijen novim impederom je sa manjim nadvišenjima, uzaniji je i kontinualniji je, a mehaničke probe spljoštavanja ovu konstataciju još više potvrđuju time da je var znatno izdržljiviji.



a) b)

Sl. 10. *Var u unutrašnjosti cevi za feritni (a) i FA impeder (b)*

Nov impeder sa FA magnetodielektrikom ćemo uporediti sa rezultatima datim u [6]. Tu su izloženi rezultati primene specijalnih impedera sa amorfnim folijama i 3% Si folijom upotrebljeni sa još feritnim impederom iz Japana.

Autori ovog rada u cilju preglednosti će prikazati uporedne karakteristike svojih naučnoistraživačkih rezultata i rezultata iz literature [6] kroz sređenu tabelu T_3. Primenom sva tri kriterijuma zaključuje se da je bolji naš nov FA impeder. Ušteda snage iz [6] iznosi 32%, što u poređenju sa novim FA impederom od 45% daje zaključak da je rešenje autora ovog rada efikasnije za 41%. Ovome treba dodati da je rešenje dato u ovom radu jeftinije od pomenutih.

Tabela 3. *Prikaz rezultata uporednih kriterijuma zaTDK i nov FA impeder i rezultata iz* [6]

Kriterijum / **Materijal za impeder**	$\frac{kWh}{t}$	$\frac{kW}{mm\ (m/min)}$	$\frac{kW}{m/min}$	**Dužina [mm]**
Feritni impeder [6]	83,3	3,57	15	400
3% Si-folija	57,11	2,45	10,3	400
Feritni - TDK imped.	50	1,35	3,52	200
Magnedial. - FA imp.	27	0,75	1,95	150

Primenom novog impedera postižu se energetske uštede u odnosu na feritni impeder do 45%, što opravdava rezultate istraživanja. Takođe, nov impeder daje uštedu i u odnosu na neke specijalne impedere iz [6], te se otvara jedna veoma korisna primena sa impederima od magnetodielektrika.

3. ZAKLJUČAK

Autori ovog rada su sebi postavili cilj da projektuju i istraže jedan nov impeder sa magnetodielektrikom koji će imati znatne energetske uštede u snazi pri zavarivanju u odnosu na TDK feritni impeder. Na osnovu višegodišnjih eksperimentalnih istraživanja, među magnetodielektricima firme Fluxtrol, autori pronalaze kao originalan materijal Flixtrol A za izradu impedera i na taj način nastaje nov impeder.

Pokazano je i dokazano da primena novog impedera donosi znatne energetske uštede u poređenju sa feritnim impederima, kao i u poređenjima sa nekim specijalnim skupim impederima. Primenom poznatih kriterijuma i novouvedenog kriterijuma, utvrđuje se da nov impeder ima bolje performanse u odnosu na feritni impeder.

Ako se izračuna godišnja ušteda, za našu referentnu cev prečnika 21,6 m, čista finansijska ušteda je cca 350.000 $. Postignuta ušteda u potrošnji električne energije od oko 45% omogućava povećanje produktivnosti, odnosno proizvodne brzine čeličnih cevi, i do 90% što opravdava napore istraživača.

Iako su eksperimenti vršeni na cevnom generatoru, rezultati menjaju pogled na induktivnu metodu zavarivanja za opseg istraživanih dijametara cevi. Rezultati menjaju i vrednost sveukupnog koeficijenta iskorišćenja cevnih generatora za zavarivanje, gledano sa aspekta ulazne snage i snage koja se predaje samoj čeličnoj cevi u procesu VF induktivnog zavarivanja.

Autori rada prezentuju stručnoj i naučnoj javnosti novo rešenje impedera sa magnetodielektrikom tipa Fluxtrol A, koji u praksi donosi znate energetske uštede što rezultati eksperimenata potvrđuju. Energetske uštede stvaraju mogućnost povećanja brzine zavarivanja, a samim tim i proizvodnje čeličnih cevi, odakle sledi povećanje produktivnosti tehnoloških linija za izradu čeličnih cevi.

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ESTIMATION THE MEASUREMENT UNCERTAINTY OF PHYSICO - CHEMICAL PROPERTIES OF COALS ACCORDING TO ISO 17025

Abstract

One of the important elements for addressing the requirements of international Standard ISO/IEC 17025:2006, specifically set forth in paragraph 5.4.6.2, is to assess the uncertainty of testing and/or calibration. For determination the coal technical analysis uncertainty (moisture, ash, volatiles and combustible substances, c-fix, total sulfur, gross calorific value and net calorific value), the certified reference materials (CRM) benzoic acid (Ref.: 33 045 and Ref.: C723, Id. No.: 32 430 00) and coal tags GBW 11107k were used. Potential laboratory reference material (RM) was also used for comparison the measurement results and uncertainty in order that, after sufficient number of measurements and statistical analysis, could be used as a laboratory RM. The results showed that both CRM and selected potential laboratory RM could be successfully applied to determine the uncertainty of technical coal analysis, what is significantly cheaper for laboratory work, and in accordance with Standard ISO 17025.

Keywords: *CRM, RM, Benzoic acid, Uncertainty, Nordtest, Eurachem, Coal, Technical Analysis.*

INTRODUCTION

Coal is a solid fuel, which dates from the ancient times. For a complete analysis of coal, sample should be carefully sampled and prepared in order to obtain more precise results. Standardized methods are means that allows repeatability and reproducibility of results. In the case of coals, first of all it is important to determine the amount of available energy and relationship of combustible substances to non-combustible parts of fuel, while determination the chemical analysis of coal is not always necessary for the user.

Technical analysis of coals is actually determination of moisture, ash, combus tible and volatile matter, coke residue, C-fix, total sulfur and gross and net calorific values. For technical analysis of coal, the analytical samples, or samples prepared with specific grain size distribution composition are used. Chemical analysis of coal is related to determining the composition of ash, which includes determination of SiO_2, BaO, Fe_2O_3, TiO_2, Al_2O_3, CaO, MgO, Mn_3O_4, Na_2O_3, SO_3 and phosphorus.

At the beginning of 1999, the international standard ISO/IEC 17025 was published, which contains the general requirements for the competence of testing and/or calibration laboratory. ISO/IEC 17025 has replaced the previous standards EN 45001 and ISO/IEC Guide 25, that was applied in laboratory work. The last edition of this standard dates from 2006. The application of this standard is important for each laboratory

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for the purpose of accreditation and implementation the management systems in their work. A lot of data can be found in the literature on application and importance of this standard [1,2].

In the quality control (QC) of measurement methods, which includes assessment of uncertainty, the reference materials play an important role. Reference material is a material or substance whose one or more values of properties are sufficiently homogeneous and well established that they can be used to calibrate the apparatus, for assessment of measurement method or assigning the evalues to materials. Reference materials can be divided into two groups: certified reference materials (CRM) and laboratory (working) reference materials (RM) [3,4]. CRM is a reference material, accompanied by a certificate, whose one or more values of properties confirmed by procedure that establishes traceability for the exact realization of the unit in which are expressed values of characteristics and for which each certified value, is accompanied with measurement uncertainty, with specified confidence level. RM is a working laboratory material available in laboratory, characterized by homogeneity and stability of material which can provide the repeatable results, at the same time low-cost and as such are eligible for laboratory. CRM are used for evaluation the uncertainty of measurement, to determine the accuracy and precision of mea-sured results, the range of measurements and other parameters of device. In other words, the quality requirements of ISO 17 025 limit the uncertainty of measurement study with acceptable confidence level, taking into account what is feasible within the available laboratory equipment and chemicals.

The uncertainty of measurement results is characterized by an interval in which the exact value is claimed to be with specified confidence level. The result of evaluation of measurement uncertainty should be the best approximation of correct values range.

Within the estimation of measurement uncertainty, there are two concepts:

- NORDTEST (QC model)
- EURACHEM (Full scale model).

The aim of Nordtest principle is to present the most important parameters that contribute to the measurement uncertainty: the bias (inaccuracy) and reproducibility (imprecision) of results, while Eurachem includes all the features that influence the measurement uncertainty.

Due to the requirements of ISO/IEC 17025 for assessment the uncertainty, this paper presents the results of using CRM: benzoic acid Ref.: 33 045, with heat of combustion (26 461±40) Jg^{-1}, (ELINCS-Nr.: 200-618-2), benzoic acid Ref.: C723, heat of combustion (26 456±8) Jg^{-1}, (Id. Nr.: 32 430 00) and coal mark GBW 11 107K in order to test the uncertainty of laboratory equipment for technical analysis of coal. Also, for checking the possibi-lity of using laboratory RM in the future laboratory work, the results were compared using the same equipment under the same conditions and with the same contractor for certified reference materials, and also for potential of laboratory RM.

EXPERIMENTAL PART

To determine the gross calorific value of coal according to the standard norms [5] the calorimeter, model C5000, IKA Werke from 2008, factory no.: 01.666060, was used. Calorimeter was used at a constant volume according to the adiabatic type bomb calorimeter method. Calorimeter is equipped with a software program IKA ® C5000 Control, Version 2.21, and a bomb calorimeter C5010-01.490589 with the following characteristics: Ps=230 bar, PT=330 bar, TS = 50°C and V = 0.260 L. To determine the net calorific value of coal to the same standard norms, it is necessary to determine the hydrogen content in coal [6]. In that purpose, the elemental analyzer, model "vario MACRO cube" from 2010, manufacturer Elementar Analysensysteme GmbH, was used.

For the determination the moisture in the analytical sample of coal using the methods described in the standard norms [7], the dryer with nitrogen stream, model RVT 500, manufacturer Heraus - Hanau, with temperature and time controller NIGOS, model 1012P, factory no.: 7404617, was used. To determine the ash using the method described in the standard norms [8], volatile matter of coal to the standard norms [9], and total sulfur by the method described in standard norms [10], the annealing furnace, type TR f2, manufacturer Iskra, was used. All weight measurements were carried out on the electronic balance, type "Sartorius BP 61S", manufactured in 2008 with accuracy 0.0001g. To determine the accuracy of laboratory equipment and evaluation the measurement uncertainty, CRM, benzoic acid powder, manufacturer AlliedSignal Riedel-de Haen, Ref.: 33 045, heat of combustion (26 461±40) Jg^{-1}, (ELINCS-Nr.: 200-618-2), which will be called the BA(1) in this work, also pelleted benzoic acid, IKA Werke manufacturers, Ref.: C723, heat of combustion (26 456±8) Jg^{-1}, (Id. Nr.: 32 43000), which will be called the BA(2) and coal combustion heat GBW 11 107K (27.54±0.19) $MJkg^{-1}$ which will be called the GBW, were used. As a potential laboratory RM for technical analysis of coal, the coal named ASSM was used. The technique of known values and comparative research technique were used in studying the results.

RESULTS AND DISCUSSION

Moisture content of coal is essential for accurate determination the other physical and chemical characteristics of coals. First, the moisture effect is important for determining the coal thermal effect, and also affects the overall fuel efficiency practically. In addition to the results of measurements the moisture, ash, volatile matter, total sulfur, hydrogen, and gross and net calorific values of coal, it is important to evaluate the uncertainty of obtained results. By comparison the experimentally obtained results with the exact values given in the reference material certificate, the method accuracy can be determined. Accuracy refers to a particular analytical result and hence represents a combination of systematic and random errors. Systematic error (bias) is the difference between the average value of a large number of measurement results and the exact value of CRM. For determination the correct values the certified reference materials BA(1), BA(2) and GBW (Table 1) were used.

Table 1 *Certified values of Gross Combustion Enthalpy (GCV) of CRM (benzoic acid BA(1) Ref.: 33045 and BA(2) Ref.: C723, and coal (GBW) and their mean values obtained by calorimeter IKA Werke, Model C5000 and bias*

CRM name	GTV CRM*	$\overline{GTV}$ CRM**	bias
BA(1) (Jg^{-1})	26 461±40	26 503	42
BA(2) (Jg^{-1})	26 456±8	26 465	-9
GBW ($MJkg^{-1}$)	27.54±0.19	27.54	0

GTV CRM - certified or true values of CRM, $\overline{GTV}$ CRM** - mean value of measurement results.*

To determine the uncertainty of results, theNordtest (1) and Eurachem (2) approach were used.

a) Nordtest approach

The Nordtest approach represents a practical approach in evaluation the methods and laboratories measurement uncer tainty. This approach aims to present the most important parameters that contribute to the measurement uncertainty, which are:

- Reproducibility (imprecision - random error),
- Bias (deviation - a systematic error).

Two ways for calculation the measurement uncertainty exist within the Nordtest concept:

- Method A
- Method B

In method A, combined uncertainty u_c (%), calculated using formula (1). Double value of u_c (%) presents an expanded measurement uncertainty U (%) with a confidence level of 95%, formula (2).

$$u_c(\%) = \sqrt{(U(Rw))^2 + (U(Bias))^2} \quad (1)$$

$$U(\%) = 2 \times u_c(\%) \quad (2)$$

Contribution to the uncertainty of reproducibility, U (Rw), is determined by assessment of internal-laboratory reproducibility, Rw, according to formula (3), where $\overline{X}$ represents the average value of measurements, while S_{RW} is internal standard reproducibility calculated as the S_{RW} = $\overline{R}/1.128$ ($\overline{R}$ mean value range).

$$Rw = \frac{S_{RW}}{\overline{X}} \times 100 \quad (3)$$

Contribution to the uncertainty from bias, U ($Bias$) (%), is calculated by formula (4).

$$U(Bias)(\%) = \sqrt{(Bias)^2 + (\frac{S_{Bias}}{\sqrt{n}})^2 + u(Cref)^2} \quad (4)$$

In formula (4), ($Bias$) from CRM, is calculated by formula (5), while the component of uncertainty the certified nominal value, u($Cref$), is calculated by formula (6). In the formula (4) S_{Bias} represents a multiple testing of CRM, and n is the number of measurements of CRM. CI in formula 6 is a confidence interval.

$$(Bias) = \frac{\overline{X} - T}{T} \times 100 \quad (5)$$

$$u(Cref) = (100 \times \frac{CI(40)}{1.96}) / CRM(26461) \quad (6)$$

Table 2 *Statistical analysis of GCV obtained with CRM benzoic acid BA(1) Ref.: 33045 for evaluation the uncertainty by Nordtest concept using methods A and B and BA(2) Ref.: C723 for calibration of calorimeter*

CRM BK (1)					CRM BK (2)
X_1 (J/g)	X_2 (J/g)	$\overline{X}$ (J/g)	$R = \lvert X_1 - X_2 \rvert$ (J/g)	$r = \lvert X_1 - X_2 \rvert / \overline{X} \times 100$ %	Calorimeter calibration by determination of water values
26716	26753	26735	37	0,138	10758
26601	26575	26588	26	0,098	10745
26645	26698	26671	53	0,199	10755
26609	26658	26633	48	0,182	10741
26417	26491	26454	74	0,280	10732
		$\overline{X}$ =26616	$\overline{R}$ =47,7	$\overline{r}$ =0,179	$\overline{X}$ =10746; s=10,57;$S_{95\%}$=13,14 RelativeSD=0,1222869%

Table 2 are presents the results of combustion heat for BA(1), which are used to estimate the measurement uncertainty of calorimeter C5000. Using the formula from (1) to (4), the results are obtained for combined uncertainty by formula (1), and the expanded uncertainty with a confidence level of 95%, according to formula (2).

Table 3 *Statistical analysis of results of technical analysis parameters using laboratory referent material (RM): (a) using analytical sample of coal ASSM and (b) a dry sample ASSM*

Date	N°	% Moisture	% Ash	% Combustible materials	% volatile materials	% Coke rest	% C-fix	S (%)	GCV (J/g)
(a) **With analytical moisture**									
1st month	**1**	0.69	12.45	86.86	6.06	93.25	80.80	0.900	29 430
	2	0.67	12.01	87.32	6.34	92.99	80.98	1.412	29 564
	3	0.67	12.01	87.32	6.34	92.99	80.98	1.004	29 802
2nd month	**4**	1.14	11.86	87.00	5.64	93.22	81.36	0.976	29 764
	5	1.16	12.76	86.08	5.75	93.09	80.33	1.089	29 415
3th month	**6**	1.42	11.70	86.88	6.42	92.16	80.46	0.944	29 656
	7	1.43	12.59	85.98	6.63	91.94	79.35	-	29 685
Statistical processing of data	$\overline{X}$	**1.026**	**12.20**	**86.78**	**6.17**	**92.81**	**80.61**	1.054	**29 617**
	$S_{68\%}$	0.345	0.401	0.544	0.365	0.53	0.653	0.186	153
	$S_{95\%}$	**0.327**	**0.371**	**0.503**	**0.338**	**0.49**	**0.604**	0.195	**142**
	RSD %		3.04	0.58	5.48	0.53	0.75		0.48
(b) Dry – no moisture									
1st month	**1**	-	12.54	87.46	6.10	93.90	81.36	0.91	20 634
	2	-	12.09	87.91	6.38	93.62	81.53	1.42	29 763
	3	-	12.09	87.91	6.38	93.62	81.53	1.01	30 003
2nd month	**4**	-	12.00	88.00	5.71	94.29	82.3	0.99	30 107
	5	-	12.91	87.09	5.82	94.18	81.27	1.10	29 760
3th month	**6**	-	11.87	88.13	6.51	93.49	81.62	0.96	30 083
	7	-	12.77	87.23	6.73	93.27	80.50	-	30 116
Statistical processing of data	$\overline{X}$	-	**12.32**	**87.68**	**6.23**	**93.77**	**81.44**	1.065	**29 924**
	$S_{68\%}$	-	0.410	0.410	0.372	0.372	0.533	0.18	199
	$S_{95\%}$	-	**0.379**	**0.379**	**0.344**	**0.344**	**0.493**	**0.97**	**184**
	RSD %		3.08	0.43	5.52	0.37	0.605		0.61

*RSD – relative standard deviation

Table 3(a) presents the experimental measurement results of coal physical-chemical characteristics (moisture, ash, evaporation of matter, total sulfur, hydrogen and gross and net calorific values) using the analytical sample of potential laboratory reference material ASSM, and the results obtained by computation like combustible materials, coke rest of and c-fix. The results in Table 3(b) are obtained using computer calculation the results from Table 3 using formula (7), corresponding to dry fuel [18].

$$S = \frac{\%\ analitical\ sample}{100 - moisture} \times 100 \qquad (7)$$

Potential laboratory RM, ASSM was measured three times in duplicate or triplicate for 3 months. Table 3, in addition to the obtained results, also gives the statistical analysis of results, so that for each value, obtained experimentally or computationally, the measurement uncertainty was calculated using the method B of Nordtest concept. According to the method B, the measurement uncertainty is directly determined by standard deviation of reproducibility by formula (8), while the expanded uncertainty is determined in the same way as in the method A of Nordtest, formula (2).

$$u_c\,(\%) = SR \qquad (8)$$

b) Eurachem approach

The Eurachem approach or full scale model represents a principle that includes everything affecting the measurement uncertainty of results, and as such provides more accurate range of estimated results than Nordtest. Parameters that contribute to complete estimation the measurement uncertainty of coal technical analysis results are:

1) Sampling of coal and sample handling,
2) Equipment (balance, calorimeter, the normal courts, standard solutions, pipette),
3) Human factors and environment (housing and environmental conditions).

Since the technical analysis of coal is performed with the already-prepared analytical sample, the parameters that contribute most to the measurement uncertainty will be included within the Eurachem principles. These parameters are expressed in the form of bias and reproducibility of used laboratory equipment, and they are directly related to the human factor. Reproducibility of results in Eurachem concept, *Rw*, is the same determined as in Nordtest, using formula (3), while formula (6) is modified and expanded for contribution of human factors to the measurement uncertainty which is reflected in handling of laboratory equipment, laboratory ware and chemicals, which involves the use of scales - *u(m)*, purity reagent - *u(n)*, laboratory glassware - *u (v)*, pipettes - *u(p)* and calibration of calorimeter - *u(k)*. CRM BA(2) was used for the C5000 calorimeter calibration, and the standard deviation is given on the basis of water value of calorimeter results, given in Table 2. The result of expanded value *u* (*Cref*), is given in Table 4 as the square root sum of squares of all contributions to the measurement uncertainty.

Table 4 *The extended value of uncertainty component of certified nominal values u(Cref) for contributions to scale measurement uncertainty u(m), reagent purity u(n), normal courts u(c), pipette u(p) and CRM BA(2) Ref.: C723 u(k) used for calibration of calorimeter*

***Extended value u(Cref)*= 0.12335%**				
u(m)	*u(n)*	*u(v)*	*u(p)*	*u(k)*
0,016140%	0,000289%	0,000585%	0,000949%	0,122287%

Table 5 presents an overview of measurement uncertainty results of combustion heat for CRM BA(1) and a potential laboratory RM ASSM. The results of measurement uncertainty heat of combustion for CRM BA(1) are, for comparison, processed by methods A and B of Nordtest concept.

Table 5 *Grain-size distribution, chemical composition and technological parameters of divided flotation of hydrocyclone overflow*

	Nordtest				**Eurachem**	
	Method I		**Method II**		**Method**	
	u_c**(%)**	***U(%)***	u_c **(%)**	***U(%)***	u_c **(%)**	***U(%)***
1BK	0,61	1,23	0,23	0,46	0,62	1,24
ASSM	-	-	0,24	0,48	-	-

Based on the results of Nordtest concept (Table 5), it is noted that the measurement uncertainty of CRM BA(1) according to the method A provides higher value than method B. These values are expected, since method A provides more accurate results of uncertainty than method B whose uncertainty value is directly calculated from the standard deviation using the same values of benzoic acid heat of combustion (Table 1). Measurement the uncertainty of laboratory RM ASSM was determined by method B. The results show that the uncertainty of ASSM has same order as CRM BA(1), and it is therefore possible to use ASSM as a laboratory RM. The results of measurement uncertainty estimation by EURACHEM show greater value than the results of methods A of Nordtest, since the method principle is more demanding, and thus a more complete and accurate.

Table 6 *Comparison of results of certified values of CRM physico-chemical characteristics for coal GBW 11 107k, with the results obtained using the laboratory equipment for technical analysis of coal*

	CRM GBW	
	Certified values	**Experimental values**
GTV ($MJkg^{-1}$)	27,54±0,19	27,54±0,15
(%) Ash	14,89±0,08	15,15±0,23
(%) Volatile mater	32,41±0,39	32,12±0,76
(%) S total	0,96±0,02	0,94±0,11
(%) H	4,21±0,13	4,30±0,23
(%) C	68,47±0,30	68,32±0,72
(%) N	1,21±0.03	1,24±0,02

Table 6 presents an overview of certified CRM GBW values in units which are given in the certificate. The experimental results are given in the same units, ensuring traceability of results. Comparing experimental data with the certified values (Table 6), it can be concluded that the obtained experimental values and their estimated uncertainty are of the same order of magnitude as the certificated values. The obtained results confirm the quality system of laboratory for coal technical analysis according to ISO 17025.

4 CONCLUSION

Evaluation the measurement uncertainty of laboratory for technical analysis of coal based on requirements of ISO/IEC 17025:2006, was successfully determined using the certified reference materials: BA(1) Ref.: 33 045, with combustion heat (26 461±40) Jg^{-1}, BA(2) Ref.: C723, with combustion heat (26 456±8) Jg^{-1} and coal CRM GBW 11 107k, with combustion heat (27.54±0.19) $MJkg^{-1}$. Uncertainties of reference materials results were used to determine the uncertainty of laboratory equipment, used for technical analysis of coal. Determined laboratory RM was also used to determine the uncertainty of laboratory equipment and it is proved that it can be a tool that laboratories can use with confidence in evaluation the uncertainty, either as an immediate replacement of CRM, or as working laboratory material. The useful information on possibilities of different methods in determining the measurement uncertainty and different materials used in the laboratory for technical analysis of coal are presented by this way. The results showed that, as certified reference materials, also and selected laboratory RM could be applied in evaluation the uncertainty of measurement the technical analysis of coal, which is significantly cheaper for laboratory work than CRM, and in accordance with ISO 17 025 standard.

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PROCENA MERNE NESIGURNOSTI FIZIČKO-HEMIJSKIH OSOBINA UGLJEVA PREMA ISO 17025

Izvod

Jedan od značajnih elemenata za rešavanje zahteva međunarodnog standarda ISO/IEC 17025:2006, posebno izneta u tački 5.4.6.2, jeste procena merne nesigurnosti laboratorija za ispitivanje. Za određivanje merne nesigurnosti tehničke analize ugljeva (vlage, pepela, sadržaja isparljivih i sagorljivih materija, c-fiks, ukupnog sumpora, gornje i donje toplotne vrednosti), korišćeni su sertifikovani referentni materijali (CRM): benzoeva kiselina i ugalj oznake GBW 11107k. Potencijalni laboratorijski referentni materijal (RM), takođe je korišćen radi upoređivanja rezultata merenja i merne nesigurnosti kako bi se, posle dovoljnog broja merenja i statističke obrade podataka, mogao upotrebiti kao laboratorijski RM. Rezultati su pokazali da se, kako sertifikovani referentni materijali, tako i izabrani potencijalni laboratorijski RM, može uspešno primeniti za određivanje merne nesigurnosti tehničke analize ugljeva, a što je znatno jeftinije za laboratorijski rad, a u saglasnosti je sa standardnom ISO 17025.

Ključne reči: *CRM, RM, benzoeva kiselina, merna nesigurnost, Nordtest metod, Eurachem metod*

UVOD

Ugalj je čvrsto gorivo koje datira od davnina. Za kompletnu analizu ugljeva, potrebno je pažljivo uzorkovati i pripremiti uzorak kako bi se dobili što precizniji rezultati prilikom analiziranja ugljeva. Standardizovane metode su sredstva koja omogućavaju ponovljivost i reproduktivnost rezultata. Kada se radi o ugljevima, u prvom redu je važno da se odredi količina raspoložive energije, kao i odnos sagorljive supstance prema nesagorljivim delovima goriva, dok određivanje hemijske analize ugljeva nije uvek neophodno za korisnika.

Kada se govori o tehničkoj analizi ugljeva, misli se na određivanje % vlage uzorka, određivanje % pepela, % sagorljivih i isparljivih materija, % koksnog ostatka, % C-fiks, % ukupnog sumpora i gornje i donje toplotne moći uglja. Za tehničku analizu ugljeva, koriste se analitički uzorci, odnosno uzorci pripremljeni tako da imaju oređeni granulometrijski sastav. Hemijska analiza ugljeva se odnosi na određivanje sastava pepela koji uključuje određivanje SiO_2, BaO, Fe_2O_3, TiO_2, Al_2O_3, CaO, MgO, Mn_3O_4, Na_2O_3, SO_3 i fosfora.

Početkom 1999. godine objavljen je međunarodni standard ISO/IEC 17025 [1], koji sadrži opšte zahteve za kompetentnost laboratorija za ispitivanje i/ili etaloniranje. ISO/IEC 17025 je zamenio prethodne standarde EN 45001 i ISO/IEC Vodič 25, koji su se primenljivali u radu laboratorija. Poslednje izdanje datira iz 2006. godine. Primena ovog standarda je važna za svaku laboratoriju u cilju akreditacije i u spro-

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vođenju sistem menadžmenta u svom radu. O primeni i važnosti ovog standarda može se naći u literaturi [2].

Za kontrolu kvaliteta (QC) merne metode, što uključuje i procenu merne nesigurnosti, važnu ulogu imaju referentni materijali. Referentni materijal je materijal ili supstanca čije su jedna ili više vrednosti osobina dovoljno homogeni i dobro ustanovljeni da mogu da se koriste za etaloniranje aparata, procenu mernih metoda, ili za pripisivanje vrednosti materijalima. Referentni materijali se mogu svrstati u dve grupe: sertifikovani (overeni) referentni materijali (CRM) i laboratorijski (radni) referentni materijali (RM) [3, 4]. CRM je referentni materijal, praćen uverenjem, čija su jedna ili više vrednosti osobina overene postupkom kojim se uspostavlja sledljivost sa tačnim ostvarenjem jedinice u kojoj se izražavaju vrednosti osobina i za koga je svaka overena vrednost praćena mernom nesigurnošću sa naznačenim nivoom poverenja. Laboratorijski RM je radni materijal sa kojim laboratorija raspolaže, a čije su osnovne karakteristike homogenost materijala i stabilnost koje mogu da obezbede ponovljivost rezultata, a istovremno su jeftini i kao takvi prihvatljivi za laboratoriju. CRM se koriste za procenu merne nesigurnosti, za određivanje tačnosti i preciznosti rezultata merenja, opsega merenja i drugih parametara aparata. Drugim rečima, zahtevi kvaliteta ISO 17025 ograničavaju nesigurnost jedne studije merenja sa prihvatljivim nivoom poverenja, uzimajući u obzir ono što je izvodljivo u okviru raspoložive laboratorijske opreme i hemikalija.

Nesigurnost rezultata merenja karakteriše interval vrednosti za koji se tvrdi da se unutar njega nalazi tačna vrednost, sa specificiranim nivoom poverenja. Rezultat procene merne nesigurnosti treba da bude najbolja aproksimacija opsega tačne vrednosti. U okviru procene merne nesigurnosti postoje dva koncepta:

- NORDTEST (QC model),
- EURACHEM (Full scale model).

Cilj Nordtest principa je da prikaže najvažnije parametre koji doprinose mernoj nesigurnosti: bias (netačnost) i reproduktivnost (nepreciznost) rezultata, dok Eurachem uključuje sve mogućnosti koji utiču na mernu nesigurnost.

Zbog zahteva međunarodnog standarda ISO/IEC 17025 o proceni merne nesigurnosti, ovaj rad prikazuje rezultate korišćenja CRM: benzoeve kiseline Ref.: 33045, toplote sagorevanja (26461±40) Jg^{-1}, (ELINCS-Nr.: 200-618-2), benzoeve kiseline Ref.: C723, toplote sagorevanja (26456±8) Jg^{-1}, (Id.Nr.: 32 430 00) i uglja oznake GBW11107K u cilju provere merne nesigurnosti opreme laboratorija za tehničku analizu ugljeva. Takođe, radi provere mogućnosti korišćenja laboratorijskog RM u budućem laboratorijskom radu, upoređivani su dobijeni rezultati koristeći istu opremu pod istim uslovima i sa istim izvođačem, kako sertifikovanih referentnih materijala, tako i potencijalnog laboratorijskog RM.

EKSPERIMENTALNI DEO

Za određivanje gornje toplotne vrednosti ugljeva prema standardnoj normi [5], korišćen je kalorimetar, model C5000, proizvođača IKA Werke iz 2008. godine, sa fabričkim br.: 01.666060. Kalorimetar je korišćen u uslovima pri konstantnoj zapremini po metodi kalorimetarske bombe adiabatskog tipa. Opremljen je softverskim programom IKA® C5000 Control, Version 2.21 i kalorimetarskom bombom C5010-01.490589 sa sledećim karakteristikama: Ps = 230 bar, PT = 330 bar, TS = 50°C i V = 0,260 L. Za određivanje donje toplotne vrednosti uglja prema istoj standardnoj normi, potrebno je odrediti sadržaj vodonika u uglju [6] i za to je korišćen elementarni analizator, model «vario MACRO cube» iz 2010. godine, proizvođača Elementar Analysensysteme GmbH.

Za određivanje vlage u analitičkom uzorku uglja prema metodama opisanim u standardnim normama [7], korišćena je sušnica u struji azota, model RVT 500, proizvođača Heraus – Hanau, sa temperaturnim i vremenskim regulatorom NIGOS, model 1012P, fabričkim br.: 7404617. Za određivanje pepela prema metodi opisanoj u standardnoj normi [8], isparljivih materija uglja prema standardnoj normi [9], kao i ukupnog sumpora prema metodi opisanoj u standardnoj normi [10], korišćena je peć za žarenje, tip TR f2, proizvođača Iskra.

Sva merenja masa uzoraka, vršena su na elektronskoj vagi, tip „Sartorius BP 61S“, iz 2008. godine, sa fabričkim brojem 80109868, a koja ima vrednost podeoka 0,0001g.

Za određivanje tačnosti laboratorijske opreme i procene merne nesigurnosti korišćeni su CRM, benzoeva kiselina u prahu, proizvođača AlliedSignal Riedel-de Haën, Ref.: 33045, toplote sagorevanja (26461±40) Jg^{-1}, (ELINCS-Nr.:200-618-2) koju ćemo nazvati BK(1), zatim tabletirana benzoeva kiselina, proizvođača IKA Werke, Ref.: C723, toplote sagorevanja (26456±8) Jg^{-1}, (Id. Nr.: 32 430 00) koju ćemo nazvati BK(2) i ugalj GBW 11107K toplote sagorevanja (27.54±0.19) $MJkg^{-1}$ koga ćemo nazvati GBW. Kao potencijalni RM laboratorije za tehničku analizu ugljeva, korišćen je ugalj nazvan ASŠM. U ispitivanju rezultata korišćena je tehnika poznatih vrednosti i tehnika uporednog ispitivanja.

REZULTATI I DISKUSIJA

Sadržaj vlage ugljeva je od presudnog značaja za tačno određivanje ostalih fizičko-hemijskih karakteristika ugljeva. U prvom redu, uticaj vlage je važan za određivanje toplotnog efekta uglja, a takođe utiče na celokupno praktično iskorišćenje goriva. Pored dobijenih rezultata merenja vlage, pepela, isparljivih materija, ukupnog sumpora, vodonika i gornje i donje toplotne vrednosti uglja, važno je proceniti i njihove merne nesigurnosti. Poređenjem eksperimentalno dobijenih vrednosti sa tačnim vrednostima datih u sertifikatu referentnog materijala, može se odrediti tačnost metode. Tačnost se odnosi na pojedini analitički rezultat i stoga predstavlja kombinaciju sistematske i slučajne greške. Sistematska greška (bias) predstavlja razliku između srednje vrednosti velikog broja rezultata merenja i tačne vrednosti CRM. Za određivanje tačne vrednosti korišćeni su sertifikovani referentni materijali BK(1), BK(2) i GBW, tabela 1.

Tabela 1. *Sertifikovane vrednosti gornje toplotne vrednosti (GTV) CRM (benzoeve kiseline BK(1) Ref.: 33045, BK(2) Ref.: C723 i uglja GBW) i njihove srednje vredvosti $\overline{GTV}$ CRM dobijene na kalorimetru IKA Werke, model C5000 sa bias-om.*

Naziv CRM	GTV CRM*	$\overline{GTV}$ CRM**	bias
BK(1) (Jg^{-1})	26 461±40	26 503	42
BK(2) (Jg^{-1})	26 456±8	26 465	-9
GBW ($MJkg^{-1}$)	27.54±0.19	27.54	0

GTV CRM - sertifikovane ili tačne vrednosti CRM, $\overline{GTV}$ CRM** - srednja vrednost rezultata merenja.*

Za određivanje merne nesigurnosti rezultata korišćeni su:

a) Nordtest pristup i

b) Eurachem pristup.

a) Nordtest pristup

Nordtest pristup predstavlja praktičan pristup u proceni merne nesigurnosti metode i laboratorije. Cilj ovog pristupa je da prikaže najvažnije parametre koji doprinose mernoj nesigurnosti, a to su:

- reproduktivnost (nepreciznost – slučajna greška),
- bias (odstupanje – sistematska greška).

U okviru Nordtest koncepta postoje dve mogućnosti izračunavanja merne nesigurnosti:

- Metod I,
- Metod II.

U okviru metode I, kombinovana nesigurnost, $u_c(\%)$, predstavlja kvadratni koren zbira kvadrata doprinosa nesigurnosti od reproduktivnosti, *U(Rw)*, i bias-a, *U(Bias)*, formula (1). Dvostruka vrednost $u_c(\%)$ predstavlja proširenu mernu nesigurnost, *U(%)*, sa nivoom poverenja od 95%, formula (2).

$$u_c(\%) = \sqrt{(U(Rw))^2 + (U(Bias))^2} \quad (1)$$

$$U(\%) = 2 \times u_c(\%) \quad (2)$$

Doprinos nesigurnosti od reproduktivnosti, *U(Rw)*, određuje se procenom unutar laboratrijske reproduktivnosti, *Rw*, prema formuli (3), gde $\overline{X}$ predstavlja srednju vrednost merenja, dok je S_{RW} unutar serijska standardna reproduktivnost izračunata kao $S_{RW} = \overline{R}/1.128$ ($\overline{R}$ je srednja vrednost opsega).

$$Rw = \frac{S_{RW}}{\overline{X}} \times 100 \quad (3)$$

Doprinos nesigurnosti od biasa, *U(Bias) (%)*, izračunava se prema formuli (4).

$$U(Bias)(\%) = \sqrt{(Bias)^2 + (\frac{S_{Bias}}{\sqrt{n}})^2 + u(Cref)^2} \quad (4)$$

U formuli (4), *(Bias)* iz CRM, izračunava se prema formuli (5), dok se komponenta nesigurnost sertifikovane nominalne vrednosti, *u(Cref)*, izračunava prema formuli (6). U formuli (4) S_{Bias} predstavlja višestruko testiranje CRM, a *n* je broj merenja CRM.

$$(Bias) = \frac{\overline{X} - T}{T} \times 100 \quad (5)$$

$$u(Cref) = \\ = (100 \times \frac{Int.poverenja(40)}{1.96}) / CRM(26461) \quad (6)$$

Tabela 2. *Statistička obrada podataka GTV CRM benzoeve kiseline BK(1) Ref.: 33045 za procenu merne nesigurnosti po metodi I i II Nordtest koncepta i BK(2) Ref.: C723 za kalibraciju kalorimetra određivanjem vodene vrednosti.*

CRM BK (1)					CRM BK (2)
X_1 (J/g)	X_2 (J/g)	$\overline{X}$ (J/g)	$R = \lvert X_1 - X_2 \rvert$ (J/g)	$r = \lvert X_1 - X_2 \rvert / \overline{X} \times 100$ %	Kalibracija kalorimetra određivanjem vodene vrednosti
26716	26753	26735	37	0,138	10758
26601	26575	26588	26	0,098	10745
26645	26698	26671	53	0,199	10755
26609	26658	26633	48	0,182	10741
26417	26491	26454	74	0,280	10732
		$\overline{X}$ =26616	$\overline{R}$ =47,7	$\overline{r}$ =0,179	$\overline{X}$ =10746; s=10,57; $S_{95\%}$=13,14 RelativnaSD=0,1222869%

U tabeli 2 su dati rezultati toplote sagorevanja BK(1), koji su korišćeni za određivanje merne nesigurnosti kalorimetra, C5000. Korišćenjem formula od (1) do (4) dobijeni su rezultati kombinovane nesigurnosti prema formuli (1), i proširene merne nesigurnosti sa nivoom poverenja od 95%, prema formuli (2).

Tabela 3. *Statistička obrada rezultata parametara tehničke analize laboratoriskog RM na (a) analitičkom uzorku uglja ASŠM i (b) na suvom uzorku ASŠM.*

(a) **Sa analitičkom vlagom**

Datum	Br. merenja	% vlaga	% Pepeo	% Sagor. Materije	% Ispar. Materije	%Koks. Ostatak	% C-fiks	S (%)	GTM (J/g)
1. mesec	**1**	0,69	12,45	86,86	6,06	93,25	80,80	0,900	29430
	2	0,67	12,01	87,32	6,34	92,99	80,98	1,412	29564
	3	0,67	12,01	87,32	6,34	92,99	80,98	1,004	29802
2. mesec	**4**	1,14	11,86	87,00	5,64	93,22	81,36	0,976	29764
	5	1,16	12,76	86,08	5,75	93,09	80,33	1,089	29415
3. mesec	**6**	1,42	11,70	86,88	6,42	92,16	80,46	0,944	29656
	7	1,43	12,59	85,98	6,63	91,94	79,35	-	29685
Statistička obrada podataka	$\overline{X}$	**1.026**	**12,20**	**86,78**	**6,17**	**92,81**	**80,61**	1,054	**29617**
	$S_{68\%}$	0,345	0,401	0,544	0,365	0,53	0,653	0,186	153
	$S_{95\%}$	**0,327**	**0,371**	**0,503**	**0,338**	**0,49**	**0,604**	0,195	**142**
	rel.stdev.%		3,04	0,58	5,48	0,53	0,75		0,48

(b) **Suv - bez vlage**

Datum	Br. merenja	% vlaga	% Pepeo	% Sagor. materije	% Ispar. materije	%Koks. ostatak	% C-fiks	S (%)	GTM (J/g)
1. mesec	**1**	-	12,54	87,46	6,10	93,90	81,36	0,91	20634
	2	-	12,09	87,91	6,38	93,62	81,53	1,42	29763
	3	-	12,09	87,91	6,38	93,62	81,53	1,01	30003
2. mesec	**4**	-	12,00	88,00	5,71	94,29	82,3	0,99	30107
	5	-	12,91	87,09	5,82	94,18	81,27	1,10	29760
3. mesec	**6**	-	11,87	88,13	6,51	93,49	81,62	0,96	30083
	7	-	12,77	87,23	6,73	93,27	80,50	-	30116
Statistička obrada podataka	$\overline{X}$	-	**12,32**	**87,68**	**6,23**	**93,77**	**81,44**	1,065	**29924**
	$S_{68\%}$	-	0,410	0,410	0,372	0,372	0,533	0,18	199
	$S_{95\%}$	-	**0,379**	**0,379**	**0,344**	**0,344**	**0,493**	**0,97**	**184**
	rel.stdev.%		3,08	0,43	5,52	0,37	0,605		0,61

U tabeli 3(a) su dati eksperimentalni rezultati merenja fizičko-hemijskih karakteristika uglja (vlaga, pepeo, isparljive materije, ukupan sumpor, vodonik i gornja i donja toplotna vrednost) korišćenjem analitičkog uzorka laboratorijskog potencijalnog referentnog materijala ASŠM, kao i rezultati dobijeni računskim putem (sagorljive materije, koksni ostatak i c-fiks). Rezultati u tabeli 3(b) su računski dobijeni na suvo gorivo preračunavanjem rezultata tabele 3(a), koristeći formulu (7).

$$S = \frac{\%\, analit.uzorka}{100 - vlaga} \times 100 \qquad (7)$$

Potencijalni laboratorijski RM, ASŠM meren je 3 puta u duplikatu ili triplikatu u periodu od 3 meseca. U tabeli 3 je, pored dobijenih rezultata, data i statistička obrada rezultata, tako da je za svaku veličinu, bilo dobijenu eksperimentalno ili računski, izračunata merna nesigurnost koristeći metode II Nordtest koncepta. Prema metodi II, merna nesigurnost se direkno određuje korišćenjem standardne devijacije reproduktivnosti prema formuli (8), dok se proširena nesigurnost određuje na isti način kao i u metodi I Nordtesa, formula (2).

$$u_c(\%) = S_R \qquad (8)$$

b) Eurachem pristup

Eurachem pristup ili full scale model predstavlja princip koji uključuje sve ono što utiče na mernu nesigurnost rezultata i kao takav daje tačniji opseg procenjenog rezultata od Nordtesta. Parametri koji doprinose kompletnoj procenjenoj mernoj nesigurnosti rezultata tehničke analize ugljeva su:

1) Uzorkovanje ugljeva i rukovanje uzorcima,
2) Oprema (vaga, kalorimetar, normalni sudovi, standardni rastvori, pipete),
3) Ljudski faktor i sredina (smeštaj i uslovi okoline).

Obzirom da se u tehničkoj analizi ugljeva radi sa več pripremljenim analitičkim uzorkom, u okviru Eurachem principa biće obuhvaćeni parametri koji najviše doprinose mernoj nesigurnosti. Ovi parametri su izraženi u obliku bias-a i reproduktivnosti korišćene laboratorijske opreme, a koji su direktno povezani sa ljudskim faktorom.

Reproduktivnost rezultata u Eurachem konceptu, *Rw*, određuje se isto kao i u Nordtestu, korišćenjem formula (3), dok je formula (6) izmenjena i proširena za doprinos mernoj nesigurnosti ljudskog faktora koja se ogleda u rukovanju sa laboratorijskom opremom, laboratorijskim posuđem i hemikalijama, a koja uključuje upotrebu vage - *u(m)*, čistoću reagensa - *u(n)*, normalnog suda - *u(v)*, pipete - *u(p)* i kalibracije kalorimetra - *u(k)*. Za kalibraciju kalorimetra C5000 korišćen je CRM BK(2), a standardna devijacija je data na osnovu rezultata određivanja vodene vrednosti kalorimetra čiji su rezultati dati u tabeli 2. Rezultat proširene vrednosti *u(Cref)*, dat je u tabeli 4 kao kvadratni koren zbira kvadrata svih doprinosa mernoj nesigurnosti.

Tabela 4. *Proširena vrednost komponente nesigurnosti setifikovane nominalne vrednosti u(Cref) za doprinos mernoj nesigurnosti vage u(m), čistoće reagensa u(n), normalnih sudova u(v), pipeta u(p) i CRM BK(2) Ref.: C723 u(k) kojim je kalorimetar kalibrisan*

***Proširena vrednost u(Cref)*= 0,12335%**				
u(m)	*u(n)*	*u(v)*	*u(p)*	*u(k)*
0,016140%	0,000289%	0,000585%	0,000949%	0,122287%

U tabeli 5 je dat pregled dobijenih rezultata merne nesigurnosti toplota sagorevanja CRM BK(1) i potencijalnog laboratorijskog RM, ASŠM. Rezultati merne nesigurnosti toplota sagorevanja CRM BK(1) su, radi upoređivanja, obrađeni metodama I i II Nordtest koncepta.

Tabela 5. *Pregled rezultata kombinovane nesigurnosti uc(%) i njene proširene vrednosti U(%) za metode I i II Nordtest koncepta i metode Eurachem.*

	Nordtest				**Eurachem**	
	Metoda I		**Metoda II**		**Metoda**	
	u_c**(%)**	***U(%)***	u_c **(%)**	***U(%)***	u_c **(%)**	***U(%)***
1BK	0,61	1,23	0,23	0,46	0,62	1,24
ASŠM	-	-	0,24	0,48	-	-

Na osnovu rezultata Nordtest koncepta, tabela 5, zapaža se da merna nesigurnost CRM BK(1) po metodi I daje veću vrednost od metode II. Ove vrednosti su očekivane, obzirom da metoda I daje preciznije rezultate merne nesigurnosti od metode II čija je merna nesigurnost direktno izračunata iz standardne devijacije korišćenjem iste vrednosti toplote sagorevanja benzoeve kiseline, tabela 1. Merna nesigurnost laboratorijskog RM ASŠM je određena metodom II. Rezultati pokazuju da je merna nesigur-nost ASŠM istog reda veličina kao i CRM BK(1), pa ga je zato moguće koristiti kao laboratorijski RM. Procena merne nesigurnosti prema Eura-chem-u je nešto viša od Metode I Nord-testa, obzirom da je sam princip metode zahtevniji, pa samim tim i kompletniji i tačniji.

Tabela 6. *Poređenje rezultata sertifikovanih vrednosti fiziko-hemiskih karakteristika CRM, uglja GBW 11107k, sa rezultaima dobijenim korišćenjem laboratorijske opreme za tehničku analizu uglja.*

	CRM GBW	
	Sertifikovane vrednosti	**Eksperimentalne vrednosti**
GTV ($MJkg^{-1}$)	27,54±0,19	27,54±0,15
(%) Pepeo	14,89±0,08	15,15±0,23
(%) Ispar.mat.	32,41±0,39	32,12±0,76
(%) S ukupni	0,96±0,02	0,94±0,11
(%) H	4,21±0,13	4,30±0,23
(%) C	68,47±0,30	68,32±0,72
(%) N	1,21±0.03	1,24±0,02

U tabeli 6 je dat pregled sertifikovanih vrednosti CRM GBW u jedinicama koje su date u sertifikatu. Eksperimentalni rezultati su dati u istim jedinicama, čime se obezbeđuje sledljivost rezultata. Upoređi-vanjem eksperimentalnih podataka sa sertifikovanim vrednostima, tabela 6, kao i rezultata tabele 1, može se zaključiti da su, kako dobijene eksperimentalne vrednosti tako i njihove procenjene merne nesigurnosti istog reda veličine kao i serifikovane. Dobijeni rezultati potvrđuju kvalitet rada laboratorije za tehničku analizu ugljeva prema standardu ISO 17025.

ZAKLJUČAK

Procena merne nesigurnosti laboratorije za tehničku analizu ugljeva na osnovu zahteva međunarodnog standarda ISO/IEC 17025:2006, uspešno je određena pomoću sertifikovanih referentnih materijala: BK (1) Ref.: 33045, toplote sagorevanja (26461±40) Jg^{-1}, BK (2) Ref.: C723, toplote sagorevanja (26456±8) Jg^{-1} i uglja CRM označenog GBW, toplote sagorevanja (27.54±0.19) $MJkg^{-1}$. Merne nesigurnosti rezultata referentnih materijala, poslužile su za odre-đivanje merne nesigurnosti laboratorijske opreme koja je korišćena za tehničku analizu ugljeva. Određen laboratorijski RM je takođe korišćen za određivanje merne nesigurnosti laboratorijske opreme i pokazao se kao sredstvo koje laboratorija može sa pouzdanošću da koristi u proceni merne nesigurnosti, bilo kao trenutna zamena CRM, ili kao radni materijal laboratorije. Na ovaj način su prikazane korisne informaciji o mogućnostima različitih metoda određivanja merne nesigurnosti kao i različitih materijala primenjenih u laboratoriji za tehničku anali-zu ugljeva. Rezultati su pokazali da se, kako sertifikovani referentni materijali, tako i izabrani laboratorijski RM, može uspešno primeniti za procenu merne nesigurnosti tehničke analize ugljeva, a što je znatno jeftinije za laboratorijski rad, a u saglasnosti je sa standardnom normom ISO 17025.

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